Influence of operation modes and fish behavior on fish passage through turbines

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Abstract. The assessment of fish passage through turbines is important to develop cost-efficient environmental solutions and strategies that avoid individual fish injuries and, therefore, enhance the fish population development in a catchment. As part of the FIThydro project, fish passage analysis were performed for the bulb turbine in Bannwil, the S-turbine in Guma and the bulb unit at the test facility in Obernach.

Numerical modelling in principle provides the most comprehensive information on hydrodynamic conditions in the turbine passage. Many details of the main relevant stressors on fishes can be derived. The information of different stressors like pressure, strike, shear and turbulence can be extracted with high accuracy assuming that a fish pathway follows a streamline through the turbine. The accurate prediction of the stressors and the validation with measurements enables the designer to develop a turbine that reduces the stress on the fish and, hence, increase the fish survival rate.

The survival rate also strongly depends on biological aspects of a fish species. Besides the reaction of the fish on the different stressors, complex parameters like swim behavior or preferred swim elevations are of high importance on the survival rate. However, these parameters vary among different fish species.

CFD simulations of different turbines are performed and simulation results were compared to measurements with the Barotrauma Detection System (BDS) sensors at the test cases in Guma and Bannwil, as well as live fish tests at the test facility in Obernach. The fish behavior was modeled in the CFD based evaluation method. Studies related to swimming speed, fish orientation and especially the actual passage location demonstrate the sensitivity of these parameters on the fish survival rate. Another aspect was the influence of operating conditions on fish passage. A wide spectrum of operating conditions was analyzed and fish passage hill-charts for different stressors were generated. This knowledge enables an adapted power plant operation related to migration movements of certain fish species. The CFD based analysis method shows to be a powerful tool to improve fish passage through a turbine by changing hydraulic design and by adapting operational modes. Relative improvements to conventional designs and operation can be quantified.

1. Introduction

As many European rivers are highly modified to serve different purposes such as irrigation, flood control, navigation and energy production, the FIThydro project was initiated to find innovative solutions and strategies to minimize the influence of these man-made modifications on fish populations. One important topic is the migration of fish at locks, weirs and power plants, both in upstream and downstream direction. This work focusses on the assessment of fish passage through the turbine at hydropower installations, which can be related to injury and mortality, caused by several damage mechanisms.

Besides physical and empirical modelling, the numerical modelling approach provides the most comprehensive information about hydrodynamic conditions during turbine passage and thus permits the most detailed assessment of related stress on fish. For project related applications, the use of stationary CFD results using streamlines through the turbine to analyze the stresses acting on the fish shows to be the practically most feasible approach. Stressors like strike, pressure, turbulence and shear can be analyzed by connecting the impact to the biological response of the fish.

The investigations within the FIThydro project where based on three European test cases; the bulb turbine in Bannwil, the S-turbine in Guma and the bulb unit at the test facility in Obernach. The main machine data is presented in Table 1.
Table 1: Summary of basic parameters for investigated Kaplan turbines

|                      | Bannwil | Guma | Obernach laboratory |
|----------------------|---------|------|---------------------|
| Power (per unit)     | 9.5 MW  | 1.8 MW | 0.35 MW             |
| Design discharge [m³/s] | 142     | 25   | 1.5                 |
| Design head [m]      | 7.2     | 8    | 2.5                 |
| Runner diameter [m]  | 4.4     | 2.1  | 0.75                |
| Runner speed [rpm]   | 107     | 220  | 333                 |
| Number of blades     | 4       | 4    | 4                   |
| Turbine type         | Bulb    | S-type | Bulb               |

The investigations focus on the variation of both operating conditions and the behavioral aspects of the fish passage, like passage location, swimming speeds or fish orientation. The main operating points of the test cases are listed in Table 2 and will be used for the analysis presented in this report. Further operating points are used for the generation of the fish passage hill-charts.

Table 2: Main Operating Points Bannwil, Guma and Obernach

| Operating Point | Head [m] | Discharge [m³/s] |
|----------------|----------|-----------------|
| Bannwil        |          |                 |
| t02            | 7.0      | 150.0           |
| t08            | 7.2      | 116.5           |
| t12            | 7.0      | 102.0           |
| Guma           |          |                 |
| t01            | 8.0      | 25.8            |
| t20            | 8.0      | 18.4            |
| Obernach       |          |                 |
| t04            | 2.5      | 1.5             |

2. CFD based fish passage modelling

In a first step numerical models for all test cases are generated in order to model the fish passage through the turbine. The simulations of the turbine are performed with stationary CFD assuming that a fish pathway follows a streamline through the turbine. The results are then evaluated using a streamline based post-processing tool applying a biological performance assessment (BioPA) developed by Pacific Northwest National Laboratory (PNNL) [1]. The information for the stressor exposure of pressure, strike, shear and turbulence can be extracted from these streamlines. For strike the velocity vectors close to the blade entrance edge are extracted in order to calculate the strike probability and the impact velocity a fish experiences when hitting the blade. For the other stressors an exposure probability is derived based on the total amount of streamlines. As presented in Figure 1 the injury risk can then be derived by combining the physical information with dose response data of respective fish species. A so called BioPA score can then be integrated over the product of exposure probability and exposure mortality of the fish. The score is high when the risk of passage injury is low. It is understood that the score does not, at this time, represent an absolute passage-survival estimate. However, it enables the designer to improve the hydraulic shape of the turbine relative to an existing design and therefore reduce the expected injury risk of a fish swimming through the turbine [2]. It offers a systematic way to evaluate trade-offs associated with various hydraulic solutions.
3. Principle passage studies for test cases

For the investigations in the specific test cases representative operating conditions as shown in Table 2 were chosen. On the one hand, comparisons to the field test data were generated and on the other hand, parameter variations were performed to identify the sensitivity of the applied model. Each simulation was performed with a 360°-CFD model. For the evaluation, the biological dose response of salmon was used.

3.1. Comparison to BDS measurement

Within the FIThydro project, Barotrauma Detection System (BDS) tests have been performed and a comparison to CFD simulations of the tested load conditions was carried out for the test cases Guma and Bannwil. The objective was to compare the lowest pressure value measured during the turbine passage, known as the nadir pressure, as it is used as reference metric for barotrauma on the fish. A stationary CFD model is used to determine the nadir pressures in the turbine model. This approach is well proven and widely used to generate pressure distributions to analyze hydraulic designs of turbines. As CFD solver the commercial code CFX from Ansys Inc. was utilized. This CFD program is well tested and established especially for turbo machinery. Turbulence is modelled by a two-layer model that takes advantage of the two-equation models $\kappa-\varepsilon$ and $\kappa-\omega$. The flow interaction between adjacent geometric components is considered by using a mixing plane interface. The inflow condition for the CFD was assumed to be uniform.

The setup of the sensor fish test and a typical pressure development are shown at the example of the Bannwil test case in Figure 2. The field tests at the Bannwil site included, four deployments at 2 different locations and 2 different operating conditions. An injection system was installed in the trash rack to deploy the sensors at specific locations. The first deployment location was in mid depth in the middle of the flow channel and the second was close to the bottom of the inlet section. Both locations were used for tests at full load (t02) and at 80% power (t12). In the following, the results are presented exemplary for full load operation. The measured pressure data showed a variation in depth of the sensors approaching the turbine. This effect can be caused by non-uniform inflow conditions or early inflation of balloon tags.
To account for a certain scattering in all directions in the CFD a circular section with a diameter of 1m is created and 30 streamlines are initiated from there to reflect the variation in passage location through the turbine as shown in Figure 3.

As a mixing plane interface is used for the stationary CFD, all possible passage locations in relation to the runner should be considered to reflect the time-dependent passage of the sensors in the field. Therefore the initial 30 streamlines were used to generate a radial distribution at the interface between guide vane and runner calculation domain, see Figure 3b. In the next step streamlines were started at this interface representing one runner section. The seeding area was clipped by the radial boundaries of the initial circular streamlines. A high number of streamlines was seeded, as shown in Figure 3c to guarantee statistical reliable results. For comparison purposes streamlines starting from the complete section with no radial boundaries were generated.

The results in Figure 4 show the variation of the BDS and CFD nadir pressure ($p_n$) distributions. It can be seen, that the distribution of nadir pressure for the CFD circle section is similar to the BDS measurements. The average nadir pressure ($p_{n,ave}$) of the CFD results is slightly higher than the measured BDS data. One possible reason for the deviations is an offset in the passage location between CFD and BDS.
measurement; also the sample size in CFD is much larger as in the field test. Additionally, there are modelling simplifications in CFD, like a uniform flow distribution at the intake.

Figure 4: Bannwil HPP - Comparison BDS measurement to CFD

3.2. Parameter variation and comparison to life fish test

Parameter variations of fish length and acclimation depth show the sensitivity of these parameters. Figure 5 presents the major effect of the acclimation depth on the pressure survival ratio for a full load operation at Bannwil and Guma power plant. This emphasizes the importance of a good understanding, of how fish acclimatize before entering the turbine. This depends on how fast a fish approaches the power plant before passing and also on the time the fish species requires for acclimatization to a certain pressure depending on the water depth.

Figure 5: Sensitivity to acclimation depth

For the laboratory test case in Obernach a CFD setup was created and simulated. The results of the full load operation point are presented in Figure 6, including a variation of fish length. Length variations depend on fish species, trash rack clearances or installed guidance measures and have an influence on strike related injuries. The results emphasize the importance of a good knowledge of the fish sizes, due to the relevance for the passage event. The CFD results confirm the field test assessment of the fish after passage, which showed no clear indication for barotrauma and shear related injury. However, the shear stress influence seems to be overestimated in numerical assessment compared to the experimental results. The length dependency of the strike survival ratio in the model is also higher than the values of the live fish experiments [6] presented in Figure 6.

Experimental tests in the Oak Ridge laboratory [3] indicated that tail strikes hardly ever lead to injury of a fish. Applying this on the Obernach model by accounting for only 2/3 of the fish length for the
strike model leads to a better agreement with the tests performed at the Obernach site. The principal definition of fish region in Figure 7 hints in the same direction. Therefore, the fish length should be corrected for passage analysis, due to the insensitivity of the tail region. Additionally, other effects like fish orientation also partly contribute to this effect. To confirm the supposition further comparison to test data is required.

![Figure 6: Results Obernach t04](image)

![Figure 7: Fish regions: Head, mid-body, tail region [4]](image)

4. Influence of operating conditions

The evaluation of individual load cases regarding fish passage helps to identify individual damage mechanisms and to evaluate them. To rate the operation scheme of a hydropower plant, however, this consideration is not sufficient. It requires the evaluation of a complete set of operating points to create a better understanding of which parameters affect the fish passage through the turbine most. Therefore, a set of operating points was chosen to investigate the test cases Bannwil and Guma by evaluating the influence of the stressors nadir pressure, strike, shear and turbulence on fish. A fish length of 10 cm was assumed and all stressors were equally rated. For a better representation of the results, the BioPA performance score was converted into a scoring system from 0 to 10, where 10 is the best score and corresponds to the BioPA score of 100. The scoring of 0 corresponds to 70 in BioPA.

The fish passage hill charts show the influence of the different stressors on a chosen range of operation. This range was extended from the original operating range in order to obtain a significant influence of each stressor and to identify trends. For the Bannwil test case, the pressure score was calculated based on an acclimation depth of 5m, the tail water level was calculated based on a constant head water level and the head of the respective operating point. Figure 8 presents exemplarily the results of the Bannwil turbine, showing the hill-charts of the different stressors, as well as a combined score with equally weighted factors. The biological response on turbulence is difficult to judge and turned out not to be relevant for the test cases using the biological thresholds for salmon. As the calculated survival rates were close to 100%, the effect of the stressor was not investigated further. It is obvious that the influence of the different stressors on fish survival is varying with the operating condition. While large blade openings with high discharge have a reduced risk related to strike, the opposite is the case for nadir pressure. Strain is closely related to flow separation zones and bad flow quality. This is not only dependent on the hydraulic shape of a turbine, but also on the operating condition. The results of the Guma test case show in principle the same tendency as the analysis of the Bannwil machine [5]. Depending on different boundary conditions like size, rotational speed and machine type, the hill charts differ in value and peak.
The fish passage hill-charts can be especially helpful to adapt the operation for particular time periods, while certain species are migrating. Instead of looking on the overall survival rate, relevant stressor variables can be selected to adapt the operational scheme of the power plant as function of the individual susceptibility of the relevant species.

5. Modelling effects of active fish behavior

In the following a closer look is taken at certain aspects of fish behavioral effects. There is some information available, but the actual fish behavior during the turbine passage remains an unresolved topic so far.

For the modelling of the fish passage, it is important to determine the influence of fish movement on the impact the fish experiences during turbine passage. Therefore, two topics were investigated. First the influence of the entrance location and resulting passage location at the turbine. As the passage location affects the intensity of each stressor the fish is exposed to. Secondly the fish swimming speed and orientation was considered.

5.1. Influence of passage location:

The influence on the survival probability of the fish based on the entering location was investigated for the Bannwil and Guma turbine. Three passage locations as illustrated in Figure 9 at hub, middle and shroud having the same area were used to analyze several operating conditions in order to evaluate the influence on the different stressors.
The results presented in Figure 10 show representative operating points at similar head and different discharge for the Bannwil power plant. For the overload operating point t02, the pressure stressor has a dominant influence, due to high flow rates and therefore lower pressures, especially in the gap regions at hub and shroud. For the operation close to the optimum, better overall flow conditions are present in the turbine, which decreases the negative impact of pressure. Strike is becoming more relevant and shows lower survival ratios in the middle region and at the shroud region. This is due to the higher impact velocities at the outer sections. The results show, that the passage location has a significant influence on survival and that a passage in the middle is favorable regarding pressure and shear influences and a passage close to the hub is favorable especially regarding strike, due to low impact velocities.

5.2. Fish swimming speed and orientation:

It is assumed that a fish swims against the main flow direction and maintains his swimming depth. This will significantly affect the strike probability and the impact velocity. In Figure 11, the impact of fish swimming velocity and positioning to the flow direction is illustrated. Based on these impacts the strike formula is adapted (Geiger 2018).
Fish speeds can be varied based on the swimming abilities of different species. The swim speed is time dependent, as the fish can keep a relatively high speed only for a short time. Most fishes can’t swim faster than 2 m/s for longer periods of time. Typical flow velocities during turbine passage are rather modest in the intake region, but as soon as the flow approaches the guide vanes the flow is accelerates and velocities increase rapidly above more than 2 m/s. This indicates that most fish will not be able to withstand the flow conditions and have only limited capabilities to control or influence turbine passage trajectories in close vicinity of the turbine. However, a change of position in the intake section is possible for most species. A principle study was performed to evaluate the influence of an active swimming fish on the strike score. The effect is shown in Figure 12 for two load cases of the Guma plant. Assuming the fish is swimming against the main flow, the passage time through the turbine increases and therefore the strike probability. Also the impact velocities increases slightly, so that the overall risk of a strike injury increases. The fact that velocities close to the turbine are typically higher than the swimming capabilities of a fish question whether a fish is actually capable to swim against the flow. Depending on turbine design and operating condition flow velocities can be significantly higher and consequently a potential influence of swimming speed could have only limited impact on mortality rates.

Another topic is the orientation of the fish in relation to the blade. The standard BioPA model uses a derivation of the von Raben correlation. It is assumed that the fish is oriented with the flow. In the following variations of the orientation are taken into account for the strike assessment. Figure 13 shows the results for a full load t01 and a close to optimum condition t20 for the Guma machine.
orientation leads to a tolerance of 1-2% in the fish passage assessment. The assumption to have the fish aligned with the flow direction provides a rather conservative approach, as it is the worst case scenario or at least close to it. Comparing to the influence of fish length presented in Figure 6 the impact of orientation is rather modest. Also, the passing location shows to be more significant related to survival rates. Further results of the CFD based analysis and the live fish test at the test facility in Obernach can be found in the FIThydro documentation [6].

6. Conclusion

Relevant stressors to fishes during turbine passage can be quantified by using enhanced techniques like sensor fish measurements and CFD calculations. In recent projects, these evaluation methods have been incorporated into the turbine design process to improve fish passage. One example is the modernization of the Ice Harbor Lock and Dam in the United States [7]. The results presented in the current paper give more insights on the survival modelling sensitivity and highlight the importance of the passage location. Also biological boundaries like acclimation depth and fish size affect the results of turbine passage modelling significantly and need to be applied accurately. The development of more complex approaches to model fish movement require a more detailed clarification of the actual fish behavior during the turbine passage. The generation of fish passage hill-charts of the entire application range, allows the possibility to adapt operation of a power plant in regard to fish migration times. In summary applying this knowledge and improving the evaluation methods leads to a great potential in modernizing hydro power plants by improving both economy and ecology. Absolute survival rate assessment is so far related to remarkable uncertainty because of insufficient knowledge on biological and behavioral aspects. However, the presented modelling approach provides detailed and accurate information for a relative comparison of physical stress levels with acceptable accuracy.

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