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Development of a fish leaping framework for low-head barriers

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ABSTRACT

Leaping is an indispensable part of the upstream spawning migration of a fish species. The natural barriers replaced with artificial dams and obstacles can obstruct the leaping process and destruct the life cycle of fish species, causing their extinction in extreme scenarios. To help design and improve the artificial barriers, many studies have been conducted to model the leaping success of fish species. However, generic results were scarcely obtained to be extended for a wide range of barriers. The main reasons can be identified as the lack of thorough understanding of the interaction between fish locomotion and water flow regime upstream of the investigated barriers. Hence, the aim of this study is to propose a leaping framework compatible with a diverse range of fish species and barriers. This framework includes a detailed hydraulic sub-model as well as locomotion model capable of tracing fish in both water and air environments. The functionality of the proposed framework is further discussed using a selected case study.

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1. Introduction

Environmental preservation is a challenging issue of the current century to mitigate the past, current, and future interference of human footprints. A recent example of the ongoing damage to the environment is fish species extinction due to the construction of geographical and physical barriers in rivers and waterways (Schlosser and Angermeier, 1995). Human fragmentation has resulted in a wide range of ecological problems such as local species extinction (Wilcox, 1980; Wilcox and Murphy, 1985). For example, fragmentation has been recognized as a cause of local extinction of small fishes in Australia (Gehrke et al., 2002).

Upstream spawning migration is a part of the life cycle of many fish species, e.g. pacific salmon, smelt, shad, striped bass, and sturgeon (McDowall, 1990). These fish are born in fresh waters, migrate downstream toward sea where they become mature in a period of a few years. Then, they return back to the same stream through a long upstream migration, and spawn in the fresh waters. A part of this upstream migration is jumping through the natural barriers. However, the artificial barriers such as road-crossings, rocks, weirs, and low head dams are common impassable obstacles, cutting the ecological connectivity of fish spawning migration.

Removal of the mentioned artificial structures is not always a practical and economical option. Therefore, as potential solutions, fish ladders, fish ways and passageways have been widely designed and constructed to help maintain the ecological life cycle of fish. Many design guidelines and instructions have been developed and implemented (Marmulla, 2001). Despite the positive functionality of the fish passageways, their effectiveness is sometimes questioned as the economical and engineering considerations are more dominant compared to the jumping ability and performance of fish species (McLaughlin et al., 2013; Noonan et al., 2012).

Various studies have been conducted to help better the understanding of the jumping ability and performance of different fish species, where the influential parameters are recognized as water flow rate, pool depth, fall height, fish body length, etc. As an early mathematical model, Reiser and Peacock (1985) calculated the maximum attainable height by a fish using the initial burst speed. Powers and Orsborn (1985) defined a more precise model by including further parameters such as maximum burst, fish length, fish frontal area, and estimated drag force. The main limitation of such model can be identified as their simplified hydraulics model.

In a more advanced study, Lauritzen et al. (2005) examined the jumping kinematic of wild sockeye salmon in natural waterfalls. They have observed the kinematic of fish jumping and developed a simple mathematical ballistic model based on the trajectory of fish in the air. They concluded that the height of waterfall and depth of pool below it are important factors in the jumping performance. The influence of environmental factors such as brown bear presence on the jumping success was further considered in this

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study. In another experimental study conducted in a water tank by Ficke et al. (2011), speed, performance and kinematics of Brassy Minnow fish were investigated for better design of fish ways. Beside the role of fish length, waterfall height, and pool depth, they have emphasised the role of water temperature in endurance jumping of Brassy Minnow. Moreover, the experiment indicated the significance of water velocity on the swimming endurance of studied species. Different regression equations of the probability of jumping success were developed based on the mentioned influential parameters. Furthermore, Salmon jumping was studied through an observational experiment conducted in an adjustable water tank (Lauritzen et al., 2010). The flow speed, pool depth, fall height and fall angels were changed to investigate the jumping success rate. In another laboratory experiment by Kondratieff and Myrick (2006), jumping performance of Brook trout was evaluated. Again, a regression model was developed based on the recognized influential parameters, including pool depth, waterfall height, fish length, trial duration, and fish condition. The impact of fish condition on leaping was assessed based on the fish level of damage in fins, jaw, eyes, and operculum condition.

Despite the various studies on understanding the relation between fish jumping success and environmental/physiological parameters, contradictory results were occasionally reported in the development of jumping models (Myrick and Kondratieff, 2004). This implies that most of these models are restricted to the laboratory and simplified conditions, and barely can be generalized to a wider range of barriers with different physical characteristics. This weakness is inherently due to the simplified details of the utilized hydraulic models on the jumping ability of fish species. While the developed models mainly recognize the importance of barriers and fish characteristics on the jumping success, they barely represent their interconnections with water flow regime. In other words, the poorly modelled water flow regime, affected and formed by barrier geometries such as pool depth and water fall height, significantly impacts the kinematic of a fish species.

The fish kinematic is the ability of a fish species to benefit from water flow characteristics to minimize the locomotion cost and maximize the success probability of the jumping. Therefore, development of hydraulic models can provide more details about the interaction between a fish and its surrounding environment compared to the traditional regression and observational models. The advantage of such models can be addressed as their capability in resolving the turbulence level and circulation strength of the flow regime. Turbulence is identified as a significant factor in attraction or repelling a fish as it can dominantly decrease or increase the locomotion cost (Enders et al., 2003; Pavlov et al., 1982, 2000; Webb, 1998). The mentioned parameters are mainly neglected in the traditional models, resulting in limited conclusions extracted from these studies. In general, fish kinematic depends on the characteristics of its species in generating locomotion forces (i.e. drag, lift, thrust and buoyancy).

Species characteristics of a specific fish itself contain the physiological and behavioural parameters. While physiological parameters of a species (e.g. weight, length, shape) are independent of the flow regime, behavioural parameters are directly impacted by constraints of the flow regime, again justifying the implementation of a detailed flow model. Behavioural parameters include the maximum swimming speed (Reiser et al., 2006), visual ability (Sweka and Hartman, 2001), temperature endurance (Holthe et al., 2005), environmental fear (Carpenter and Summers, 2009), and learning ability (Odling-Smee and Braithwaite, 2003). It is widely studied that fish use their sensory and locomotion systems to navigate efficiently within the water with changing their swimming kinematics according to the flow regime (Liao, 2007). Liao et al. (2003) showed how fish surf in water and use underwater vortices to minimize their swimming energy. Takagi et al. (2013) showed how Pacific Bluefin Tuna can reduce its locomotion cost through a glide and upward swimming rather than a continuous horizontal one. As another example, reported by Lauritzen et al. (2005), straightening bodies, closing mouth, stretching the fins, and continuous beating of the tail can be respectively justified as minimizing drag and maximizing thrust forces.

Hence, the aim of this study is to develop a framework, performing as a roadmap to develop simulation models of the jumping mechanism of various fish species over a variety of barriers. It should be noted again that the goal of this research is to explore the functionality of the proposed framework rather than generating reliable results for a specific fish species, which requires a thorough calibration with that of realistic behavioural and physiological parameters. The proposed framework can be later used to evaluate the jumping favourability of any low-head barrier and to calculate the total energy budget of a fish species through several jumps required for its spawning migration. The proposed framework consists of flow details as well as physiological and behavioural characteristics of a fish species. Furthermore, it contains a sub-model to trace the fish trajectory in the air when it departs the water surface. The functionality of the proposed framework and its sub-models is shown with a selected case study.

2. Jumping mechanism

The proposed framework, encompassing the mentioned flow and fish parameters of the jumping, is exhibited in Fig. 1. The framework describes the dynamic interaction between a fish and its environment. After being positioned at the initial point of a jump, a fish tries to benefit from its physiological abilities (i.e. weight, volume, and hydrodynamic) against the water flow regime of a pool to generate an optimum thrust force and swim angle, heading toward the water surface. During the burst process, a fish continuously adjusts its thrust force and swim angle to achieve a successful jump. The latter behavioural ability is unique for each fish species and corresponds to its eyesight, response time, and learning rate. In general, fish optimal solution on a specific situation can result in a failure in jump due to the miscalculation in the jumping process related to its species and also to micro flow complexity associated with the low-head barrier. Therefore, the proposed framework attempts to simulate the jumping process from the fish species point of view.

The presented framework in Fig. 1 contains four individual sub-models, forming a holistic jumping model. The model firstly starts with the flow regime, barrier characteristics, and initial condition of the fish as inputs to the first sub-model, the hydraulic CFD model. This sub-model is thus able to predict the flow characteristic for different spillway design and parameters. Evidently, any change in such parameters will change the flow regime that can be again regenerated with the CFD sub-model. The sub-model is assumed to be 2-dimensional and steady-state while it is decoupled from the fish water kinematic model. This implies that CFD model only provides the flow characteristic to be inserted as inputs into the fish water kinematic model. Then, the flow field simulated by the hydraulic CFD model, in addition to physiological parameters of the fish species, are transferred to the second sub-model, the fish water kinematic model to calculate the hydrodynamic forces; the fish trajectory is simulated as a particle trajectory. The hydrodynamic forces in addition to the behavioural abilities again serve as inputs to the third sub-model, the swimming optimization model, which calculates the minimal energy-consumption path from fish point of view. Thus, at this point, the fish is able to generate a thrust force and swim with a certain angle to reach the water surface. This dictates that the fish reaches a new location between its decision and response time when the fish

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