

Mathematical Modeling For Fish Adaptive Behavior In A Current

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Abstract

A mathematical model has been developed to simulate the behavior of fish in reservoirs and rivers. This model is based on a 3-dimensional flow model and it uses mass particles for the modeling of the fish. An artificial life method is applied to define the characteristic behavior of the mass particles, i.e. the fish, such as adaptive and distributed behavior in a current. We call this model the "adaptive particle model". All parameters in the model have simple, well defined meanings and they have been estimated from various flume experiments using real fish. Simulations have been carried out to validate the model. The simulation results agree satisfactorily with the experimental results. The particles in the numerical model show natural behavior of fish. This study indicates that this approach is a good method for the evaluation of an ecological system.

Keywords: fish, adaptive behavior, particle, artificial life, 3-dimensional flow model, reservoir, stream

1. Introduction

A 1-dimensional model is generally applied to estimate the water temperature distribution, and flow condition for environment prediction in a reservoir. Such a model expresses water quality, and plankton in terms of their concentrations. This type of model is suitable for the prediction of long term trends in water quality [1]. However, it is difficult to apply this model to the trapping of fish by intake works and in situations where the fish population is changing in size. Fish exhibit considerable diversity and complexity in their behavior, which is influenced by the flow characteristics in the reservoir and the associated daily changes in the spatial distribution of plankton, the group interaction of small fish, and the preying upon them by large fish. Existing models generally describe the situation in terms of concentrations. These equations do not describe the adaptive and distributed behavior of plankton and fish well. It is for example difficult to include the trapping of fish in such a model. Therefore, the artificial life (A-life) method has been applied to model the behavior of the fish [2]. This model describes fish and plankton as mass particles with certain behavior characteristics.

The A-life model determines the behavior of the particles, such as adaptive and distributed behavior, by following a number of simple logical rules. Quantitative rules of change are also applied to the particles. This adaptive particle model makes it easy to define the equations governing the above mentioned phenomena. This is a big advantage over the modeling approach based on the concentration equations. Different kinds of particles can be defined by changing the particle characteristics.

2. Mathematical Model

The first part of the mathematical model is based on a 3-dimensional flow simulation model. The flow characteristics are important for the motion of the particles. The flow equations are the continuity and momentum (Navier-Stokes) equations as follows.

$$\Delta A u = 0 \quad (1)$$

$$\frac{\partial u}{\partial t} + \frac{1}{V} A u \nabla u = -\frac{1}{\rho} \nabla P + \frac{\mu}{\rho} \nabla^2 u + g \quad (2)$$

Where, u is velocity, P is pressure, ρ is density, V is obstacle volume rate, A is space rate, G is gravity acceleration, μ is viscosity coefficient, and ∇ is $\partial u / \partial x + \partial v / \partial y + \partial w / \partial z$. V and A are based on FAVOR (Fractional Area Volume Obstacle Representation) method. The viscosity μ is computed using an eddy viscosity model, here the $k-\epsilon$ model was used. The grid is the rectangular grid.

The second part of the model treats fish and other objects as particles. These particles can also be defined as groups, if time and space are long and large. The particles have a mass, and are influenced in the current by drag forces. There is, however, no reverse effect of the particle motions on the current. The dynamics of the particles is governed by the equation,

$$\frac{\partial u}{\partial t} = \frac{1}{\rho} \nabla P + g + \beta(u - U)|u - U| \quad (3)$$

Where, U is particle mean velocity, and β is a drag coefficient. The drag coefficient can be defined using an empirical relation, which is a function of Reynolds number $Re (= d \rho (u - U) / \mu)$ of the flow around the particles, where d is the particle diameter.

$$C_D = \frac{4d}{Re} \beta = \frac{24}{Re} + \frac{6}{1 + \sqrt{Re}} + 0.4 \quad (4)$$

The action of the particles is influenced a few simple rules, such as increasing and decreasing speed, changing direction because of interaction with the other particles and particle groups. The rules of behavior are [3]:

- (1) Adjustment of speed: A particle moves by keeping its optimum cruising distance (L_{oc}) to the nearest particle. The particle slows down its speed to avoid collision when the distance L_{BF} to the nearest particle in front is smaller than L_{op} . The other particle will speed up. If the distance is larger than L_{op} but smaller than the range of vision, the reverse will happen. The optimum cruising distance is approximately 0.5 of particle size. The particle tries to match its cruising speed also to a steady cruising speed (U_{ad}), which is almost constant for every particle. The particles have a maximum cruising speed (burst speed) and they never exceed it. Further, α_1 is the acceleration ratio, α_2 is deceleration rate, and L_{BB} is the distance to the back particle.

$$\begin{aligned} U(n+1) &= \alpha_1 U(n) & L_{BF} < L_{oc} \text{ or } L_{BB} > L_{oc} \\ &= \alpha_2 U(n) & L_{BF} > L_{oc} \text{ or } L_{BB} < L_{oc} \end{aligned}$$

$$\begin{aligned} U(n+1) &= \alpha_1 U(n) & |U(n)| > U_{ad} \\ &= \alpha_2 U(n) & |U(n)| < U_{ad} \end{aligned} \quad (5)$$

- (2) Adjustment of the moving vector: A particle moves parallel to the nearest one. The particle moves to the center of gravity of another particles group. It moves in the opposite direction of the flow when the flow velocity exceeds its maximum speed. It moves so as to avoid obstacles and it has a specific favorite area. Some particles follow other particles for preying upon them and the other particles try to escape from the predators. Furthermore, some random variation is added to the moving direction when the above conditions do not apply. This is shown in Fig. 1. The adjustment of the moving vector is governed by the equation.

$$D = \frac{U(n)}{|U(n)|} + \sum_{i=1}^8 \beta_i \frac{F_i}{|F_i|} + \sqrt{2} \beta_9 R$$

$$U(n+1) = |U(n)| \frac{D}{|D|} \dots \dots \dots (6)$$

- (3) Territory and other factors: Particles follow the above law within their territory, so as to avoid collision, and ensure cruising, grouping, search, and blind territory. Finally, equations are included for increasing the number of particles, and for decreasing them due to preying and life span [4].

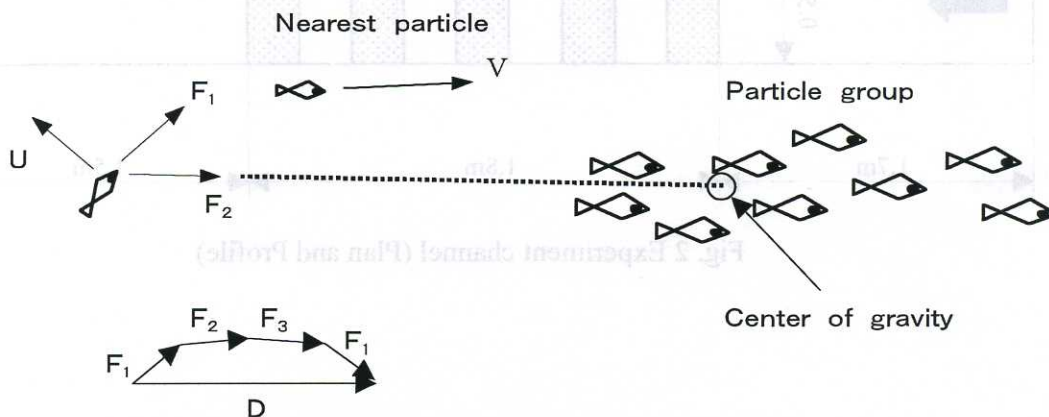


Fig. 1 Adjustment of moving vector

3. Model Parameters

In this study the experiment and analysis were done using Japanese char (Body length: 11-15cm). The experimental waterway determining the model parameters is shown in Fig. 2 and Photo 1. The key model parameters are shown in Table 1. The Parameters 1-3 in Table 1 define the characteristic swimming speeds and Parameters 4-6 determine the other fish adaptive behaviors. The parameters in Table 1 are obtained from literature and flume tests using two kinds of fish: White cloud mountain minnow (small) and Japanese char (large). Generally, it is difficult to do experimental tests using large fish. Especially, a huge experimental facility (like a channel) is required for determining the swimming speed parameters. Therefore, the characteristic speeds of the small fish have, for the moment, also been applied to Japanese char. The simulations have been carried out using the parameters settings indicated in Table 1. The results are shown in Photo 2 and 3.

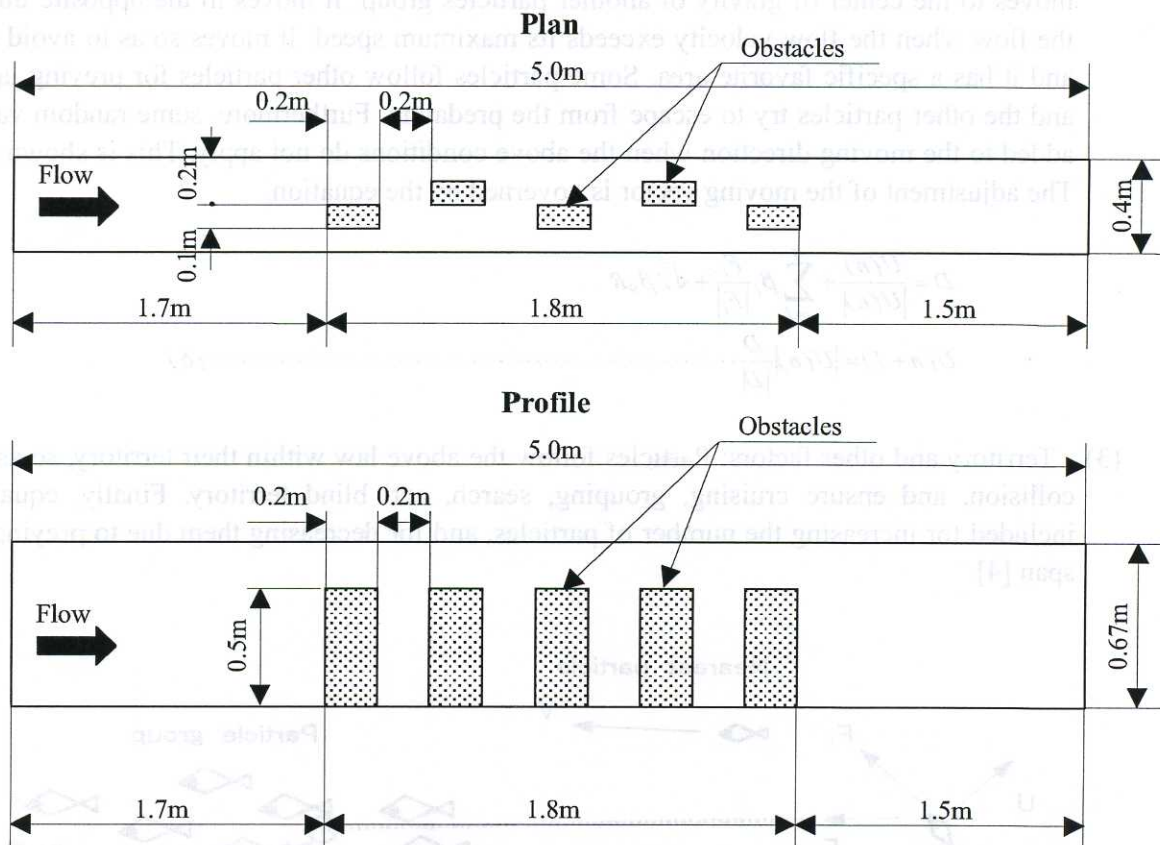


Fig. 2 Experiment channel (Plan and Profile)

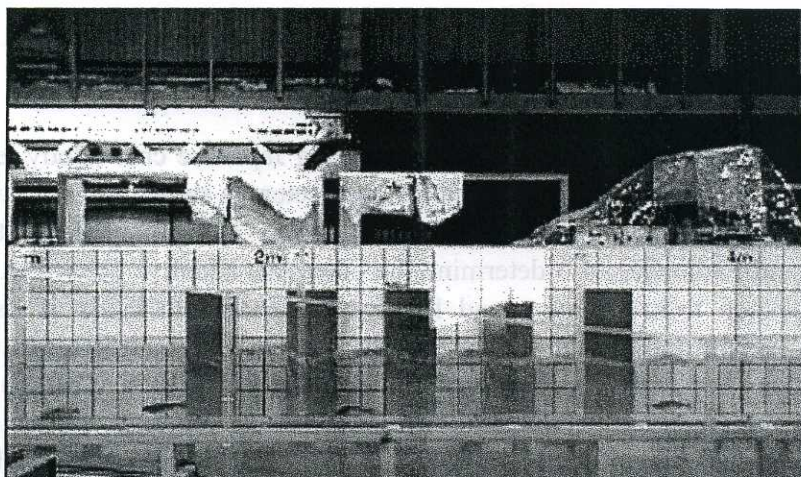


Photo 1 Experiment channel

Table 1 Model Parameters

Item (A-life model) No.		Parameter from references	White cloud mountain minnow ^(*)2)	Japanese char ^(*)3)	
			Parameter from experiment	Estimated parameter ^(*)4)	Parameter from experiment
1	Cruising speed	2 - 4 BL/s ^(*)1)	2-13.3 BL/s	▶ 2-13.3 BL	—
2	Maximum speed	10 BL/s	16.5-30.0 BL	▶ 16.5-30.0 BL	—
3	Judging speed for upstream moving	—	6.0 cm/s	6.0 cm/s	—
4	Visual limit distance	—	21.0 BL	▶ 21.0 BL	—
5	Optimum cruising distance	Optimum distance: 1.0 BL Minimum distance: 0.3 BL	1.8 BL	▶ 0.3 BL	—
6	Collision avoidance distance	—	3.6 BL	—	3.0 BL

*1) BL: Body Length (cm)

*2) White cloud mountain minnow (Scientific name: *Tanichthys albonubes*) BL=2.8-3.0cm

*3) Japanese char (Scientific name: *Salvelinus leucomaenis*) BL=11-15cm

*4) These parameters are estimated from the references and the experimental parameters using "White cloud mountain minnow"

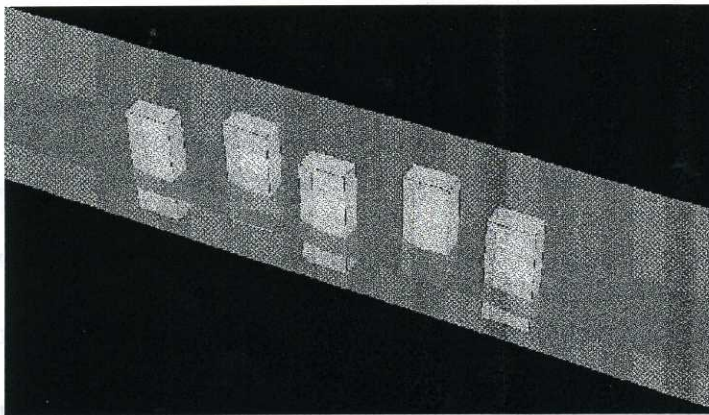


Photo 2 Simulation of Fish Behavior at the beginning

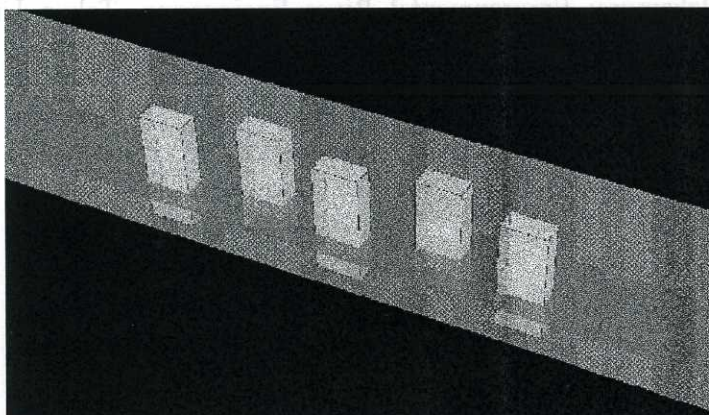


Photo 3 Simulation of Fish Behavior after few minutes later

4. Conclusions

In this paper, mathematical modeling for fish adaptive behavior in a current is discussed.

The following conclusions have been drawn.

- (1) The behavior of fish in a stream can be described by the adaptive model, which is based on the A-life method.
- (2) Some parameters were obtained from experimental tests for fish adaptive behavior using real fish.
- (3) The parameters were applied to the "adaptive particle model" which is based on a 3-dimensional flow model.
- (4) The simulations have confirmed that this modeling approach describes the fundamental behavior of particles such as fish in a stream.

Finally, our recommendations are as follows:

It is necessary to determine a review method, and establish the qualitative and quantitative characteristics of particles. For the future development of this model and for making predictions using this model, it will be necessary to determine the characteristic parameters from actual measurements and experimental tests. If it is possible to satisfy the above conditions, this approach can be applied to study the trapping of fish by intakes in a reservoir, and for the evaluation of fish ways.

References

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