Ecological Engineering 88 (2016) 217–225

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

A new Eulerian–Lagrangian agent method to model fish paths in a vertical slot fishway

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ARTICLE INFO

Article history:
Received 24 April 2015
Received in revised form
21 December 2015
Accepted 22 December 2015
Available online 7 January 2016

Keywords:
Individual-based model
Vertical slot fishway
Computational fluid dynamics
Trajectory
Fish mortality
Modelling
Turbulence

ABSTRACT

An individual-based model (IBM) to simulate the movement of a single fish through a vertical slot fishway has been developed. The turbulent water flow in the fishway was first obtained using CFD-software. Trajectories of live fish measured by Rodriguez et al. (2011) were superimposed on several different parameters characterizing the flow, such as the turbulent kinetic energy (TKE). The correlations between these hydrodynamic parameters and the measured trajectories were examined and TKE was identified as the single most important stimulus. To mimic positive rheotaxis, the mean velocity was adopted as a secondary agent. The new Lagrangian IBM-model was combined with the Eulerian CFD-model to an Eulerian–Lagrangian agent method. This ELAM approach was used to compute the trajectory of a virtual fish. The simulated trajectories were in good agreement with their measured counterparts in the same fishway. Both the preferred direct route and the alternative longer route through an active pool were faithfully reproduced.

1. Introduction

The vertical slot fishway is one of the most widely built fishways in hydraulic engineering, and is designed to enable fishes to pass artificial barriers in the river, such as a dam or a sluice. Fishways play significant roles in protection of fish, but the corresponding design work is complex with considerations of practical hydraulic engineering design criteria, preferences of the fish swimming in the fishway (path selection), and evaluation of the corresponding fish mortality; i.e. fishway passage efficiency. Researchers all over the world have been devoting great efforts in solving these problems, aiming for more precise quantitative predictions of efficient fish-pass and an optimum design of the hydraulic structure (Calles and Greenberg, 2005; Rodríguez et al., 2006; Jansen et al., 2007; Alvarez-Vázquez et al., 2008; Calles and Greenberg, 2009; Pon et al., 2009a,b; Roscoe and Hinch, 2010; Roscoe et al., 2011; Katopodis and Williams, 2012; Puertas et al., 2012; Calles et al., 2013; Marriner et al., 2014; Smith et al., 2014; Silva et al., 2015). A historical perspective on the development of fish passage research was recently provided by Katopodis and Williams (2012).

Reduced fish mortality (or improved fishway passage efficiency) is the end objective of almost all attempts to model fish trajectories. The evaluation of the mortality has two-fold aspects. The first is from the perspective of the fishway itself since the fishway can cause injuries or scale loss through the fish' interactions with the infrastructure and thereby increase the mortality. The second is based on an overall view of the entire migration since even a successful passage through the fishway can have deleterious effects on the fish that, for instance, can negatively affect the fitness and possibly be mortal. In the work of Roscoe et al. (2011), migration failure occurred in all sections of the migration route including the fishway. Of a total of 56 fish, 18% failed in the fishway whereas the mortality in the lakes upstream of the fishway was higher for fish that were released downstream of the dam/fishway (27%) than for fish released upstream of the dam/fishway (7%). This finding supports the hypothesis that dam/fishway passage has post-passage consequences on survival. This implies that one should consider fish mortality from a holistic point of view (Calles and Greenberg, 2009) and not only as an isolated problem limited to the stretch of the fishway. We should therefore not only know how many fish that swim through the fishway (known as *explicit* fishway passage efficiency because some fish may either swim back or perish in

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http://dx.doi.org/10.1016/j.ecoleng.2015.12.038
0925-8574/

the fishway), but also monitor the health of each fish first when it arrives at the entrance to fishway and later on when it leaves at the exit of fishway, i.e. alterations in fitness during the swimming through the fishway, which in some cases will cause death in the post-fishway journey (*implicit* fishway passage efficiency).

To clarify these issues an experimental evaluation method using electromyogram telemetry (EMG) and radio-tagged or PIT-tagged fish combined with physiological biopsy (Calles and Greenberg, 2009; Pon et al., 2009a,b) is effective. The basic idea underlying their experimental method is based on a Lagrangian perspective. The procedure is as follows: (i) tracking individual fish samples; (ii) recording their physiological indices (only at some specific locations); (iii) producing statistics to evaluate the passage system where the physiological indices should be obtained by physiological biopsy. By means of this experimental approach, tracking signals are only gathered at certain discrete locations and we are unable to determine the path taken by the fish and the exact distance the fish has swum. In spite of this deficiency, we can use the same approach to develop a numerical model. The different components and potential challenges in the mathematical modelling are outlined in the following.

The primary difficulties first encountered in path modelling (or tracking individual fish samples) is the combined perspectives in the problem description. The hydraulic information of the fishway, which is also regarded as a stimulus or an agent, is in the Eulerian water flow field, while the response of a fish to these stimuli is in a Lagrangian frame of reference. A method which combines these two perspectives of fishway design is therefore needed. Successful examples of applying this idea into practical engineering design were provided by Goodwin et al. (2006, 2014), who developed a model called ELAM (Eulerian–Lagrangian-agent method). This is an individual-based-model (IBM) approach, see e.g. Grimm (1999), which combines a computational fluid dynamics (CFD) model of the flow field in the forebay of a hydropower plant with a behavioural model in which the simulated fish adjusts its movement according to the varying flow field. Goodwin et al. (2006, 2014) chose the local fluid strain and the local fluid acceleration as the stimuli for the fish to select its path during its migration. However, before this method can be used to simulate the fish movement, it is essential to know the preferred stimulus for a target fish species and experimental-based path information is required to calibrate and validate the model.

Path experiments were performed by Rodriguez et al. (2011). By virtue of a computer vision technique they recorded the trajectories of two individual fish within a full-scale physical fishway model without disturbing their natural swimming behaviour. The focus of their work was to utilize a non-intrusive measurement technique in a fishway. The paper was therefore concluded by a superposition of the two measured fish trajectories onto the water velocity field. Nevertheless, the experimental data which resulted from their work may provide valuable guidance as to enhance our insight in how a fish responds to various stimuli. Before we embark on a detailed analysis towards this goal, two essential questions need to be addressed: (a) Is a three-dimensional (3D) simulation of the flow field required? (b) Which are the most likely stimuli to attract the fish?

From the perspective of hydraulics, extensive research on the hydraulics of fishways has been conducted in recent years. Major achievements have been made, such as experimental flow field measurements performed by Rajaratnam et al. (1992), Wu et al. (1999), Puertas et al. (2004), and Tarrade et al. (2008), and computer simulations carried out by Cea et al. (2007), Heimerl et al. (2008), and Chorda et al. (2010). On the basis of these studies, it is widely accepted that the flow field in a vertical fishway can be approximated as a two-dimensional (2D) flow provided that the bed slope is small. Moreover, qualitative experimental observations of fish movement showed that when a single fish enters into a fishway, the fish soon finds its preferred water depth (or hydrodynamic pressure) and thereafter swims in the same water layer (often near the bottom of the fishway). This implies that the trajectory of the fish varies mainly in the horizontal plane. The water in the fishway is often shallow, typically about 1.0 m, and modest variations in the water depth (or pressure) is unlikely to lead to a behavioural change of the fish. Indeed, the real fish trajectories recorded by Rodriguez et al. (2011) were presented in a plane, i.e. in two dimensions, and thus disregarding any vertical excursions. Therefore we resort to 2D simulations in the present work, neglecting any variations in the vertical direction.

Next, concerning the second question, Bian (2003) considered the fish movement as a two-step process: first, the fish evaluates the attributes of various agents within the detection range of its sensory system; second, the fish executes a response to an agent by moving. As a part of the first step, the mechanisms by which migrating fishes orient themselves and finally arrive at their destinations, for instance swimming upstream hundreds of kilometres along the river in spite of changing circumstances, are still not well understood, e.g. Willis (2011). One theory is based on the assumption of geomagnetic and/or chemical cues which the fish use to guide them back to their birthplace. The fish may be sensitive to the Earth's magnetic field, which could allow the fish to orient itself in the ocean, so it can navigate back to the estuary of its natal stream (Lohmann et al., 2008). In the experiments by Rodriguez et al. (2011), however, the length of the physical fishway model was only about 20 m, which is negligible as compared to the distance of the long home journey of the fish. The variation in geomagnetic field over a 20 m stretch can definitely be ignored. The actual location of the fishway model was totally different from the prototype in the natural river and the Earth's magnetic field cannot be a suitable stimulus in our case. The water flowing in a fishway model is believed to be recirculated water from a reservoir or tank in the laboratory. This means that also chemical cues can be disregarded as stimuli. Although both geomagnetic and chemical cues can be excluded, the fish still swims upstream against the flow in the fishway. This implies that the fish movement is likely to be hydraulically mediated, as suggested by Goodwin et al. (2014), i.e. the local fish movement is initiated by stimuli in the adjacent flow field. Therefore, if the distributions of hydraulic characteristics are superimposed on the fish trajectories (Goettel et al., 2015), we can identify the hydraulic parameters that are the best agents to model the stimuli of the local fish movement.

As to the second part of this two-step process, the response of a fish to a certain agent is probably affected by the fitness and vitality of the fish. If, for example, a fish is exhausted and with poor physiological indices, the fish cannot do anything but to drift along with the stream even if an attractive stimulus has been detected. Therefore, in order to realistically model the response, sufficient experimental data should be accumulated to model the relationship between the stimulus, the physiological indices, and the response. Ideally, since the physiological indices may change after a response have been made, one should also track the variation in physiological indices along the trajectory. However, in spite of the absence of physiological indices in the experimental study of Rodriguez et al. (2011), one can safely assume that the physiological indices remained constant since their fish only swam through 7 pools with a total swimming distance of about 14 m during the period of recording the real trajectory. This is indeed a very short distance for a fish to swim and it is reasonable to assume that not only the physiological indices were almost constant but also that the response of the fish to the flow stimulus remained the same. This implies that a fish will swim with similar speed through all the seven pools. This assumption will be utilized later in Section 3.