Evaluation of the effects of shear stress on crucian carps passing through turbines

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Abstract: Turbine-passed fish is inevitably exposed to one or more physical forces, such as fast pressure change, blade strikes and shear stress, which can lead to injury or fatalities. The injury mechanisms of these forces to fish and related criteria are necessary for fish-friendly-turbine design and optimization. The effects of shear stress on crucian carps are studied in a specially designed experimental system. Crucian carps are exposed to a submerged water jet at velocities ranging from 5m/s to 20m/s. High-speed, high-resolution digital videos of the exposure process was recorded for motion-tracking analysis. Fish sizes, flow directions and water jet velocities are key factors considered during the tests. Injury rate, degree of severity, site of trauma, and death rate of crucian carps after tests were studied according to repeated tests with different factors. Injuries such as shedding of fish scales, tearing of gill cover, laceration of eyeballs are observed at different water jet velocity and with different size of crucian carps. The injury mechanisms were concluded and design criteria for fish-friendly-turbine are proposed according to the study.

keywords: Shear stress, crucian carps, injury mechanism, experiments, fish-friendly-turbine

1 Introduction

Replacing aging turbines at existing plants with new hydropower facilities would be a good chance to gradually achieve a balance between environmental protection and clean power generation for next few decades. It is expected that these next-generation turbines simultaneously permit the efficient generation of electricity and minimize the damage to fish and fish migratory habits[1]. Fish-friendly turbine will be one of the choices.

Knowledge of fish injury mechanism for specific physical forces and fish’s tolerance to these forces are required for developing fish-friendly turbine or pump. The injury mechanism of rapid pressure change, blade strike and shear stress on several fish species were analyzed by different researchers in the past 20 years. Blade strike in the above-mentioned forces, believed to be the first and most important reason for fish mortality, was mostly concerned in fish friendly turbine design and study. The effects of
quick pressure change and low pressure on crucian carps were also studied by different researchers, including our team[2, 3]. Shear stress, however, was not studied as deeply as blade strike and pressure change.

Some researchers designed fish-friendly turbines or pumps by decreasing the blades number. The design was effectively by cutting down the blade strike probability. Blade strike was the key reason for fish injury, but not the only reason. Concerns have been expressed that strain rates associated with passage through turbines, pumps and spillways may injure or kill fish, especially when shear stress is high[4]. Figuring out the reasons for fish injury caused by shear stress and obtaining the safety shear stress value is necessary for fish-friendly turbine improvement. Because of the difficulties in understanding the flow phenomenon and determining the shear stress magnitude and distribution inside the turbine, tests with fish inside real turbines for shear stress study is difficult and unrealistic. Simulated shear environment in labs is more effective for studying the injury mechanism for different species of fish.

The objective of our study was to locating and quantifying the damage caused by shear stress on fish, especially on crucian carps, to contribute to a better understanding of how fish are affected by turbine passage that can lead to further development of fish-friendly technologies[5]. An under-water jet flow system was designed to simulate the shear stress that fish would experience when passing through turbines. The shear stress distribution was obtained according to earlier simulation results, and different sizes of crucian carps were exposed to the jet with different orientation. After the exposure, the fish were collected for observation or anatomical examination.

2 Method

2.1 Test fish
Three sizes of crucian carps in good condition were tested in this study. The test fish were around 6 months old and ranged from 30mm to 130 mm in length and from 5.2g to 50.0 g in mass. All the fish were kept in a 24 m³ recirculated fishpond for at least two weeks before tests.

The water quality in the fishpond was controlled by using UV lamps, biological filter and water quality monitoring system. Adding fresh water, draining dirty water, using oxygen machine were also measures to maintain water quality according to ammonia, PH, dissolved oxygen and temperature daily detection. The mean PH of the water in the pond was in the range of 7.60 ± 0.30, dissolved oxygen was in the range of 7.40 ± 0.50 mg/l, water temperature was in the range of 21.00 ± 2.00°C during the experiment period.

Before the tests, fish were randomly captured from the fishpond, and they were measured and weighted. All the fish were divided into three categories according to their width: Size I, 1.0 cm; Size II, 1.4 cm and Size III, 1.8 cm. Crucian carps after the tests were kept separately in the same fishpond for more than 48 hours for observation and histological examinations.

2.2 Test facility
As shown in Figure 1, a test facility designed according to the testing system introduced by Zhiqun Deng[6] to generate a quantifiable shear environment consistent with conditions inside a turbine. The
system containing a flume, pipes, valves and a nozzle, was driven by a centrifugal pump. Above the nozzle, a fish introduction tube was applied to guide the fish to the shear zone. Because the fish can actively swim away to escape the high-speed water jet, the outlet of the introduction tube was specially designed to increase the successful exposure rate. Fish were released to the shear zone in two directions, headfirst and tail-first.

The velocity of the jet flow out of the nozzle ranged from 5m/s to 19.8m/s and can be controlled by the valve opening and the pump rotational speed. Fish were exposed to the following nozzle velocities: 7.5m/s, 9.0m/s, 10.5m/s, 12.1m/s, 13.9m/s, 16.0m/s, 17.9m/s and 19.5m/s during the tests. The tests were recorded with high-speed camera at 1000 frames/s. The fish in red color inside the tube in Figure 1 was just for taking photos, the tested fish were normal color.

![Fish introduction tube above the nozzle](image)

**Figure 1.** Fish introduction tube above the nozzle

3 Results

3.1 Injury rate

The tested fish was observed to identify their injury conditions. If no visible injuries were found during the tests, and they can normally swim and breath after the tests, they were regarded as not injured. The others were regarded as injured. The stress reaction of the fish during the exposure may increase the uncertainty of results, repeated tests were applied to reduce interference factors.

In the tests, the fish size, flow velocity out of the nozzle, and exposure orientation were changed to find their correlation with injury or mortality rate. The exposure orientations were named as headfirst and tail-first, such as shown in Figure 2. For the tail-first orientation, the flow comes from head side.

![Exposure orientation of headfirst (left) and tail-first (right)](image)

**Figure 2.** Exposure orientation of headfirst (left) and tail-first (right)

The injury rate is highly affected by the fish direction and the flow velocity. As shown in Figure 3,
when fish was exposed to the shear zone with a tail-first orientation, no injuries were observed until the velocity speed reached 17.9 m/s, as a contrast, the fish in opposite direction began to show signs of injury at 9m/s, as shown in Figure 4. Scaly fish species have evolved their appearance into spindle shape and their scales stronger to the decrease the flow resistance and protect themselves from shear stress of flow. But in the turbine, the violent flow can bring fish disorientation, high speed flow can attack fish from any direction. In this study, most of the fish were tested with the orientation of headfirst.

In Figure 4, it can be seen that, no significant differences were found between three sizes of fish. For Size I, fish began to show signs of injury at 10.5m/s, while Size II and Size III fish injured from 9.0m/s. When flow velocity was bigger than 10.5m/s, Size III fish injury percentage was slightly higher than Size I fish. The difference was smaller than 10%. As the shear stress value equals to the velocity change over distance (fish width), the velocity change was larger if the size of fish was bigger. The shear stress value did not vary greatly between three sizes of fish.

The mortality rate for three sizes of fish, however, showed difference. The bigger the fish was, the higher healing probability after injured with similar injury degrees it has. Which means that, if injured, Size I fish has higher mortality.

![Figure 3. Injury rate for tail-first condition](image1)

![Figure 4. Injury rate for headfirst condition](image2)

![Figure 5. Percentage of fish injured with descaling under different velocity](image3)
The injury rate was highly affected by the flow velocity, as shown in Figure 4 and 5. The injury rate was proportional to the flow velocity after the nozzle. The tendency of injury rate with flow speed between different injury types was similar. Such as, in Figure 5, the percentage of fish injured with descaling was plotted under different flow speed, it can be seen that the descaling rate for three sizes of fish was different when the flow speed is lower than 13.9m/s. When the flow speed is higher than 16.0m/s, the change tendency was similar to each other, the descaling rate rose as the nozzle velocity increased.

3.2 Injury types
After the tests, the injury conditions were analyzed. Minor descaling, severe descaling, minor gill cover laceration, severe gill cover laceration, gill arch mutilation, and eyeball abscission were the main injury types. If any of the injury conditions were observed on tested fish, the fish was regarded as injured.

In Figure 6–9, four typical injuries during the tests and after the tests were shown. In Figure 6, lots of scales around the fish body were seen during the test, this was because the scales removed by the shear stress have a relative speed to the fish in jet flow. After the test, one side of the fish were descaled. As we can see in Figure 6 that more than 50% percent of the scales lost after the test, this is classified as severe descaling injury. In Figure 7, one side of the gill covers was torn into two pieces during the test. After the tests the fish failed to close its gill cover, which would adversely affect its breath. In Figure 8, one part of the gill arches was cut off by the shear stress during the test. After the test, blood can be seen near the gill. In Figure 9, an eyeball shed from the fish during the test.
After tests

**Figure 8.** Gill arch mutilation  
**Figure 9.** Eyeball abscission

Not all the injuries result in mortality. Even for the situation showed in Figure 9, the injury was serious, this fish did not die after the test. But lots of fish didn’t heal after the injury because of infection.

The injuries were mainly caused by the difference of shear stress on adjacent surface of fish, the injury types and degrees were influenced by the shear stress value and impact area.

### 3.3 Degree of injury

As mentioned above, the injury rate was directly affected by the flow speed. For one specific injury type, the injury degree also changed as the velocity increased. Take the descaling injury as example, if less than 50% of the scales on one side of the fish was descaled, they can be regarded as minor descaling injury, else, the fish were regarded as severe descaling injury. Such as the percentage change shown in Figure 10 and 11, when the flow speed was smaller than 13.9m/s, percentage of minor descaled fish increased as the flow speed increased. When the speed was larger than 13.9m/s, more fish were injured as severe descaling, and the minor descaling percentage began to drop.

**Figure 10.** Percentage for minor descaling  
**Figure 11.** Percentage for severe descaling

According to the tests and records, different kinds and degrees of injury were found, the injury were classified into 4 degrees: 1) No injury, no observable physical injury during and after the tests; 2) Minor injury, visible but not life-threatening injuries, such as slight gill bleeding, descaling and minor gill cover tear; 3) Severe injury, life-threatening injuries, such as tore of gill, shed of eyeballs, which may lead to mortality after 120 hours; and 4) Mortality, immediate or delayed mortality (within 120 hours after tests).
The degree of injury under different conditions was displayed. When the flow speed was smaller than 9.0 m/s, no injury was observed. No mortality was found when the flow speed was lower than 10.5 m/s. When the flow speed was 19.5 m/s, more than 50% of the fish died in 5 days after tests. Less than 10% of the fish were not injured when the speed was larger than 17.9 m/s, the fish were not injured under this speed mainly because they entered the shear zone with a relatively safe angle, some of the fish successfully adjusted their body angle to shear stress. But the higher the speed was, the lower probability for the exemption was.

### 4 Conclusions

Three sizes of crucian carps were tested in a circulated water tank with high-speed shear environment. The injury reason, types and degrees of injuries were analyzed. The injuries were mainly caused by the uneven shear stress distribution on fish body. Descales, tore of gill cover, loss of eyeballs were the main injury types, while some of them leaded to mortality in 5 days. The exposure orientation directly affected the injury rate while the sizes of fish shown small influences on injury rate. The statistical analysis showed high levels of positive correlation between injury degree and the nozzle velocity.

The nozzle velocity under 7.5 m/s is safe for crucian carps, the shear stress is about 700 for Size I fish. While the nozzle velocity is 13.9 m/s, almost 50% of the fish would be injured. When the nozzle velocity reached 19.5 m/s, more than 90% of the fish would be injured and more than 50% of the fish could be killed. The shear stress distribution inside turbines and pumps should be studied and evaluated for small fish with this knowledge. Geometric designs that would introduce high shear stress that kills more than 50% of fish should be avoided. The operation can also be optimized according to this study results and further simulation.

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