Research on Casualty Characteristics of Fish in Tubular Turbine based on IB-LBM method

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Abstract. The IB-LBM numerical method particularly effective at simulating the motion dynamics of individual or more fish in the turbine. Based on this method, the pressure and pressure gradient damage of the fish passing through the tubular turbine are analyzed. From the results, it can be found that the low pressure and excessive pressure gradient in the runner can result in irreversible damage on the swimming bladder and eyes of the fish. So the runner is the main component induces fish casualty, and its minimum pressure and pressure gradient need to be limited in the design process.

1. Introduction
The ecological problems caused by the development and utilization of hydropower resources have not been solved so far. One of the prominent aspects is the negative impact of hydropower projects on fish ecology. The construction of water conservancy projects such as dams seriously affected the survival of fish, especially for fish that migrate and lay eggs. And it may lead to the extinction of certain ethnic fish in the long term.

For hydro turbines, the main factors causing fish casualties are pressure, blade strike, shear stress and cavitation [1]. The low pressure and large pressure gradient zone appearing in the flow channel will injures fish. The injuries mainly includes eyeball bulging, broken fishbone, internal bleeding caused by vascular burst and embolism of blood vessels, etc. [2]-[3]. Abernethy [4] and Richmond [5], who comes from the Pacific Northwest National Laboratory (PNNL), focused on the biological mechanisms of fish damage. Among them, Abernethy conducted a series of experiments to research the frequency of damage, the location of injury and the severity of injury in different types of fish.

2. Solver Theory
The Immersed Boundary (IB) method was originally proposed by Peskin and was successfully applied to simulate blood flow in the heart [6]-[7]. The IB method represents the solid boundary with a set of Lagrangian points, and then the flow field inside and outside the immersed boundary is covered by a series of Euler nodes. The density distribution function is defined on the Euler node and is added on the solid boundary. The physical force that characterizes the interaction of the fluid with the particles is shown in Eq. (1). This equation will be combined with the incompressible fluid flow equations to solve the flow field.
\[
f(x,t) = \int g(X,t)\delta(x-X)ds
\]

The lattice is the LBM-based discretization calculation unit based on mesoscopic particles. It consists of a discrete point Cartesian distribution and a discrete velocity set. The discrete velocity set has a common expression, that is, the dimension of the problem and the number of discrete velocities \( D_nQ_m \). In this paper, the D3Q19 model was used. The model is shown in Figure 1.

![D3Q19 model](image)

3. Validation of Numerical Method
A tubular turbine was used as the research object in this paper. The parameters of this turbine are shown in Table 1. And the geometry of this turbine is shown in Fig. 2.

| Main Parameters            | Symbol | Unit | Value | Main Parameters            | Symbol | Unit | Value |
|---------------------------|--------|------|-------|---------------------------|--------|------|-------|
| Nominal Diameter          | \( D_1 \) | m    | 3.6   | Rated Speed               | \( n_r \) | r/min | 150   |
| Rated Output              | \( P_r \) | kW   | 5500  | Rated Flow                | \( Q_r \) | m\(^3\)/s | 76    |
| Rated Water Head          | \( H_r \) | m    | 7.3   | Rated Efficiency          | \( \eta_r \) | /   | 92.9% |
| Number of Guide Vanes     | \( N_1 \) | /    | 16    | Number of Runner Blades   | \( N_2 \) | /   | 3     |

![Three dimensional model of the whole flow passage of the turbine](image)

The number of lattices will affect the efficiency and accuracy of the simulation. The number of lattices increases with the resolution, and the torque and efficiency values of the turbine gradually stabilize. Finally, according to the lattice independence analysis, 4.94 million was selected as the number of lattices.

In the simulation, the following three working conditions are selected. From the table 2, it can be seen that the error between the simulation and experimental data of hydroturbine power is less than 5\%. Therefore, the IB-LBM numerical method is reliable and effective. It can be used to research the casualty characteristics of fish when they passing through tubular turbine.
### Table 2. Working conditions

| Number | Flow Rate $Q \text{m}^3/\text{s}$ | Unit Speed $n_{11} \text{r/min}$ | Unit Flow Rate $Q_{11} \text{m}^3/\text{s}$ | Time mean value of Torque $T \text{kN}\cdot\text{m}$ | Power Operating $P_c \text{kW}$ | Actual Operating Power $P \text{kW}$ | Power Error Rate |
|--------|-------------------------------|---------------------------------|---------------------------------|---------------------------------|-------------------------------|---------------------------------|-----------------|
| Condition 1 | 77.000 | 189.0 | 2.07 | 353.44 | 5551.85 | 5689.24 | 2.41% |
| Condition 2 | 65.819 | 188.2 | 1.77 | 299.76 | 4723.56 | 4917.19 | 3.93% |
| Condition 3 | 98.178 | 238.2 | 3.33 | 268.81 | 4222.50 | 4383.39 | 3.67% |

### 4. Results and Discussion

To simplify the modeling process, the fins of fish are omitted and the shape of the fishtail is simply modified. The 3D model of fish is shown in Fig. 3.

Figure 3. 3D model of fish

In order to obtain the pressure value of the fish in the water flow, three monitor points were selected on the fish body to monitor the pressure of the fish. The three monitor points were selected on the fisheye range, the bottom of the fish abdomen and the tail of the fish respectively. The distribution of these three monitor points on the fish is shown in Fig. 4.

4.1. Changes of pressure on the surface of fish

When the fish passing through the tubular turbine, its pressure state is shown in Fig. 5. Six characteristic times are selected to analyze. From Fig. 5, it can be seen that the pressure state of the fish at various positions is different. When the fish moves from the bulb region to the draft tube region, the pressure changes from the high value to the low value. After passing through the runner, the fish enters the draft tube region, and the pressure on fish slowly increase.

Figure 5. Attitude of fish passing through tubular turbine
According to the simulation results, pressure distribution on fish at different times are shown in Fig. 6. From the figure, it can be seen that the pressure distribution on the fish is not uniform. When the fish moves from the bulb region to the draft tube, the pressure on the fish decreases first and then increases. The minimum pressure on the fish appears at the point 1, which represents the fishtail. And the minimum pressure appears when the fish is close to the suction surface of the runner blade. The value of the minimum pressure is 44.734 kPa, which is lower than the pressure damage threshold of 50.66 kPa. So the fish will suffers from pressure damage in the runner.

![Figure 6. Changes of the pressure at monitor points and the velocity of fish](image)

**Figure 6.** Changes of the pressure at monitor points and the velocity of fish

**Figure 7.** Surface pressure distribution of fish through a turbine

4.2. Changes of pressure gradient on fish surface

In order to establish the pressure gradient distribution, the research carried out by the Thomas [8] and Hecker [9] is used for reference. Based on their research, the pressure gradient can be calculated by the following Eq. (2).

\[
\tau_\theta = \frac{dp}{dt} = V_x \frac{\partial p}{\partial x} + V_y \frac{\partial p}{\partial y} + V_z \frac{\partial p}{\partial z}
\]  

(2)

Based on the Eq. (2) and the simulation results, the pressure gradient of the whole flow field can be calculated. And the changes of the pressure gradient at the three monitor points is shown at Fig.8.
Figure 8. Changes of the pressure gradient at monitor points

It can be seen from the Fig.8 that the water flow in the bulb region is stable, so the pressure gradient in this region is nearly zero. When the fish comes into guide vane region, the pressure gradient on the fish begins to turn negative, and the absolute value is increasing, which means that the pressure gradient of fish subjected also increases. When the fish enters into the runner region, the pressure gradient is rapidly reduced. But it rise again slowly when the fish enters intodraft tube region.

Reference the experiment data of the PNNL [8], it can be known that if the absolute value of pressure gradient greater than 3.5 MPa/s, the swimming bladder and eyes of fish would be injured. So this pressure gradient threshold also be adopted in this paper. Based on this threshold and Fig. 8, it can be seen that the pressure gradient at point 1 and point 3 are below the threshold in the runner. The point 3 locates in the eyes of fish, so it means the fish eyes will be injured by the excessive pressure gradient. The point 1 locates at fish tail where without important organs, so it won't cause obvious damage to fish.

5. Conclusion
The main conclusions of this paper are as follows:
1). The IB-LBM numerical method can effectively simulate the movement of the fish passing through the tubular turbine. Due to the advantages of this method, the pressure distribution and movement velocity of fish at any time can be obtained when it passing through the turbine.

2). Based on the results, it can be found that the fish will be injured by the low pressure when it passing through the region near the suction surface of the runner blade. And the excessive pressure gradient in the runner also bring about the irreversible damage on the swimming bladder and eyes of the fish. So the runner is the main component results in fish casualty in the tubular turbine.

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