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Quantifying barotrauma risk to juvenile fish during hydro-turbine passage☆

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ABSTRACT

We introduce a method for hydro turbine biological performance assessment (BioPA) to bridge the gap between field and laboratory studies on fish injury and turbine engineering design. Using this method, a suite of biological performance indicators is computed based on simulated data from a computational fluid dynamics (CFD) model of a proposed hydro turbine design. Each performance indicator is a measure of the probability of exposure to a certain dose of an injury mechanism. If the relationship between the dose of an injury mechanism (stressor) and frequency of injury (dose–response) is known from laboratory or field studies, the likelihood of fish injury for a turbine design can be computed from the performance indicator. By comparing the values of the indicators from various turbine designs, engineers and biologists can identify the more-promising designs and operating conditions to minimize hydraulic conditions hazardous to passing fish. In this paper, the BioPA method is applied to estimate barotrauma induced mortal injury rates for Chinook salmon exposed to rapid pressure changes in Kaplan-type hydro turbines. Following the description of the general method, application of the BioPA to estimate the probability of mortal injury from exposure to rapid decompression is illustrated using a Kaplan hydro turbine at the John Day Dam on the Columbia River in the Pacific Northwest region of the USA. The estimated rates of mortal injury increased from 0.3% to 1.7% as discharge through the turbine increased from 334 to 564 m^3/s for fish assumed to be acclimated to a depth of 5 m. The majority of pressure nadirs occurred immediately below the runner blades, with the lowest values in the gap at the blade tips and just below the leading edge of the blades. Such information can help engineers focus on problem areas when designing new turbine runners to be more fish-friendly than existing units.

1. Introduction

Anadromous fish often must pass through hydroelectric facilities during their migration to the ocean. Fish may pass a facility over the spillway, through the turbines, or using an engineered by-pass route (Schilt, 2007). Even at facilities where by-pass routes are present, a significant number of fish pass through the turbines (Hockersmith et al., 2005; Ploskey et al., 2006; Hansel et al., 2008). Field studies generally indicate that turbine passage is hazardous, with mortality rates ranging between 2% and 19% (Whitney et al., 1997). This incremental mortality is magnified when fish have to pass through multiple hydropower facilities during their downstream migration, as occurs on the Columbia and Snake River systems in the Pacific Northwest region of the USA (Ham et al., 2005).

Over the past decade, many studies have described injury mechanisms associated with turbine passage, the response of various fish species to these mechanisms, and the probability of survival through specific dams under certain conditions. But transforming and integrating these data into tools to design turbines that improve survival by minimizing impacts to fish during passage has been difficult and slow. Although identifying the locations and hydraulic conditions where injuries occur is challenging, a more robust quantification of the turbine environment has emerged through integration of balloon tag and sensor fish

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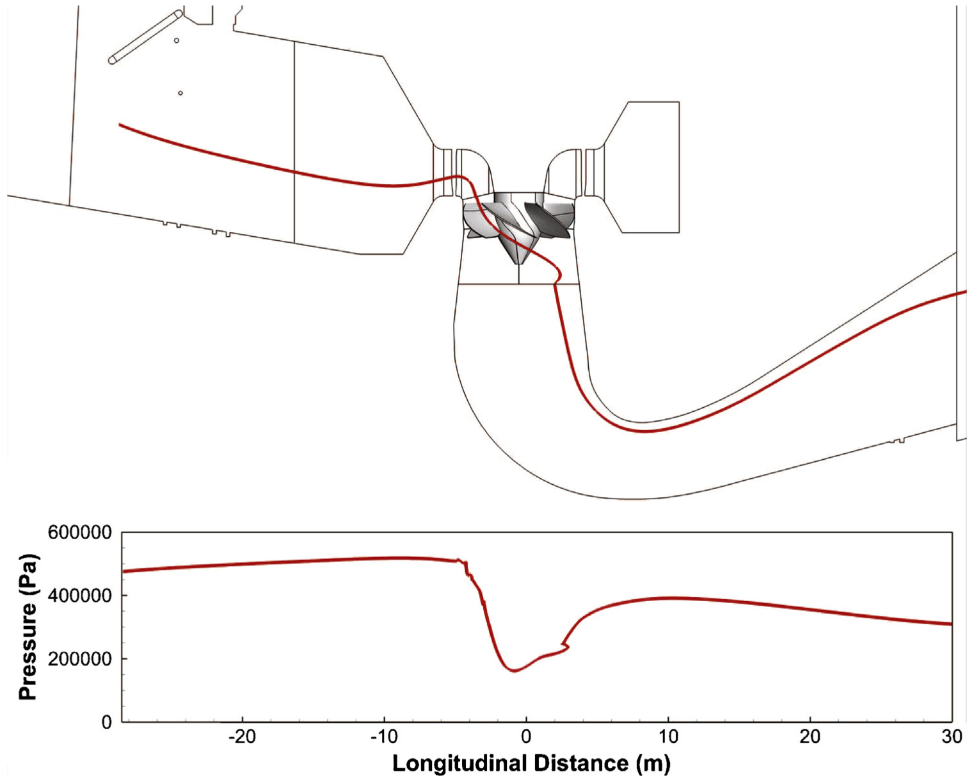

Fig. 1. Typical Kaplan turbine passage pressure profile along a streamline.

data with computational fluid dynamics (CFD) modeling (Dauble et al., 2007). Field-testing new hydro turbines is very expensive, so engineering design tools that improve the linkage between fish injury data and turbine characteristics are needed to identify the most promising designs before full-scale construction begins.

Past attempts to predict the risk to fish passing through the turbine environment have focused on identifying the locations and sizes of potentially hazardous regions (Garrison et al., 2002; Keller et al., 2006; Čada et al., 2006). Improving passage survival was a matter of reducing the volume and number of these regions. However, the presence of dangerous zones within the turbine may be biologically inconsequential if few fish experience them. For example, the undersides and tip regions of runner blades generally have very low pressures, which can be harmful to fish, but only a small fraction of the population may pass through these locations.

More recent work has described the use of minimum pressure threshold criteria to guide turbine design (Brown et al., 2012a). An advantage of using minimum pressure criteria is that it is straightforward to implement because it need not consider the non-uniform distribution of pressure within the turbine environment. However, minimum pressure criteria may have a limitation of assuming, when calculating an estimate of mortal injury rates, that all fish passing the turbine are exposed to the same minimum pressure value. In some cases it is possible that minimum pressure design criteria could be overly conservative and lead to the selection of more costly (e.g., lowering the centerline elevation of the unit through civil structure modifications) and less hydraulically-efficient designs.

The Pacific Northwest National Laboratory (PNNL) has developed a new probabilistic design method, the biological performance assessment (BioPA), for bridging this gap between laboratory studies on fish injury and turbine design. With this method, a suite of biological performance indicators for injury and mortality are computed based on data from a CFD model of a proposed turbine design. Each performance indicator is a measure of the probability of exposure to a certain dose of an injury mechanism. If the relationship between the magnitude of exposure to an injury mechanism and frequency of injury is known from laboratory or field studies, the likelihood of fish injury for a turbine design can be computed from the performance indicator. By comparing the values of the indicators from various turbine designs, the engineer can identify the more-promising designs.

In this work, we introduce the BioPA method with a description of its theory, assumptions, and implementation. To illustrate the concepts, we apply the BioPA to estimate fish mortal injury caused by rapid pressure changes in a Kaplan-type hydro turbine.

2. BioPA method

In order to evaluate the significance of the low pressure regions, the BioPA method estimates the probabilities that fish will encounter specific conditions during passage. This is done with a proportional sampling scheme that uses streamtraces in a numerical flow simulation to model potential pathways through the turbine.

2.1. Response of fish to pressure change

Rapid change in barometric pressure, or barotrauma, is a potential cause of injury and mortality for juvenile salmonids passing through hydro turbines (Brown et al., 2012c). Computational fluid dynamics (CFD) models (Keller et al., 2006) and field studies (Carlson et al., 2008) show that turbine passage exposes all fish to a slow compression in the intake followed by a rapid decompression as they pass either the pressure side or the suction side of the runner blades. This is followed by a return through the draft tube to hydrostatic conditions in the tailrace. A typical profile of pressure along a streamline is shown in Fig. 1.

Research into barotrauma in fish can be traced back to the work of Sutherland (1972) and Tsvetkov et al. (1972) who found a significant potential for injury due to rapid decompression. More detailed studies were performed by Abernethy et al. (2001), who subjected