A review of existing design principles for fish-friendly hydro turbines.

Álvaro Guglielmin Becker

Department of Electrical Engineering, Federal University of Rio Grande do Sul, Porto Alegre, Brazil,
alvarogbecker@gmail.com

Abstract. Freshwater fish whose migration course is blocked by a hydroelectric power plant often pass through the turbine rather than through safer passageways in their effort to reach the tailrace. As such, they are often subjected to harmful interactions with the turbine mechanism, which can result in injuries or death. This study investigated the main causes of injury to fish in these conditions, and existing design solutions to mitigate these harmful effects, through a literature review. It was found that the main mechanisms for fish injury are strikes against moving and stationary parts, grinding from being stuck in small gaps, decompression from sudden pressure shifts, shock waves from gas bubbles, deformation from shear stress, and disorientation from turbulence. Additionally, fish size and species are two of the most important factors for their survivability, and must be taken into account for the specific river where a turbine is set to be installed. The main existing design proposals for fish-friendly Kaplan and Francis turbines which seek to mitigate these issues are the reduction of gaps between the runner blades and both the hub and turbine housing; the reduction of gaps between stay vanes and wicket gates; a decrease in blade count and consequent creation of more space for fish passage; and turbines with controllable rotational speed and guide vane angles, to allow for operation in the maximum efficiency range, with minimum pressure change and turbulence.

Keywords. Fish-friendly turbine, fish mortality, hydropower, fish passage, state of the art.

1. Introduction

Freshwater fish who live in rivers occupied by hydroelectric power plants suffer a variety of negative effects due to such structures, many of which are related to the dams blocking their migration route. In their effort to continue their passage through the obstruction, many fish end up passing through the power plants' turbines, enduring serious and often lethal injuries in the process.

Despite the existence and employment of systems designed to prevent fish from passing through the turbines and direct them to safer passageways, these vary in effectiveness and present deployment issues. Behavioral barriers, which use sensorial stimuli to redirect the fish's movement to a safer escape route, have their effects heavily dependent on the species of fish [1][2]. Physical barriers, in the form of grids, are effective, but represent a loss in power generation [1], and retrofitting them to older power plants can be very expensive [2].

Due to these factors, it becomes an inevitability that fish will end up passing through the turbines in many cases. As such, the need arises to mitigate the harmful impacts of the turbine mechanisms through fish-friendly design practices. With fish survivability as a priority, new turbines can be designed and implemented with modifications to accommodate for safer passage of aquatic life.

This paper aims to understand and summarize the state of the art in fish-friendly turbine design, locating the mechanisms of traditional turbines which harm migrating fish, the existing design solutions intended to mitigate those issues, and their effectiveness in reducing indices of fish injury and mortality.

2. Research methods

To identify the areas where turbine design can be improved upon for the sake of diminishing harm to aquatic life, a literature review was performed on studies researching the impact of hydroelectric power plants on fish populations.

Through a qualitative analysis of the literature, a list was organized of the harmful impacts exerted on aquatic life which are directly caused by fish passing through the turbines of power plants. For each of the identified injury mechanisms, a summarized description was produced describing the specific harms they cause to fish, and the underlying principles behind them, which would show the areas for possible design improvements.

A second literary review was then conducted on articles and technical reports showcasing proposed and implemented solutions for the design issues identified. These solutions were paired with the issues they aim to resolve, with a summary of the design principles they employ to solve or mitigate said issues, along with quantitative data regarding their viability, when available.

3. Results and discussion

The main factors of risk for fish passing through the turbines of power plants come from mechanical, pressure, and hydraulic mechanisms [3].

The percentage of injuries originated by each mechanism in relation to the total injuries varies by case; factors such as fish size–and, consequently, the available species in a given river–alter the likelihood of certain injuries [1][3][4], as does the turbine type [5][6][7]; as such, fish mortality rates can vary significantly between measurements. Table 1 shows different mortality rates provided by different studies, for both Kaplan and Francis turbines.

Tab. 1 – Fish mortality rates

Study	Mortality Rate	
	Kaplan Turbine	Francis Turbine
[5]	4-15%	5-50%
[7]	11-22%	20-27%
[8]	5-20%	5-90%

While the precise rates vary, the general trend holds that mortality rates are lower in Kaplan turbines than in Francis turbines. This is due to geometric differences between the two turbine types, as well as difference in head–with Kaplan turbines being installed within a head range of 1.5 to 80 m, while Francis turbines are installed within a head range of 30 to 550 m [5]. Turbines designed for even higher head installations, such as Pelton turbines, usually present a mortality rate of 100% [6][8]. This difference in head represents differences in pressure variation and flow turbulence, the effects of which are discussed further on.

3.1 Strike and grinding

Strike is the physical collision of the fish against structures of the water passage, both moving and unmoving, such as the draft tube walls, stay vanes, wicket gates and turbine blades [1][5].

Grinding is a squeezing injury that occurs when fish pass through narrow gaps in the structure, such as between the turbine blades and the hub, the blade tips and the turbine housing, and between wicket gates at certain configurations [5][9][10].

Both of these mechanical injury mechanisms can cause bruising on the fish, while grinding can also cause deep cuts and even decapitation [5][10].

Many factors alter the likelihood and severity of mechanical injuries, such as turbine diameter, number of runner blades, sharpness of the blade edges, rotational speed, flow rate, and characteristics of the fish [5][7][10].

At lower flow rates, grinding between the blades and hub have been found to become more likely, but grinding between the blades and turbine housing becomes less likely [9].

The chance of strikes occurring is increased linearly with the length of the fish, being able to reach 100% for large fish [11], and is also proportional to the number of blades and the rotational speed. In a test between a turbine with 6 blades and one with 5, both otherwise operating in the same conditions, the 5 bladed unit had a survival rate of 87.8% compared to the 6 bladed unit's 80.4%. Another test with a different species of fish yielded survival rates of 62,4% versus 54.8%, respectively. However, injury rates did not improve, with the 5 bladed turbine actually producing an increase in injured fish in the second test, compared to the 6 bladed one [3].

One design principle implemented to prevent grinding is the Minimum Gap Runner (MGR) turbine, developed by Voith Hydro, which aims to minimize gaps between the blades and both the hub and the turbine housing. MGR design is based on a "three-sphere" concept, in which the hub, blades and housing profiles are all concentric spheres, nesting into each other with minimal gaps. A prototype is shown in Figure 1, highlighting the points where the gaps have been minimized.

Fig. 1 – Prototype of MGR Kaplan turbine. Adapted from [12].

In a test run in 2000 comparing a traditional Kaplan turbine to an MGR turbine, fish that passed through the blade tip had a survival rate 3% greater than those who passed through the normal turbine, and am overall injury rate of 1.4% compared to the traditional turbine's 2.5%. Both units displayed similar survival rates for fish passing near the hub (≥97%) and through the mid-blade (95 to 97%) [6].

Another turbine designed to minimize mechanical injury is the Alden Fish Friendly turbine, developed by Alden Research Laboratory. It is shown in Figure 2. The turbine uses a similar design to traditional Francis turbines, but operates at low heads of up to 30 m. It uses three long runner blades with thick entrance edges to minimize both the occurrence and severity of strike events [3].

Additionally, the Alden turbine uses a lower number of stay vanes and wicket gates, to lower the likelihood of strikes, as well as minimizes the gaps between the stay vanes and wicket gates to lower the risk of grinding. Furthermore, the turbine as a whole is bigger than traditional turbine designs, creating larger distances between both consecutive wicket gates and runner blades, allowing for safer passage of larger fish [3].

Fig. 2 – Alden turbine. Source: www.voith.com/hydro

Fish-friendly turbines designed by Andritz Hydro also reduce gaps between the runner blades and the hub and discharge ring, and between the stay vanes and wicket gates. The blades also present a blunt leading edge, to minimize damage from strike injuries [13].

3.2 Decompression and cavitation

In reaction turbines, such as Kaplan and Francis turbines, water reaches the turbine at very high pressures and exits at low pressures. This means that fish passing through the turbines experience a drastic variation in pressure over a very short time interval (sometimes less than a second), possibly going from pressures of several times atmospheric pressure to subatmospheric pressures [5][6][14].

Injuries caused by this rapid decompression are classified as barotrauma, and include formation of emboli in the gills, damage to the vasculature and the swim bladder, hemorrhaging, eversion of the stomach through the mouth and dilation of the eyeballs [1][3][14].

Cavitation is the formation of gas bubbles that occurs when water pressure reaches or goes below vapor pressure. As these bubbles travel upwards and meet higher pressures, they can collapse, creating violent shock waves which can injure and kill fish [5][14].

The high pressure gradient which causes both decompression and cavitation injuries occurs at the extreme operating points of the turbine. Turbine designs which are able to minimize pressure reductions to no greater than 60% of ambient pressure will not cavitate [10]. This can be achieved by operating at the ideal efficiency range, below certain flow and runner velocity threshold values, diminishing these effects [4][9][12], which can be maintained by using variable speed turbines and controlling the angle of the guide vanes [13].

3.3 Turbulence and shear flow

The high flow rates at which turbines operate can cause turbulence in the water, such as vortices, wakes and backflows [3]. These can send fish to collide against structures, resulting in mechanical injuries, or disorient them and leave them vulnerable to predators in the tailrace [5].

Shear stress is caused by forces parallel to the fish's body, and is originated by changing flow velocity and turbulence [9]. High levels of shear stress can deform the fish's body, potentially leading to injury or even death [10].

Turbulence and shear stress events are more common and severe in Francis turbines than in Kaplan turbines, due to geometric differences between the two turbine types, as Francis turbines typically operate at higher heads, and water enters the runner in the radial direction, which results in heavier and more turbulent flow [5].

The rotational movement of the runner creates a vortex in the water that flows downstream, submitting fish to higher turbulence as they exit the power plant. Furthermore, the water passing through the gaps between the runner blades and both the hub and the turbine housing is expelled with greater velocity due to a "squeezing" effect, creating high shear flow [9]. Therefore, design solutions which aim to decrease the likelihood of grinding injuries also help reduce shear flow, such as MGR turbines [6] and reducing the gaps between the stay vane trailing edges and wicket gate leading edges [3].

4. Conclusion

Most of the existing quantitative data regarding the efficacy of fish-friendly design solutions relates to the mitigation of mechanical injury mechanisms; existing design solutions operate mainly on the principles of increasing space for free passage (by decreasing the number of runner blades and the rotational speed) to mitigate strike injuries, and eliminating gaps in the runner and between the stay vanes and wicket gates to minimize grinding events.

Issues related to pressure change are the ones that most consistently affect fish regardless of species and size, as the pressure gradient is fundamental to the operation of most turbines. This also explains why turbines which operate at higher heads have far higher mortality rates–usually 100%–since their pressure variation is much higher. However, for Kaplan and Francis turbines, these issues can be mainly mitigated by controlling water flow and keeping the turbine operating at the maximum efficiency range.

Data on turbulence and shear flow is the least abundant, and these are mainly treated as minor injury mechanisms, since turbulence's negative impacts are mostly indirect, and shear flow tends to occur in areas of the turbine where mechanical injuries and cavitation are also likely. Existing solutions to these issues are also solutions to the other mechanisms, namely controlling water flow and minimizing gaps.

The principle of most importance for any fish-friendly turbine design proposal is that effectiveness will greatly vary depending on the species of fish passing through the turbine. Different types of fish will be injured more often or severely by different injury mechanisms, and accommodated better by different design choices. As such, implementation of fish-friendly turbines ought to take into consideration the characteristics of the species native to the river where the turbine will be installed. To that end, turbine designs which allow for adjustable operation parameters, such as intake water flow, rotational speed and runner blade angle, prove efficient and versatile.

5. References

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