Numerical Simulation and Experimental Verification of Downstream Fish migration in a Kaplan turbine

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Abstract. Fish migrating downstream may face an increased risk of injury when passing through hydropower turbines. The overall influence on fish populations remains unknown. Still, it is undoubtedly linked to the damage potential of the turbines, the stage of maturity and the size of the migrating individuals as well as the proportion of migrating fish in relation to the total population. The sources of injury are usually the contact to the turbine blade and the rapid pressure drop in the turbine as well as shear forces, and large-scale turbulence. The authors investigated the conditions experienced by fish migrating through a 5-bladed vertical Kaplan turbine, each of the two units with a nominal power of 45 MW. Therefore, so-called “Barotrauma Detection Sensors (BDS)” were applied to determine the physical parameters during the turbine passages. Additionally, live fish, fitted externally with Barotrauma Detection Sensors, were introduced.

1. Introduction
When fish migrate downstream, they may be entrained in hydropower turbines. During entrainment, they may be exposed to physical conditions which increase the risk of injury and mortality, and which depend on the fish species, life stage and size as well as on turbine type and operating conditions. The effect of turbine related injuries in fish populations is still not known. Still, it is undoubtedly linked to the damage potential of the turbines, the stage of maturity and the size of the migrating individuals as well as the proportion of migrating fish in relation to the total population. Until now, investigations concerning downstream migration have focused predominantly on diadromous fish, and there exist several models to calculate injury and mortality rates due to turbine entrainment for eel and salmon. For potamodromous species, investigations are rare, but knowing these rates is one key criterion for the assessment of the effectiveness and thus, the necessity of any fish protection measures.

The primary injury mechanisms have been identified based on laboratory and field trials with live fish, and are known to be the contact with the turbine blade and the pressure drop in the turbine.
Additional mechanisms are shear forces and turbulence. The project Downstream fish migration in mean-sized rivers in Austria – Population biological basis and implication for the fish protection and downstream fish migration [7] deals with potamodromous fish species and investigates the pressure conditions at a large hydropower plant experimentally and numerically. Transparent decision-making is essential for appropriate fish protection regulations, mainly due to the relatively high cost of measures for fish protection and the related technical and/or operational risks. Alternative measures such as population support can be an exciting alternative in case the fish are provided with habitats that meet all their needs. In some hydropower plants, downstream migration is already possible, with practically no damage. The results of this investigation may help in the development of new and improved techniques to reduce damage rates due to turbine entrainment.

2. Study Site
The most powerful hydropower plant at the river Drau in Austria produces 400 GWh of electricity per year. The two vertical 5-blade Kaplan units have a nominal diameter of $D = 5.1$ m. One of the units is a 50 Hz machine, and the second is a 16 2/3 Hz traction power unit. Both units have the same hydraulic components with the same hydraulic shape and differ only regarding their rotational speed. In 1981, after decades of planning and five years of construction works, the hydropower plant went into operation with a nominal head of $H = 24.3$ m and a nominal flow rate of $Q_{\text{Nominal}} = 205$ m$^3$/s. The two Kaplan units have a nominal power of 46 MW each. For a summary of the primary data, see Table 1 and for a meridional view Figure 1.

| Table 1. Nominal data HPP Annabrücke, operator Verbund |
|-----------------------------------------------|
| **Manufacturer** | Voith, 1976-1981 |
| **Type** | Vertical Kaplan concrete half spiral |
| **Nominal head $H_{\text{Nominal}}$** | 24.3 m |
| **Runner nominal diameter** | 5.1 m |
| **Runner blades / guide vanes** | 5# / 24# |
| **Spec. speed ($n_{\text{BEP-HILLCHART}}$)** | 162 rpm |
| **Unit 1** | **Unit 2** |
| **Frequency** | 50 Hz | 16 2/3 Hz |
| **Max. flow rate $Q_{\text{MAX}}$** | 230 m$^3$/s | 233 m$^3$/s |
| **$P_{\text{MAX}}$ [1]** | 46.59 MW | 46.99 MW |
| **Rotational speed** | 136.3 rpm | 142.9 rpm |
| **Spec. speed ($n_{\text{r,P_MAX}}$)** | 545 | 574 |

3. Numerical simulation
For the CFD calculation, the unit was split into components (“domains”), as shown in Figure 1. The calculation starts with the spiral (concrete half spiral) domain in the flow direction. This domain also contains the stay vanes. It is worth noting that the stay vane region is not rotationally periodic (different sizes of stay vanes). Thus the integration of the stay vane region into the spiral domain was possible. Due to the complicated geometric situation, an unstructured grid was generated for this component to provide a proper realistic inflow situation to the guide vanes. Furthermore, the guide vane domain was connected to the spiral. The guide vane mesh passage was generated utilizing Turbogrid®, copied into the model 24 times and connected with a 1:1 interface.

For the stationary calculations, a mixing plane approach available in the software package was chosen for the multiple frames of reference interface between stationary and rotating domains, i.e., between the guide vane and the runner domain [2]. In the transient CFD simulations, the rotor position is updated at every time step during the simulation according to the rotor’s rotational speed. The mesh for the passage of the runner domain itself was also generated with Turbogrid® and connected employing a 1:1 grid interface between the five runner blades. The mesh of the runner domain consists
of the main passage and an outblock domain (internally connected by a 1:1 interface). The draft tube domain was then connected with a frozen rotor domain interface (Figure 2c). Downstream of the draft tube, an additional component, the so-called outblock, was connected to the draft tube. The function of this component is not exactly a representation of the tailwater. Still, it helps to avoid the setting of boundary conditions directly at the draft tube outlet, which would influence the draft tube simulation and prescribe the flow situation. In Figure 2a, the full model is displayed with different colors for its single components. In Figure 2d, the mesh at the guide vane shroud is displayed, including the gap between the guide vane and the shroud. Also, the small negative concavity in the real machine (see Figure 2d marked in yellow) was modeled. The guide vane is colored green, and the runner is visualized orange (both structured meshes). The stand-alone generated meshes were combined to a complete unit for different guide vane positions. Pressure type boundary conditions were set for inlet and outlet, and thus the flow rate resulted.

**Figure 1.** Meridional section of the Kaplan unit (a), detail of the runner (b) [1], fish injection system (c) [3].

As the turbulence model, the SST model developed by Menter [4] was applied to the stationary calculations. This two-equation approach, based on an Eddy-viscosity concept, is commonly used for hydraulic turbomachinery combining the 2-equations-turbulence-models k-ε- and k-ω. The transient analyses were carried out with the SAS-SST turbulence model by Menter. Though the SST turbulence model could be used for transient simulations (URANS), experience has shown that it does not always provide satisfying results, even if the grid and time step resolution would be sufficient for that purpose. That is why the scale resolving turbulence model SAS-SST was utilized. The concept of the SAS turbulence model is based on the introduction of the Von Karman length scale into the turbulence scale equation. So, the model dynamically adjusts to resolved vortex structures in the URANS (Unsteady Reynolds Averaged Navier Stokes) method, which results in a LES-like (Large Eddy Simulation) behavior in unsteady regions of the flow field. For the investigations presented in this paper the Shear-Stress-Transport turbulence model for Scale Adaptive Simulations (SST-SAS), in combination with the Curvature Correction (CC) model developed by Smirnov and Menter [5] and a production limiter model according to Kato-Launer [6], was chosen for the transient simulations.

With the help of the commercial CFD code Ansys CFX V17.1 [2], the Navier-Stokes equations were solved. These Navier-Stokes equations describe the fluid motion in all three dimensions and
were used with a Reynolds averaged Navier-Stokes (RANS) formulation. RANS applies equations where the instantaneous variables are decomposed into mean and fluctuating values with the help of a Reynolds decomposition, whereas these variables are time-averaged. Additionally, an MFR (multiple frame of references) approach was used for the rotating domain (= runner). The final CFD calculations were performed with a model of more than 14 million nodes.

Figure 2. CFD Modell, (a) Model overview full setup, (b) Detail of inlet with regions, (c) Runner cavitation lip and interface from runner to draft tube surface, (d) Guide vane detail

4. Experimental data and live fish experiments
The project “Downstream fish migration in middle-sized rivers in Austria Population biological basis and implication for the fish protection and downstream fish migration” [6], aims at an understanding of the downstream migration of adult and juvenile fish including injury related to the operation of hydropower plants. To gather physical data within the turbine, we introduced so-called Barotrauma Detection Systems (BDS) into the turbine. The BDS were developed by the Centre of Biorobotics, Tallinn University of Technology [7]; these sensors measure the rate of rotation, linear acceleration, temperature and total pressure (3 redundant sensors) and all are contained in one single polycarbonate housing into which data are recorded to a microSD card and can be retrieved wirelessly via WiFi [7]. Neutral buoyancy of the BDS is achieved by estimating the water temperature at the beginning of the tests and by manual adjustment of the sensor length (adjustment of the total volume of the sensor versus the constant weight of 143 g). The BDS applies a high-speed digital sampling architecture with a 400 kHz clock rate and real-time temperature compensation; data are stored at 100 Hz (see Figure 3 left). The sensors are designed using triple modular redundancy, which allows each individual pressure reading to be evaluated by three pressure readings, and provides data in case one or more of the sensors is damaged during deployment. The BDS have automatic atmospheric pressure compensation algorithm which removes the effect of local altitude and weather conditions from the data sets, making the BDS barotrauma data directly cross-comparable for any given site and operating condition.
Additionally, we introduced live fish, fitted externally with Barotrauma Detection Sensors. For these live fish experiments, balloon tags, developed by Normandeau Associates [8], and BDS, developed by the Centre of Biorobotics of the Tallinn University of Technology [3], are attached to the fish as depicted in Figure 3, middle. The fish are then exposed utilizing an injection unit at different height levels in the intake of the turbine (see Figure 1, area marked with a red circle). After the turbine passage, fish are collected in the tailwater – for this purpose, the balloon tags inflate and thus bring the fish to the water surface (Figure 3, right).

![Figure 3. Left – Barotrauma detection system with balloon tags, middle – fish with sensor and balloon tags, right – balloon tags in action with fish [7]](image)

5. Stationary calculation results with particle tracks
For this purpose, 5000 particle tracks of the stationary calculations were evaluated. In Figure 4, the position of the lowest pressure occurring at each of the particle tracks is marked with a sphere whose color reflects the pressure level. It can be seen that this occurs mostly on the suction side of the runner blades at the runner outlet. These pressures are depicted in a histogram in Figure 5. The unit chosen for both figures was the meter water column, with zero as ambient pressure. The lowest pressure sometimes also falls below the vapor pressure, which consequently means cavitation – this observation also corresponds to the turbine damages found [9]. Figure 4 also shows that the range of local minima of the pressure of a particle track extends into the suction tube cone, meaning that not only the bladed area but also the area after the runner is a zone of particular stress for the fish during migration.

![Figure 4. Location of lowest pressure on particle track: left – part-load operation point, right – full load](image)
experimental (BDS and fish data) results for the downstream migration in the Kaplan turbine. The color and the locations correspond to Figure 2b. The results match very well, with generally lower Nadir at part load and lower values at bottom injections then at top injections (Fig. 6, Table 2). The tracks were shifted in time with the lowest pressure occurring during turbine runner migration.

For the full load operation point, the experimental data also shows lower values for the minimum Nadir pressure than for the part-load operation point and both operation points for the injection at the bottom of the lower values. In the CFD calculation, no cavitation model was used and therefore, the lowest pressure from the single-phase CFD calculation is 0 kPa.
Table 2. Results Nadir pressure in kPa

|                | Experiment | CFD |          |          |          |          |          |
|----------------|------------|-----|----------|----------|----------|----------|----------|
|                | Top        | Middle | Bottom | Top      | Middle   | Bottom   |          |
| Experiment     | Sample size|       |         |          |          |          |          |
| Min            | 31         | 7     | 17      | 15       | 11       | 26       |          |
| Averaged       | 73.4       | 83.9  | 48.5    | 103.9    | 99.2     | 96.2     |          |
| Max            | 103.6      | 106.7 | 72.2    | 130.7    | 107.6    | 127.6    |          |
| CFD            | Sample size|       |         |          |          |          |          |
| Min            | 1645       | 1677  | 1678    | 1645     | 1677     | 1678     |          |
| Averaged       | 108.3      | 90.5  | 78.6    | 155.7    | 144.1    | 137.5    |          |
| Max            | 143.4      | 141.6 | 169.1   | 175.8    | 173.8    | 164.2    |          |

6. Transient calculation results

The focus of the transient calculation was on the formula (equation 1) used for the achievement of a mortality rate according to [10] and based on [11]:

$$ P_{\text{Mortality, Strike}} = \frac{\lambda \cdot N \cdot L}{\text{Pre factor}} \left[ \frac{\omega}{2 \pi V_s} + \frac{\sin \alpha_a}{2 \pi r} \right] $$

(equation 1)

$$ \lambda = 0.15533 \ln \left( \frac{L}{100} \right) + 0.0125 $$

(equation 2)

with N as the blade number (in this case, 5) and L as the length of fish (in this case, approx. 0.2 m). The mutilation ratio $\lambda$ was analyzed, and an empirically developed regression equation for different fish lengths was found [12]. The result is a mortality coefficient or the proportion of fish that are killed after the impact of the blade leading edge. Then the expression in parentheses was evaluated directly in CFD post-processing and denominated as the blade coefficient with the angle $\alpha_a$, see Figure 7 left. The evaluation was performed on locators before the runner blades. A total of 6 hub-to-shroud lines were evaluated; each of them was twisted by 12° in the circumferential direction, see Figure 7 right.

![Figure 7. Angles and post-processing locations](image-url)

These results are displayed in Figure 8. At the same time, the entire evaluation plane (plane generated by the circumferential rotation of the line locators shown above) was also colored with this...
value and shown in Figure 9. Now, the mortality rate is a mere linear function of the number of blades and the length of the fish. High values, especially in the area of the hub, are a fact.

Figure 10 shows the evaluation of the blade coefficient for the transient calculation. The mean value of the blade coefficient and the variance to this mean value are shown. It is now possible to calculate the risk of mortality for different fish lengths with equation 2 [12], whereas we see that it is of crucial importance whether the fish pass the turbine hub or near the shroud (Figure 11). This is especially the case for larger, longer fish where the risk tends to be much higher than for smaller, shorter fish.

**Figure 8.** Blade-coefficient before runner on six different locations, transient behavior

**Figure 9.** Blade-coefficient before the runner, one time step.

**Figure 10.** Blade-coefficient before runner on six different locations, transient behavior

**Figure 11.** Blade-coefficient before the runner, one time step.

7. **Discussion of transient calculation results**

The transient calculation was performed with different boundary conditions of the start condition for the particle tracks. Below, the results of such a simulation are presented in more detail if the starting point of the particle tracks remains the same over the calculation, and the achieved streamline paths are plotted continuously.

Figure 12 shows the resulting streamlines for different time steps. It is shown in Figure 13 that streamlines towards the machines burst open wide. In the actual passage through the turbine; however, this has a significant influence on possible damage, since, as shown above, the mortality rate is an entirely different one when following the standard formulas.
In other words, based on a stationary as well as in a transient calculation, it is not possible to say where the passage through the runner exactly happens, at least for the turbine configuration under investigation, since this very much depends on the time of addition of a particle which corresponds to the real fish (e.g., with the position of the runner connected to it). Figure 14 shows the region of migration in the runner with streamlines and the lowest pressure (marked with a colored sphere). It is visible that the radius, as well as the lowest pressure, varies in a wide range.

An evaluation of where the addition of the fish is made and the evaluation of a possible damage rate is, therefore only a short snapshot and may look quite different only a short time later. The proper movement of the fish is not discussed here.

**Figure 12.** Streamlines for different time steps of a transient calculation

**Figure 13.** Burst of streamlines

**Figure 14.** Nadir pressure of burst streamlines
8. Conclusion
For investigations of the impact, turbines have on fish populations, a powerful hydropower plant on the river Drau in Austria was chosen as a case study. Investigations with so-called “Barotrauma Detection Sensors (BDS)” were carried out to determine physical parameters during the turbine passages. The numerical flow simulation included the entire turbine with the intake, the spiral with stay vanes, the guide vanes, the runner with anti-cavitation lip, the draft tube and the tailwater. The grids – mostly structured – were assembled to a model with 14.2 million nodes and simulated in different setups with the commercial software package Ansys CFX. Transient simulations were carried out with the scale-adaptive turbulence model developed by Menter combined with a particle tracking model to find out the correct flow path of the machine. These trajectories provided the input information based on which the magnitudes of injury mechanisms could be quantified. The transient simulations were set in comparison to steady-state simulations and compared to measurement data from the field test. These field measurement data were collected utilizing the BDS, as well as on live fish equipped with miniature versions of the BDS.

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