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ПРИМЕНЕНИЕ МЕХАНИКИ РАЗРУШЕНИЙ ДЛЯ ПРОГНОЗИРОВАНИЯ РЕСУРСА РАДИАЛЬНО-ОСЕВЫХ ГИДРОТУРБИН

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Резюме: *Для планирования своевременной реконструкции, модернизации, ремонтов или замены оборудования важно достоверно прогнозировать момент его перехода в предельное состояние, определяющее ресурс. В настоящее время не существует нормативных методов оценки ресурса гидротурбин на стадии эксплуатации. Представленный в докладе подход использует методы механики разрушений для построения долгосрочного индивидуального прогноза развития опасных дефектов в основных элементах гидротурбин с учетом конструктивных, технологических и эксплуатационных особенностей. Прогноз строится на базе трехмерных математических моделей, описывающих изменение технического состояния оборудования во времени в условиях фактической эксплуатации. Для расчетов используется программный комплекс Ansys. Модели учитывают размер и положение обнаруженных или возможных дефектов. Рост трещин определяется совокупностью низко- и высокочастотных нагрузок. Критическая длина трещины соответствует моменту изменения механизма развития трещин, когда резко возрастает риск разрушения. Использование предложенного подхода позволяет существенно снизить риск внепланового или аварийного останова гидроагрегата в межремонтный период вследствие его разрушения.*

Ключевые слова: *механика разрушения, гидротурбина, отказ, трещина, оценка ресурса.*

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THE APPLICATION OF FRACTURE MECHANICS TO PREDICT THE FRANCIS HYDRAULIC TURBINES LIFETIME

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Abstract: *To plan for timely reconstruction, modernization, repairs or replacement of equipment it is important to reliably predict the instant of its transition to the limiting state that* *determines the lifetime. Currently, there are no regulatory methods for assessing the lifetime of hydraulic turbines at the operation stage. The approach presented in this paper uses the fracture mechanics methods to build a long-term individual forecast of the dangerous development defects in the main elements of hydraulic turbines taking into account design, technological and operational features. The forecast is based on three-dimensional mathematical models that describe the change in the technical condition of the equipment during time under actual operation. The ANSYS software is used for calculations. Models take into account the size and position of detected or possible defects. Crack growth is determined by the combination of low- and high-frequency loads. The critical length of the crack corresponds to the instant of change of the crack development mechanism, when the failure risk increases sharply. Proposed approach can significantly reduce the possibility of unplanned or emergency shutdown of the hydraulic unit due to its destruction during the overhaul period.*

Keywords: *fracture mechanics; hydraulic turbine; failure; crack; lifetime assessment*.

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Introduction

For many years in hydropower dams, especially high dams, have been considered as a main potential source of danger. Little attention was paid to ensuring the reliability and safety of hydraulic equipment. Stable trouble-free operation of the equipment for dozens of years has also contributed to this. Many hydraulic units were put into operation more than 40-50 years ago, and some crossed the 100th anniversary.

At the time of their development computational methods of fluid dynamics, theory of elasticity and fracture mechanics for 3D-dimensional objects with difficult shape, characteristic for elements of hydraulic turbines, have not yet been used. In addition, the technology of manufacturing large parts did not allow minimizing their thickness. As a result, the main lifetime-determining elements of hydraulic turbines had multiple margins on static strength.

However, over time even this surplus margin has become insufficient to keep the equipment operational, as evidenced by the constantly growing list of accidents and incidents at HPP [1-7]. The accident at the Sayano-Shushenskaya HPP in 2009 showed that exhaustion of the lifetime by separate turbine elements can lead to a serious catastrophe that killed many people and caused huge economic damage (Fig. 1).

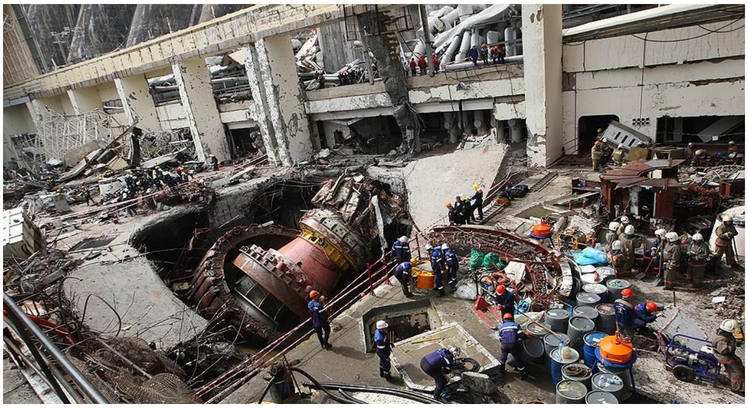
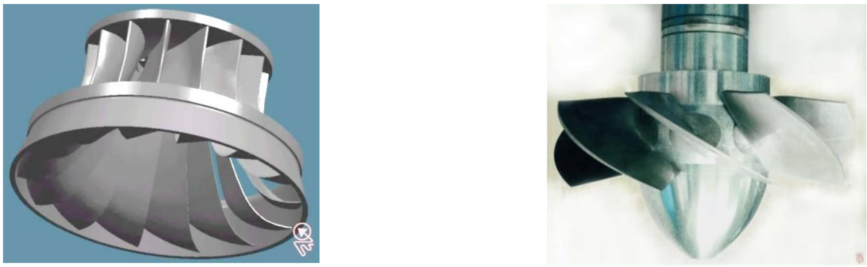


Fig. 1. View of the machine room after the accident

Features of hydraulic turbines operation

Also new renewable energy sources (solar, wind, wave, tidal) have been widely used over the past two decades. These sources are characterized by strong instability of the output power. Therefore, hydraulic units that differed by high maneuverability were forced to significantly change the operating modes. As a result, the number of starts and shutdowns of equipment and the time of its operation at non-optimal capacities increased significantly, large dynamic loads acted on the unit, causing high stresses in its elements.

This problem is especially relevant for Francis turbines. In contrast to Kaplan turbines, whose blades can be rotated to ensure optimal flow through the blades at different operating modes, the runner of the Francis turbine has a rigid connection of the blades to hub and rim (Fig. 2).



a) runner of Francis turbine b) runner of Kaplan turbine

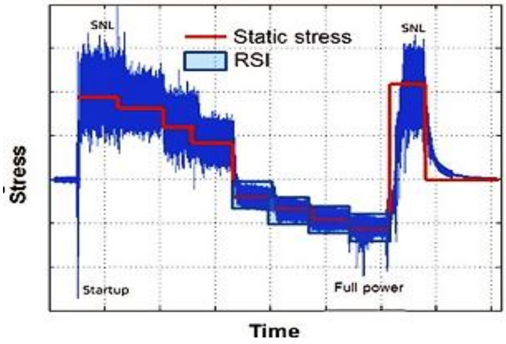
Fig. 2. View of the machine room after the accident

The characteristic pattern of relative dynamic stresses at various operation modes are presented on Fig. 3 for blades based on the results of Francis turbine testing [8].

At many stations this regime changes caused the accelerated growth of fatigue cracks in the unit elements and led to a untimely shutdown of the equipment for carrying out repairs. In Fig. 4 shows some examples of the most characteristic damages of Francis turbine runners - crack in the zone of welding blade to hub.

An important practical task is to predict the time of occurrence of such fatigue damage at actual operation conditions of hydraulic turbines and forecast the kinetics of their growth up to the critical level corresponding to the stage of destruction.

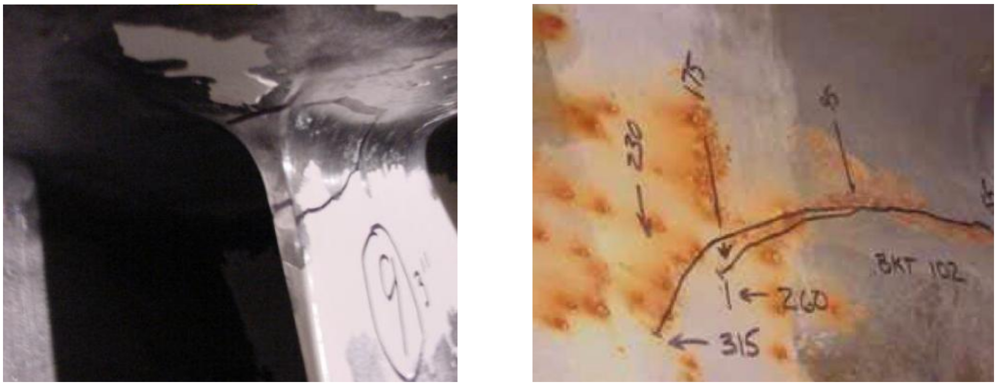
This can be done by calculation estimate of the lifetime, taking into account the features of the structures, the conditions of the actual loading and the material degradation under corrosive environment. Such forecast makes it possible to plan timely repair, reconstruction, modernization or replacement of hydraulic equipment, avoiding failures and accidents with serious consequences.



RSI – Rotor-stator interaction, SNL – speed-no-load

Fig. 3. Fragment of strain gauge recording [8]

a) Source [3] b) Source [4]



c) Source [5] d) Source [2]

Fig. 4. Examples of fatigue damage in Francis turbine runner

The technique of crack growth evaluation

To estimate the time of sustainable crack growth it is proposed to use approach based on the methods of linear fracture mechanics. Now this approach can be realized by modern calculation software products, for example, Ansys. The computational capabilities make it possible to predict the progress of a crack for difficult 3D-dimensional elements of hydro turbines almost without any limitations. The main obstacle is the reliable determination of the dynamic component of the load at various operating modes, especially on non-stationary and transient [9].

The crack growth rate $d\ell/dN$ is determined by kinetic diagram of fatigue failure (Fig. 5) depending on the magnitude of the stress intensity factor variation ΔK at the crack tip. The well-known Paris empirical equation [10] is the most widespread. It describes well the stage of stable crack growth for many structural materials:

$$\frac{dl}{dN} = C \cdot \Delta K^n, \tag{1}$$

$$\Delta K = \Delta\sigma \cdot f \cdot \sqrt{\pi \cdot l} \tag{2}$$

where N – number of cycles; C, n – experimentally defined material characteristics; $\Delta\sigma$ –dynamic stresses variation; f – form coefficient.

A more precise expression are given by different refined equations, for example, (2) – Yarema formula [11], which describes all three stages of crack growth (Fig. 5), but requires knowledge of more constants of the material:

$$\frac{dl}{dN} = C\left[\frac{K_{\max} - K_{th}}{K_C - K_{\max}}\right]^n , \tag{3}$$

where K_{max} – the maximum value of the stress intensity factor; K_C, K_{th} – material constants characterizing the viscosity and the threshold value.

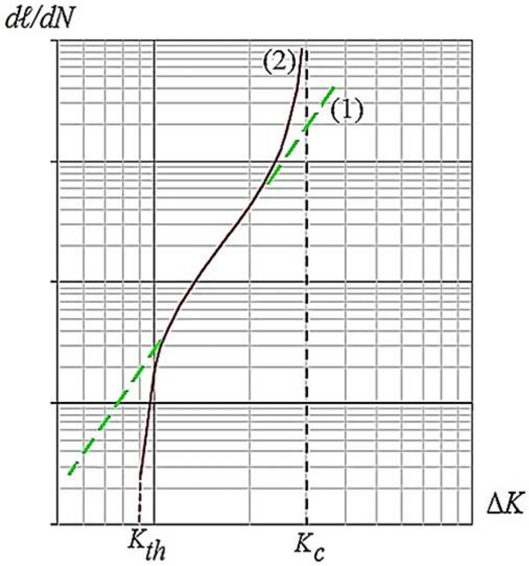


Fig. 5. Kinetic diagram of fatigue failure

Material characteristics *C*, *n* differ from each other in formulas (1) and (2).

Some methods of predicting and assessing the risk of defects are presented in the British standard BS 7910:2005 «Guide to methods for assessing the acceptability of flaws in metallic structures» [12].

Practical difficulty

In practice, the detection of cracks in the elements of hydraulic turbines is not such a simple task [13-15]. This is due to the following main factors:

- large dimensions of hydraulic units and their components;
- actual sensitivity of non-destructive testing methods (NDT);
- limited accessibility of control sites;
- rare scheduled repairs;
- location of possible defects;
- quality of checked surfaces and the possibility of their careful preparation for control.

Even modern non-destructive inspection methods usually do not allow detecting cracks in hydro turbines at an early stage, until their length has exceeded at least 3–5 mm long. In addition, it is possible subsurface defect grow, which can be detected only by ultrasonic inspection methods. As a result, it can be allowed to operate unit up to next repair with elements that are already damaged. The overhaul period is usually about 5–8 years. Therefore, in order to justify the timing of the next repair and diagnostic, it is necessary to perform a calculation prediction of such possible defects growth.

The forecast is based on mathematical models that describe the change in the distribution of the stress-strain state of a real structure in time under actual operation conditions. The model takes into account the size and position of the detected defects, and also models possible defects that do not exceed the sensitivity level of NDT. The size and location of such defects are chosen on the basis on many year's diagnostic experience and operating characteristics at particular HPP.

The criterion of cracks danger

Curve dependence the crack length ℓ from the operating time T is designed on completed calculation base. The critical crack length ℓ_c corresponds to the instant of time T_c, when a qualitative change in the fracture mechanism occurs.

Low-frequency loads with large amplitude that arise in transient and non-stationary operation modes (see the Fig. 3) are the motive force at the early stages of crack growth. Under their influence the initial defects, which are always present in the material, slowly grow up and reach a threshold value.

Further, the influence of high-frequency loads accompanying the unit's operation at all modes becomes decisive. Despite the small amplitude these loads lead to a rapid destruction of the structure due to a high frequency and high growth rate of defects exceeding the threshold value.

For example, the characteristic frequency of RSI-action (see the Fig. 3) caused by the interaction of the water flow with the fixed and rotating profiles is usually 40-80 Hz for large unit.

Justification of the overhaul period

Schematically, the forecasting process is shown in Fig. 6.

The value of ΔT is determined by the standard interval between repairs, $\ell_{NDT} = \ell(T_{NDT})$ – the minimum crack length that is assuredly detected by NDT, T^* and T^{**} – the instant of previous and current repair respectively. During previous repair the crack was not detected because its length $\ell^* = \ell(T^*)$ was less than ℓ_{NDT}.

The forecast of crack growth from the length ℓ^* to the critical size ℓ_c is constructed on the assumption that the crack expansion was began from the initial defect ℓ_0 and occurred for a long time under the action of actual loads. In our example, the crack will reach a critical value in time interval ΔT_c after the unit is taken out of the last repair.

It is important to note that interval ΔT_c is much less than the standard overhaul interval ΔT. The instant of real failure (the "failure" point) will be determined by the margin factors accepted during the calculation. Typically, the margin factors on the crack length is 2–2.5, and the material viscosity is 1.5.

Failure can occur before the planned output to repair with a high probability. As a result, there is a high risk of an emergency shutdown or equipment damage.

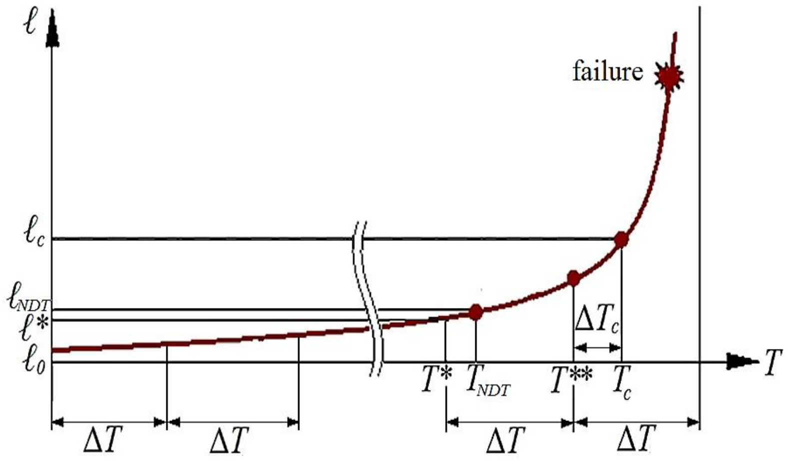


Fig. 6. Forecasting of repairs by technical condition

Conclusion

The proposed approach has a relatively low cost and small time for performing settlement work. At the same time, it allows building long-term forecasts of the hydraulic turbine lifetime and just in time planning repairs or replacement of equipment. This can significantly improve the reliability and safety of HPP operation.

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