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A Review of Research on the Design of Fish-Friendly Hydraulic Turbines

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Abstract: Fish suffer injuries and often die when passing through common hydraulic turbines. This occurrence is not only causes harm to fish, but also pollutes the water and raises objections with respect to the environmental viability of hydropower projects. This study aims to determine measures that enable the safe downstream passage of fish and ameliorate existing problems, and four types of injury mechanisms are investigated: mechanical, pressure, shear force, and cavitation injures. It is evident that the degree of injury that a fish suffers is related to its body type and size and the route through which it enters the hydraulic turbine system. The current designs of fish-friendly hydraulic turbines are presented, and their criteria and the associated philosophies are expounded.

Key words: fish-friendly hydraulic turbine; fish injury mechanism; hydrodynamic force; design optimization

1 Introduction

Hydropower is classified as a renewable energy source. In this respect, the *13th Five-Year Plan for the Development of Renewable Energy* (hereafter referred to as the *13th Five-Year Plan*) states that renewable energy is the main source of non-fossil energy in China and thus underpins any changes made to China's energy sources. During the period of the *13th Five-Year Plan*, the total installed capacity of renewable energy will reach an average annual growth of 4.25×10^7 kW, and total investment will reach 2500 billion yuan. In addition, clean low-carbon energy will represent the main proportional increase with respect to the entire energy supply during the period of the *13th Five-Year Plan* [1,2]. The report of the 19th National Congress of the Communist Party of China proposes to adhere to this new concept of development. In this respect, scientific development is the foundation and key to solving China's problems, and the developmental concepts of innovation, coordination, green, openness, sharing, and the harmonious coexistence of humanity and nature must be unswervingly adhered to. Protection of the ecological environment is currently a priority for both global governments and societies.

Green organizations in the United States have been demanding the demolition of the four dams of Bennevilee, Dalles, John Day, and McNary in the lower reaches of the Columbia River because of the ecological problems relating to salmon. Furthermore, the Edwards dam on the Beck River in Kenna, Maine, was demolished in 1999, which is now known as a landmark event. In 2015, construction of the Xiao Nanhai Power Station was halted by the Chinese Ministry of Ecology and the Environment, which reflects the huge ecological problems associated with the development of hydropower in China. It is thus necessary to coordinate the development of hydropower projects with strict environmental protection. Numerous studies have been conducted to determine ways to alleviate damming the migration of fish using fish ladders, fish lifts, fish locks, and other passageways

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upstream, and to enable fish to be safely released through the spillway or turbine, however, an effective solution has not yet been found.

2 Problems for fish downstream of dams and associated measures required

Fishing facilities constructed downstream influence the movement and existence of particular fish species, and some fish facilities are expensive, difficult to construct, and can affect the power generation capacity of the hydropower station [3]. Reports and studies have determined the following information on facilities involved in protecting fish within rivers that are dammed:

(1) A considerable amount of manpower and financial resources are employed when fish are transported by machinery, and fish can also be injured when being fished for transportation and during the moving process.

(2) The spillway is the common route used by fish downstream to cross the dam, and the survival rate of fish descending through the spillway is related to the velocity and water head. Therefore, this route is not ideal for ensuring fish safety.

(3) Small fish bypass the system. Constructing bypass waterways across dams is not considered ideal in conventional engineering practices. However, the use of barges and trucks to transport the fish would be expensive, require a considerable amount of manpower, and would cause the death of small fish during transportation.

(4) After using the open channel, small fish must be collected and mechanically transported or they will overflow into the spillway.

After the researchers' assessment of the survival rate of fish passing through the various fishing facilities, it was found that all fishing facilities have a certain degree of impact on fish. In fact, no matter what measures are provided downstream for fish to cross a dam, some inevitably enter the turbine in the water flow. It is thus important to modify the turbine to reduce fish damage and improve survival. Studies have shown that the survival rate of fish through well-designed turbines is higher than that through the spillway.

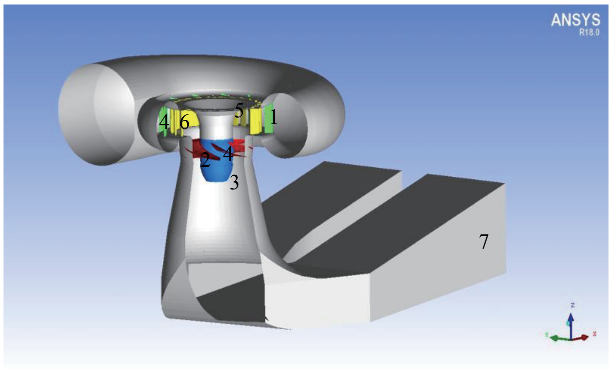
3 Study of mechanisms that damage fish when passing through turbines

The survival rate of fish passing through a turbine is mainly dependent on the path taken by the fish through the turbine system. Once the fish leaves the forebay and enters the turbine system, the amount of damage is closely related to the rapid changes occurring with respect to the geometry, physics, and flow characteristics of the channel. In 1995, the United States Army Corps of Engineers (USACE) established a group to conduct scientific research on the survival rate of fish passing through a turbine. Through analysis, the experts determined four main mechanisms that can damage fish: mechanical, pressure, shear stress, and cavitation [4–6]; these are presented individually in the following text. Fig. 1 shows the possible injury mechanisms associated with different parts of the turbine.

3.1 Mechanical factor

When fish pass through the flow passage of a turbine, they directly collide with the rotating blade and are injured via friction. The degree of frictional damage suffered depends on the flow rate and velocity, the number of blades, the spacing between the turbine blades, and the geometry of the channel. It is thus difficult to accurately determine and distinguish the amount of damage that is caused by friction. Nevertheless, it is evident that fish mortality increases with an increase in the circumferential speed of the runner. The amount of scratches on the body of a fish can be ascertained by examination, and local bruises, deep cuts, and even beheading injuries are clearly visible. However, scratches can also be caused by the fixed mechanical components, such as movable and fixed guide vanes, or by fish becoming stuck between the end of the blade and the outer shell. Therefore, it is not possible to accurately determine whether an injury is caused by friction or scratches, as scratches may also be associated with other injury mechanisms.

Fish can be injured by colliding with any of the parts within the hydraulic turbine system, and the chance of this occurring depends on several factors such as the size of the fish, the number and spacing of the turbine blades, the speed of the turbine, and the velocity and flow rate of the turbine. As early as 1957, Raben [7] proposed a blade impact model to predict the potential probability of a fish colliding with a turbine blade. However, direct visual observations have failed to observe the mortality associated with impact, and it is impossible to prove the probability prediction model. Nevertheless, this model has since been developed by subsequent researchers to different turbine machines. Plosky et al. [8,9] applied a definite and random blade



1–Pressure increase; 2–Pressure drop; 3–Cavitation; 4–Strike;
5– Scratch; 6–Shear stress; 7–Turbulence

Fig. 1. Mechanisms within turbine that can injure fish.

impact model to hydraulic turbines to compare the fish-passing performance of new type turbines and existing turbines; the results showed that the injury rate predicted by the deterministic model was higher than that found during experiments, whereas the prediction results of the stochastic model were similar to the experimental results. In addition, Esch et al. [10,11] applied the blade impact model to a pump and put carps into an axial-flow pump to study the damage rate of fish during a wide operational range. Their results showed that the measured mortality of carp coincided with the data obtained from the blade impact model. Furthermore, based on observations and a study of the use of a float as a prototype that was the size of a live fish with a physical model of a hydraulic turbine, Deng et al. [12] determined that the two kinds of impingement probability prediction models were equivalent. Nevertheless, the prediction of the stochastic model was closer to that of the experimental data than the prediction of the deterministic model, because the stochastic model considers the direction from which the fish approaches the leading edge of the turbine runner blade. Pan et al. [13] studied a blade impact mathematical model applied in an axial flow pump and predicted the passing performance of the fish, the blade impact probability, impact mortality, and fish mortality.

3.2 Pressure factor

To conserve energy, the pressure of water changes as it flows through the turbine channel. Fish are damaged when they move from the high pressure side to the low pressure side because of the sharp change in pressure. This degree of damage depends on the magnitude and gradient of the pressure difference and the type and size of the fish. The pressure changes that fish can withstand are related to the pressures they have adapted to before entering the turbine system. According to the USACE study, the range of pressure that fish are subjected to is between the absolute pressure of the low-head hydropower station (146 kPa) to the absolute pressure of the high-head hydropower station (605 kPa).

Some studies have suggested that fish are more sensitive to lower pressure than higher pressure, and that decompression damages the swim bladder and causes mortality. Fig. 2 shows the fish mortality rate measured in the laboratory as a result of a sharp decrease in the pressure drops. Xu et al. [14] studied the movement of grass carp and their injuries sustained in a jet pump. Their results showed that the stress caused by changes in pressure and velocity caused damage to gills and scales, and asymmetric diffusion within the channel caused fish to collide with the solid wall.

3.3 Shear stress and turbulence factors

As previously mentioned, to conserve energy, the water pressure changes as it flows through the turbine runner. As the fish move through the turbine, the shear stress is greater near solid boundaries, and the greater the shear stress and turbulence the greater the risk of fish injury. Maximum shear stress occurs near the interface between the fluid and the solid, such as the leading edge of the blade, the fixed guide vane, and the movable guide vane. The Voith team used computational fluid dynamics (CFD) analysis to verify the high shear stress in these regions and found that fish are harmed and sometimes killed when they enter the destructive shear stress zone of the turbine system. However, the degree of injury depends on the type and size of the fish and the route through which they enter the shear zone.

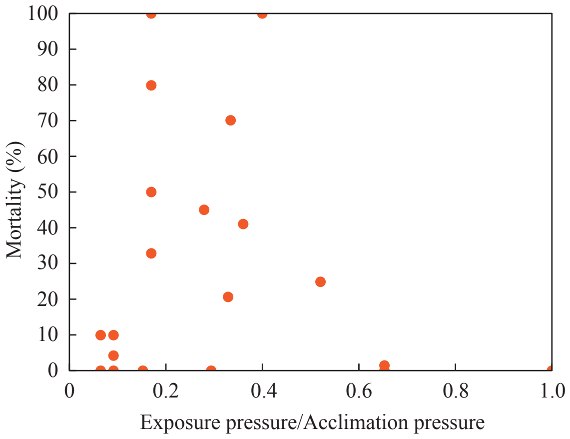


Fig. 2. Laboratory measurements of fish mortality due to sharp pressure drops.

There are gaps between the movable guide vane and the runner blade in most axial flow turbines. Leakage from these clearances and non-optimal turbine conditions lead to the separation of flow and a vortex in the high shear stress region. For example, the blade is maximally inclined in axial flow turbines, and the leading edge of the blade and the velocity vector are matched to reduce the vortex and shear stress region. In the Francis turbine, there is also shear stress in the vortex in the draft tube, which could be a major contributor to the shear stress that injures fish. Therefore, quantifying these high shear stress regions can assist in designing and operating hydraulic turbines, with the aim of reducing shear stress areas and thus enhancing fish viability.

Neitzel et al. [15] conducted experiments to obtain the safety limit for fish with respect to shear velocity and found that the limit value was affected by the species and orientation of the fish. The strain rate was used as the strength index to describe the hydrodynamic force of the fish in the shear environment; when the strain rate was equal to or less than 500 $\mathrm{cm \cdot s^{-1}}$, the fish did not suffer any obvious damage. In addition, Cada [16] studied shear damage to juvenile salmon using a numerical simulation and prototype experiment. Their results showed that the shear force regions in the runner of a hydraulic turbine that cause damage or death to fish are the regions near the fixed guide vane, the movable guide vane, the runner area, and the draft tube area.

3.4 Cavitation factor

High pressure shock waves are produced by cavitation bubbles when they collapse, causing damage to fish. Turnpenny et al. [17] used an underwater spark generator to generate cavitation bubbles. Their experiments found that as a group of continuous bubbles collapsed around the head and body of a fish, they caused no tissue damage. However, this does not negate the effect of cavitation bubbles in the turbine causing damage, and researchers believe that the device does not reach a high generated energy level when the turbine bubbles collapse. Shao et al. [18] used an artificial simulation method to simulate the damage caused to carp, grass carp, and crucian carp under different hydraulic turbine conditions; they found that the pressure gradient under negative pressure poses a threat to the survival of the fish by damaging the swim bladder and causing areas of bleeding in the liver and kidney.

4 Fish-friendly hydraulic turbine design concepts

4.1 Current concepts involved in fish-friendly turbine design

Researchers throughout the world are currently trying to design a fish-friendly turbine that is capable of efficiently generating electricity while ensuring the safe passage of fish downstream [19–22]. Studies conducted to design fish-friendly turbines have mainly focused on the following: (1) determining design and evaluation criteria, such as the target fish survival rate and target turbine efficiency value; (2) preliminary calculation of the shape and size of the turbine and conducting three-dimensional geometric modeling; (3) simulating the flow field of the hydraulic turbine using CFD technology, and optimizing the turbine according to calculation results to ensure that the above-mentioned damaging factors (such as mechanism, pressure, shear force, and cavitation erosion) meet the targeted survival rates for fish while meeting the efficiency target of the turbine.

4.2 Fish-friendly hydraulic turbine designs

Various fish-friendly hydraulic turbines have been designed, and these are listed individually in the following text.

4.2.1 Design of fish-friendly Kaplan turbine

The US Department of Energy launched the Advanced Hydraulic Turbine System research program (AHTS) in 1994. The purpose of this project is to propose a design scheme for a fish-friendly turbine that reduces the risk of damage to fish and improves the efficiency of turbine operation. In this plan, Voith proposed the design theory of a fish-friendly Kaplan turbine, in which the rotor turbine runs efficiently and there is no cavitation erosion, thus reducing the risk of fish injury and death. In the design, the gap near the center of the rotor, the blade, and the runner chamber is removed (including the gap between the guide blade, and the gap between the runner body, the blade, and the outlet ring) thus reducing the risk of injury. The design also improves the efficiency of the hydraulic turbine by removing the prominent part of the guide vane and reducing clearance by replacing the cylindrical outlet ring with a spherical outlet ring. Furthermore, the fixed guide vanes and movable guide vanes are properly arranged to eliminate the possibility of injury to fish caused by impact [23,24]. The movable guide vanes either use biodegradable lubricating grease or are grease free, therefore preventing harmful pollutants from entering the water, and all surfaces are polished to reduce the risk of fish being scratched.

4.2.2 Design of fish-friendly tubular turbine

At present, the fish-friendly tubular turbine design has mainly been optimized using the following methods: (1) enlarging the diameter of the runner and reducing the rotational speed of the runner accordingly; (2) reducing the number of runner blades, the volume of the runner body and the length of the blade, and adopting a thick blade leading edge; (3) reducing the protrusion of the guide blade; (4) increasing the distance between guide vanes and runner blades; (5) providing a reasonable arrangement of the movable guide vane and fixed guide vane to ensure a consistent position and direction; and (6) optimizing the pressure gradient and reducing pressure mutation.

4.2.3 Design of fish-friendly Francis turbine

The fish-friendly Francis turbine design mainly includes the following changes: (1) reducing the number of blades and enlarging the size of the runner passage; (2) adopting a thicker blade inlet edge to flatten the efficiency and head characteristic curve of the runner; (3) reducing the cantilever of the guide vane to eliminate the gap of the harmful eddy current, increase the gap between the guide vanes and runners, and align the distance between the guide vane and the fixed guide vane.

4.2.4 Design of other fish-friendly hydraulic turbines

The studies of Alden Research Laboratory (ARL) focused on designing a new type of turbine [25]. In the Alden turbine, a spiral blade and the blade of the leading edge rotating cover are used to eliminate the low-pressure eddy current resistance occurring near the blade edge. Fish can then pass directly through the area of clearance between the runner blade and the seat ring, as shown in Fig. 3. A CFD numerical simulation has shown that flow moves downstream near the blade and there is no separation of flow on the blade surface between the hub and runner edge, as shown in Fig. 4. The design objective of the Alden turbine is to eliminate key factors causing fish casualties. However, the model test results showed that although the high efficiency of the turbine can be guaranteed, a large number of swirls exist in the draft tube, which may cause fish to pass through the draft

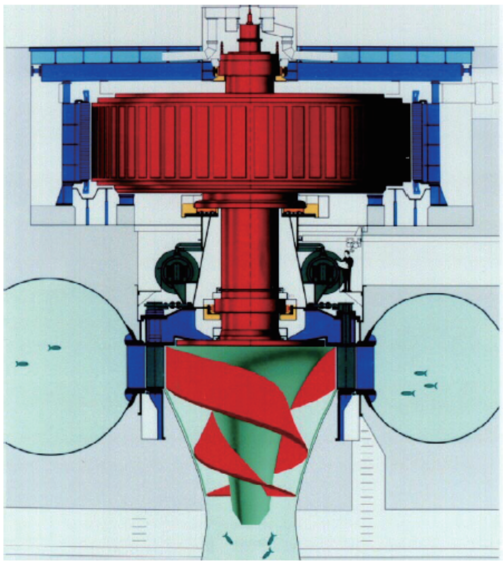


Fig. 3. Diagrammatic sketch of ARL/NREC fish-friendly turbine.

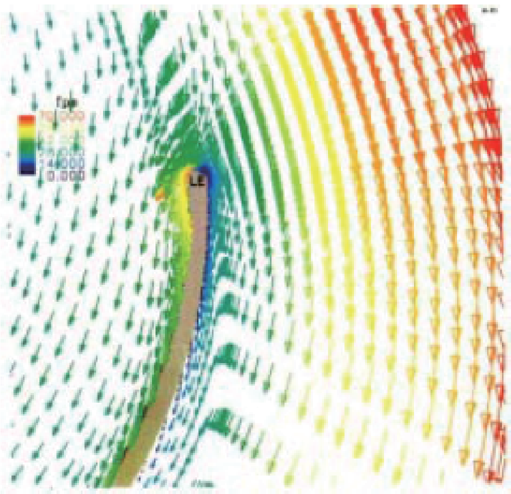


Fig. 4. Velocity distribution of ARL/NREC runner front edge.

tube, become dizzy, and then make them vulnerable to predation by other fish or birds downstream.

ALSTOM has developed a minimal gap runner (MGR) that has either no clearance or minimal clearance between the blade and hub, and the blade and runner compartment, but provides the structural clearance required [26]. The MGR design also reduces damage caused by clearance-related grinding, cavitation, shear stress, and turbulence. The ALSTOM designers have also proposed a method called the minimum gap guide vane (MGGV), which completely eliminates the guide vane extension structure. This innovative design incorporates the insertion of an object into a rotary surface bottom ring. An insert is present in each guide blade, and its shape ensures that there is no gap between the guide vane and the bottom ring under any guide blade opening. Application of the MGGV completely negates the need for the guide vane extension structure and greatly reduces shear force in the flow field and the turbulence that currently exists in the downstream region of the guide vane, thereby improving fish survival rates. In addition, ALSTOM has also developed a Vortex Turbine that uses a vortex shell to replace the fixed guide vanes and movable guide vanes, all of which cause frequent damage to fish in traditional turbines. The turbine causes water to flow into the runner at a suitable inlet angle and reduces damage caused to fish. However, this type of turbine is mainly for use in small hydropower stations, and although its straight tapered draft tube is favorable for enabling fish to pass, it increases scouring to the downstream riverbed and, thus, the excavation elevation of hydropower stations.

A team of engineers from the Public Utility District of Grant County and representatives from Voith have also conducted fish-friendly turbine research [3,27] that has been backed by the Wanapum Hydropower Station of the United States (10 turbine units), as shown in Fig. 5. Research proposals include changing the runner size and blade number, reducing the runner installation height to improve cavitation performance, extending the fixed guide vane to improve the flow pattern, aligning the movable guide vane and fixed guide vane, and modifying the draft tube. Through comprehensive design and research, the flow pattern of the turbine can be made more stable and the hydraulic performance can be improved.

5 Conclusions and prospects

This study has determined that the tolerance thresholds of precious migratory fish to damage factors, such as pressure and shear stress, in turbines of large hydropower stations in China are still unclear; therefore, further in-depth research focusing on their biological and behavioral characteristics is required.

However, the risk thresholds of fish injury under various special hydrodynamic conditions have been determined, and the corresponding biological criteria required to enable a fish-friendly turbine design are established.

It is necessary to design a reasonable experimental system to analyze the quantitative effects of pressure, flow, shear stress, cavitation characteristics, and mechanical collision that cause fish injury and death, and to observe the behavioral characteris-

Fig. 5. Fish-friendly turbine at Wanapum power station.

tics and responses of fish in different experimental environments. Most existing fish-friendly turbines are based on the axial-flow turbine, and it is considered that more research focused on the fish-friendly Francis turbine would be beneficial.

China is currently vigorously developing marine energy resources. Therefore, conducting future studies on the damage mechanisms caused to typical marine fish by marine power generation equipment under hydrodynamic conditions would be of considerable significance.

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