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Review

State of the Art in Designing Fish-Friendly Turbines: Concepts and Performance Indicators

Phoevos (Foivos) Koukouvinis and John Anagnostopoulos *

Laboratory of Hydraulic Turbomachines, Department of Mechanical Engineering, National Technical University of Athens, Heroon Polytechniou 9, 157 80 Zografou, Greece
* Correspondence: anagno@fluid.mech.ntua.gr; Tel.: +30-210-7721080

Abstract: The expanding role of renewable energy sources in the electricity market share implies the increasing role of hydropower and the exploitation of unharnessed hydraulic potential, in the scope of sustainability and net zero emissions. Hydro-turbine design practices are expected to expand beyond achieving high efficiency goals, to multi-objective criteria ranging from efficient reversible operation to fish-friendly concepts. The present review paper outlines fundamental characteristics of hydropower, summarizing its potential impact toward aquatic life. Estimates of lethality for each damage mechanism are discussed, such as barotrauma, blunt impact and shearing, along with relevant advances in experimental techniques. Furthermore, numerical techniques are discussed, ranging from simple particle tracking to fully coupled six-degree-of-freedom tracking, which can be used to investigate candidate designs and their fish-friendly performance, presenting their advantages and disadvantages. Subsequently, a link to the individual damage mechanisms is established, to proposed holistic performance metrics, useful for providing estimates of fish-friendliness of a given hydropower installation. Finally, recent developments and design practices for fish-friendly turbine concepts are presented.

Keywords: fish-friendly hydropower; hydropower statistics; fish injury assessment; experimental methods; numerical methods; turbine design considerations

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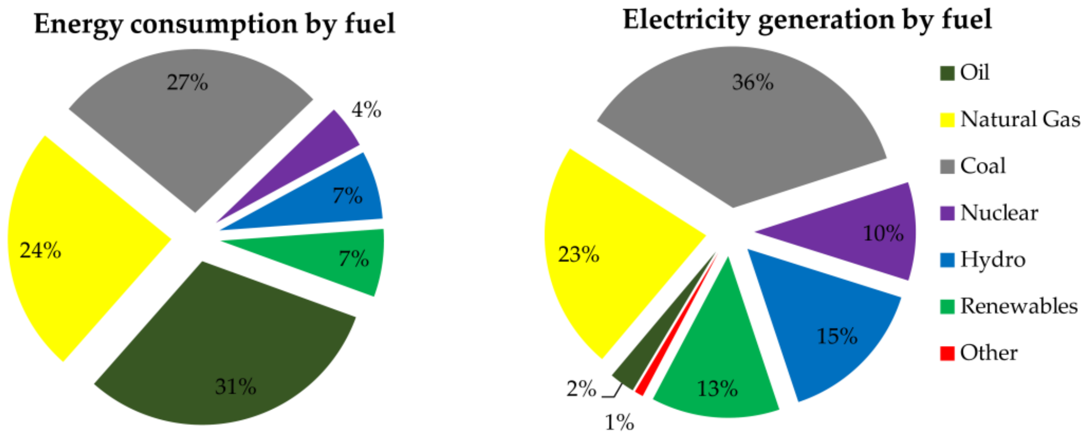
1. Introduction

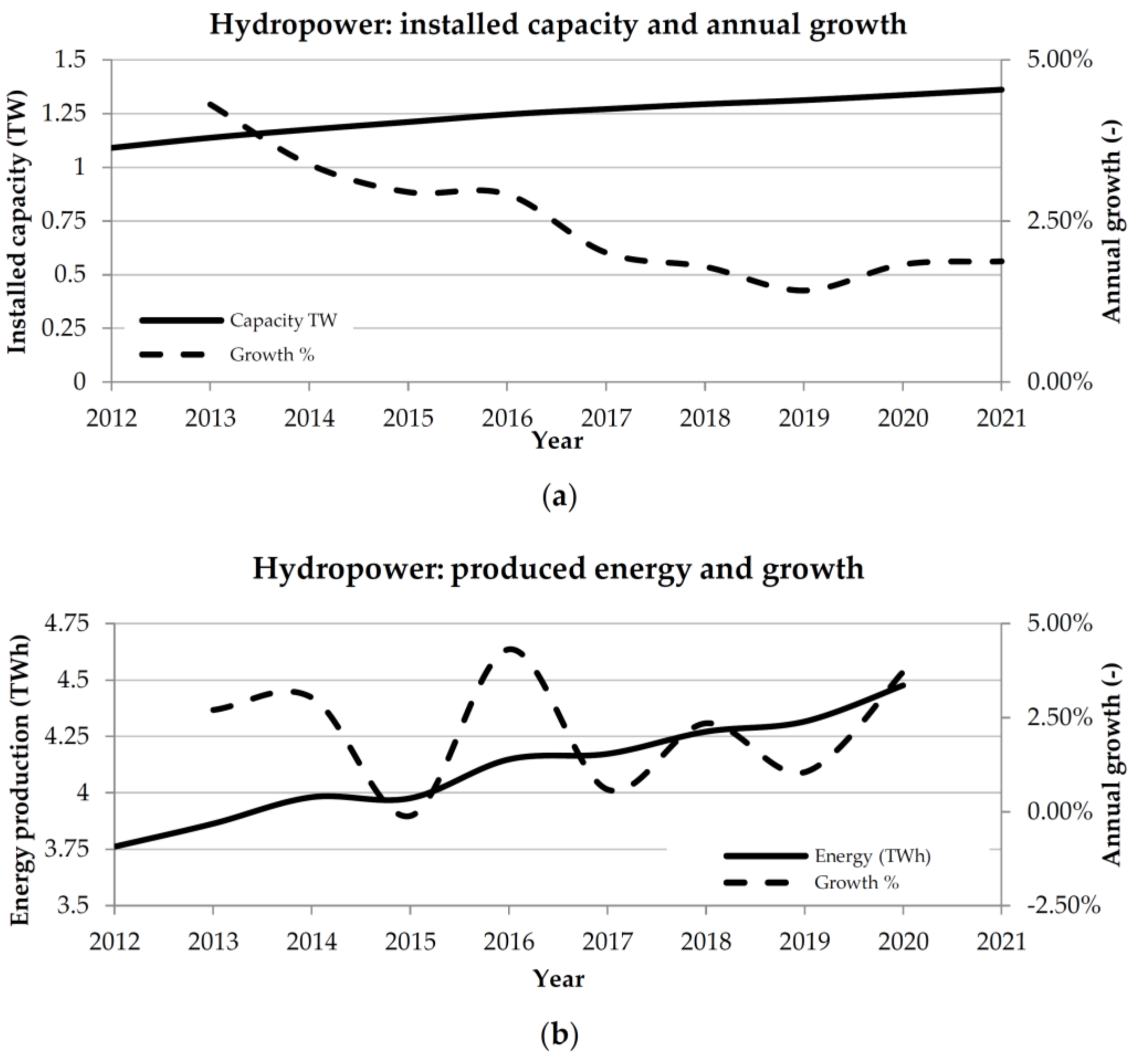
Hydropower is perhaps the oldest form of renewable energy resource, and it plays a paramount role in energy production worldwide. Indicatively, Figure 1 shows the contribution of hydropower, compared to other resources globally; in terms of global energy consumption (that is, including transportation), hydropower contributes 7% of the total, whereas in terms of electricity production, hydropower contributes almost 15% of the total (see also [1]). It is also notable that the contribution is effectively comparable to all the other renewable energy resources combined; indicatively, it has an estimated contribution of almost 60% compared to other renewable energies based on 2021 data [2].

The role of hydropower has been constantly increasing over the years. Indicatively, as shown in Figure 2, the recent trend both in terms of installed capacity and produced energy per year shows an annual growth of 1.8% and 2.3%, on average for the last 2–3 years, respectively. Despite the minor drop in annual growth of installed capacity for the year 2019 and, given the goal for a Net Zero Emissions by 2050, hydropower is expected to maintain an average annual generation growth rate of about 3% in 2022–2030 [3]. The growing role of hydropower is justified for two main reasons:



(**a**) (**b**)

Figure 1. (**a**) Global energy consumption by fuel source and (**b**) global electricity generation by fuel type (source, BP Energy Statistics 2022 [1]).



(**a**)

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Figure 2. Hydropower statistics and trends over the recent years: (**a**) Installed capacity and (**b**) annually produced energy. (source, IRENA Renewable Energy Statistics 2022 [2]).

(A) It can greatly contribute as an energy storage solution, in the form of pumped hydropower (also abbreviated as PHP), along with batteries, allowing for the increased penetration of other renewable sources [4], such as wind and solar energies. Pumped hydropower not only generates electricity and serves as daily or weekly balancing, but also provides additional services to the grid, such as system inertia, frequency response and grid regulation. Indicatively, as of 2020 statistical data [5], pumped hydropower contributes more than 90% in installed capacity. Estimates indicate that the installed capacity of reversible hydro/pumped storage will increase by 42% until 2026 [6].

(B) There is a considerable quantity of unharnessed hydropower potential, with rough estimates indicating that about 25% of the technically achievable and 50% of the economically feasible potential (for the current technologies) is presently being utilized, see [7–9]. Indicatively, an appreciable hydraulic potential can also be found in existing infrastructure that currently lacks generating units (e.g., existing barrages, weirs, dams, canal fall structures, water supply schemes) by adding new hydropower facilities.

Despite the renewable nature of hydropower, it unavoidably has an impact on the local ecosystems and aquatic life. In particular, the following aspects have been identified and recognized [10]:

- The direct destruction of fauna and flora habitats, by changing the use of land and by submerging large areas, to achieve the formation of a reservoir;
- Indirect disturbance to local life, due to building infrastructure (e.g., roads, electrical grid, etc.) and gaining access to previously inaccessible areas. This can also involve induced disturbance due to population living in the reservoir area being resettled to formerly natural areas;
- Disruption of the natural flow of a water stream, by forming a reservoir. Inherently, the construction of any sort of dam implies a partial or total impedance of free migration of aquatic species, the blocking of sediments that would replenish downstream ecosystems and the change in the downstream flow patterns of the river.

The first two points mainly affect terrestrial vegetation and fauna, while the third point refers to impacts on hydrobiology (fish and other aquatic life). Whereas there are methodologies for assessing the impact both on terrestrial vegetation, as well as fauna, and taking proper mitigation measures, see indicatively [10], fish fauna is considered to be particularly susceptible to the disruption caused by hydropower facilities [11,12]. In particular, the presence of the dam and the introduction of the hydraulic turbine, necessary to extract energy from the water stream, inherently alter the natural course of a river stream and affect the active (migration) and passive (drift) movements of aquatic organisms' travelling routes. In the last decade, severe declines in the freshwater populations has been observed and a major contribution to this decline is believed to be due to river ecosystem fragmentation [13,14]. Undoubtedly, the fish fauna of a river is, in every case, affected in a major way by a hydropower project; hence, it has to be one major focal point of design considerations.

Over time, measures for enabling fish passage through a hydropower project have been developed in the form of fish passages, a term generally used to refer to any structure built to facilitate the travel of fish through a water stream. These can be classified as:

(A) Passive, in the form of:

- Artificial fishways incorporate artificial flow reduction elements such as baffles (also known as Denil fishways) or steps (e.g., pool-and-weir, vertical-slot fishways or fish-ladders, see Figure 3a,b, respectively);
- Nature-like fishways contain natural features that increase bottom roughness such as cobble and boulders (see, e.g., Figure 4a), although they may incorporate some engineered elements such as anchored concrete blocks or other artificial elements that may be found in technical fishways.

(**a**) (**b**)

Figure 3. (**a**) Pool-and-weir fish ladder, (**b**) vertical-slot fish ladder.

(**a**) (**b**)

Figure 4. (**a**) Rock–ramp fishway, (**b**) fish lift at Tallowa dam.

(B) Active systems, such as fish locks and fish lifts that use mechanical locking gates to direct fish and lifting devices such as baskets to physically move them past barriers, see, e.g., Figure 4b.

Nevertheless, despite these measures which enable fish to pass through the installed infrastructure, systematic studies have demonstrated that these are not perfect remedies [15]; in fact, extensive statistical analysis of fish mortality indicates that bypasses pose a decreased injury risk relative to controls, whereas turbines and spillways were associated with the highest injury risks relative to controls [16]. Furthermore, despite the existence of general guidelines or risk factors for aquatic life (e.g., Kaplan turbines are known to be safer comparing to Francis turbines [16]), the development of methodologies estimating damage/mortality [17–19] or the compilation of extensive statistical data on mitigation measures and fish mortality (see [15,20–25]), there is lack of a widely accepted indicator or methodology that could characterize reliable fish-friendliness. Such an assessment is critical in determining the effectiveness of potential remedies to alleviate risks, since fish passage is highly dependent on details of each particular site and fish species [16].

As underlined at the beginning of this section, it is clear that hydropower will continue playing an important role in power generation either in the form of production or energy storage and grid regulation. Moreover, it is expected that, in the future, previously unharnessed water resources (such as unpowered dams, unexploited low-head streams, small reservoirs, streams of impaired quality, etc., all the previous also denoted as "hidden hydro"), will be further exploited (see for example [26–28], or the recent HORIZON-CL5-2021-D3-03-11 call [29]). Hence, hydropower penetration in the near future is expected to place more pressure on aquatic life [30,31], rendering fish-friendly design concepts essential considerations for any prospective hydropower infrastructure (see [32,33]). The aforementioned observation is the motivation behind the present paper, aiming to condense existing know-how on fish-friendly hydropower concepts, identify challenges and propose further fields of study.

The present paper is structured as follows: Section 2 provides a brief overview of the structure of a hydropower facility, Section 3 presents potential mechanisms and phenomena due to hydraulic machinery operation that can adversely affect fish, along with relevant biological investigations on the topic and Section 4 examines methodologies for predicting fish injury, derived through experiments or simulations. Then, Section 5 discusses attempts on deriving fish-friendliness indices and Section 6 investigates fish-friendly turbine concepts. Finally, Section 7 is the conclusion, discussing challenges and future perspectives.

The methodology for performing the literature review involved a literature search to six electronic journal databases relevant to engineering, energy and environmental sciences, as well as the US Department of Energy resources and Google Scholar. The search was performed using terms such as fish-friendly hydropower, environmentally friendly turbines, fish barotrauma, turbine blade strike, fish injury mechanism and turbine design optimization. The literature resources were included if relevant to the scope of each section of the present paper.

2. Structure of Hydropower Station

For the sake of completeness, a short description of a typical hydropower plant is depicted in Figure 5 and is discussed to demonstrate its main components and mitigation measures for aquatic life; it will also assist in the understanding of damage mechanisms, which will be discussed in Section 3.

Inherently to their method of operation, hydroelectric power plants direct a water stream through the hydraulic turbine to extract energy [34]. This can be achieved in two ways: in the form of impoundment hydroelectric power plants or in the form of diversion hydroelectric power plants.

The first type, shown in Figure 5a, implies the construction of an obstruction, termed as dam. This obstruction cuts off the normal water path, forming a reservoir and forcing the main water stream to pass through the turbine. This type of hydropower implies heavy capital costs due to large civil engineering projects and is commonly associated with large hydropower facilities (>15 MW [34]). Such facilities also include reversible hydropower plants in the form of pumped storage systems, if the turbine is designed to be operated as a pump. Apart from the infrastructure for directing water through the turbine, common additional components involve regulating systems, such as control gates to regulate incoming flow, or safety systems, such as spillways in case hydraulic energy needs to be rejected. Furthermore, to protect aquatic life, it is common to introduce grates or racks at the intake pipe of the turbine to prevent large objects/fish to enter the turbine, potentially causing damage; recently, electric [35,36], electromechanical [37] or acoustic [38] deterrence techniques are also proposed to prevent fish from entering the turbine intake. Additionally, fishways/fish ladders may be incorporated at a bypass stream.

In the diversion design the main path of the water stream remains unaffected, but only a small, diverted flow actually passes through the hydraulic turbine and then merges further downstream with the main river, see Figure 5b. Additional preventive measures, such as intake grates, may be employed to prevent large fish entering the turbine intake as well. Naturally, this type of project is more fish-friendly, since the majority of the water stream remains relatively unaffected; however, a large part of the water stream remains inherently unexploited. Hence, it is suitable for small hydropower projects (<15 MW [34]). Furthermore, pumped storage is not an option for this type of project, since there is no upper reservoir to store water.

In terms of turbine technologies, it is common to categorize hydropower facilities depending on the available head, commonly indicated with the symbol H. Commonly, low-head plants use bulb turbines ($H < 20$ m) or Kaplan ($20 \text{ m} < H < 60$ m). Medium-to-high head plants ($40 \text{ m} < H < 400$ m) use Francis turbines (see Figure 5c) and finally plants of very high head ($350 \text{ m} < H < 1100$ m) use Pelton turbines (see Figure 5d). Many variations or alternatives to the aforementioned turbine types exist, such as Turgo, which is similar to Pelton, or the Archimedes screw design which can be an alternative to bulb turbines for very low heads (1 m < *H*); some of them will be discussed in Section 7 as more fish-friendly alternatives.

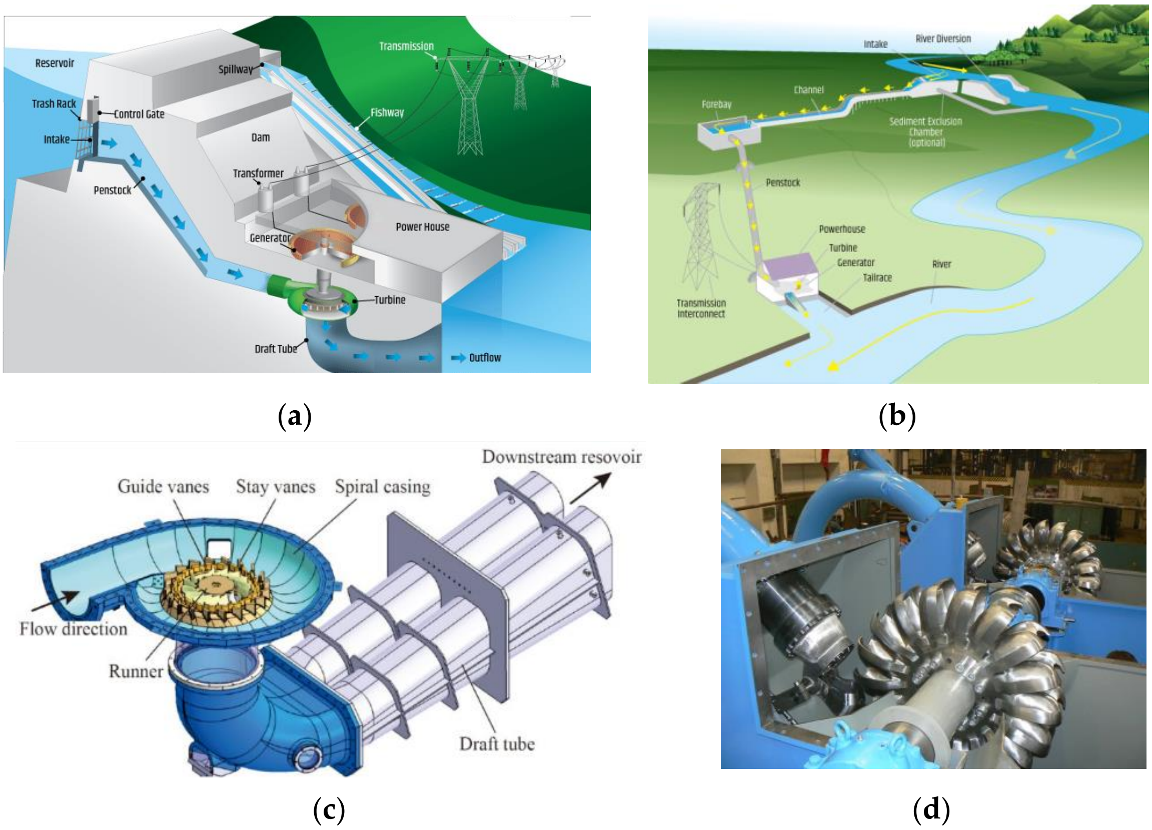


Figure 5. Typical structure of hydroelectric power plant with the main components shown (**a**) impoundment type (**b**) diversion type (Credit: U.S. Department of Energy). Images adapted from [39]. Typical turbines in hydropower: (**c**) Francis turbine (adapted from [40]) (**d**) an indicative view of a Pelton impulse turbine.

A distinct classification of the turbine designs, however, can be made in terms of reaction and impulse turbines. The distinction lies at the location of the pressure drop, whether it takes place at the stator (impulse turbine) or the rotor (reaction turbines), as this affects the operation of the turbine. Impulse turbines, such as Pelton turbines, operate inherently in a non-immersed environment. Hence, they cannot play the role of a reversible turbine, unless a dedicated pump is also used [41].

3. Mechanisms of Fish Damage and Mortality during Passage through a Turbine

In order to define criteria for the design of fish-friendly turbines, it is necessary to identify the mechanisms relevant to fish damage. Such mechanisms have been identified since the early 2000s, in an effort to improve designs, provide guidelines and develop novel turbine concepts with minimum effect on passing fish. In particular, several critical damage mechanisms have been identified [24,42–44], which are presented below, following the flow direction from the inlet racks toward the draft tube (see also Figure 6).

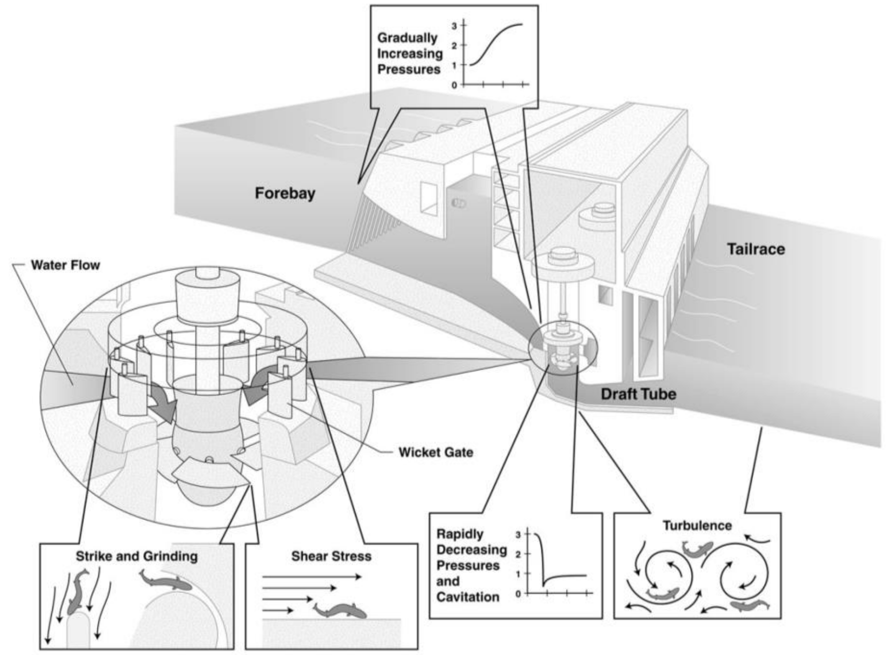
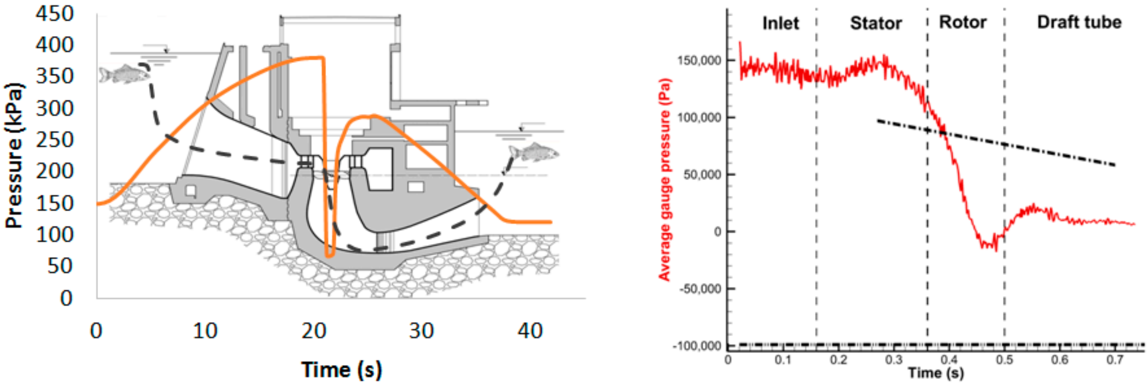


Figure 6. Illustration of locations where fish damage may occur (adapted from [45]).

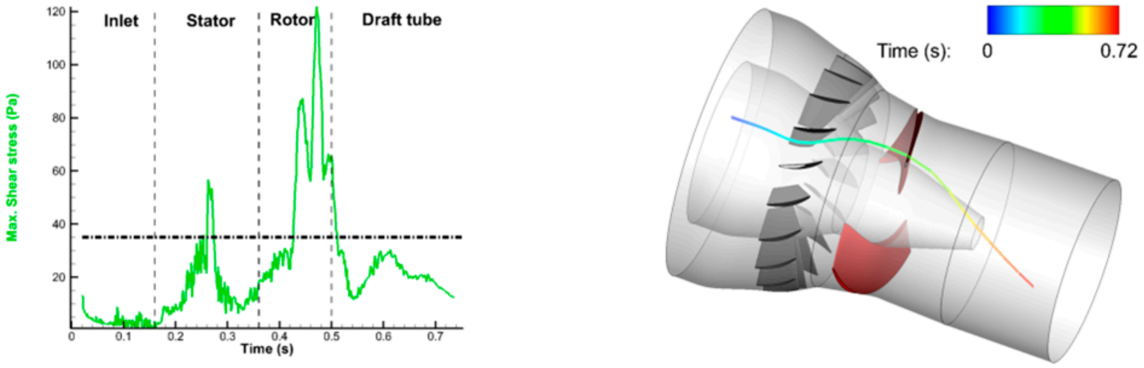
3.1. Pressure Changes

As a passing fish moves through the turbine intake, through the turbine, the draft tube and finally downstream the tailrace, it experiences severe pressure changes. After the racks and inside the penstock, pressure gradually increases, due to hydrostatic pressure [46]; an indicative of such variation is shown in Figure 7a; however, depending on the elevation change, this can be in the order of 1 bar to more than 10 bar. Then, at the vicinity of the stator blades, and especially the runner, pressure drops rapidly, much faster than the pressure rise. Gauge pressure can drop even below zero (vacuum), near the suction side of the blades [47,48], or the spiraling vortex tube, also known as vortex rope in the relevant literature, emanating from the turbine hub [40,49]; indeed, the latter is well known to induce strong low-frequency vibrations to the whole turbine, which potentially threaten the integrity of the whole installation [50–53]. In any case, as the trajectory of a passing fish reaches the tailrace, pressure recovers gradually to near atmospheric conditions.



(**a**) (**b**)

Figure 7. *Cont.*



(c) **(d)**

Figure 7. (**a**) An indicative pressure variation (orange line, based on data from [46]) that a fish experiences as it passes through a Kaplan turbine (fish track is the dashed line). (**b**) An indicative pressure variation and (**c**) shear stress magnitude, as a fish passes through an axial turbine (based on authors' work, see Section 4.2.3). In (**b**), the dashed–dotted (sloped) line indicates the depressurization rate of 90 kPa/s where the onset of mortality is observed [54]. The dashed–dotted–dotted (horizontal) line at the bottom indicates the onset of cavitation. In (**c**), the dashed–dotted (horizontal) line indicates a threshold of 35 Pa, which was found damaging for fish larvae [55]. (**d**) The indicative trajectory is examined and colored according to time. Black indicates the stator vanes, red the rotor blades.

Given the fact that fish are equipped with a gas bladder to adjust buoyancy, it is expected that pressure changes will greatly affect their capability to float and adjust their motion. Nevertheless, extensive research with controlled pressurization and depressurization of fish [56–59], both in terms of magnitude and rate, has shown that, in general, a pressure increase is rather well received; even at high pressurization rates, fish damage is minimal and no direct mortality was observed [43]. On the other hand, depressurization, and especially at a fast rate (indicative values for onset of mortality in the order of 90 kPa/s [54]), is rather problematic, leading to barotrauma [60,61]. Typical effects of barotrauma-related injuries include ruptured swim bladder, exopthalmia, internal hemorrhaging and gas bubbles (emboli). Extensive studies, using X-rays at fish exposed to rapid decompressions [60], indicated that the most prevalent theory for fish barotrauma is the rupturing of the fish gas bladder, which subsequently releases gas inside the bloodstream causing the aforementioned effects, eventually leading to severe mortality. While factors such as the pressure history (e.g., acclimation at high pressures) or the structure or existence of the fish gas bladder (e.g., physostomous fish can expel gas from the bladder naturally; lampreys lack gas bladder; both cases are expected to be more resilient to decompression [60]), an extensive compilation of experimental studies indicated that decompression mortalities can even reach 100% [43].

In cases of local pressure drops at vapor pressure levels, a more severe case of barotrauma may occur due to cavitation. Given the highly transient nature of cavitation and the associated rapid decompression and pressure recovery, formed vaporous pockets tend to collapse violently; indicatively, cavitation collapse is known to produce very fast microjets [62] that can pierce tissues [63] and even pit metallic surfaces [64] and to emit powerful shockwaves [65]. Despite the resulting aggressiveness of cavitation collapse, experimental investigations have shown mixed results [66], with a range of mortalities between 0 and 60% when fish are exposed to cavitating conditions. Nevertheless, there is a limited number of investigations on fish passage through a turbine in association with cavitation effects; possibly, this is because turbines are designed or controlled to limit operation in cavitating conditions [43], as this has severe adverse effects on their operation, longevity and efficiency.

3.2. Mechanical Damage

A more direct cause of fish mortalities is the interaction of fish with the rigid, structural/operational elements of the turbine rotor/stator. This can be classified into three categories, as: (1) strike, in the case of fish impact on surfaces, (2) grinding, in the case of fish being trapped in small gaps or clearances and (3) friction and abrasion.

Mechanical injury due to strike is expected to depend on various parameters, such as the fish size, the turbine passage, blade shape, rotating speed and flow rate. Indeed, numerous studies ([22,67–69]) have attempted the derivation of correlations for estimating the effect of the aforementioned factors on fish mortality; however, simplifying assumptions are commonly being involved, and thus confidence varies greatly [43]. Moreover, such estimations may be skewed by the exact fish species' behavior and characteristics. For example, fish behavior affects the outcome of the impact, since some fish species tend to move as a rigid body through the turbine, whereas other tend to react and actively avoid collision [43]. Additionally, aside the influence of fish dimensions, fish weight can play a role in the impact outcome, since smaller fish have less inertia; hence, they tend to be dragged by the flow around the blades, instead of colliding with them. Indicatively, studies indicated that fish with a mass of less than 20 g were unlikely to suffer a blade collision [70]. Nevertheless, extensive testing with different blade profiles and rotational velocities has shown that blunt, thick blades rotating at low velocities are the least threatening to fish [70,71]. Indicatively, collision velocities at ~5 m/s with thick blades were found to cause little damage and no mortality, whereas impacts on thinner blades at collision velocities of 6–7 m/s caused severe damage.

Considering grinding, there are very few references or investigations relevant to its influence. While it is directly related to the existence of gaps and clearances, where passing fish may get entrained, it is considered to be related more to fish dragged by leakage flows (e.g., at various control gates), rather than the main flow path. Hence, a general guideline involves eliminating gaps, as minimizing them at a size of less than 2 mm is expected to prevent fish injuries due to grinding [72].

The last category of mechanical damage, friction and abrasion refers to the shearing of fish along the solid turbine walls. As an effect, it is observed mainly in the draft tube [43] and is related to the swirling motion, imparted to the passing flow due to turbine operation. Despite the existence of dedicated techniques to investigate the occurrence and extension of external damage [73], it is, in practice, rather difficult to distinguish friction/abrasion from the other types of physical damage [74]. Efforts to devise techniques for the quantification and distinction of abrasion from shearing are ongoing [75]. In any case, the existence of irregularities on the draft tube, such as protrusions from welding, or bolts used for pipe connections, greatly increases the potential risk of abrasion [74].

3.3. Shear Stresses

The flowing water streams inherently develop from boundary layers, recirculations and flow detachments, all attributed to viscosity effects; thus, shear stresses are induced in all these cases due to the interaction of fluid layers moving at different velocities. Indicatively, shear stresses in water streams/rivers may be in the order of 100 Pa, whereas in the draft tubes of turbines they are in the order of 5000 Pa [76]. Even though these values are much lower than pressure magnitude (which can be two or three orders larger—see indicatively Figure 7b,c), fish are much more sensitive to shear, since exposure to high shear levels can be comparable to exposure to friction forces generated by two solid surfaces contacting and sliding against each other [77]. Common injuries resulting from high levels of shear are loss of mucous layer, descaling, tissue tearing or bruising and even decapitation [78].

Quantification of shear thresholds for fish damage has been performed in the past with various methods. The most common approach involves a high-velocity jet that is expelled in a stagnant water container, in which test subjects are kept. The jet produces a shear layer around its axis and shear stresses can be quantified in terms of the radial distance from the center of the jet and the axial distance from the source of the jet. This technique has been employed several times to identify damage/mortality thresholds (see indicatively [70,79,80]), with values exceeding 3400 Pa being tested; damage was strongly dependent on fish species (indicatively, eels seemed to be the most resilient), though a threshold of 1600 Pa was proposed for onset of descaling [81]. A drawback of this method is that it does not allow for a precise control of the actual shear stress fish are exposed to, since shear stress magnitude is strongly related to exact position around the jet axis. Additionally, the formation of a fast-moving jet may involve the generation of shear layer cavitation [43,80], which can further blur the actual influence of shear stresses as a damage mechanism. Alternative approaches involve a Taylor–Couette-type apparatus [55], where concentric cylinders form an annular passage filled with water and test subjects, though it has been tested on fish larvae, demonstrating mortalities at shear magnitudes of even 35 Pa.

3.4. Vorticity and Turbulence

The flow in hydraulic turbines and relevant piping can be classified as turbulent, given that the Reynolds number is in the order of 10^6–10^7, or even more. Turbulent flows inherently imply a highly fluctuating unsteady flow, with many different scales of motion; in practice, this means that there are strong variations of local pressure and velocity which can cause strain to the body of passing fish [43], either in the form of normal or shear stresses, respectively. Hence, high turbulence levels are expected to cause mortalities for both large fish and their eggs or larvae [82].

Despite the existence of limited investigations on correlating turbulence and fish mortality, its influence is not clearly understood. There are very few investigations relating turbulence directly with fish mortality; indicatively, in [83] the authors employed a water jet to create a turbulent flow field of variable intensity, in an annular passage, in which fish larvae and eggs were exposed for different durations. A near to 80% mortality rate was found, after a 10 h exposure to high turbulence conditions, which were quantified as velocity fluctuations of ~0.55 m/s and pressure fluctuations of ~6300 dynes/cm^2 (~630 Pa). The turbulence level was found to contribute more to lethality than to frequency of disturbance.

In other works, turbulence is considered as only indirectly affecting survivability, given that it contributes to the disorientation of passing fish at the tailrace [15,84]; these fish are subsequently more susceptible to being preyed upon. Indeed, turbulence and shear stress influence is considered to be the most difficult to describe [77].

4. Assessing Fish Damage

4.1. Experimental Methods

Numerous studies have been conducted with experimental means to understand the mechanisms of fish passage and potential damage and to extrapolate these findings to fish-friendly turbine concepts. These mainly involved tagging fish with various means, followed by their subsequent release upstream a specific hydropower plant, while also tracking their position and their recapture further downstream.

An example of such investigations involved the use of inflatable balloons, to ensure the recapture of fish passing through the turbine. In particular, the inflatable tagging device was externally mounted and triggered before release. A delayed chemical reaction, whose timing can be pre-adjusted accordingly, released gas inflating the balloon tag shortly after turbine passage, facilitating easy tracking and recapture for further examination. This technique allowed for up to 96% of tagged fish being recaptured and the derivation of statistics for Kaplan and mixed-flow turbine types, showing a low percentage of injury. In particular, one study showed that only 5% of the tested fish exhibiting small lacerations [85], whereas another study found that only 5.7% of the tested fish had severe injuries (severed body, lacerations, bruises and hemorrhaging or major scale loss) [86].

Similar tagging methods involving less invasive means were performed with passive integrated transponder (PIT) tags [87]. Such tags have a small footprint (0.1 g) and do not require battery, as transceiver antennas at installed locations externally energize them. Such tags have been used to identify paths of preference of migrating fish in hydropower plants and to obtain water allocation routines between bypass and turbines that optimize both fish guidance efficiency and hydroelectric production.

Despite the small signature of PIT systems, radio-telemetry can provide more insight into the survivability of fish that pass through hydropower plants. Such a study involved small devices weighting 4–5 g surgically embedded to the bodies of the examined fish (e.g., eels) [84]. The fish were subsequently released upstream the examined hydropower stations and their status was tracked by stationary or portable receiver antennas placed downstream the examined site. The identification of dead fish was not straightforward, as a stationary transmitter may not necessarily indicate mortality, as the fish may intentionally remain stationary at specific river locations. For this reason, a number of fish were also released downstream the hydropower facility as a control group. This study found that at least 92–96% of the fish passing through the turbine stations were likely to survive; however, it did not find direct turbine mortalities, as it showed that no fish actually passed the turbine. Instead, any detected mortalities were related to injuries at the bypass routes. Alternative to radio signals, which inherently have a small transmission range within water streams, recently developed technologies involve acoustic telemetry. The latter has several advantages over radio telemetry, aside the greater transmission distance; acoustic telemetry transmitters are less invasive, as they do not involve the trailing antenna of the former. In a recent study [88], such a system employed multiple receivers, cabled or autonomous, to determine the 3D fish track by measuring the time of arrival information for the valid detection of embedded tags to fish, revealing the specific route of passage (spillway or turbine) [89].

Aside from the techniques used for tracking fish, the assessment and analysis of the results of such investigations is another topic that requires care. Indeed, it has been recently demonstrated that capturing fish after the hydropower installation and handling them may introduce additional injuries [90]. Specifically, frequently occurring injuries, such as scale loss, tears in the fins, dermal lesions, hemorrhages or bruises could be also induced by subsequent handling after testing, though the intensity of the trauma can be an indication of its origin.

Apart from the aforementioned techniques that involve handling live fish and the associated ethical issues of exposing them intentionally to danger, experimental investigations may involve autonomous sensor devices [91,92] that replicate fish trajectories through a turbine. Such sensor devices, termed as "sensor fish", can provide much more detailed information and analytical data of local accelerations and even pressure and temperature, with sampling rates in the order of 200–2000 Hz. Such devices have been tested in large Francis [93] and Kaplan turbines [94], providing details on the pressure field experienced along the trajectory of "sensor fish", as well as accelerations indicating collisions with blades and structural elements of the turbine. Data from the sensors have been used as pressure input for other studies, see, e.g., [46].

4.2. Assessing Fish Damage—Numerical Methods

4.2.1. Early Attempts

The advancement of computer technology enabled more recent works to be carried out in combination, or in their entirety, with computer models, thus allowing for a much greater insight into hydraulic machinery operation and possible interactions with passing fish. These computer models involve various assumptions, encompassing different degrees of physical mechanisms, complexity and computational cost. One of the first attempts to describe the fish-friendliness of hydraulic turbine systems was to estimate the volume of locations where various metrics relevant to fish damage and mortality, such as pressure, shear or turbulence, as mentioned in Section 3, exceeded specific limits, see [81,95–97]; this volume was subsequently correlated with the possibility of fish mortality. While this straightforward indicator could be employed as a criterion for optimization studies, it can be misleading, since the existence of locations exceeding a particular stressor metric, or its volume, does not necessarily mean that a fish will pass through this location. Further refinements involved the simplification of treating a fish trajectory as a flow streamline [81,98,99] and deriving pressure or shear stress variation along this path; subsequently, averaging of the calculated values along sampled paths can provide metrics relevant to fish mortality. Still, using streamlines ignores fish inertia and can be misleading.

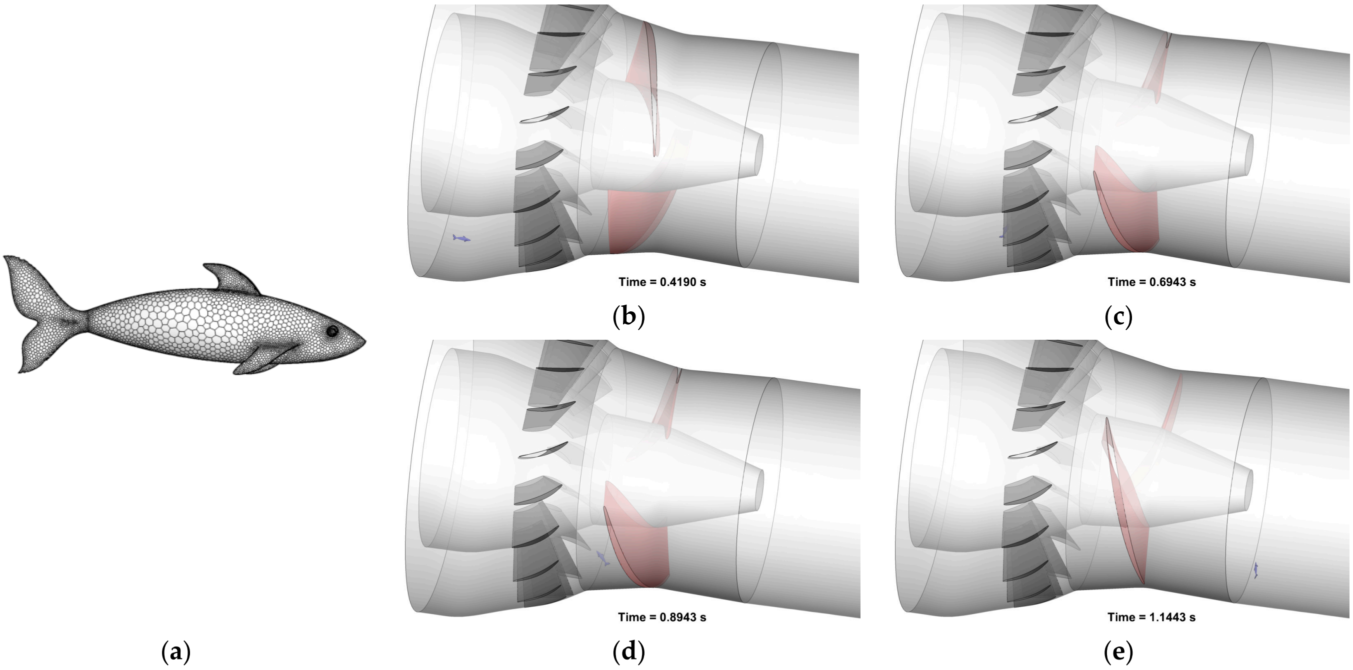
4.2.2. Particle-Based Methods

More recent investigations involve a Lagrangian perspective for tracking fish motion; in such an approach, a fish is approximated as a particle [100] or some configuration of linked particles with the discrete element method (DEM) [101]. Such Lagrangian, particle-based methods, in any of the forms of the discrete particle method, dense discrete particle method or discrete element method, are very popular in computational fluid dynamics for tracking populations of objects dragged by the flow; hence, they have been investigated for tracking fish motion in hydraulic turbines, see particularly [100–103]. A common characteristic in all Lagrangian methods is that the motion of the tracked bodies is captured by integrating Newton's law of motion, considering various forces that are applicable per case. On the downside, a basic limitation is that in most cases the forces arising from the interaction of the flow with the body are derived based on the assumption of tracking spherical particles. Even if some models may feature corrections for non-spherical shapes, in their core, the three-dimensional body orientation is not taken into account. Moreover, particle-to-particle or particle-to-boundary interactions are also performed assuming point-like objects with no volume, with a notable exception being the discrete element method, which can handle objects approximated as simple, general shapes (e.g., ellipse, cylinder, etc.).

4.2.3. Fully Coupled 6-Degrees-of-Freedom (6-DoF); Overset Meshes

Overset mesh (also known as "Chimera" or "Overlapping" mesh/grid) is a method of manipulating multiple overlaying and disconnected computational domains, by performing interpolations and by enabling/disabling suitably chosen cells, in order to form a single computational continuum over which a flow field can be resolved. The fact that the individual domains are topologically disconnected renders the method highly suitable for the handling of complex motions/deformations [104]. In general, it involves a background mesh and several component meshes, which, in the case of the interest of the present paper, are attached to moving bodies. Thus, during calculations, connectivity between the topologically disconnected meshes is redefined at every time step, whereas the motion of the tracked body is captured accurately, inherently taking into account the volume and exact shape of the tracked body, whereas motion can be described by resolving the 6-DoF equations of motion coupled with the fluid flow. It is a well-established, accurate and versatile method to handle 6-DoF body tracking, indicatively see, e.g., Figure 8, where an accurate fish model was tracked through an axial turbine.

While highly accurate, the main drawbacks of coupled overset 6-DoF are: (a) high computational cost, (b) lack of a default collision detection handling and prevention method, (c) special requirements for constructing the computational meshes, mainly in terms of sizing at the overlap region between component/background meshes and (d) per-case adjustment of schemes for cell-cutting and grid priorities, to reduce the number of cells without suitable interpolation neighbors (also called orphan cells).

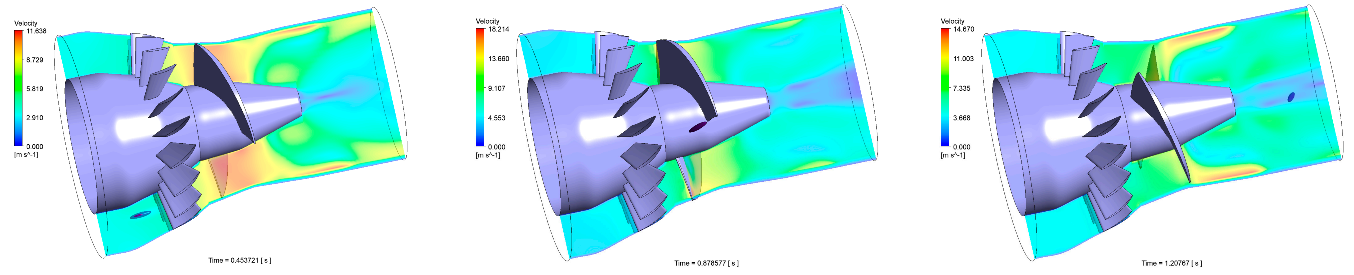


(**a**) (**b**) (**c**) (**d**) (**e**)

Figure 8. Indicative sequence of an fish model, tracked with overset mesh 6-DoF, in an axial flow turbine (for more details refer to [105]). (**a**) The detailed fish model used to construct the computational mesh of the overset zone (refinement is also visible), (**b**–**e**) overset tracking simulation instances (at 0.42, 0.69, 0.89 and 1.14 s) for an axial turbine.

4.2.4. Fully Coupled 6-Degrees-of-Freedom (6-DoF); Immersed Boundaries

The immersed boundary method (IBM) is a technique of mapping solid geometry on a background mesh [106]; this can be achieved either by altering the flow equations, e.g., through the introduction of appropriate source terms in the momentum equation, or by actually altering the computational mesh through cell-cutting to conform to the body shape. Similar to overset meshes, it is an accurate technique that can describe the precise shape of a tracked body and is rather computationally expensive. Since the method relies on the mapping of the described body to the computational mesh, a natural requirement is that the mesh is fine enough to describe all the necessary details of the body; otherwise, the solid mapping to the fluid domain may fail or will not be accurate (non-smooth surface, artificial gaps/holes). This requirement poses practical resolution restrictions if the tracked body is much smaller than the turbine dimensions, since the required computational mesh will be highly refined and the computational cost intractably high. Recently, the lattice Boltzmann method with immersed boundaries was employed for tracking fish motion through axial turbines [107]; the reported computational cost was in the order of 500–800 h for 1–3 simulated fish. In the author's experience [105] (see also, e.g., Figure 9), immersed boundary techniques can be efficiently applied for bodies roughly 50 times smaller than the turbine; beyond that point, the computational cost becomes prohibitive, unless adaptive refinement is used around the tracked object.



(**a**) (**b**) (**c**)

Figure 9. Indicative sequence of an ellipsoid body (the dark blue ellipse), tracked with immersed boundaries, in an axial flow turbine (for more details refer to [105]). Time instances (**a**) 0.45 s, (**b**) 0.87 s and (**c**) 1.21 s.

4.2.5. Uncoupled 6-Degrees-of-Freedom (6-DoF)

A recent variant [108] to the more computationally expensive 6-DoF techniques decouples the flow field from the body tracking. This decoupling makes it possible to solve the flow field with steady-state moving reference frames, which greatly speeds up the solution by roughly two orders of magnitude, allowing for the derivation of statistics (see indicatively Figure 10, where a specifically designed reversible, fish-friendly Deriaz turbine [109] was tested). Since the flow is decoupled from the body motion, the pressure field around the moving body is approximated through the dynamic pressure of the slip velocity. Pressure can be integrated to calculate forces and torques acting on the body. External forces from collisions with rigid boundaries (blades, draft tubes, etc.) can also be taken into account (indicatively, see Figure 11, where an ellipsoidal fish model collides with the rotor of an axial turbine, causing it to tumble).

The major underlying assumption is that the body mass of the tracked object is insignificant compared to the flow momentum; hence, it does not significantly alter the flow field. Numerical experiments have shown that this assumption seems valid when considering fish sizes with characteristic dimensions at most 50 times smaller than a turbine (see [105,108]); indeed, the predicted trajectory with the uncoupled fast tracking is very similar to the fully coupled 6-DoF either with immersed boundaries [105] or overset meshes [108], in the case of axial and diagonal (Deriaz)-type turbines.

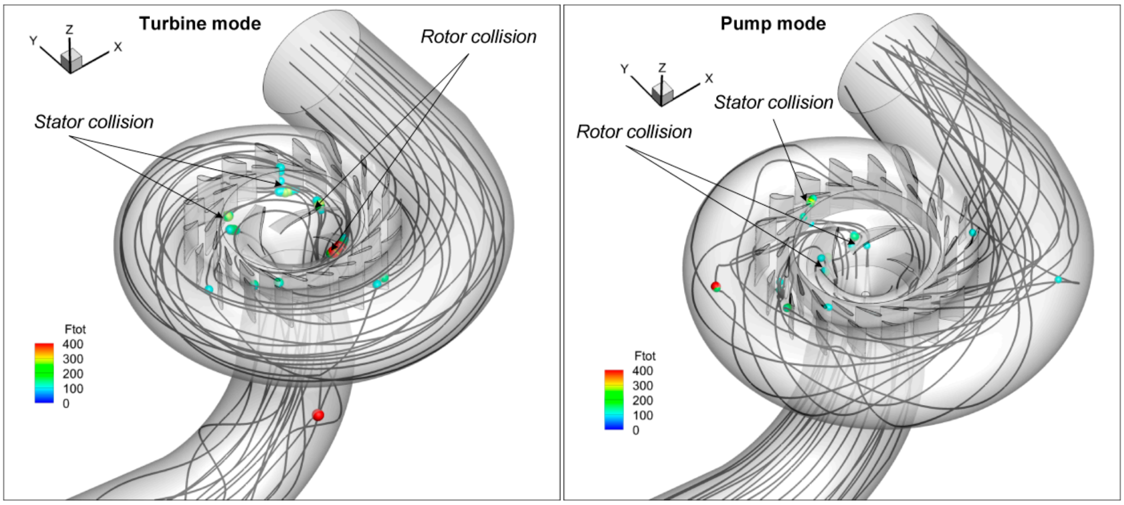


Figure 10. Trajectories and observed collisions of fish for different starting positions for a fish-friendly Deriaz-type turbine [109], at turbine mode (**left**) and pumping mode (**right**). Colored spheres indicate the forces above 10 N, corresponding to collisions.

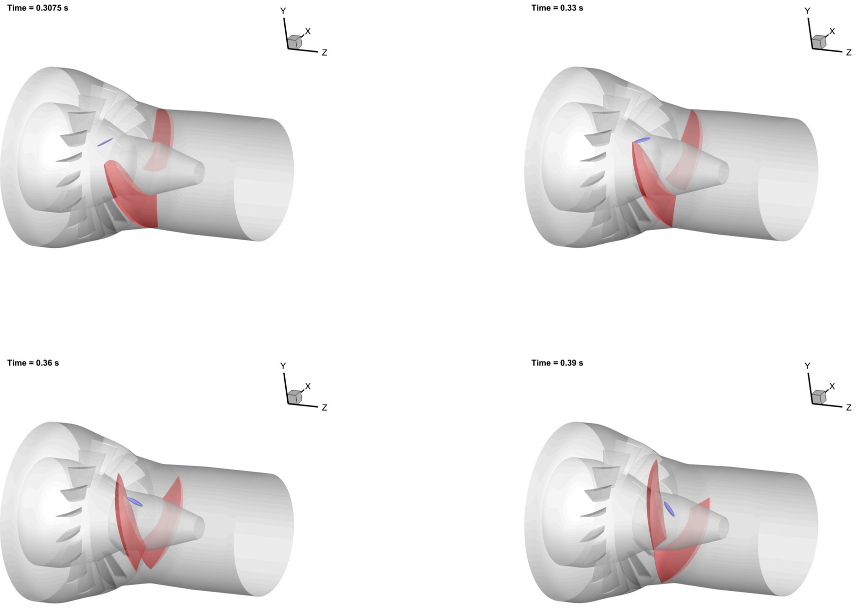


Figure 11. Indicative sequence of an ellipsoid body (the dark blue ellipse), tracked with the fast uncoupled 6-DoF, the fast tracking method. The method also includes collisions, as evidenced at 0.33 s, which causes the tracked body to tumble.

4.2.6. Summary of Computational Methods

Here, a concise qualitative comparison of the different methods is presented in the form of a table, see Table 1. Comparison criteria involve accuracy, computational cost and ability to handle collisions for estimating blade impact.

Table 1. Summary of different methods for tracking fish motion through hydraulic turbines/estimating fish-friendliness of concept designs. Plus sign (+) indicates advantage, minus sign (−) indicates disadvantage.

Method	Accuracy	Computational Cost	Collision Detection
Volume-based criteria	−	++++	−
Streamlines	++	++++	−
Particle-based	+++	+	+
Fully coupled-overset	+++++	−	−/(not by default)
Fully coupled immersed boundary	+++++	−	−/(not by default)
Uncoupled 6-DoF	++++	+++	+

5. Derivation of Indices/Metrics to Assess the Fish-Friendliness of Hydro-Turbines

The aforementioned methods, either experimental correlations or numerical techniques, are helpful to quantify the severity of different stressor factors that affect fish survivability. However, the combinatory effect of all these stressors has to be integrated into a metric that can be used in the design and planning phase of hydropower infrastructure. One of the first attempts involved only blade-strike estimations to estimate the probability of such events [110], based on the fish size, the turbine type and the operating conditions of the turbine.

Subsequent iterations involved refinements and considerations of additional factors aside blade strike. Such a metric, developed by the Pacific Northwest National Laboratory, is the biological performance assessment (BioPA) method [19]; this method estimates the probabilities that fish will encounter specific conditions during passage through a hydraulic turbine. This metric also relies on specific dose–response relationships between species of fish and known injury mechanisms, which are determined by subjecting a suitable number of fish to various magnitudes of a stressor (see Section 3) and computing the probability of injury or mortality at each magnitude. BioPA employs four metrics for assessing mortality: nadir pressure, shear, turbulence and blade strike, which are integrated over time, to estimate the BioPA score for each individual stressor factor. Indicatively, mortality probability, P_{mort}, due to pressure is estimated through the following relation [25]:

$$P_{mort} = \frac{e^{-5.56+3.85 \cdot LRP_i}}{1 + e^{-5.56+3.85 \cdot LRP_i}} \tag{1}$$

where LRP stands for the natural log of the pressure change ratio of acclimation pressure p_A, to nadir (i.e., lowest possible) pressure, p_L:

$$LRP_i = \ln\left(\frac{p_A}{p_L}\right) \tag{2}$$

The overall risk of mortal injury during passage is evaluated with a performance score, β, accounting for the probability, $P(p_L)$, of exposure at different minimum pressure levels, by sampling all the examined streamlines:

$$\beta = \left(1 - \sum_{i=1}^{N} P_{mort,i} \cdot P(p_L)_i\right) \cdot 100\% \tag{3}$$

The authors of the method highlight that Equation (1) does not describe delayed mortality effects. For blade strike, the probability P_{blade} is estimated through the following equation [111]:

$$P_{blade} = \frac{nNL\cos(\theta)}{60V_{ax}} \cdot 100\% \tag{4}$$

where n stands for runner rpm, N is the number of blades, L is the fish length, θ is the angle between absolute and axial (or radial) velocity vector and V stands for the velocity, either axial or radial, depending on the application (axial/radial turbine). In any case, various stressor scores are combined into a single operating condition score using a weighting algorithm. Statistical sampling is used for fish tracks, approximated as streamlines, i.e., neutrally buoyant particle traces, which are emitted uniformly from the turbine inlet section (unless site-specific information is available and suggested otherwise). Inherently, this method requires a numerical solution of the flow field in the turbine, using computational fluid dynamics, to provide the stressor values and the streamlines. This metric has been used in several studies, see [25,76], with the aim to expand its scope to more complex physical mechanisms, such as considering fish inertia and turbulence effects.

Another, more recent, metric is the European fish hazard index (EFHI) [17], which integrates species-specific sensitivities of the ambient fish community, derived from species' life-history traits and conservation value, and the specific operational, constructional and technical characteristics of a hydropower plant site. The input information for this index is: (1) turbine dimensions, type and operating conditions; (2) fish migration or protection facilities; (3) target species and (4) stream reach. These categories are then cross-tabulated and contrasted to the rounded integer value of the species' biological sensitivity to produce a numerical score for each hazard and species. The EFHI heavily relies on semi-empirical data, relations and regressions, to derive these scores; for example, blade strike mortality, denoted as M_{Monten}, is estimated as:

$$M_{Monten} = \frac{0.5L_{max}}{S_{rel}} \cdot 100\% \tag{5}$$

where L_{max} is the ratio of intake screen gap-width to a geometric parameter, b, dependent on the fish species (e.g., 0.11 for fusiform fish, or 0.03 for eel-like body shapes) and S_{rel} is the relative space between blades, taking into account the blade angle, annular passage diameters and number of blades. Barotrauma risk is simply related to the barrier/dam height and hence classified as low for $H < 2$ m, moderate for 2–10 m and high for >10 m; subsequently, it is adjusted to the particularities of each examined fish species (in particular, the structure and presence of their gas bladder, e.g., physostomous or physoclistous). In any case, the entire process is performed within an Excel worksheet, which, based on the aforementioned user input, determines individual hazard scores with values of 0, 0.25, 0.5, 0.75 or 1, with higher scores indicating a more severe hazard. The implementation as is can involve ensemble estimations for up to five target species that are considered by the user to best reflect the local fish population, conservation status and river region. In case of specific conservational status or environmental concern, selected species can be individually categorized to the highest sensitivity class. The final EFHI score is finally calculated as an aggregation of all hazard scores.

A general observation, based on the aforementioned details of the BioPA and EFHI, is that BioPA relies more on detailed flow field information data of a particular turbine design (i.e., manipulations of a 3D flow field with streamlines, etc.), whereas the EFHI relies on regressions and empirical data entirely. It is thus expected that the EFHI may be more successful in assessing traditional turbine concepts and existing installations/refurbished sites, for which the assessment criteria fall within the calibration range of the regressions/models used. On the other hand, BioPa, even though more detailed, is expected to be much more computationally intensive; hence, seems suitable to designing new turbine concepts.

6. Fish-Friendly Hydropower Design Concepts

The US Environment Protection Agency has established specific considerations and engineering-based criteria that are considered critical in the design of fish-friendly turbines; these criteria involve [16,44]:

- Blunt, thick blades (see indicatively the Restoration Hydro Turbine or RHT in [71], or Figure 12a);
- Low rotational speed of the turbine runner;
- Large passages;
- Few blades;
- No exposed gaps.

However, these criteria mainly address the blade/fish collision, rather than consist in a holistic approach in assessing all potential mechanisms of fish damage. In any case, when considering existing designs, field studies indicate that Francis turbines resulted in a higher immediate mortality risk than Kaplan turbines relative to controls [16].

In recent years, several new turbine concepts, or modifications/variations of existing concepts, have emerged, specifically to address fish-friendly passage. One such example is the minimum gap runner (MGR) turbine [112], see Figure 12b; this design is very similar to the Kaplan turbine, but the blades, the hub and the discharge ring have a more spherical profile to reduce clearances; hence, it was expected that the performance against mechanical injury would be improved. This design modification also removes part of the leading edge and, as a result, also reduces the local pressure gradients and shear stresses, while also having a positive effect in the efficiency of the turbine [113]. Indeed, the testing of the MGR turbine showed improvement in fish injuries compared to a traditional Kaplan turbine, with only 1.4% of the fish being injured, compared to 2.5% of the statistical control group tested with a Kaplan turbine [114].

Similar to the MGR, the very low head (VLH) turbine can be considered a Kaplan-type turbine, specifically engineered for safe fish passage [115]. This turbine was originally developed in France, to be installed at an existing low head hydropower facility, for heads of 1.4–4.2 m and flows between 10 and 30 m^3/s, mounted in an inclined position (30–50°) from horizontal and using an eight-bladed Kaplan-style runner, as seen in Figure 12c. The unit is designed to be compact and easily integrated to existing facilities, by reducing intake and outlet structure sizes by maximizing the diameter of the turbine runner. The large diameter of the turbine contributes to slow rotational speeds, which is a major requirement for safe fish passage. Indeed, testing in Europe indicated mortality rates of less than 5% [115]; however, similar projects in North America have been hampered by extremely cold temperatures and ice.

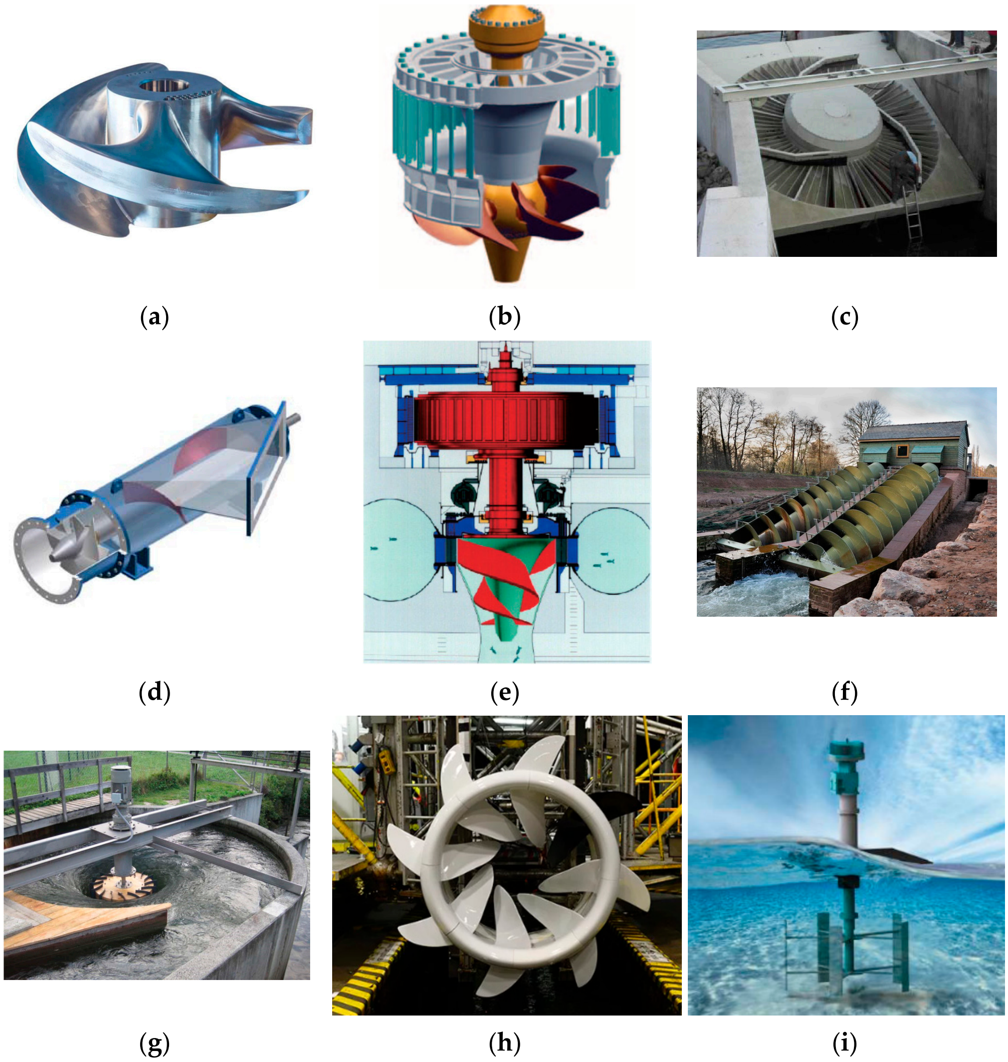

(**a**) (**b**) (**c**)
(**d**) (**e**) (**f**)
(**g**) (**h**) (**i**)

Figure 12. Fish-friendly turbine concepts: (**a**) Natel energy blunt, thick-blade runner, (**b**) minimum gap runner (MGR) turbine, (**c**) very low head (VLH) turbine, (**d**) vaneless swirl injector Kaplan turbine, (**e**) Alden turbine, (**f**) Archimedes turbine, (**g**) vortex turbine, (**h**) hydrokinetic hub-less turbine, (**i**) Darrieus-type hydrokinetic turbine.

Another Kaplan turbine design variation is the vaneless swirl injector system [116], seen in Figure 12d; in this design, the traditional inlet guide vane (IGV) array is replaced with a vaneless casing, which is coupled with a fish-friendly Kaplan turbine and is applicable for a head up to 6 m. The vaneless casing creates the required swirl velocity component necessary for the runner by guiding the flow through a spiral-shaped track. Since there are no vanes, fish mortality caused by strike damage is dramatically reduced.

An innovative turbine concept that was developed at the same time as the MGR turbine is the Alden turbine [112,117], seen in Figure 12e. It is a low head turbine (H~25 m) developed jointly by Alden Research Laboratory, Inc./Northern Research and Engineering Corporation (ARL/NREC) and Voith Hydro, Inc. (Voith) in 1995. The final proposed design has three helical blades, which are attached both to the hub and to an external rotating shroud, hence eliminating gaps and the possibility of grinding injury. The casing of the turbine has a traditional scroll/spiral shape, directing the flow through a radial space with few but long vane blades (also termed as wicket gates) and then through a gradual downturn toward the runner entrance. The long helical shape of the rotor blades was specifically designed to reduce pressure changes and to improve fish survival due to barotrauma through the turbine. Furthermore, the blades of the Aden turbine feature a thick leading edge, which has been demonstrated to reduce blunt body impact injury. Thus, these design choices in the Alden turbine concept, namely the reduction in the number of blades, the reduction in the operating speed, the minimization of pressure differences and the thick leading edges, have been demonstrated to greatly improve fish survivability.

The Archimedes turbine [118,119], seen in Figure 12f, although not new, is a very simple design, well suited for low head installations ($H < 10$ m). The Archimedes turbine consists of a screw-shaped runner, placed within a co-axial, tubular shroud. When water enters the top of the shaft, the weight of the water pushes on the screw blades, causing the shaft to rotate and allowing for the water to fall to the lower level. Such designs are intended for low heads and have diameters between 1.5 and 3.5 m. Their low rotational speeds, minimal pressure changes and shear forces minimize injury to fish that pass through this turbine. The Archimedes screw turbine particularly as a fish-friendly solution has been installed and tested at several sites in Europe and the UK with positive results [120–122]. Studies indicate minimal to no injuries and no mortalities from the downstream passage of adult European eels, larval and juvenile river lamprey, sea-run Brown Trout and Atlantic Salmon kelts.

The vortex turbine design Is installed as a by-pass system to a dam or classical weir, and which is intended to permit two-way fish migration [123], as seen in Figure 12g. It consists of a vortex pool where a strong free-surface vortex develops, in the center of which a Francis-like turbine is located. The water leaves the pool through an orifice at the bottom and flows back into the river through an outlet channel. The turbine is inherently designed to be operated as a low-head device (as low as H~0.7 m) [124], operating at low rotational speeds (indicatively, 30 rpm). The rotating speed of the runner makes it possible to achieve a very small slip tangential velocity, so there is a low risk of fish/blade impact. Additionally, clearances can be adjusted, to allow for fish to pass freely in both ways.

Entirely alternative to reservoir-based, or diversion-based hydropower discussed so far, are in-stream turbines, which can be placed directly in the water stream, thus relying heavily on the flow kinetic energy of the incoming water. A version of this concept, seen in Figure 12h, was recently proposed [125], which resembles a hub-less axial turbine. This concept was found to satisfy pressure drop and strain rate criteria [125], conforming to requirements for safe fish passage [74]. However, the authors of the work identify that the design is an extremely low head turbine and has a low efficiency (in fact calculated to be much lower than the Betz limit). Similar concepts of in-stream turbines have been examined for vertical-axis turbines, such as Darrieus-type [126] turbines, as seen in Figure 12i, which are found to have an efficiency of up to 50%, whereas the estimated survivability through them is of more than 98% [127].

Finally, some additional factors, even if not directly related to turbine technologies/subsystems, still affect fish mortality [128]:

- Oxygen deficiency in the water of reservoirs of hydropower plants, which can cause damage to downstream ecosystems. Hence, artificial aeration of the flowing water is a consideration that needs to be taken into account for successful fish-friendly turbines [129];
- Oil leaks; oil is used both as a means of lubrication and as a means of actuation of turbine blades (e.g., in the case of Kaplan turbines). To date, several Kaplan–Bulb and Francis turbines have been upgraded so as to make them work free from oil, and new materials and lubricants are being developed.

7. Conclusions and Future Perspectives

It is clear that hydropower will continue to play an important role in energy production worldwide; thus, ecological pressure to aquatic life is expected to increase. The necessity to design new concepts that holistically approach aquatic life, either as a mean of deterrence, i.e., leading migrating fish through a bypass stream, or protecting passing fish through the turbine, is becoming apparent.

While there are guidelines and estimates for the damage thresholds of various fish species, useful to predict potential damage as they pass through a turbine, these thresholds vary wildly and are strongly dependent on the exact specie examined. This fact, along with the inherent site-specific nature of hydropower sites, renders estimations of survivability unique for each case and difficult to generalize easily. Some success was found with semi-empirical models; however, the progressive integration of computational fluid dynamics (CFD) in the design phase of hydropower can provide much more insight than any experimental technique. Moreover, CFD predictions can be combined with damage thresholds to assess the survivability of a candidate design.

Indeed, CFD predictions already have contributed greatly to the design of existing fish-friendly concepts. However, all these concepts are applicable only to low head applications (<40 m). A future challenge is clearly the development of such fish-friendly concepts at higher operating heads and other turbine types (e.g., Francis and Pelton).

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