Model-based study of fish damage for the Pentair Fairbanks Nijhuis Modified Bulb Turbine and the Water2Energy Cross Flow turbine

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1 Introduction

The Pro-Tide project aims at developing, testing, and promoting the use of tidal energy in coastal and estuarine areas. The project is led by the province of Zeeland, together with sub partners province of Zuid-Holland and the Dutch Ministry of Infrastructure and the Environment (RWS). Other partners are The Isle of Wight, Port of Dover (English partner), ULCO Université du Littoral - Côte d'Opale (French partner) and Waterwegen en Zeekanalen N.V (Belgian partner).

The Dutch project Pro-Tide-NL is involved in identifying the best available technology for the conditions that are anticipated for the Brouwers dam tidal power plant (lake Grevelingen, The Netherlands). Conditions at this site include a very low head (1 m average) and a large volume flow rate (2,500 m³/s average).

The Pro-Tide R&D advisory board prioritized the available technologies (Van der Klip and Van Berkel, 2015). Based on this study it was advised to select two different turbine designs for further consideration: the Nijhuis horizontal axis tidal turbine and the Water2Energy (W2E) vertical axis cross-flow turbine. Both turbine designs were evaluated with respect to their hydraulic performance and fish handling capability (i.e. fish mortality rate). The following is a chronological list of steps that were performed:

1. Formulation of requirements and guidelines for fish safety tests in (model-scale) turbines (Vriese, 2015-a).
2. Design and construction of a test-rig for model-scale turbines at Maurik Island, the Netherlands (Van Berkel, 2015-a,b).
3. Assessment of the hydraulic performance of the W2E turbine(1) based on scale model tests (Van Berkel, 2015c).
4. a) Model-based prediction of expected fish mortality rates prior to the actual scale model testing.
   b) Definition of turbine operating conditions for the fish tests.
5. Performance of fish tests for the Nijhuis and W2E turbines (Vriese, 2015-b).
6. a) Comparison of model-based predictions with measured fish mortality rates during testing.
   b) Prediction of expected fish mortality rates for the full-size turbines at HPP Brouwers dam.

In this report, a detailed account of steps 4 and 6 will be given.

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(1) The hydraulic performance of the Nijhuis turbine was provided by the manufacturer.
2 Fish damage in hydropower turbines

2.1 Mechanisms for fish damage

Research on the mechanisms responsible for fish damage in pumps and turbines gained momentum after the start of the US Department of Energy's Advanced Hydropower Turbine Systems (AHTS) program in 1994. One of the goals of this program was to develop a new or improved runner for a hydropower turbine system that would reduce the risk of injury and mortality to fish passing through. An important step in the AHTS program was to study the biological criteria for fish injury and mortality. The laboratory experiments that were conducted were aimed at the three main mechanisms for damage to fish passing through turbine systems: mechanical damage, velocity shear, and pressure fluctuations (Cada et al., 1997).

Mechanical injury by blade strike is generally regarded as the primary cause of damage to fish passing through turbine systems (Turnpenny et al., 2000; Cook et al., 2003; Amaral et al., 2011). It can lead to bruises, haemorrhage or even severing of the body. Strike probability models can be used to estimate the probability of a fish being hit by a blade. This theoretical blade strike probability is subsequently corrected with a factor to account for the mutilation rate following blade strike, to arrive at the probability of severe injury and/or mortality.

In a recent study by Van Berkel et al. (2014), fish damage in hydropower station Linne (The Netherlands) was investigated. Based on CFD analyses of the internal flow, blade strike model calculations, and comparison with measurements of fish damage it was concluded that mechanical damage by blade strike is the most likely cause of damage. With static heads of about 4 m, velocity shear and expansion rate (in areas of low pressure) were found to be of minor influence to fish damage. With heads in the range 0-1 m, this will most likely also be true for the Brouwers dam.

Another allegedly important cause of mechanical injury is grinding in gaps between rotating runner blades and the stationary casing or hub. It has been suggested by many that eliminating the gaps would lead to a substantial reduction of fatalities (see e.g. Odeh, 1999). Within the framework of the US Department of Energy’s Advanced Hydropower Turbine Systems (AHTS) program, Voith developed a minimum gap runner (MGR) turbine, which was essentially a modified Kaplan turbine. A number of these MGRs have been installed since, but the supposed favourable effect of reduced gaps on fish damage remains questionable, as reported in Cada (2001), Cada & Amaral (2011), and Deng et al. (2011).

In the present study, it is assumed that blade strike is the most important cause of fish damage. Even though never examined for a Darrius type of cross-flow turbine, this is most likely also the case for the Water2Energy turbine in this study. It is further assumed that the turbine designs are optimized to reduce the risk of grinding in small gaps.

2.2 Blade strike model

The probability of a fish lethally damaged during turbine passage depends on two factors:

(1) The theoretical probability $P_{th}$ that the fish collides with the leading edge of a runner blade. This depends on the axial velocity of the fish, its length and orientation, the speed of the runner, and the number of runner blades.
2.2 Blade strike model

(2) The probability that a blade strike will lead to instant death or lethal injury. This probability is often designated “mutilation ratio” or “mortality ratio” \( f_{\text{MR}} \).

Thus, the probability of mortality \( P_m \) of a fish passing through the turbine can be calculated as

\[
P_m = f_{\text{MR}}P_{\text{th}}
\]  

(2.1)

For the mortality ratio \( f_{\text{MR}} \) a correlation by Van Esch (2012) of the most recent measurements for rainbow trout by EPRI (2008/2011) was used. The graph in figure 2.1 presents the dependency of the factor \( 1-f_{\text{MR}} \) on the velocity \( v \) at impact and the ratio of fish length \( L_f \) to leading edge blade thickness \( d \). \( f_{\text{MR}} \) being the mortality ratio, the factor \( 1-f_{\text{MR}} \) can be interpreted as the survival rate in the long run following a blade hit. From the measurements it follows that trout can be lethally injured by a blade if the collision speed exceeds 5 m/s. The severity of the damage increases with collision speed and with increasing ratio of fish length to blade thickness.

A similar correlation for collision damage of eel is given by Van Esch (2014). Eel appears to be less vulnerable than trout; lethal damage starts at collision speeds of 8 m/s and up.

\[
\begin{align*}
L_f &= \text{fish length} \\
d &= \text{blade leading edge thickness} \\
f_{\text{MR}} &= \text{mutilation ratio} \\
v &= \text{velocity difference between fish and blade}
\end{align*}
\]

Figure 2.1 Probability of survival for rainbow trout after blade collision (EPRI, 2011)
2.3 Fish behaviour and other sources of uncertainty

In this study, the fish mortality rate is calculated by a blade strike model, assuming that:

- the flow enters the runner with no pre-swirl
- fish enter the runner aligned with the direction of the flow, i.e. in pure axial direction
- fish move with the flow as passive objects
- fish are uniformly distributed over the entrance

The actual situation may be quite different, of course. Fish can have a preferent position in the water column. For example, eel tend to swim in deeper layers of the water, close to the bottom. It means that, in case of a horizontally mounted (bulb) turbine, they may enter the runner of the turbine near to the tips of the blades where the impact velocity is largest. Fish may also actively swim with or against the flow, leading to a greater or lesser exposure to the moving blades. Because of this kind of unpredictable behaviour, “estimates of the probability of strike and strike related injury/mortality may have wide confidence boundaries” (Cada et al., 1997). This is obviously the case in Bakker & Gerritsen (1992) who observed quite different results in field monitoring studies for Linne hydropower station, performed in fall and in spring.

There is, however, another reason why measurements of fish damage and mortality have wide confidence intervals. This is due to statistics and has nothing to do with fish behaviour. Measurements of fish damage are often based on a limited number of fish, likely in the range of ten to one hundred. Even if a trial consists of one hundred fish, the so-called 95%-confidence interval will range from ±4 % to ±10 %, depending on the measured probability. See also table 3.3.

Model calculations of fish damage should therefore be considered as indicators of the measured damage that can show a large spread.

2.4 Validation of the model

Damage to fish in HPP Linne

Measurements of mortality and lethal damage of scale fish and eel were done during monitoring studies at hydropower station Linne, the Netherlands (Bakker and Gerritsen, 1992; Brujs et al., 2003; Kemper et al., 2012). Linne has 4 axial bulb turbines with a diameter of 4 m and a shaft speed of 88 rpm. The volume flow rate varies between 30 and 100 m$^3$/s per turbine. Measured mortality rates for scale fish range between 0 and 10%, depending on fish type and flow rate. Mortalities for eel vary between 0 and 27%, again depending on flow rate.

The blade strike model is validated by comparing calculated results of fish damage with measured rate of mortality (Van Berkel et al., 2014). Differences between measured and calculated mortalities are small (error < 3-4%) for various types of scale fish except for pike perch which, in this study at least, appears to be a much tougher fish than all the other species that were considered in this particular study. Also for eel, calculated values are in fair agreement with the measurements, with deviations smaller than approx. 5%.
2.4 Validation of the model

Damage to eel in Nijhuis model-scale turbine

Winter et al. (2012) presented tests of damage to eel in a scale model of a fish-friendly bulb turbine of Nijhuis (figure 2.2). The turbine has a diameter of 0.80 m and three runner blades with a shape similar to the Pro-Tide Nijhuis turbine. The turbine is equipped with guide vanes that add to the incoming flow a swirling motion in the direction of rotation, effectively reducing the velocity difference between the fish and the blades.

Water head at the test location was 5.5 m on average. Turbine rotation speed varied between 250 rpm and 280 rpm. Water velocity in the turbine was 4.5 m/s which corresponded to a flow rate of 1.8 m³/s.

Two different tests were performed: with the guide vanes fully opened, and with guide vanes open at an angle of 30 degrees. Average length of the eel was 40 cm. Measured mortality (after 96 h holding period) amounted to 0% for 30 degrees opening angle and 1.2% for fully opened guide vanes. Measurements were, however, inconclusive as to the origin of this mortality: a control group of eel showed similar mortality but it could not be ruled out that these individuals had actually passed through the turbine during a previous trial.

Blade strike model calculation of the probability of mortality resulted in 0% for 30 degrees opening angle. For swirl-free entrance at fully opened guide vanes, the calculated mortality rate is a little higher. Depending on the runner shaft speed it ranges between 1.3% (@250 rpm) and 3.2% (@280 rpm). These calculated mortality rates agree well with the measurements.

Figure 2.2 Fish damage tests for eel in the Nijhuis modified bulb turbine at Leeghwater pumping station (left) and drawing of the turbine (right).
3 Fish damage in the Pro-Tide turbine test-rig

Within the framework of the Pro-Tide project, a dedicated test-rig was built near Maurik, the Netherlands, to evaluate turbine performance and fish-handling capabilities on model-scale (Van Berkel, 2015-a,b). An aerial view of the test-rig is given in Figure 3.1.

Tests of fish damage are performed for two different types of turbines; the Nijhuis horizontal bi-directional bulb turbine and the Water2Energy (W2E) vertical axis cross-flow turbine.

Both turbines are tested with three types of fish: rainbow trout (approx. 18 cm), pike perch (approx. 18 cm), and eel (approx. 20 cm). In this report, only the measured mortality rate after 48 h holding period will be mentioned. A detailed account of the fish damage tests is given in Vriese (2015-b).

Prior to the actual measurements, the expected fish damage was estimated using the blade strike model of section 2.2. Based on these calculations it was decided whether to perform the fish tests at the (scaled) rated operating conditions, or to change the flow rate, head and shaft speed in an effort to reduce the expected mortality rates to an acceptable value.

3.1 Nijhuis turbine

The Nijhuis turbine is designed as a low head tidal turbine. It has no inlet or outlet guide vanes and the runner is equipped with two adjustable blades to accommodate the changing of direction of the flow during a tidal cycle. The shape
of the blades resembles that of a Hidrostal pump, with forward‐leaned leading edges to improve fish‐friendliness. Figure 3.2 presents a photograph of the scale model version of this turbine, as well as a CAD drawing showing the specific shape of the blades.

The specifications of the Nijhuis turbine design for a rated head \( H \) of 1 meter is given in Table 3.1, for the full scale turbine (at \( 235 \text{ m}^3/\text{s} \)) as well as for the 16:1 model‐scale version (at \( 0.92 \text{ m}^3/\text{s} \)).
3. Fish damage in the Pro-Tide turbine test-rig

Fish mortality at model-scale

Since the mortality rate for a specific turbine depends on the length of the fish, its species, the flow rate, and the shaft speed of the runner, probabilities of mortality can be displayed as Hill-graphs, as a function of head and flow rate. Calculations are based on a Hill chart of the runner speed, as provided by Nijhuis (figure 3.3). The (scaled) rated operating point at \( H = 1 \) m is depicted in this figure as well. As an illustration, the probabilities of collision \( P_{th} \), mutilation \( f_{MR} \), and overall mortality \( P_m \) are presented in figure 3.4 for trout of 18 cm, and in figure 3.5 for eel of 20 cm.

The Nijhuis turbine owes its improved fish-friendliness to the shape of the runner blades, along with its low number of blades. The specific shape of the blades serves to reduce the collision speed, effectively by reducing the velocity of impact in a direction normal to the leading edge. This favourable effect is incorporated in the blade strike model of section 2.2.

Expected mortality at the rated operating point is 7% for trout and 0% for eel. Since the mortality for trout was considered too high, two operating conditions at slightly more favourable damage rates were selected for the fish tests: \((Q,H,N) = (0.7 \text{ m}^3/\text{s}, 0.45 \text{ m}, 175 \text{ rpm})\) and \((Q,H,N) = (0.8 \text{ m}^3/\text{s}, 0.7 \text{ m}, 190 \text{ rpm})\). These test conditions are also presented in the graphs of figures 3.4 and 3.5.

Model calculations were repeated for the average fish lengths that were used in the measurements (Vriese, 2015-b) and results are compared in table 3.2. The agreement between the measured and the calculated mortality rates of 0% for eel is good.

![Figure 3.3 Hill chart of the shaft speed, for the Nijhuis scale model turbine. The rated operating point is indicated at 1 m head, 0.92 m$^3$/s and 208 rpm. The dashed line denotes maximum efficiency.](image)

<table>
<thead>
<tr>
<th>Nijhuis model scale turbine</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>( Q ) [liter/s]</td>
<td>700</td>
<td>800</td>
</tr>
<tr>
<td>( N ) [rpm]</td>
<td>175</td>
<td>190</td>
</tr>
<tr>
<td>( H ) [m]</td>
<td>0.45</td>
<td>0.7</td>
</tr>
<tr>
<td>( L_f ) [cm]</td>
<td>mortality [%]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>model</td>
<td>measured</td>
</tr>
<tr>
<td>Pike perch</td>
<td>17.2</td>
<td>0.6</td>
</tr>
<tr>
<td>Rainbow trout</td>
<td>17.4</td>
<td>0.6</td>
</tr>
<tr>
<td>Yellow eel</td>
<td>25.1</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Table 3.2 Calculated and measured fish mortality for the model-scale Nijhuis turbine for different fish species and average fish lengths \( L_f \)
Calculated values for the mortality of scale fish (rainbow trout and pike perch) shows a fair agreement with the measurements. A remarkable result is the fact that the measured mortality rate for pike perch is higher than for trout. This is true for the measurements at both operating conditions. This is quite unexpected since pike perch is generally considered to be less vulnerable to blade strike damage (see section 2.4) than most other types of scale fish. The blade strike model does not distinguish between the two fish species. The mortality rate for trout is somewhat overpredicted by the blade strike model. For pike perch, the calculations underpredict the measured values. On average, the model provides a good estimate of the mortality of scale fish.

It should be noted that the measurements suffer from inaccuracy due to the limited number of fish that were used in the tests (typically 100 per tests). If the probability
3. Fish damage in the Pro-Tide turbine test-rig

The number of dead fish is denoted by $n$, the total number of fish in the trial is $N$. If a fish damaged is assumed to have a binomial distribution, then the 95% confidence interval (CI) can be calculated. Some typical results are given in table 3.3. It shows that the measured mortality rates should be interpreted with care.

<table>
<thead>
<tr>
<th>$n$</th>
<th>$N$</th>
<th>$p$</th>
<th>95%-CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>100</td>
<td>0%</td>
<td>0 - 3.6%</td>
</tr>
<tr>
<td>1</td>
<td>100</td>
<td>1%</td>
<td>0 - 5.5%</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>2%</td>
<td>0.2 - 7.0%</td>
</tr>
<tr>
<td>6</td>
<td>100</td>
<td>6%</td>
<td>2.2 - 12.6%</td>
</tr>
</tbody>
</table>

Table 3.3 Probability $p$ and 95% confidence interval (CI) for a binomial distribution.

Figure 3.5 Calculated probability of collision $P_{th}$, the mutilation ratio $f_{MR}$, and the overall probability of mortality $P_{m}$ for eel of 20 cm in the Nijhuis model-scale turbine.

...
3.2 W2E turbine

The W2E turbine is a Darrius type of cross-flow turbine with three vertical blades mounted onto a vertical shaft. Figure 3.6 presents a photograph and a drawing of the scale model version of this turbine. As this turbine can accommodate flows in both directions, it is particularly suited as a tidal turbine. The dimensions of the W2E turbine are given in Table 3.4, for the full scale turbine as well as for the model-scale version.

The scale model W2E turbine was equipped with an active blade pitch control system to maximize the efficiency. The hydraulic performance was measured by Van Berkel (2015-2) and results showed that best efficiency performance (BEP) was reached at two operating conditions: \((Q,H,N) = (0.63, 0.3, 75)\) and \((Q,H,N) = (0.75, 0.42, 95)\). These BEP operating conditions are indicated in the QH-graph in Figure 3.7. From this it was concluded that the W2E turbine attains its optimal performance at a tip speed ratio \(\text{TSR}\) of 1.17 and a discharge coefficient \(C_D\) of 1.04, where

\[
\text{TSR} = \frac{\Omega R}{v_a} \quad \text{and} \quad C_D = \frac{v_a}{\sqrt{2gH}}
\]

with \(\Omega\) the shaft speed (rad/s), \(R\) the runner radius, \(v_a\) the axial velocity through the runner, and \(H\) the head.

From Figure 3.7 it follows that the scale model turbine has maximum efficiency at the rated head of 1 m for a shaft speed of 147 rpm and a flow rate of 1.16 m³/s. This rated performance scales to \((Q,H,N) = (295 \text{ m}^3/\text{s}, 1.0 \text{ m}, 14.7 \text{ rpm})\) for the full-scale turbine (see Table 3.4).

![Figure 3.6: Scale model version of the W2E vertical axis turbine with 70 cm rotor diameter and 28 cm rotor height: photograph (above) and schematic drawing.](image-url)
3. Fish damage in the Pro-Tide turbine test-rig

Fish mortality at model-scale

The hydraulic performance tests have not provided enough information to construct Hill charts for shaft speed and efficiency. That is why figure 3.7 only shows the calculated fish mortality at best efficiency (BEP) performance. The rated operating point at $H = 1\ m$ is indicated in the figure as well as the calculated mortality rates for trout (18 cm) and eel (20 cm) at BEP conditions. For these model-scale fish tests, the expected mortality at the rated operating point of $H = 1\ m$ is 20.5% for trout and 0.8% for eel. Since the mortality for trout was considered too high for testing, two operating conditions at more favourable damage rates were selected for the fish tests: $(Q,H,N) = (0.57\ m^3/s, 0.3\ m, 75\ rpm)$ and $(Q,H,N) = (0.785\ m^3/s, 0.4\ m, 95\ rpm)$. These test conditions are also indicated in figure 3.7.

<table>
<thead>
<tr>
<th>W2E turbine</th>
<th>full scale</th>
<th>model scale</th>
<th>scale factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor diameter [m]</td>
<td>7</td>
<td>0.7</td>
<td>10 : 1</td>
</tr>
<tr>
<td>Rotor height [m]</td>
<td>7</td>
<td>0.28</td>
<td>25 : 1</td>
</tr>
<tr>
<td>Housing cross section [m2]</td>
<td>8x8</td>
<td>0.9x0.28</td>
<td>254 : 1</td>
</tr>
<tr>
<td>Blade number</td>
<td>3</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Nominal performance</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flow rate [m3/s]</td>
<td>295</td>
<td>1.16</td>
<td>254 : 1</td>
</tr>
<tr>
<td>Head [m]</td>
<td>1</td>
<td>1</td>
<td>1 : 1</td>
</tr>
<tr>
<td>Shaft speed [rpm]</td>
<td>14.7</td>
<td>147</td>
<td>1 : 10</td>
</tr>
<tr>
<td>Axial velocity [m/s]</td>
<td>4.60</td>
<td>4.60</td>
<td>1 : 1</td>
</tr>
<tr>
<td>Tip speed ratio (TSR)</td>
<td>1.17</td>
<td>1.17</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.4  Dimensions and nominal performance of the full scale and model-scale W2E turbine.

Figure 3.7  Performance curve and estimated fish mortality rates at BEP operating conditions for the model-scale W2E turbine. Actual fish test conditions are also indicated.
Model calculations were repeated for the average fish lengths as used during the fish test measurements (Vriese, 2015-b) and results are compared with the measurements in table 3.5. The agreement between the measured and the calculated mortality rates of 0% for eel is good.

Calculated and measured values for the mortality of scale fish (rainbow trout and pike perch) show the same trend as for the Nijhuis turbine; measured mortality for pike perch is higher than predicted, and measured damage for trout is lower than for pike perch. On average, the model still provides a good estimate of the mortality rate of scale fish; for the majority of cases, the calculated values are within the 95% confidence intervals of the measured mortality rates (see table 3.3).
4 Estimated fish mortality for full-scale turbines

Fish mortality tests were done at model-scale in an effort to establish the turbines’ fish handling performance before actual instalment of the full-sized turbines. However, direct up-scaling of the test results to full-scale turbines requires both geometric and dynamic similarity between the two scales. This is obviously not the case in this particular study:

- The differences in size between the full-scale and the model-scale turbines are much larger than the differences between the fish sizes at model-scale testing and the ones considered of interest in practice (Vriese, 2015-a).
- Fish mortality for the model-scale fish tests at the rated operating point of 1 m was considered too high. For this reason, operating conditions during the fish tests were relaxed to obtain acceptable damage rates (sections 3.1 and 3.2). As a consequence, the results can no longer be used for up-scaling to the rated conditions at full scale.

For these reasons, it was decided in the Pro-Tide project to use model-based predictions of fish mortality and compare the results of these calculations with fish tests at model-scale. The results of this validation step were presented in section 3. Since the calculated values agree fairly well with measured fish mortality, it was considered feasible to use the blade strike model to predict the expected fish mortality in the full-sized turbines.

For the Brouwers dam location, the following fish species and lengths are considered critical in terms of their chances of survival:

- Salmon or trout smolts of 15 cm
- Sea bass of 25 cm
- Eel of 75 cm

In this section, the mortality of these fish is estimated for the full scale version of the Nijhuis turbine and the W2E turbine.

4.1 Nijhuis turbine

Results of blade strike model calculations for the full-size Nijhuis turbine are given in figure 4.1 for smolts (15 cm), bass (25 cm), and eel (75 cm). Calculated mortality at the rated operating condition (\( H = 1 \) m) is given in the graphs and in table 4.1.

It turns out that fish mortality for the species and sizes considered is well below 1%.

**Nijhuis full scale turbine**

| Q [m³/s] | 235 |
| N [rpm] | 13  |
| H [m]   | 1   |

<table>
<thead>
<tr>
<th>mortality [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smolts 15 cm</td>
</tr>
<tr>
<td>Bass 25 cm</td>
</tr>
<tr>
<td>Eel 75 cm</td>
</tr>
</tbody>
</table>

Table 4.1 Calculated expected mortality for the Nijhuis full-scale turbine operating at rated condition (\( H = 1 \) m).
4.1 Nijhuis turbine

Figure 4.1 Estimated mortality $P_m$ for smolts (15 cm), bass (25 cm), and eel (75 cm) in the Nijhuis turbine at full scale. The rated operating condition at $H = 1$ m is indicated in the graphs.
4. Estimated fish mortality for full-scale turbines

4.2 W2E turbine

Blade strike model calculations are also performed for the full-size W2E turbine operating at maximum efficiency (BEP). Results of expected mortality are given in figure 4.2 for smolts (15 cm), bass (25 cm), and eel (75 cm). Mortality at the rated operating condition \((H = 1 \text{ m})\) is given in table 4.1.

It turns out that fish mortality for the species and sizes considered is well below 1%.

![Performance curve and estimated fish mortality rates at BEP operating conditions for the full scale W2E turbine.](image)

<table>
<thead>
<tr>
<th>W2E full scale turbine</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Q ([\text{m}^3/\text{s}])</td>
<td>295</td>
</tr>
<tr>
<td>N ([\text{rpm}])</td>
<td>14.7</td>
</tr>
<tr>
<td>H ([\text{m}])</td>
<td>1</td>
</tr>
<tr>
<td>mortality [%]</td>
<td></td>
</tr>
<tr>
<td>Smolts 15 cm</td>
<td>0.30</td>
</tr>
<tr>
<td>Bass 25 cm</td>
<td>0.90</td>
</tr>
<tr>
<td>Eel 75 cm</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Table 4.2  Calculated mortality of the W2E full-scale turbine operating at rated condition \((H = 1 \text{ m})\).
4.2 W2E turbine
5 Summary and conclusions

In this report two different low-head turbine designs are evaluated for their fish-friendliness: the Nijhuis horizontal axis tidal turbine and the Water2Energy (W2E) vertical axis cross-flow turbine. Both turbine designs are suited for application in a tidal power plant situated in the Brouwers dam, with a rated head of 1 m (average value).

As an intermediate step, fish mortality tests were foreseen at model-scale in an effort to establish the turbines’ performance before actual installment of the full-sized turbines. The test conditions for these model-scale fish tests were selected based on estimations of the expected fish mortality. Use was made of a model to predict fish mortality following mechanical injury from blade strike. This model was extensively validated in previous studies.

The results of the blade strike model calculations indicated that model-scale fish testing at the rated head of 1 m would lead to mortalities that were considered too high for animal testing. For this reason, operating conditions were somewhat relaxed to lower heads, shaft speeds, and flow rates.

Model-scale fish tests were subsequently performed for various fish species: rainbow trout (18 cm), pike perch (18 cm), and yellow eel (25 cm). Measured mortality rates showed a fair agreement with a priori calculated values: deviations were well within the 95% confidence interval of the measurements. Surprisingly, mortality among pike perch was seen to be much higher than for trout at otherwise identical circumstances, both for the Nijhuis turbine and for the W2E turbine. Calculated mortality rates tend to over-predict those for trout while under-predicting the mortality for pike perch.

Since the calculated values agree fairly well with measured fish mortality at model-scale, it was considered feasible to use the blade strike model to predict the expected fish mortality in the full-sized turbines. Calculations were done for trout and salmon smolts (15 cm), sea bass (25 cm) and eel (75 cm) at the rated head of 1 m. Results suggest that expected mortality rates are low, typically lower than 1%. 
4.2 W2E turbine
6 References


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