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Chapter

Laboratory, Bench, and Full-Scale Researches of Strength, Reliability, and Safety of High-Power Hydro Turbines

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Abstract

Large hydropower plants (HPPs) are categorized as critically and strategically important infrastructure facilities in industrialized countries. Therefore, the issues of ensuring HPPs safety are of paramount importance. In this chapter, the basic aspects of the safety analysis of HPPs, calculation and experimental substantiation of the strength, and resource and reliability of the main equipment are discussed. The scientific and technical measures to ensure safety of HPPs are presented. As a defining measure of safety, it is proposed to ensure the protection of HPPs from severe accidents and disasters according to risk criteria. The main provisions of the risk assessment are presented on the basis of a sequential analysis of loads, features of stress-strain states, characteristics of mechanical properties, and limit states of hydraulic equipment of HPPs. The issues of calculation and experimental evaluation of hydro turbine's resource, which limit the safety of HPPs, are considered. The features of technical diagnosis of hydraulic turbines are considered; characteristic defects and damages are described. The main provisions of the estimated residual life of hydro turbines are presented. The results of the risk estimates of HPPs and hydro turbine resource are given.

Keywords: hydropower plants, hydro turbines, safety, risk, protection, strength, resource, experimental studies, technical diagnostics, operational state

1. Introduction

Hydropower plants are among the most important elements of the life support infrastructure of many countries. Currently, there are over 100 hydropower plants with a capacity of over 100 MW with a total installed capacity of about 45 GW in Russia. This number includes 10 large hydropower plants with a capacity of more than 1000 MW and 5 largest hydropower plants with a capacity of over 3000 MW. The latter include the Sayano-Shushenskaya HPP with a capacity of 6400 MW, with a dam height of 245 m and a length of 1074 m; Krasnoyarskaya HPP with a capacity of 6000 MW, with a dam height of 128 m and a length of 1072 m; Ust-Ilimskaya

HPP with a capacity of 3840 MW, with a dam height of 105 m and a length of 1475 m; Bratskaya HPP with a capacity of 4500 MW, with a dam height of 124 m and a length of 924 m; and Boguchanskaya HPP with a capacity of 3000 MW, with a dam height of 96 m and a length of 2690 m (**Figure 1**). In the world, there are 7 large hydropower plants with capacity from 5000 to 14,000 MW.

In the presence of extensive national and international experience in the design, construction, and operation of large hydropower plants, accidents of various scales occur on them, including great economic losses and human losses. The largest in the history of hydropower is the Sayano-Shushenskaya HPP disaster, accompanied by the destruction and flooding of the machine room, damage to hydraulic units, and the death of people (**Figure 2**). In this regard, the development of measures and means to ensure the safety of hydropower facilities is of paramount importance.

(a) (b) (c) (d)
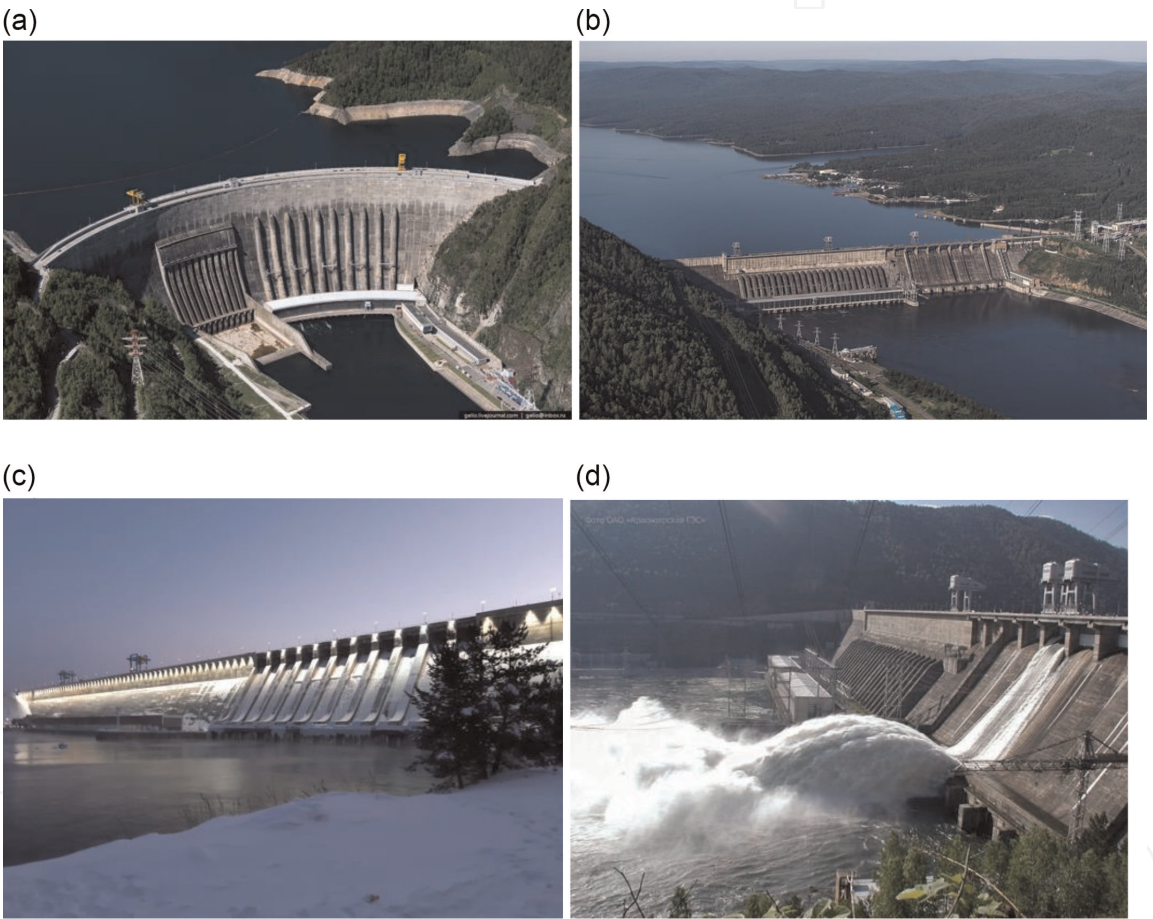
Figure 1.
Sayano-Shushenskaya (a), Krasnoyarskaya (b), Ust-Ilimkaya (c), and Bratskaya (d) hydropower plants.

Figure 2.
Disaster of Sayano-Shushenskaya HPP.

For many years, the safety of technical systems was based on the assumption that a technical object is sufficiently reliable and safe if it meets the requirements of the current regulatory documents. However, the operating experience of such objects showed that compliance with the design, manufacturing, and operating regulations does not exclude the possibility of emergency situations, accidents, and disasters. From this it follows that the security system for hydropower plants should be based not only on traditional approaches but also on new, scientifically based methods of computational-experimental analysis within the concepts of "security—protection—risk—safety—survivability—reliability—resource—strength." Such an analysis requires adjustment of the existing traditional methods of design, construction, and operation of hydropower plants, with the solution of problems of strength and service life of structures and equipment from the standpoint of ensuring the lowest possible risk of accidents. This chapter outlines the main provisions of such an approach for hydro turbines, which are the main equipment of hydropower plants. The scientific and technical tasks, considered here, reflect the experience of research and ensuring the strength, resource, and safety of the technical objects [1–3].

2. Concept of computational and experimental substantiation of hydropower plant safety

Taking into account the consequences of accidents and disasters, hydropower plants with a capacity of 1000–5000 MW can be attributed to critical infrastructure objects. Hydropower plants with a capacity of more than 5000 MW can be considered as strategical objects of infrastructure. For such objects, along with the provision of generally accepted standards and requirements of strength, resource, and reliability, the problems of protection from severe accidents and disasters with survivability and risk analysis should be considered [4]. General requirements for ensuring the protection of hydropower plants from severe accidents were formulated in [5]. For water power plants, along with abidance of generally accepted requirements of technical regulations and standards, protection against the most severe catastrophes (design, beyond design and hypothetical) and terrorist impacts must be considered. When solving safety problems, the following should be analyzed:

- Types of disasters

- Scenarios and sources of occurrence

- Critical elements, critical zones, and critical points of the most critical nodes

- Probability characteristics of disasters

- Consequences of the emergence and development of disasters

- Methods and systems of protection against disasters (rigid, functional, natural, combined)

- Measures to counter disasters and analyze and reduce the risks of disasters at water power plants for the region and the country

The results of the investigation into the causes of the Sayano-Shushenskaya HPP catastrophe [2, 4, 5] indicate the need for conducting special studies of the causal

complex of accidents at similar facilities to create scientifically based regulations of risk analysis, survivability, and safety criteria. These researches should include next computational and experimental works [5]:

1. Develop a fundamentally new methodology for assessing and improving the protection of hydropower plants, as critical facilities, from severe disasters according to risk criteria.

2. Conduct a computational modeling and experimental analysis of the new parameters of the resource, survivability, safety, and risks in the conditions of a severe disaster of hydroelectric power plants.

3. Develop a methodology for refined estimation of the dynamics, hydrodynamics, and aerodynamics of the occurrence and development of a severe catastrophe on typical hydraulic units.

4. Develop a methodology for constructing a special control system and automated protection of hydro turbines and hydroelectric power plants in the transition from standard to emergency and catastrophic situations.

In order to form a general regulatory framework for the protection of hydropower plants, it is necessary to implement the following measures with the preparation of the relevant regulatory documents:

1. Develop standards and carry out categorization of hydropower plants as critically and strategically important infrastructure facilities according to the risk levels of national, regional, and local disasters.

2. Develop a nomenclature of emergency and catastrophic situations at hydropower plants and levels of protection from them.

3. Build scenarios for the development of severe disasters; identify the damaging factors and the degree of vulnerability of hydropower stations in severe accidents.

4. Develop a methodology for assessing the strategic risks of severe disasters at hydropower plants, taking into account all stages of the life cycle.

5. Develop principles, methods, and systems for protecting hydropower plants from accidents and disasters.

6. Develop the diagnostic methods of hydropower plants and automated protection systems in the event of emergency and catastrophic situations.

7. Determine the role of human factors and responsibility at the stages of decision making, project implementation, and operation of hydropower plants to prevent severe disasters.

8. Perform the complex computational and experimental studies' survivability, safety, and protection of hydropower plants from severe disasters on models and objects.

9. Develop safety criteria for hydraulic engineering dams and methods for assessing actual safety factors.

10. Develop computational models of dams and computational technologies for analyzing the characteristics of their stress-strain state, taking into account the actual changes in the characteristics of concrete and the presence of cracks and damage.

11. Develop criteria for the performance of hydroelectric equipment based on the models of cavitation processes, fatigue, and corrosion damage.

12. Conduct model calculations of emergency situations and scenarios of their development for all existing hydropower plants of Russia.

13. Develop models and methods for assessing the social, environmental, and economic consequences of accidents of hydropower plants.

To ensure the protection of hydropower plants from severe accidents and disasters, their design, construction, and operation should fully address traditional tasks:

- Carrying out normative calculations for static and cyclic strength

- Conducting bench studies of hydrodynamic processes in the flow part of the hydroelectric station

- Control and repair work on the damaged items of equipment

In addition to this, it is necessary to conduct:

- Calculation and experimental analysis of hazardous mechanical and hydraulic processes in power systems of hydropower plants in regular and emergency situations

- Calculation and experimental analysis of the limiting states of critical elements for normal and extreme loads and impacts

To solve these problems, it is necessary to develop fundamental research in the following areas:

- Study of hazardous processes in the environment and technical systems of hydropower plants, taking into account the role of the human factor

- Development of methods and tools for mathematical (computational) modeling of mechanical, hydrodynamic, and electromagnetic processes that affect the conditions for the occurrence and development of severe accidents and disasters

- Development of new methods and means of prompt diagnosis of emergency situations

- Development of the theory and methods to ensure the protection of hydropower stations from severe accidents and disasters

The scientific and methodological basis for ensuring the protection of hydropower plants from severe accidents and disasters is a risk analysis. Risk assessments can be performed in the classical form:

$$R_{\Sigma}(t) = \sum_i R_i(t), \tag{1}$$

$$R_i(t) = P_i(t) \times U_i(t + \tau) \tag{2}$$

where $P_i(t)$ is the probability of reaching the ith limiting state leading to disaster with damage $U_i(t + \tau)$ and τ is discounting time.

The probability $P_i(t)$ is determined by the given criteria of the limiting state for the most critical zones of highly loaded elements of hydraulic equipment structures:

$$P_i(t) = F_p\{\sigma_c, e_c, d_c, l_c, t\} \tag{3}$$

The values of critical stresses σ_c, deformations e_c, damage d_c, and size of crack-like defects l_c depend on the complex of operating technological and operational loads:

$$Q(t) = F_Q\{Q_M(t), Q_H(t), Q_E(t), Q_V(t), Q_S(t)\} \tag{4}$$

where Q_M is mechanical loads from the weight and installation and welding of elements and from the rotation of the hydraulic turbine; Q_H is hydrodynamic loads from pressure and pressure of water, water hammer, and pressure pulsation; Q_E is electromagnetic load from the interaction of the rotor and the stator of the turbine; Q_V is vibration loads; and Q_S is seismic loads.

The components of stresses σ and deformations e, which characterize the stress-strain state of the structure, are determined by calculation and experimental methods according to the values of the indicated loads:

$$\{\sigma, e\} = F_\sigma\{Q(t), \alpha_\sigma, E, \mu, m, A, W\} \tag{5}$$

where E, μ, and m are modulus of elasticity, Poisson's ratio, and strain hardening coefficient, A and W are sectional areas and moments of resistance of the considered elements of hydro turbines, and α_σ is stress concentration factors.

Characteristics E, μ, and m of the mechanical properties of materials are determined by laboratory testing and full-scale sample testing. The stress concentration coefficient α_σ is determined experimentally or by calculation methods.

Based on Eq. (5), the characteristics of cyclic loading of hydro turbine elements are determined: stress amplitudes σ_a and deformations e_a, mean stresses σ_m and deformations e_m, and cycle asymmetry coefficients $r = \sigma_{min}/\sigma_{max}$. Next, determine the number of loading cycles to failure:

$$N_c = F_N\{\sigma_a, e_a, \sigma_m, e_m, r, S_c, \psi_c, \sigma_{-1}, m_N, m_\sigma, \omega\} \tag{6}$$

where S_c and ψ_c are tensile strength and ultimate plasticity of the material, σ_{-1} is material fatigue limit, m_N and m_σ are the characteristics of the sensitivity of materials to cyclic loading, and ω is the loading frequency.

The ratio of actual N_e to critical N_c loading cycles establishes damage level:

$$d(N, t) = \sum_i d_i(N, t), d_i(N, t)$$
$$= N_e^{(i)}/N_c^{(i)} \tag{7}$$

If there are crack-like defects in the structural elements, the resources $l(t)$ or $N(l)$ are determined at the crack growth stage from initial l_0 to critical l_c sizes:

$$l(t) = F_l\{Q(t), l_0, N_e, \Delta K\} \qquad (8)$$

$$N(l) = F_{Nl}\{Q(t), N_e, l_0, l_c, \Delta K\}. \qquad (9)$$

where ΔK is the magnitude of the stress intensity factor.

The estimation of probabilities $P_i(t)$ is carried out taking into account Eqs. (3)–(9) under the assumption that the form of the probability functions F_P, F_Q, F_σ, F_N, F_l, and F_{Nl} and their parameters is defined. Damage assessment $U_i(t + \tau)$ is performed by actual losses or calculated by economic methods for the considered scenarios of possible accidents of hydro turbines.

The calculated estimates of the probability of damages to equipment and structures of hydropower plants in accordance with the above principles gave the following accident probability values:

• Normal working conditions of hydropower plant (regulatory loads)

$$P_i = 2.2 \times 10^{-4} - 1.5 \times 10^{-3}$$

• Violation of normal operating conditions of hydropower plant (increased loads)

$$P_i = 6.0 \times 10^{-3} - 3.1 \times 10^{-2}$$

• Emergency situations (extreme loads)

$$P_i \geq 0.1$$

Qualitative estimates of potential damage for the enlarged scenarios of accidents of hydropower plants were given the following values (in rubles):

• Overflow over the dam 10^8–10^9

• The destruction of the dam (breakthrough of the pressure front) 10^9–10^{11}

• Destruction (flooding) of hydropower plant 10^9–10^{10}

Taking into account the indicated probabilities and damages, the following generalized risk assessments (in \$) of accidents for hydropower plants of the Angaro-Yenisei cascade of Russia were obtained:

• Risk of breaking the pressure front

$$R_\Sigma = 3.6 \times 10^5 - 2.5 \times 10^6$$

• Risk of destruction of hydropower plant

$$R_\Sigma = 1.0 \times 10^6 - 5.0 \times 10^6$$

• Risk of terrorist threat

$$R_\Sigma \leq 5.1 \times 10^4$$

The aggregated statistical estimates of major accidents of hydropower plants give probabilities $P_i = 3.3 \times 10^{-2}$–2.3×10^{-3}. Direct damages from such accidents reach 5×10^9 \$, and indirect damages are $(1.8$–$2.5) \times 10^{10}$ \$.

It should be emphasized that the approach outlined requires statistical information on all parameters, which is included in the calculations. Particular attention should be paid to characteristics of mechanical properties, parameters of stress-strain states, and structural damage. Such information can be obtained by conducting large volumes of tests and experimental studies. At the same time, the most preferable are methods and means allowing to evaluate the determining parameters (stresses, deformations, sizes of defects), taking into account the peculiarities of the micro- and macrostructure of structural materials.

3. Computational models and experimental evaluation operational state of hydro turbines

The main source of the most severe HPP accidents and disasters are damage and destruction of hydro turbines. Therefore, the problem assessing resource, diagnosing damage, optimizing the operating modes of hydro turbines, and timing of repair works takes a special place in ensuring HPP safety. Until recently, the hydro turbine resource received little attention, since it was assumed that the hydraulic turbines have sufficient strength for long-term safe operation. However, the statistics of failures of hydro turbines shows [6, 7] that large safety margins do not guarantee long-term safe operation of hydro turbines.

The hydro turbine resource must be justified taking into account the peculiarities of the loading modes and damage accumulation processes. With this in mind, the interest in assessment of the resource of hydro turbines is steadily growing. This is facilitated by the following circumstances [8]:

- An increase in the number of powerful hydro turbines that have fulfilled the standard operating time

- Operating modes of hydro turbines with a high level of power variation

- Constantly increasing design requirements for efficiency, maneuverability, and reliability of hydro turbines

- The use of new methods and means of technical diagnostics, indicating the presence of defects and damage not previously detected

- The emergence of new perspectives for studying the behavior and state of hydro turbines based on the achievements of experimental and computational technologies

The main factors that reduce the life of hydro turbines are fatigue, corrosion-fatigue and cavitation damage, degradation mechanical properties of materials, and redistribution of stress and strain fields in the most loaded local zones. Fatigue damages are caused by a complex loading spectrum of hydro turbines, containing components with different frequencies. Low-frequency loads (with a frequency below or equal to rotation frequency) are dangerous the high amplitudes that cause formation and development of cracks in the most loaded zones. High-frequency components have small amplitudes, but the number of cycles can reach 10^9–10^{10}, which ultimately also leads to the formation and development of cracks. A significant danger is represented by "start-stop" cycles, in which parasitic vortex structures, hydraulic shocks, and flow instability zones with nonoptimal flow around the blades arise. The most dangerous are the loads caused by water pressure pulsations

due to the interaction between the stator and the rotor at the blade frequency, as well as the loads caused by Karman vortices. Special attention should be paid to resonance phenomena, when the proximity of the natural frequencies of the elements of hydro turbines and the frequencies of external influences occurs.

The level of resource exhaustion is determined by the results of special calculations. These calculations consist in determining the time t or the number of loading cycles N as a function of amplitudes σ_a and average values σ_m of the loading cycle, defect sizes l, characteristics of the mechanical properties of materials (conditional yield strength $\sigma_{0.2}$, temporary fracture resistance σ_b, fatigue limit σ_{-1}, destructive deformations ε_f), and safety factors for stresses n_σ, for a number of cycles n_N and for size of defects n_l. The results of the calculations usually defined the fatigue diagrams of the main elements of hydro turbines, the residual resource, and the probability of failure at a given operating time.

The main elements of hydraulic turbines requiring the design justification of the resource are an impeller, a turbine shaft, a turbine cover with fastening elements, a shoulder blade of guide, and other elements. Calculation justification is carried out on the basis of data on operating modes, acting loads, defects, and damages detected during the diagnostics [9].

One of the main stages of resource assessment is the determination of external loads for equipment components and the corresponding internal stresses. Despite the great interest of this topic and the significant achievements of recent years, the problem of correctly describing the dynamic behavior of hydro turbine under partial power conditions and during transients has not been fully resolved. With this in mind, it is becoming a more common method of computational modeling [10]. These methods are based on mathematical models that include three main elements: geometric model, model of external loads, and model of boundary conditions. The accuracy of each model can have a decisive influence on the results of numerical experiments, including the issues of resource estimation [8].

The main problems of estimate resource for hydro turbines today are:

- The complexity of accounting technological and operational defects, stress concentration, residual stresses in welded joints, and heat-affected zones

- The poverty of database on the characteristics of materials for a reliable assessment of the resource

- The complexity of the damage summation mechanism in condition uncertainty of external loads and non-design modes of operation

- The difficulty of predicting crack growth under the conditions of actual spectra and loading conditions

The trends in the development of hydro turbine resource assessment methods at the present stage are characterized by the following circumstances:

1. Increasing interest for the problem resource assessment in connection with emergence of new technical capabilities

2. The desire to increase the reliability and accuracy of solving problems at all stages the assessment of hydro turbine resource

3. The need to take into account the non-project operation condition influence on the resource

4. Predicting the growth of cracks in the process of operating time for the purpose of determining the optimal time between repairs

5. An increase in the share of the numerical experiment due to partial replacement of the model and natural experiments

6. Resource management due to the choice of optimal operational parameters, taking into account the capabilities of the power system

7. Increased interest of resource estimates of hydraulic turbines in the absence of the recommended calculation methods and regulatory requirements for service life and criteria for the admissibility of operation

8. The lack of systematic studies of the residual life of hydro turbines, similar to how it was done for the turbines of thermal and nuclear power plants

Thus, the problem of calculation and experimental evaluation operational state of hydro turbines has a number of unsolved or difficult tasks that require in-depth basic research on the nature of the stress-strain state of hydraulic units, features of damage development mechanisms, and degradation of mechanical properties of materials.

4. Technical diagnostics of hydro turbines

The technical condition assessing of hydro turbines is crucial for the estimated assessment of residual life. Such works are performed in accordance with the provisions of the norms and standards [11, 12]. These works include a wide range of studies of actual state of hydraulic turbines by destructive and nondestructive control methods [13]:

- Analysis of design, maintenance, and repair documentation

- Nondestructive testing of structural elements and welded joints

- Experimental studies of metal and welded joints (measurement of hardness, determination of mechanical properties, conducting metallographic studies, and determination of chemical composition)

- Visual measurement control of geometry, surface defects, and shape defects with the determination of their sizes

- Nondestructive penetration control for substance detection of surface defects

- Nondestructive ultrasonic testing of structural elements and welds for detection of internal defects and cracks

- Ultrasonic thickness gauging of elements and determination of the internal stratification of the metal

In addition to the listed methods of nondestructive testing, stress-strain state studies using strain-gauge methods [14] and optical methods of electronic speckle interferometry [15] are performed.

This complex of methods and means is used in diagnosing the technical condition of hydro turbines with over standard operating life. Such work was carried out at the abovementioned hydropower stations in recent years. The main attention was focused on the most loaded structures: the impeller, the turbine shaft, the turbine cover, and the blade of guide.

The systematization and classification results of nondestructive testing showed that the main defects of the impeller blades of hydro turbines are:

- Cavitation erosion

- Corrosion fatigue cracks of the base metal and fatigue cracks of welded joints

- Corrosion damage
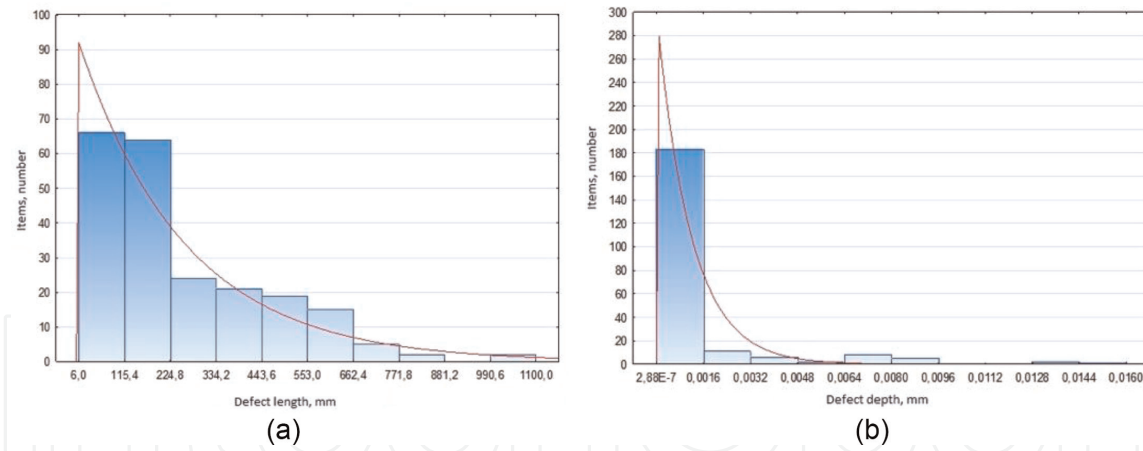
- Technological defects of welds
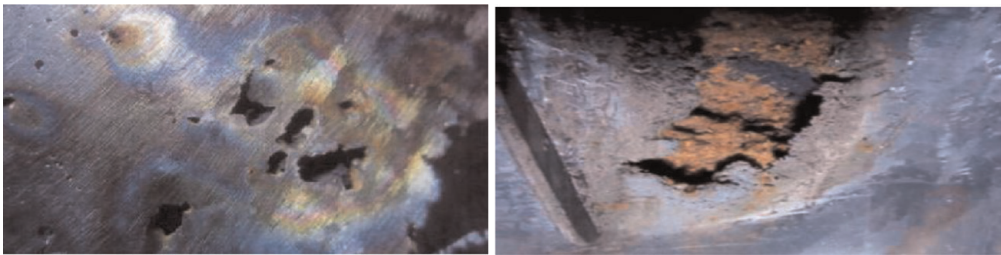
Figure 3.
Corrosion damage and cavitation damage metal of impeller blades.
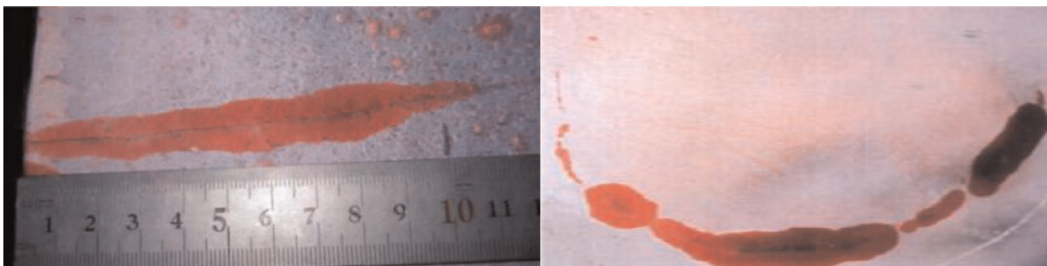
Figure 4.
Cracks in metal of impeller blades.
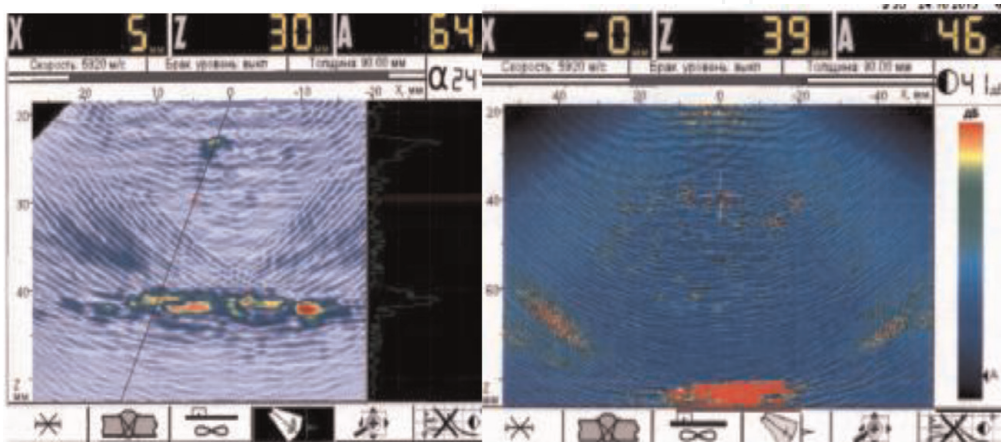
Figure 5.
Internal defects of impeller blades, detected by ultrasound tomography.

Figure 6.
Distribution corrosion damages of length (a) and depth (b).

The nature of the defects and damage is presented in **Figures 3–5**. Similar defects were detected and investigated previously in the impellers of the Sayano-Shushenskaya HPP and Krasnoyarskaya HPP [6, 7].

Statistical analysis of the nondestructive testing results for cavitation erosion zones allowed determining the main geometrical parameters for these defects: the length, width, and depth (**Figure 6**).

5. Estimated justification resource of hydro turbines

Standard operating life of hydraulic units is established by project documentation and for most units are 30–40 years. Currently, a significant part of hydraulic units of powerful hydroelectric power plants is carried out outside the standard operating time. This leads to a decrease in the overall level of reliability of the structure as a whole and its individual elements and to an increase in the probability of failures and financial costs for technical diagnostics and repairs. The exhaustion of the standard operating life of the elements of hydro turbines raises the question of the assessment of the residual resource as one of the priorities in the field of ensuring the safety of hydraulic structures [7–9]. At the same time, as noted in [8], there are no generally accepted methods for assessing the residual life and the regulatory framework that defines the procedure for extending the service life of the impellers and making decisions about their replacement.

Taking into account the specified circumstances, the authors formulated the basic provisions for the calculation of the residual life of hydraulic turbine elements. The calculation of the resource before the formation of cracks is carried out on the allowable stresses:

$$[\sigma] = \min\left\{\frac{R_{02}}{n_{02}}; \frac{R_{\mathrm{m}}}{n_m}\right\} \tag{10}$$

where R_{02} and R_m are regulatory design resistances of the metal and n_{02} and n_m are dimensionless safety margins.

The estimated allowable number of loading cycles of the elements of the turbine at the stage of the occurrence of cracks, for the "start-stop" mode and mode control with the transition through the "forbidden" zone of operation modes, is determined by the formula:

$$[N] = \frac{1}{4n_N} \left[\frac{Ee_c}{\sigma_a - \sigma_{r0}/(1 + \sigma_{r-1}r)} \right]^2,$$

$$\sigma_{r0} = \frac{\gamma\varepsilon\beta}{K_\sigma} \sigma_{-1} \sqrt{1 - \sigma_m/[\sigma]}$$

(11)

where σ_{-1} is fatigue limit of given loading mode; σ_m is stress average of cycle; σ_a is stress amplitude of cycle; r is the asymmetry coefficient of the loading cycle; γ, ε, and β are dimensionless coefficients that take into account the influence of the medium, scale factor, and surface quality; and K_σ is stress concentration factor.

The estimated allowable number of loading cycles at blade and blade frequencies is determined by the following formula:

$$[N] = \frac{N_0}{n_N} \left(\frac{\sigma_{r0}}{\sigma_a} \right)^m$$

(12)

where N_0 is the base number of loading cycles and m is dimensionless fatigue pattern indicator.

The influence of the multifrequency component of the loading mode from Karman vortices is taken into account through the reduced stress amplitude:

$$\sigma_a = \sum_{i=1}^{n} \sigma_{ai}(\omega_i/\omega_1)^\alpha$$

(13)

where σ_{ai} is stress amplitude at the frequency ω_i, ω_1 is the frequency of reduction, α is dimensionless coefficient taking into account the influence of the multifrequency nature of loading, and n_N is the safety factor by the number of loading cycles.

The total accumulated fatigue damage for the considered loading modes is defined as the sum of the ratios of the actual N_{ei} and the calculated loading cycles:

$$d = \sum_i \frac{N_{ei}}{[N]} \leq 1$$

(14)

The number of cycles N_l at the stage of crack growth is determined by the following formulas:

For single-frequency loading mode

$$N_l = \frac{1}{n_l} \frac{2}{(m-2)CY^{\frac{m}{2}}\sigma^m} \left[\frac{1}{l_0^{\frac{m-2}{2}}} - \frac{1}{l^{\frac{(m-2)}{2}}} \right]$$

(15)

For multifrequency loading mode

$$\frac{dl}{dN} = q \frac{\pi}{8} \left(\frac{K_{th}}{R_{0.2}} \right)^2 \left\{ 1 + (1-\beta) \frac{\left(1 - \widetilde{K}_{th}^2\right)^2 - \left(\widetilde{K}_{max}^2 - \widetilde{K}_{th}^2\right)^2 \omega\mu^2}{\left(\widetilde{K}_{max}^2 - \widetilde{K}_{th}^2\right)^2 \omega\mu^2} \right\}^{1/(\beta-1)}$$

(16)

where q, β, and μ are parameters of the cyclic crack growth diagram, $\widetilde{K}_{th} = K_{th}/K_C$ and $\widetilde{K}_{max} = K_{max}/K_C$ are relative threshold and maximum stress intensity factors, K_c is the crack resistance characteristic of steel, ω is relative frequency of loading, and K_{th} is the threshold stress intensity factor.
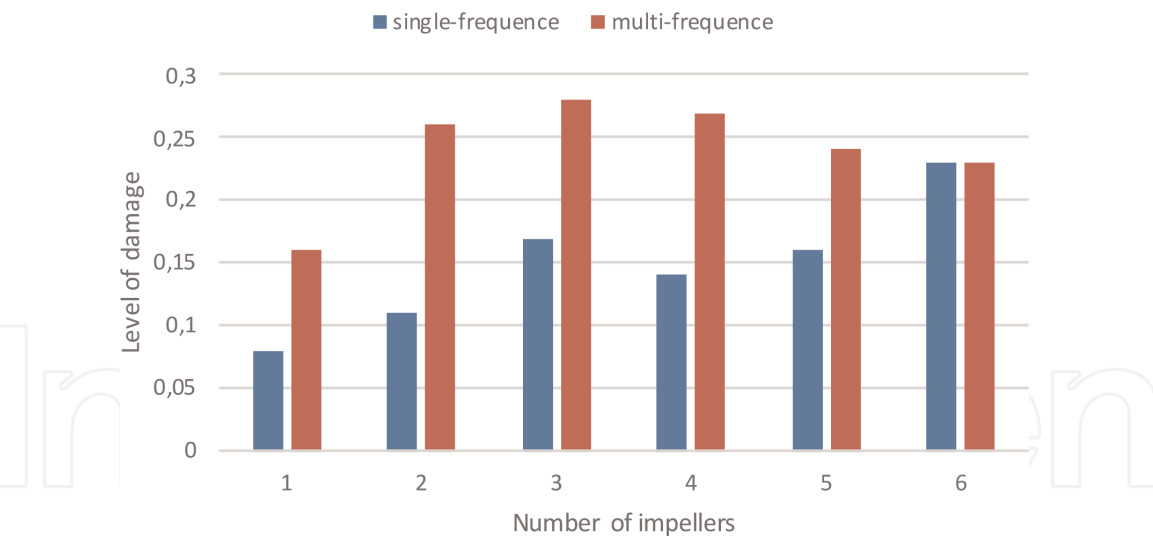
Figure 7.
Estimated cumulative damage for impeller blades.
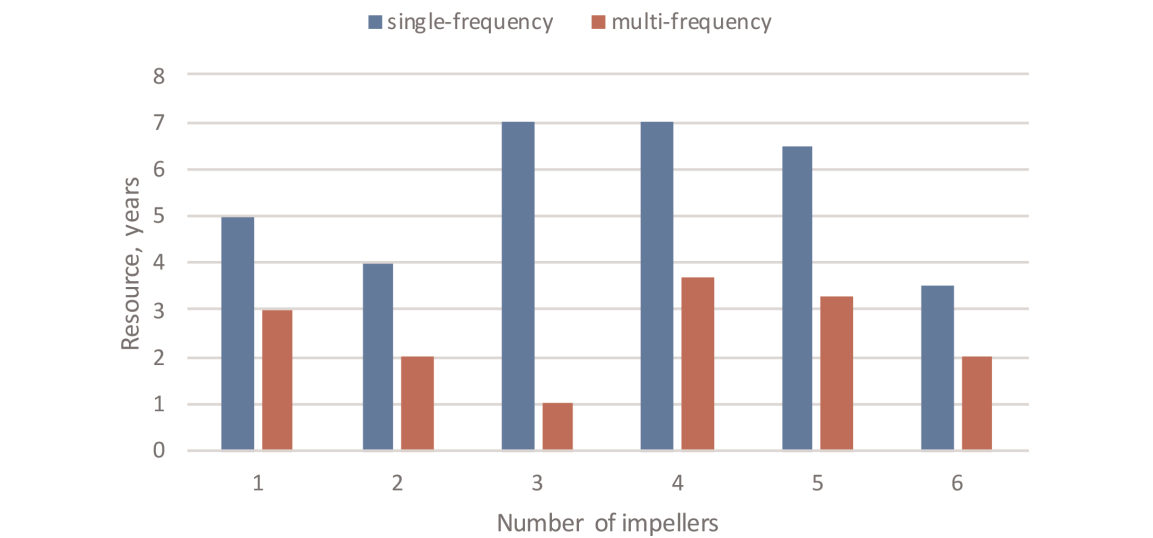
Figure 8.
Estimated residual life of impeller blades by the criterion of cracking.
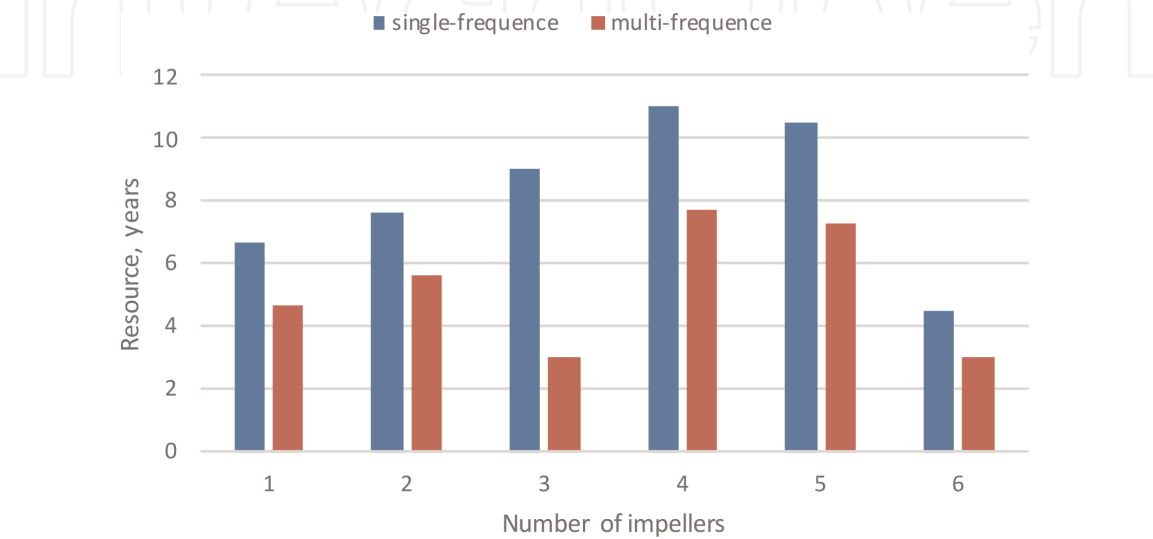
Figure 9.
Estimated residual life of impeller blades at the stage of crack development.

Figures 7–9 show the comparison of the results of the resource calculation according to the above procedure for the elements of hydro turbines of the Krasnoyarskaya HPP. The calculations were carried out on the basis of the results of a comprehensive diagnosis of the technical condition, with an assessment of the characteristics of the stress-strain state, the characteristics of the mechanical properties, and the defectiveness of the structural elements. The calculations took into account loading cycles: "start-stop," mode control, on blade frequencies, and at the frequencies of the Karman vortices.

As can be seen from the figures, the resource has a wide range of values. This is due to the different levels of metal damage detected during technical diagnostics and the initial dimensions of crack-like defects in structural elements.

The calculation results show that the hydraulic units surveyed using modern means of technical diagnostics and nondestructive testing have a resource reserve sufficient for planning and carrying out work to replace the impellers with more modern units.

It can also be assumed that an integrated approach to the problem of ensuring the reliability and safety of hydraulic units makes it possible to reliably predict the possibilities, terms, and conditions for their further operation.

6. Conclusion

Analysis of domestic and foreign studies and the practice of operating hydraulic equipment of large hydroelectric power plants indicate the need for the development of more advanced computational methods for estimating the life of hydro turbines that have completed their standard (design) service lives. When solving problems of resource assessment, special complex methods of technical diagnostics and modern computational and experimental technologies should be applied. These methods should be based on a combination of engineering design models that take into account the individual characteristics of hydraulic units based on routine monitoring and diagnostics and systems of reasonable safety factors (fatigue, crack length, stress, etc.) reflecting the uncertainty of the task with the required degree of accuracy design loads, material properties, and modes of operation.

It should be emphasized that the purpose, role, and place of technical diagnostics and assessment of the hydraulic equipment resource should be linked to the task of assessing the protection of hydropower stations from severe accidents and disasters according to risk criteria. In technical assignments for the design of hydroelectric power plants, new quantitative safety indicators should be introduced that implement the design-experimental complex "strength—resource—reliability—survivability—safety—risk—security".

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References

[1] Makhutov NA. Strength and Safety: Fundamental and Applied Research. Novosibirsk: Science; 2008. 528 p

[2] Makhutov NA, Gadenin MM, Moskvichev VV. Formation of the regulatory framework for the safety and security of hydropower plants of Siberia from severe disasters. Security and Emergency Issues. 2011;**4**:28-32

[3] Lepikhin A, Lepikhina I. Probabilistic models for risk assessment of disasters. Safety and Security Engineering IV. 2011:83-90

[4] Makhutov NA, Gadenin MM. Technical diagnostics and risk monitoring for HPS equipment. Destruction of hydro turbine No. 2 of Sayano-Shushenskaya HPP: Reasons and lessons. M: Format-D; 2013. pp. 26-35

[5] Makhutov NA. Proposals for creating a system to prevent and minimize the risk of accidents at all stages of life cycle. Destruction of hydro turbine No.2 of Sayano-Shushenskaya HPP: Reasons and lessons. M: Format-D; 2013. pp. 51-67

[6] Bryzgalov VI, Klyukach AA. The condition of the impellers of hydraulic units of the Sayano-Shushenskaya HPP and the main directions for maintaining their performance. Hydraulic Engineering. 2000;**1**:26-29

[7] Sivkov VG. Problems of cracking in the blades of impellers of hydraulic units of the Sayano-Shushenskaya HPP. Hydraulic Engineering. 2003;**11**:51-52

[8] Vasiliev Yu S, Petrenya Yu K, Georgievskaya EV. On hydro turbine resources: A review of foreign literature. Scientific and Technical Statements SPbPU. Engineering and Natural Sciences. 2017;**2**:184-204

[9] Gavrilov SN, Georgievskaya EV. Ways to improve the reliability of hydro-turbine equipment: An integrated approach to the assessment of residual life. Destruction of hydraulic unit No. 2 of Sayano-Shushenskaya HPP: Reasons and lessons. M: Format-D; 2013. pp. 200-205

[10] Cherny SG, Chirkov DV, Lapin VN, Skorospelov VA, Sharov SV. Numerical Simulation of Currents in Turbomachines. Novosibirsk: Science; 2006. p. 202

[11] STO 17330282.27.140.001-2006. Methods of assessing the technical condition of the main equipment of hydroelectric power plants. UES of Russia; 2006. p. 281

[12] GOST R 55260.3.2-2013. Hydroelectric power. Part 3-2. Water turbines. Techniques for assessing the technical condition. M.: Standartinform; 2015. p. 93

[13] Non-destructive control. Directory. In: 8 volumes. Klyuev VV, editors; M: Mashinostroenie; 2006. p. 840

[14] Aniskovich EV, Moskvichev VV, Makhutov NA, Razumovsky IA, et al. Assessment of residual stresses in the blades of impellers of hydraulic units. Hydraulic Engineering. 2018;**11**:178-184

[15] Makhutov NA, Gadenin MM, Odintsev IN, Razumovsky IA. Development of methods for the calculation and experimental determination of local residual stresses for complex loading spectra. Problems of Engineering and Machine Reliability. 2015;**6**:53-62