Sustainable hydro-power plants with focus on fish-friendly turbine design

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Abstract

The impact of hydro-power plants on the ecosystem was studied with focus on the fish mortality and types of damage for many years. The fish mortality have a wide range of causes. Types of damage can be different and are caused by different parts of the power plant. The most dangerous part of the system are the fast moving turbine blades. They can cause blade strike and barotrauma due to the high speeds. Different types of turbines were developed for a better survival rate. Five different types of different research groups and manufacturers are presented in this paper. By considering those newly developed turbine designs, a fish survival rate from 96 % to 100 % is achieved.

Keywords: fish-friendly turbine, fish injury, sustainable hydro-power, Alden turbine, Minimum Gap Runner

1 Introduction

Hydro-power stations are an important part of renewable energies. Moreover, they are built in an existing ecosystem and bring about changes. For a good interaction between efficient power station and low harm in the ecosystem they have to be well tested. Fish protection is one big topic for eco-friendly hydro-power stations. If possible, fish are led past the hydro-power plant via a bypass. However, some of the fish is passed through the power plant. To improve a fish-friendly turbine design, we have to understand the way of damage a turbine can cause, so that fish mortality is increased. Mortality can be caused by different parts of the turbine structure and by physical effects in the whole passage.

2 State of the art

2.1 Research methods

To investigate the impact of hydro turbine to different fish species, field and laboratory experiments must be conducted. Three methods provide the common investigation method.

The first method is used in field studies which analyzes the research on balloon-tagged fish [1]. For this method the fish is equipped with an external attachment of a small uninflated balloon-type tag. Injected with a small volume of water the balloon gets inflated with gas. This tag inflates after an adjusted time between 2 to 60 minutes depending on outer parameters e.g. water temperature or configuration of the study site. Preferably the inflation is set to the time the fish passed the turbine passage. The inflated balloon floats on the surface and the fish can be caught and analyzed. This examination method has the disadvantage that the component of the hydro-power station which caused the injury cannot be detected. Another aspect is that the fish has to be handled to attach the balloon-tag, with the result that they are more susceptible to injury.

The use of biotelemetry is another method to study the use of acoustic telemetry. Upstream and downstream sensors can be attached to determine the number of fish that passed the hydro-power plant [2].

Lastly, to study the effect of turbine passage is the use of a sensor fish. This sensor fish is a device which collects data during passing the hydro-power station. It is a small, neutrally buoyant autonomous sensor package [3]. The parameter can be collected are for example the pressure, acceleration and velocity. The sensor fish itself does not conclude that the fish has been injured but in laboratory experiments the measured data can correlated to fish injury [4].

2.2 General problems

Figure 1 shows the possible position for injury in a hydro-power station. At the beginning of the plant passage is the gradually increasing pressure. After this the stay vanes and wicket gates cause strike, collision and shear stress. The turbine itself causes additionally strike, rapidly decreasing pressures and cavitation. In the draft tube and the following underwater passage turbulence causes confusion. Examination of fish have indicated that the ratio of fish length to blade thickness (L/t) is an very important factor to measure

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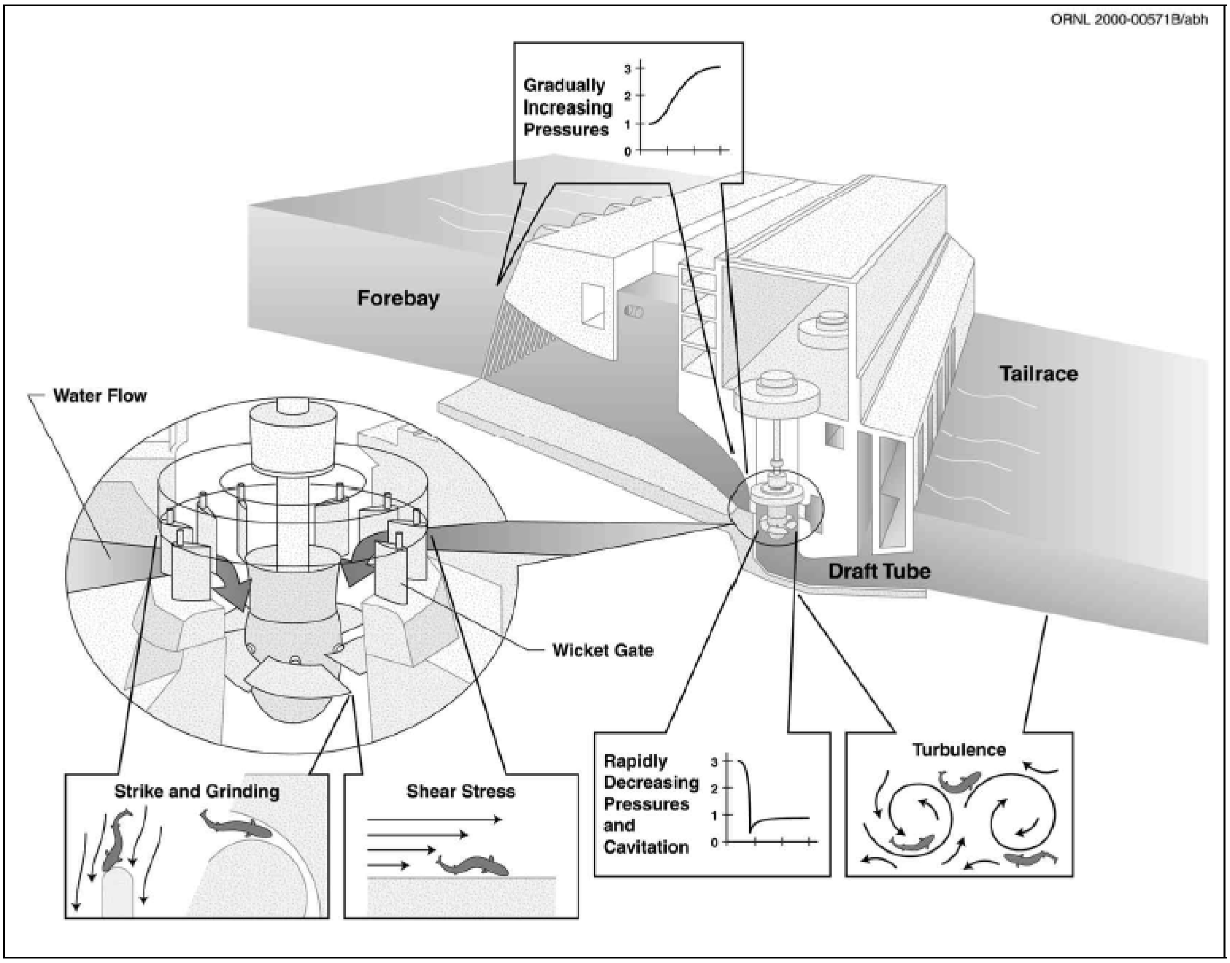

Fig. 1: Possible locations of fish injury passing a hydro-power station [5]

fish mortality [6]. Decreasing the ratio increases the fish survival. Additionally, a higher blade velocity decreases the fish survival. The fish mortality is nearly 0 % with blade velocities of about 5 m/s or less for all fish length-to-blade thickness ratios. Also the slant angle and the position of strike along the body has an effect on the survival rate [7, 8]. Another problem is that the type of turbine, e.g. a Francis or a Kaplan turbine, have different mortality rates.

2.3 Pressure changes

Pressure changes are not always dangerous for fish. If the pressure were slowly decompressed from 101 kPa to 13.8 kPa in more than 3.3 min the fish could expel gas from their swim bladder [9]. The time of decompression is the crucial factor. The intake and stay vane/wicket gate region show a minor change of pressure [3]. When fish pass between turbine blades, there is a sudden drop of pressure, in less than 0.5 s. Martinez et al. [3] measured a wide range of pressure changes between 253 and 860 kPa. The pressure changes below 300 kPa were measured with a fish-friendly turbine. Past the turbine, the pressure slowly increases again in the drafttube.

The rapid decompression can lead to barotrauma, which arises from two different pathways [9]. The first way can be explained by Boyle's Law, shown in equation 1.

$$P_1 \cdot V_1 = P_2 \cdot V_2 \qquad (1)$$

The volume of gas is inversely proportional to the pressure. If the surrounding pressure of the fish decreases, the volume will increase. The fast decompression in less than 0.5 s causes ruptured swim bladders, exopthalmia (eyes popped outward), everted stomach or intestine.

The second approach can be explained with Henry's law [9]. Gas can dissolve in body fluids. If the pressure decreases, the solubility will decrease, too. The gas comes out of solution and resulting a bubble formation [10]. Temporarily grown bubbles can lead to great damage of organs and as the gas bubbles increase, they lead to massive internal rupture of vasculature.

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2.4 Strike and collision

Another cause of injury and mortality for fish is the collision and strike with the turbine blades. Typical characteristics of conventional low head hydro-power turbine are the high rotational speeds, high strike velocities and thin leading edges [7]. The primary source of mortality for fish is collision with the leading edge of turbine blades [11] Mentioned in chapter 2.2 the fish length to blade thickness ratio (L/t) is a good indicator for fish mortality.

The foreseeability of blade-strike injury is higher at low discharge than at high discharge [8]. The probability of strike can be described with equation 2 established by Von Raben (1957) [12].

$$P = \frac{l \cdot cos\theta \cdot n \cdot N}{V_{\text{axial}} \cdot 60} \tag{2}$$

Where l is the length of the fish, θ the angle between the velocity between V_{axial} and $V_{absolute}$, n the number of blades and N the runner speed in revolutions per minute (RPM).

2.5 Grinding, shear stress, cavitation and turbulence

Grinding occurs when a fish is squeezed between narrow gaps of two components of the power plant. In a conventional turbine this happened between the turbine blade and the fixed structures [5]. Shear stress is caused by two parallel bodies of water from different velocities or moving water near a solid structure [13]. The research on shear stress is difficult because in a controlled laboratory environment the reproduction is limited. In up-scaled hydro-power plants the distinction between the different sources of mechanical injury is not straightforward. Turbulence are irregular motions of the water caused by different static and moving components. These turbulence cause localized injuries or disorientation. Cavitation is formation of vapor bubbles caused by extremely low water pressures. The low water pressure is caused by fast rotating turbines.

3 Examples for fish friendly turbine design

3.1 Universal design

In general the turbine efficiency has great effects on fish survival [5]. The cause of physical injury is clearly visible in pressure changes, shear stresses, and turbulence as previously explained. A low operating efficiency caused by adversed turbulence and other losses for example frictional resistance. Those turbulences constitute one particular source of high fish mortality. Optimizing the operating efficiency can improve the survival rate of fish.

Beside the turbine design itself the other components of the whole power station influence the fish mortality. Components, for example the wicket gates or the stay vanes, can be modified in position and geometry: is a minimal spacing between the wicket gate leading edges and stay vane trailing edges important [14]. Otherwise the fish could pass between these components and physical injury are possible. Odeh [15] set up criteria for a fish friendly turbine design. He named a flow rate of 28.3 m^3/s and a head of 23 - 30 m. The minimum pressure is 68.8 kPa with a maximize rate of change of 550.3 kPa/s. The acceptable velocity is about 12 m/s.

3.2 Restoration Hydro Turbine

The Restoration Hydro Turbine (RHT) developed by *Natel Energy* is a turbine with high performance, safe fish passage and a short draft tube [16]. It is optimized for low head between 2 - 10 m with, a single units capacities from 32 kW to 1,400 kW and a flow between 1 and 200 m^3/s. The fish-friendly character is created by special curved turbine blades. With those thick leading edges the turbine reaches an L/t ratio of 2 or less with body lengths up to 400 mm. Additionally the number of blades is reduced compared to conventional turbines. The blunt, slanted leading edge reduces the severity of strike and collision and allowing high runner rpm. According to the manufacturer the most appropriate candidates for RHT retrofit are high-speed, low-head Francis turbines. A RHT prototype unit was tested by Jim Walsh of Rennasonic Inc. with a peak hydraulic efficiency above 90.5 % and good correlation to CFD simulation results. Amaral et al. [7] tested different configurations of the RHT turbine. With a slant angle of 45° and 30° and an L/t of 2 at 10 m/s the survival rate was around 96 % and 98 %.

3.3 Alden turbine

The Alden turbine is a newly developed turbine by the *Voith* company which also provides a fish-friendly system. It was initially developed using two- and three- dimensional Computational Fluid Dynamics (CFD) models [6]. The main changes of the Alden turbine constitute the reduced number of blades, a slower rotational speed and the number of stay vanes and wicket gates was reduced from eighteen, nineteen or twenty to fourteen (each). The Alden turbine is designed with just three runner blades. The other improvement is the slower rotational speed. These two factors provide the main reason for an estimated approximately fish passage survival of 98 % for 200 mm fish and the predicted survival rate of 100 % for fish 100 mm and less in length [14].

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3.4 Minimum Gap Runner

The Minimum Gap Runner (MGR) is a modified version of the Kaplan turbine in which the gaps between the moving and the static parts are reduced to a minimum at all blade positions. The conventional Kaplan turbine reaches survival rates about 88 % [5]. This modified version can achieve about 98 % to 100 % of survival rates. The first MGR Turbine was installed at the Bonneville Dam between the U.S. states of Washington and Oregon. Beside the good results of fish survival the expected efficiency gain is about 15 % compared to to the old Kaplan turbine [6]. Because of that benefit the Bonneville First Powerhouse replaced all 10 of the old Kaplan turbines with MGRs.

3.5 Very low head

The Very Low Head Turbine (VLH-Turbine) is a developed turbine for net head ranges between 1.5 and 3.4 m [17]. The flow range extends from 10 to 27 m^3/s and the range of power is between 100 and 500 kW per unit. A VLH-Turbine is shown in figure 2. The velocities are between 4.5 and 8 m/s and are

Fig. 2: VLH-Turbine in operation position [17]

lower than the acceptable velocity for the fish friendly design.

3.6 Screw Turbine

Archimedes Screw Turbines are naturally fish-friendly. The normal rotational speed is about 4 m/s. This speed causes no significant pressure changes or damaging shear forces. However, the uses and electrical performances of Archimedes screws are limited. They are suitable for sites with a head of 10 m or less [6]. Rohmer et al. [18] names the following common parameters, shown in table 1, for the application area of screw turbines:

Tab. 1: Most common field application of screw turbines [18]

Parameter	Value
head in m	1 to 6.5
flow rater in m^3/s	0.25 to 6.5
capacity in kW	1.7 to 300
overall efficiency in %	69 - 75

4 Conclusion

The different types of damage at fish show that a fish friendly turbine design is not the single factor to reduce fish mortality. Fish mortality is influenced by different characteristics of the whole power-plant. In addition to the moving components, the static components are also a cause. The different types of damage are rapid pressure changes, strike, grinding, shear stress, turbulence and cavitation. Strike, grinding and shear stress can influenced by different turbine designs. The number of stay vanes and wicket gates or the gap between these are an example for parameters which can be varied. Turbulence and cavitation can be reduced with a good overall efficiency. A lower radial velocity reduce the rapid pressure change. In this case, the best balance must be found between turbine efficiency and fish mortality. The examples of various fish-friendly turbines, that have already been developed, show that it is technically possible to build an economical and efficient turbine. They also show, that different operating places have different requirements to the turbine design for example for different head ranges.

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