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

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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 Rodrigues et al. (2011) were superimposed on several different parameters characterising 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 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 behavioral 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 behavior. 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 have 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 kilometers 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 20m, which is negligible as compared to the distance of the long home journey of the fish. The variation in geomagnetic field over a 20m 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 meters 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.

In the present study, a numerical model is developed aimed to simulate trajectories of a virtual fish through vertical slot fishways. We first compute the turbulent flow field in the

same vertical slot fishway as considered by Rodriguez et al. (2011) using Ansys Fluent. The influence of several different hydrodynamic parameters (stimuli) is considered, of which the flow velocity and the turbulent kinetic energy (TKE) turn out to be the most relevant. The trajectory of a given fish in the numerically simulated flow field is then obtained by an ELAM method (Goodwin et al. 2006, 2014) and programmed in C language based on the Ansys Fluent enhancement tool of User-Defined Functions (UDF). Predicted trajectories of the virtual fish are finally compared with the results from the fish trajectory experiments by Rodriguez et al. (2011) with which a convincing match is observed.

2 Flow Field and Stimuli Identification

Fig. 1. Geometry of the fishway consisting of 11 pools

The geometry of the computational domain of the fishway is exactly the same as in the experimental set-up used by Rodriguez et al. (2011). The full-scale fishway consists of 11 identical pools and the flow configuration is shown in Fig. 1. The dimensions of each pool are 1.85m×1.5m (length × width). The water flow is from right to left so that Pool 8 – Pool 10 are inlet pools, in which the inlet conditions are forgotten and the flow gradually develops to a stable state. Pool 0 is an outlet pool in which the flow adjusts to the outlet conditions. The remaining seven pools, i.e. Pool 1- Pool 7, are the active pools, in which the trajectories of fish are recorded and superimposed on the flow field. The Reynolds-

Averaged Navier-Stokes (RANS) equations of mass and momentum conservation for an incompressible fluid, e.g. water, can be written in Cartesian tensor form as follows:

$$\frac{\partial u_i}{\partial x_i} = 0 \quad (1)$$

$$\rho \frac{\partial u_i}{\partial t} + \rho u_j \frac{\partial u_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \mu \frac{\partial^2 u_i}{\partial x_j \partial x_j} + \frac{\partial}{\partial x_j} (-\rho \overline{u'_i u'_j}) + \rho g_i \quad (2)$$

where, $i, j = 1, 2$ and u_i is the mean fluid velocity in the x_i -direction. p is the mean pressure and ρ and μ are the density and molecular viscosity of the fluid, respectively. The gravity g_i is not included in the present study since the governing equations are solved only in the horizontal plane. The Reynolds stress tensor $-\rho \overline{u'_i u'_j}$ represents the effects of the turbulent velocity fluctuations on the mean flow. The set of governing equations (1, 2) is closed by means of a standard two-equation k - ε turbulence model with default parameters.

Fig. 2. The unstructured mesh in Pool 5 with mesh refinement around the baffles

The computational domain in Fig. 1 is discretized by an unstructured mesh with a total of 77 926 cells. The layout of the mesh in Pool 5 is shown in Fig. 2. A velocity-type

boundary condition is prescribed at the inlet to the fishway as a uniform velocity profile with a speed of 1.02m/s normal to the entrance to Pool 10. A pressure-type outlet boundary condition is given at the exit of the fishway through Pool 0. Regular wall boundary conditions are imposed all along the walls of the fishway as well as at the baffles. Even though the turbulent flow is inherently unsteady, the mean flow field computed by FLUENT approaches to a steady state.

The magnitude of the computed mean velocity vector in the seven active pools is shown in Fig. 3. The mean flow appears to repeat itself from one pool to the next one. The largest velocity magnitudes are observed in the narrow passage from one pool to the other. This is a direct consequence of the incompressibility of the fluid (water). Indeed, the computed mean flow in Fig. 3 is in good agreement with that found by Rodriguez et al. (2011).

Fig. 3. Mean velocity magnitude contours computed in the present study. Black and red dots are the trajectories of FishA and FishB, respectively, adopted from the experiments by Rodriguez et al. (2011)

The close correspondence between the present computed flow field in Fig. 3 and the flow field shown by Rodriguez et al. (2011) supports the current CFD-modelling of the Eulerian flow field. However, the experimentally obtained Lagrangian trajectories of two different trouts (FishA and FishB) exhibit almost no correlation with the mean velocity

magnitude. Let us therefore proceed and explore if the measured fish paths correlate better with some other flow characteristics. If so, that characteristic is likely to be a stimulus or agent to make the fish swim through the vertical slot fishway.

Velocity *vectors* are believed to be a more likely stimulus than the velocity *magnitude* since the vectors provide information also about the flow *direction*. Fig. 4 shows velocity vectors in four representative active pools together with the real fish trajectories superimposed. The velocity vectors reveal that recirculating eddies are developed on both sides of the high-speed jet which enters into a given pool through the narrow passage formed by the gap between the baffles. A third eddy is formed in the lower left corner of each pool. However, neither of the two real fish trajectories included in Fig. 4 seem to correlate with the direction of the velocity vectors. We are therefore inclined to conclude that neither the magnitude nor the direction of the mean flow act as active stimuli in the present case. However, the rheotaxis of fish is closely related to the velocity field, as will be discussed in Section 3.

Fig. 4. Velocity vectors in the active Pool3 – Pool 6 with the real fish trajectories superimposed. The velocity vectors correspond to the mean flow field shown in Fig. 3. The vectors are all of the same length to enable also the slowly moving fluid to be seen. The orientation of the vectors gives the local direction of the flow whereas the colours of the vectors give the magnitude of velocity.

Three other alternative flow quantities, which may serve as a stimulus, are displayed in Fig. 5. The mean turbulent kinetic energy (TKE) is shown in Fig. 5(a), while the turbulent eddy dissipation and the strain rate are plotted in Fig. 5(b) and Fig. 5(c), respectively. These three flow parameters exhibit rather different variations through the fishway. It is readily seen from the experimental trajectories that the fishes tend to avoid regions in which the turbulent kinetic energy exceeds about 0.35 J/kg or $0.35\text{m}^2/\text{s}^2$, but rather prefer regions with TKE in the range from about 0.1 to 0.3 J/kg and thus also avoid areas with the lowest energy levels, i.e. $\text{TKE} < 0.1 \text{ J/kg}$. Areas with such intermediate levels of TKE form a continuous “passage” along the upper part of the fishway in Fig. 5(a) which is followed by both fishes through five pools. However, while Fish A continues to follow this upper passage when it enters Pool 6, Fish B surprisingly selects a completely different route in order to avoid the excessively high TKE-level in the center of the pool. Smith et al. (2014) and Goettel et al. (2015) recently claimed that the flow turbulence might be a factor in fishes’ path selection, and Charles (1998) suggested that there might be optimal levels of turbulence for migrating salmonids. The results in Fig. 5(a) provide evidence for these conjectures.

While the turbulent kinetic energy is associated with the large-eddy turbulence, the turbulent eddy dissipation shown in Fig. 5(b) stems from the small-scale eddies. The turbulent dissipation appears to attain high levels along the flow passage through the slotted fishway, but no clear-cut correlations with the fish trajectories can be seen. The strain-rate of the mean flow in Fig. 5(c) reaches high levels in the narrow passages between the baffles,

Fig. 5. The simulated distribution of (a) turbulent kinetic energy, (b) turbulent eddy dissipation, and (c) strain-rate in Pool1 – Pool7. The same experimental trajectories for FishA and FishB as in Fig. 3 are superimposed onto the flow field. Note that the colour bar for part (a) is linear whereas the colour bars for parts (b) and (c) are logarithmic.

similarly as the velocity magnitude in Fig. 3. Strain rates were used as a stimulus in the investigation of Goodwin et al. (2006). In the present study, however, the strain-rate shows no particular correlation with the fish trajectories and can therefore not be considered to act as a primary stimulus.

On the basis of the results presented and discussed in this Section, we can safely conclude that the mean turbulent kinetic energy TKE is by far the best stimulus in modelling of fish movements in a slotted fishway.

3 Sensoring and Behavioural Model

The sensory processing of fishes in streams and currents is a multimodal sensory task. The inner ear, vision, tactile sense, and mechanosensory systems all make significant contributions (Montgomery et al. 2000). However, fish biologists suggest that the lateral line system of fish can be regarded as a “hydrodynamic antenna” that is configured to retrieve flow signals (Montgomery et al. 1995, Goodwin et al. 2006, Ristroph et al. 2015). A fish evaluates all stimuli in the detection area, i.e. within the so-called *sensory circle*. Generally, the sensory area is a three dimensional space which is often partitioned into horizontal and vertical components for the convenience of analysis and simulation. For the present 2D flow field, however, we only need to consider the horizontal movement of the fish. Therefore a 2D sensory area is considered. The radius of the sensory circle is defined as the sensory query distance (SQD) introduced by Goodwin et al. (2006). SQD thus represents the sensory range of the fish’ lateral line mechanosensory system, as depicted in Fig. 6.

We adopt the definition of the fish’ sensory model proposed by Goodwin et al. (2006):

$$SQD_b = \Delta t \cdot S_f \cdot D_a \quad (3)$$

$$SQD = \max \{ SQD_b, SQD_{CFD} \} . \quad (4)$$

Fig. 6. The circle patch represents the circumference of the detection area (sensory circle) of the fish. At a given moment, the fish in the fishway is located in the center of this circle (dark red spot). From this position the fish will evaluate the stimulus along the circle. If the dark red spot to the lower right has the preferred value, the path from the center to this spot indicates the direction of the fish movement. The distance between the two dark red spots is SQD . In addition, if the fish happens to be close to a solid wall, the fish movement has to be re-directed in order to avoid collisions with that wall.

where SQD_b and SQD_{CFD} are the biological and CFD-model sensory query distances, respectively. The biological sensory query distance is determined by means of the fish body length S_f , the operating range of the fish sensory system D_a in a 1.0s time increment, and the time increment Δt . In the study by Goodwin et al. (2006) SQD_{CFD} exceeded SQD_b and SQD fluctuated randomly from time to time between 100% and 150% of SQD_{CFD} (determined by trial and error). Goodwin et al. (2006) also emphasized that animals may

perceive time according to the rate of events and not according to a fixed time increment typically used in computer programming (Hills and Adler 2002). It is conventionally suggested that the “active space” of the lateral line system is from 1 to 2 body lengths S_f , but the actual range depends on a number of other factors, including the size and form of the disturbance source (Coombs 1999). Farnsworth and Beecham (1999) also indicated that randomness is a fundamental feature of animal choices. By integrating this information, we assume that the fish will make a response to an agent at a distance of about one fish body length with random fluctuations ($0 < RN < 1$). This gives the modified equation:

$$SQD = L_f \cdot (1 + 0.5 \cdot RN) \quad (5)$$

used in the present study, in replacement of equation (4). The fish body length L_f is 19.1cm for FishA and 20.2cm for Fish B according to experiments by Rodriguez et al. (2011). Thus, the longer the fish is, the further away can a given hydrodynamic stimulus source be detected.

In the present study, based on the results and discussions in Section 2, the fish prefers to follow areas where the TKE-level is between 0.1 and 0.3 J/kg. In the simulations, the fish will evaluate the TKE-level along the periphery of the sensory circle and the mesh cells with preferred TKE values will be selected. If preferred values are found simultaneously both upstream and downstream of the fish, the fish will always select the upstream mesh cell(s). This behaviour can be explained by the positive rheotaxis of the target fish. Positive rheotaxis is a form of taxis observed in many aquatic organisms, e.g., fish, whereby they will generally turn to face into an oncoming current. Rheotaxis is directly related to the direction and magnitude of the flow. However, as shown in Fig. 4 in Section 2, the velocity

vectors alone are not sufficient to reproduce the trajectory of the fish movement. Nevertheless, when combined with the selected TKE stimulus, rheotaxis is an essential agent to assure that the fish keeps moving upstream most of the time. In other words, the fish will always choose the upstream stimulus rather than the downstream one. Only if the fish can not find any upstream agent, it will select a downstream one. This orientational behaviour is adopted and implemented in our modelling.

Furthermore, the mesh cells are scattered and multiple cells may sometimes have almost the same TKE values. Our solution to this problem is to make a weighted-average of all values in the preferred grid cells. The cell which possesses the value closest to the weighted-average value is selected. Once the preferred grid cell is determined, the direction of fish movement is decided accordingly.

Speed and time are also two important parameters in our model. Unfortunately, however, there are rarely any detailed experimental data available for the time that the fish spends along a given trajectory. Based on their experiments, Rodriguez et al. (2011) used an average ascending velocity of 1.0m/s (relative to the ground). This constant average ascending velocity in some sense validate our assumption in Section 1, namely that the physiological indices can be regarded as constant during the recording of the real trajectories in the experiments of Rodriguez et al. (2011). If so, the response made by the fish to a flow stimuli is also constant, which means that the fish swim with similar speed in each of the fishway pools. Here, we adopt 1.0m/s as a rough estimate of the velocity of the fish's movement in each sensory circle. This choice is not only convenient in the translation of the movement process into the computer code, but also close to the observed

phenomenon: the fish is clever enough to swim straightforward to the bait or shelter regardless of its local flow environment. This is supposed to be an ability that has developed through evolution over billion of years. This speed should be considered as a fishway-scale averaged velocity. In a given sensory circle, the velocity might be quite different from the real local velocity. Considering also the random features of the fish movement, this technique guarantees that the total ascending time of a fish swimming through the fishway is of the same order of magnitude as the time consumed in the full-scale laboratory experiments. Thus, with $SQD \approx 0.3\text{m}$ (about 1.5 times the fish body length) and the resultant speed $\approx 1.0\text{m/s}$, the average ascending time in each sensory circle is about 0.3s.

In the present computational model, we also invoked the constraint that, during each time step Δt , the distance of the fish movement can not exceed SQD , i.e. the perception distance SQD is always larger than the distance that the fish could actually move in one time step. Recall the previously stated reasoning by Bian (2003) that the second stage of the movement process is that executing a response to the agent by moving. In our modelling, this implies that the fish will swim directly forward to the place where the preferred TKE level is perceived, but the fish cannot move out of the sensory circle in a single time step Δt .

In summary, following the detection and evaluation of a stimuli, in our model the fish moves a distance $\Delta \vec{X}$ in accordance with the following equations:

$$\Delta \vec{X} = \vec{X}_{t+1} - \vec{X}_t = \Delta \vec{X}_{water} + \Delta \vec{X}_{fish} \leq SQD$$

$$\Delta \vec{X}_{water} = \vec{V}_{water} \cdot \Delta t$$

$$\Delta \vec{X}_{fish} = \vec{V}_{fish} \cdot \Delta t$$

Here, $\vec{V}_{water}$ is the water velocity at the center of the sensory circle and $\vec{V}_{fish}$ is the velocity of the fish in the sensory circle, see also Fig. 6. Based on our assumptions, the resultant velocity is not representative of the real efforts made by the fish and only the actual swimming velocity is of relevance. If one therefore can establish a relationship between the physiological indices of the fish, e.g. bioenergetic costs, and the kinetic parameters $\Delta\bar{X}_{fish}$ and $\bar{V}_{fish}$, the resting behaviour of the fish in the fishway, and thus an estimate of how long the fish will rest, can be included in further modelling work.

4 Results

Finally, the proposed behavioural model with the parameter values suggested above was implemented as a user-defined algorithm in the CFD software Ansys Fluent. Two virtual fish were released to the left in Pool 1 at the position indicated by a red star in Fig. 7. Their paths through the fishway in the already computed two-dimensional flow field reported in Section 2 were tracked forward in time. The resulting trajectories of the fish are shown as blue squares in Fig. 7, where also the trajectories measured by Rodriguez et al. (2011) have been plotted.

The simulated path of Fish A proceeds upstream through the seven different pools in a similar manner as the experimental trajectory. Fish A all the time avoids the central zone with prohibitively high turbulent kinetic energy (TKE) by moving along the upper wall of each and every pool. It should be recalled, however, that the TKE-level is not the only stimulus considered. A positive rheotaxis is assumed under otherwise equal circumstances in order to assure that the fish preferentially swims upstream rather than downstream.

(a) Trajectory simulation of Fish A with fish length $L_f = 19.1\text{cm}$

(b) Trajectory simulation of Fish B with fish length $L_f = 20.2\text{cm}$

Fig. 7. Predicted trajectories (blue squares) using the proposed model. (a) Fish A; (b) Fish B.

The fish is released at the upper left corner of Pool1 and swims upstream through the fishway. The black and red dots show the measured trajectories of Fish A and Fish B from the experiments by Rodriguez et al. (2011).

Indeed, subjected to these stimuli the virtual Fish A proceeds rather persistently upstream all through the fishway

The behaviour of the virtual Fish B is fairly similar to that of Fish A, with the important exception of the path chosen through Pool 3. Upon entering that particular pool, Fish B chose an alternative path around the large central zone with too high levels of TKE (red colour in Fig. 7(b)). In spite of this longer route, the fish is able to leave Pool 3 through the narrow passage into Pool 4. From then on, Fish B again follows the upper and shorter route throughout the remaining pools, just as Fish A did.

We are inclined to conclude that the choice between the upper (short) and lower (longer) route through a given active pool is made randomly (recall the random number RN in eq. (5)), but with a strong preference for the shorter path. This conjecture is supported by the trajectory of Fish B, as measured by Rodriguez et al. (2011). After the real Fish B has followed the upper route through the first five pools, the alternative longer route is chosen through both Pool 6 and Pool 7, as seen in Fig. 7(b). Although the mean flow field and the turbulence level is almost identically the same in the seven active pools, even the real Fish B chose a completely different route through some of the pools.

5 Discussion on Mortality Predictions

Fish mortality (or fishway passage efficiency) is the end objective of the modelling of fish trajectories. Due to the lack of physiological experiments, physiological indices could not be taken into account in the present study. Nevertheless, a framework for how to

incorporate physiological indices into our modelling approach can be outlined as follows. The process of assessing fish mortality is divided into three stages. In the *first stage*, the prior experience of the migrants before they arrive at the entrance to the fishway should be considered. Every virtual (i.e. Lagrangian) fish is digitally “tagged” and its fitness level and physiological indices (representing the mortality rate) quantified. This information will serve as biological/physiological boundary conditions at the entrance to the numerical fishway, analogous with the hydrodynamic boundary conditions routinely used in CFD. Then, in the *second stage*, the variation of physiological indices should be tracked along the particular trajectory followed by an individual fish in order to account for example for the longer time it takes the fish to follow a longer path, the inevitable excess energy costs, and the associated variation of the physiological indices, which eventually may increase the mortality.

At the *third stage*, the final status of the physiological indices for each digitally tagged virtual fish should be recorded at the end of the swimming period. This information is essential, not only for fishway efficiency evaluation, but also for assessment of the post-passage. This three-stage digital experiment mimics the popular experimental approaches such as electromyogram telemetry (EMG) (Pon et al. 2009a, b), radio-tagged or PIT-tagged techniques (Calles and Greenberg, 2009), the acoustically-tagged method (Goodwin et al. 2006), and computer vision (Rodriguez et al. 2011) combined with physiological biopsy. The essential features of the proposed three-stage modelling approach and these experimental techniques are the same: they are based on Lagrangian tracking of individual fish, including the gathering of statistics which enables an evaluation of the passage system.

Accuracy is an important feature of any evaluation method for fish mortality. Our modelling approach is essentially a digital experiment similar to real experimental approaches. Therefore, with access to accurate model parameters, we should in principle be able to provide estimates of the mortality rate almost as accurate as a real experiment. The required model parameters can be obtained in several different ways. By survey and physiological biopsy, biological/physiological boundary conditions can be specified in our model. Or like in the work by Gislason et al. (2010) where an empirical formula for the relationship between fish size, temperature, growth characteristics, and natural mortality was recommended. Similarly, a relationship between fish size, hydraulic parameters, and fish mortality (expressed by physiological indices) and the fish trajectory can possibly be established.

Due to the existing gap between hydraulics and biology in fishway design, the functioning of a specific fishway is only rarely evaluated (Calles and Greenberg, 2005). In practice, traditional methods for fishway passage evaluations are based only on simple hydraulic indices like, e.g. the maximum velocity or energy dissipation in a pool, turbulence characteristics of the flow, or the velocity distribution in the fishway and is only marginally related to the performance of fish in the fishway, e.g. swimming capabilities (Rodríguez et al. 2006). The rough estimates thus obtained are insufficient for sustainable fishway design.

However, once sufficiently reliable model parameters become available, we believe that our predictive model can provide a mortality rate estimation almost as accurate as an experiment and definitely better than traditional evaluation methods used in hydraulic

engineering. Like the explosive usage of CFD in fluids engineering development and design, we believe that numerical simulations combined with physical tests, or even numerical simulations alone, will be used in future fishway design and evaluation. Moreover, the present ELAM modelling approach can be applied not only to fishway design, but also to the entire migration journey for various fish species.

6 Concluding Remarks

In this paper, a simplified individual-based model (IBM) to simulate the movement of a single fish in a vertical slot fishway has been developed. Firstly, however, we computed the flow in the fishway by means of a modern CFD software tool. The mean flow field was validated with experimental results and additionally comprised also essential turbulent flow quantities. Fish trajectories measured by Rodrigues et al. (2011) were then superimposed on several different hydrodynamic parameters such as the mean flow velocity, turbulent kinetic energy (TKE), turbulent eddy dissipation, and strain rates. The correlations, if any, between the different hydrodynamic parameters and the measured trajectories were examined in detail and the turbulent kinetic energy (TKE) was identified as the single most important stimulus. In addition, the mean velocity was adopted as a second agent in order to mimic positive rheotaxis.

Finally, an ELAM (Eulerian Lagrangian Agent Method) model, i.e. the combined Eulerian CFD-model and the Lagrangian IBM-model, was used to reproduce the trajectory of a virtual fish. The simulated fish trajectories were in good agreement with their measured counterparts (Rodrigues et al. 2011) in the same vertical slot fishway. Both the

preferred short route and the alternative longer route through an active pool were faithfully reproduced.

By applying an IBM-model in a fishway study, we can conclude that:

- (1) the trajectory analysis and replication, as a method to understand the causal rules behind fish navigation, is the basis of this method and should be a focus area for further research;
- (2) the accurate computation of the flow field in the fishway is necessary since one need to identify the single or multiple hydraulic parameters that mostly affect fish movement. The present calculations were based on the RANS formalism which normally returns a more realistic mean flow field than turbulence field, although the latter may affect further stimuli-response analysis;
- (3) by excluding possible contributions due to the fish's inner ear, vision, and tactile sense to their orientation and movement in the aquatic environment and only consider the function of the mechanosensory lateral line system, our understanding is still limited. Those other factors, which may affect the selection of *SQD*, have to be considered based on empirical research. This is also the case for the movement law in each *SQD* area. Nevertheless, *SQD* does provide the important linkage between the Eulerian CFD model and the fish movement in the Lagrangian reference frame;
- (4) in the present study, TKE and the water velocity turned out to be the most important variables for the ascending and resting behaviour of the fish.

Nevertheless, other variables excluded here might also influence the fish locomotion.

Some of the parameters involved in the present modelling study are uncertain or even completely unknown. For this reason we invoked several relatively crude assumptions. However, these assumptions were not made arbitrarily but either based on general observations of the biological nature of fish or based on former studies. It is anyhow awarding that the predicted fish trajectories obtained with the present ELAM modelling correspond favourably with measured trajectories of alive fish. It appeared to us that the lack of experimental data limits the popularity of this type of modelling. The present study may therefore pave the way for a new modelling approach aimed to simulate fish trajectories in fishways with complex geometries which are easily handled with modern CFD-tools.

In spite of the existing limitations mentioned above, we believe that as the secrets of the fish behaviour are discovered by the biologists and more accurate and detailed flow data are provided by hydraulic and fluids engineers, the assumed model parameters can be more accurately estimated and possible new parameters included in a more robust model. The IBM method combined with some statistical tools, e.g. Monte-Carlo simulations, might be the best way to proceed towards better design and evaluation of hydraulic structures in aquatic environments.

Acknowledgement

This study has been supported by Engineering Research Center of Eco-environment in Three Gorges Reservoir Region, Ministry of Education, China Three Gorges University (KF2015-01), the National Natural Science Foundation of China (51409151, 51579136), Program for Changjiang Scholars and Innovative Research Team in University (IRT1233) and Department of Energy and Process Engineering, Norwegian University of Science and Technology (NTNU), Norway. The anonymous reviewers kindly pointed out three essential references to us and also encouraged us to include a discussion on fish mortality. Finally, thanks are due to Wang Yu and Shi Xiaotao for helpful suggestions.

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