

In situ characterization of the biological performance of a Francis turbine retrofitted with a modular guide vane

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HIGHLIGHTS

- Sensor Fish used to characterize biological performance of a modified Francis.
- Nadir pressures measured during runner passage were between 56.6 and 74.7 kPaA.
- 50–64% of releases experienced an acceleration event in the guide vane region.
- Results comparable to other Francis turbines studied using Sensor Fish.

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ABSTRACT

There are two strategies to lower overall project costs to an extent that will make many potential sustainable hydropower sites economically viable: (1) design standardized/modular components; (2) use advanced tools to reduce environmental evaluation costs. In this study an autonomous sensor device (Sensor Fish) was used to study a Francis turbine retrofitted with a modular guide vane. The median nadir pressures measured were 74.7, 66.6, and 56.6 kPaA for 90-, 190-, and 380-kW operating conditions respectively. These nadir pressures were compared to other Francis turbines studied using Sensor Fish and were found to be within the same range. The proportion of Sensor Fish releases with severe acceleration events (acceleration $\geq 95G$) was also investigated. The proportion ranged from 73 to 80% (runner region), 50 to 64% (guide vane region), and 9 to 28% (draft tube region), which was within the range of the other turbines used for comparison. The Sensor Fish testing that was conducted at Hurley Dam demonstrates that the modular guide vane that was retrofitted to the existing Francis turbine is potentially a suitable replacement that can provide biological performance similar to the guide vane used with other existing Francis turbines, but with the benefit of reduced fabrication costs.

1. Introduction

Hydropower is the largest renewable energy source in the world, with 1,114 GW of installed capacity at the end of 2017, which accounts for over 50% of the world's renewable energy [1]. In Europe, conventional hydropower accounts for about 59% of renewable energy [2] and in the United States (US) it accounts for over 50% of the renewable energy, with a total capacity of 79.6 GW installed at the end of 2014 [3]. Although conventional hydropower is the largest source of renewable energy, the rate of further development is slower than other forms of renewable energy, such as wind or solar power. Between 2006 and 2016 the hydropower capacity in the US has increased by 2.03 GW, with 70% of this increase resulting from refurbishing and upgrading existing hydropower projects [4]. Of the remaining 30%, most of the

new hydropower projects involved adding power generation capabilities to non-powered dams or conduits, with only 5 of the 118 new hydropower plants involving new stream-reach development (NSD) of primarily small hydropower plants (SHP). Although there is no single standard definition of SHP, a commonly used definition is a hydropower project with a capacity of between 0.5 to < 10 MW [3]. Although there has been NSD of large hydropower plants in South America [5] and Asia [6], most NSD in North America and Europe have focused on SHP. At sites where the dam impoundment would not exceed the 100-year flood plain, there is a technical resource potential for 65.5 GW of NSD within the US [3], where most of the sites are low-head. However, when various factors related to economics and environmental impacts are taken into consideration the likelihood for NSD is significantly reduced. With low cost financing and advanced

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technology that can balance economics, efficiency, and environmental sustainability there is a potential for 17.2 GW of NSD by the year 2050 [3]. However, without technology that can reduce the environmental impact the potential for NSD by the year 2050 would be reduced to 1.7 GW, and under a “business-as-usual” scenario it is predicted that there will be no NSD [3].

The proliferation of SHP will require research and development of new innovative technologies and design philosophies in order to be cost effective and ensure sustainable deployment. One way to achieve this is through the designing of standardized and modular components that are “plug-and-play”. These standardized and modular components would lead to lower overall project costs compared to traditional custom site-specific designs, and as a result many low head sites can be economically viable where previously they were not [7]. A recent paradigm shift in SHP in the US is the research of Standard Modular Hydropower (SMH), where a SMH facility is composed of standardized modules that each serve dedicated functions that can be independent or interdependent and will lead to cost reductions and environmental compatibility [8]. The types of modules included in a SMH facility can include, but are not limited to foundation, generation, and passage modules. The foundation modules are required to prevent the other modules from sliding and overturning, the generation module is the module that produces the electric power, and passage modules are modules that accommodate minimum and flood flows but can also be used to pass fish, sediment, boats, and debris depending on the specific characteristics of the facility.

Components of the hydropower generation modules include the turbine runner, guide vanes, generator, and powerhouse. Since the economics of the hydropower plant is highly dependent on the power generation, much effort has gone into the innovation and refinement of the relevant technologies. The selection of the turbine runner for a hydropower plant requires considering the hydraulic characteristics of the site, such as the operational range of hydraulic head and volumetric flowrate. Some examples of conventional turbine designs include Francis [9], Kaplan [10], bulb [11], Pelton [12], Turgo [13], and crossflow turbines [14]. These conventional turbine designs can be divided into two categories: impulse turbines (e.g., Pelton, Turgo, and crossflow) which use the velocity of water impacting a bucket on the runner which causes the runner to rotate, and reaction turbines (e.g., Francis, Kaplan, and bulb) where the runner is submerged in the flow and uses the pressure and velocity of the water to rotate the runner. Characteristics of the site determine which turbine type is most suitable, for example impulse turbines are often used for sites with high head and low flow while reaction turbines are often used at sites with lower head and higher flow. In addition to the conventional turbine designs that have existed for decades, there are also several newer unconventional turbine designs that are coming to the market. A couple examples of the unconventional turbine designs include Archimedes screw turbines [15], which are based on Archimedes screws used to pump liquids or convey solid particles from a lower to higher elevation, and the Linear Pelton by Natel Energy, which is an adaptation of a Pelton turbine that is designed to be modular, operate at low heads, and be more fish-friendly [16]. The traditional turbine design philosophy, especially for large scale dams, is to select the type of turbine best suited for the specific site and then having the turbine designed for that site to obtain the best efficiency over the anticipated range of operating conditions. The process of having the turbine custom designed for the specific site significantly increases the cost. In order to reduce the cost of turbines to make SHP sites economically viable, turbine designers are producing standardized turbine designs that allow the SHP developer to save money by greatly reducing the amount of design effort required. A couple examples of standardized turbine designs that manufacturers are producing are the TM Modular Micro Turbine by Mavel [17], and the PROPEL-Turbine by Rickly Hydro [18]. The TM Modular Micro Turbine is a siphon turbine with a Kaplan-type runner which uses either a drop structure or siphon to convey water up and over the dam, which

significantly reduces the civil works required. The PROPEL-Turbine is an axial flow turbine with a Kaplan-type runner that can be deployed in a water pipeline or other existing infrastructure. Another consideration for developing generation modules for SMH is considering the tradeoffs between competing priorities. Chen and Engeda [19] document the development of a SMH generation module for low-head applications based on a Kaplan-style runner. The authors note that the traditional design philosophy for the turbine specification at a site with low head would designate using a smaller runner operating at higher speeds, which contradicts the SMH goal of low fish mortality and as a result requires more novel turbine designs.

Hydropower plants require passing non-generating flows around the turbines for a variety of purposes. This includes passing flows to maintain minimum instream flows downstream of the plant, to prevent ecological disturbance, as well as being able to safely pass flows in the event of flooding. These aspects of water passage can be achieved using spillways, weirs, and other outlet structures. Traditionally this was achieved by constructing large concrete structures, which does not fit well in the SMH philosophy. One method for reducing the amount of concrete and labor required to build a spillway or weir is through designs that use gates which are actuated by inflatable rubber bladders that are anchored to a concrete base [20]. Another important purpose to pass non-generating flows is to provide safe downstream fish passage. Determining how to safely pass fish while balancing the conflicting goal of producing power requires understanding the characteristics of the fish species of interest as well as the hydraulic characteristics of the turbine design being installed. With innovative “fish-friendly” turbine designs [21] being brought to the market, turbine passage may be a suitable method to pass fish downstream at some hydropower plants. By understanding the characteristics of both the specific fish species and the turbine, informed decisions can be made regarding the need for appropriate screening technology, spill weirs, or other downstream fish passage structures that will help lead to a hydropower facility that provides a sustainable source of renewable energy.

When fish pass through a turbine they can be exposed to injury mechanisms that usually include exposure to rapid and extreme decompression, strike, collision, grinding, shear stress, cavitation, and turbulence [21]. As a fish passes through a reaction turbine it can be exposed to a rapid decompression during passage from the high-pressure upstream side to the low-pressure downstream side of the turbine runner blade, which typically occurs over a very short period. Depending on the species of fish, this rapid decrease in pressure can lead to barotrauma injuries [22–24]. Brown et al. [23] reported that the most significant predictor of mortal injury related to barotrauma in juvenile Chinook salmon (*Oncorhynchus tshawytscha*) was the ratio between the pressure that the fish were acclimated to prior to simulated turbine passage and the nadir (i.e., lowest) pressure experienced during simulated turbine passage. In addition to rapid decompression, as a fish passes the turbine runner it can be struck by the rotating turbine blade. The probability that a fish will be struck is dependent on factors related to the flow, the size of the fish, and the size and geometry of the turbine components [25,26]. Not only can fish be injured by blade strike, they can also collide with stationary structures like guide vanes, runner shafts, or draft tube walls. When fish pass through the turbine near areas where there are small gaps, such as between the turbine runner blade and the runner housing, they can experience grinding [21]. During turbine passage, fish can encounter regions where there are intersecting volumes of water traveling at different speeds. As fish pass through the intersection of these water volumes they can be exposed to hydraulic shear stress [27] that can potentially lead to injury or mortality depending on the level of shear stress [28,29]. When the pressure on the downstream side of the turbine runner is lower than the vapor pressure of the water, cavitation can occur where bubbles form and subsequently collapse, resulting in a shockwave that can injure fish [21] and damage components of the turbine. The turbulent flow passing

through the guide vane, turbine runner, and draft tube can lead to fish becoming disoriented, experiencing reduced swimming capability, loss of equilibrium, and an increased rate of oxygen consumption which can lead these fish to be more susceptible to predation [30,31].

In addition to the designing of standardized and modular components that are “plug-and-play”, another strategy to make the development of SHP more cost effective and sustainably deployed is to use advanced tools to expedite, improve, and reduce the costs of environmental evaluations. One such tool is the Sensor Fish [32], which is a small, neutrally buoyant autonomous sensor device package that can be used to collect in situ force and motion data from a variety of sensors. The size and density of the Sensor Fish was designed to be similar to a migrating juvenile salmon. The components of the Sensor Fish were positioned to create a device with a center of gravity that coincides with the geometric center of the Sensor Fish. This was done to create a neutrally buoyant device that can follow the surrounding flow while minimizing the level of rotation that would have otherwise resulted from having a center of gravity away from the geometric center. Although the cylindrical shape of the Sensor Fish is substantially different from the organic shape of a juvenile salmon, early-stage development of the initial Sensor Fish prototype revealed that the cylindrical packaging of the device resulted in motion that was more representative of a live fish than a fish-shaped packaging. The Sensor Fish can be used to understand both the susceptibility of different fish species to a variety of injury mechanisms and the hydraulic characteristics of a turbine. To understand how parameters calculated from Sensor Fish data relate to biological effects in fish, laboratory experiments are conducted to develop dose–response relationships. Brown et al. [23,24] used Sensor Fish pressure data collected during turbine passage to program custom designed hypo/hyperbaric chambers to expose juvenile Chinook salmon to simulated turbine passage [22]. These tests were conducted to develop a dose–response relationship between nadir pressure and mortal injury. In addition to studying the effects of barotrauma on fish, laboratory experiments have been conducted to investigate the effects of shear stress on juvenile Chinook salmon [29,33] and blade strike [34] on gizzard shad (*Dorosoma cepedianum*), rainbow trout (*Oncorhynchus mykiss*), and hybrid striped bass (striped bass *Morone saxatilis* X white bass *Morone chrysops*). Richmond et al. [33] found that the acceleration measured by Sensor Fish was the best predictor for understanding the probability of shear injuries, and used the information collected to develop a dose–response relationship. Additional laboratory tests have been conducted to develop dose response relationships for a diverse set of fish species including Murray cod (*Maccullochella peelii*) [35], silver perch (*Bidyanus bidyanus*) [36], and silver shark (*Balantiocheilos melanopterus*) [37].

The objective of this study was to use Sensor Fish to evaluate the hydraulic characteristics that can impact the biological performance of a Francis turbine in North Carolina, USA that was retrofitted with the modular guide vane that is utilized by the modular PROPEL-Turbine. This guide vane will be utilized in the 92 Series of PROPEL-Turbines, and as a result there is interest in understanding the fish passage characteristics of the PROPEL system in a stepwise manner. Data from each Sensor Fish release was subdivided into regions of interest and parameters such as the number and magnitude of severe acceleration events, nadir pressure, and rate of pressure change. The results from this study were compared to results from other Francis turbines that have been studied using Sensor Fish as well as results from a study investigating a low-head siphon turbine.

2. Methods

2.1. Study site

Hurley Dam is located on the Little River in North Carolina (Fig. 1). This dam consists of a stonemasonry gravity spillway that is 66.4-m long and is located between a 5.8-m long stonemasonry non-overflow

section on one end and a 33.8-m long stonemasonry and steel head-gate structure on the other side. The non-overflow side adjoins rock, and the head-gate structure adjoins natural ground that has been lined with shotcrete. The canal leading to the powerhouse is formed by an earth embankment that adjoins a stonemasonry emergency spillway and head-gate structure on one side and natural ground on the other side. This dam is owned by Rickly Hydro and is used as both an operating asset as well as a test ground.

The powerhouse at Hurley Dam includes three turbine bays, although currently only one bay is being utilized. The turbine installed in Bay 1 is an S. Morgan Smith (now Voith Hydro) Type S Francis turbine deployed in a radial open flume configuration where the guide vane is in an open flume as opposed to a scroll case. This turbine has a diameter of 0.76 m and rotates at 400 rpm at peak efficiency. This turbine has been retrofitted with the modular guide vane that was designed as part of the 92 series fully regulated PROPEL-Turbine, which is a modular axial-flow turbine with a Kaplan style runner. The advantage of using this guide vane is that the modular nature reduces the time and effort required to manufacture a traditional guide vane. Rather than using complicated castings to create the guide vane, this modular guide vane uses sub-assemblies that fit together. A guide vane similar to the one in this study will be used in 12 turbine units that are planned for deployment at Hurley and several other dams.

2.2. Sensor Fish device

The hydraulic characterization data from the turbine passage at Hurley Dam was collected using an autonomous sensor device known as Sensor Fish [32] (Fig. 2). The Sensor Fish is a cylindrical device that is 89.9 mm long with a diameter of 24.5 mm. The mass of the Sensor Fish is approximately 42 g, resulting in a device that is neutrally buoyant in fresh water. The Sensor Fish was designed to be similar in size and density to a migrating salmon smolt. The Sensor Fish includes a suite of sensors that can be used to obtain quantitative measurements of forces and motions that a fish could experience passing through a hydraulic structure like a turbine or spillway. The Sensor Fish includes a highly dynamic pressure sensor for capturing rapid pressure changes that can occur during turbine passage, a three-axis accelerometer for measuring three-dimensional (3D) linear acceleration, a three-axis gyroscope for measuring 3D rotational velocity, a three-axis magnetometer for measuring 3D magnetic field strength to determine 3D orientation, and a temperature sensor. All the sensors in the Sensor Fish are sampled at a rate of 2,048 Hz, with a maximum sampling duration of approximately 4.8 min. Prior to field deployment, each sensor of each Sensor Fish was calibrated in a laboratory setting.

2.3. Sensor Fish releases

Sensor Fish were released into the intake of the Francis turbine on March 25–26, 2019 using a 38-mm diameter polyvinyl chloride (PVC) pipe and a 19-mm diameter PVC capped pipe which was used as a plunger to push the Sensor Fish through the deployment pipe. Sensor Fish were released through the turbine under three operating conditions based on power generation: 90, 190, and 380 kW. The deployment pipe was initially deployed just behind the stop gate (Fig. 3), with the bottom approximately 0.91 m below the water surface, for the 90-kW operating condition. During the testing at this operating condition, several of the Sensor Fish releases were found to have not gone through the turbine prior to the built-in recovery system activating, likely due to the open flume configuration. To get the Sensor Fish to more consistently enter the guide vane during the data collection period, the release pipe was moved into the powerhouse and deployed so it was above and to the side of the guide vane at a depth of 1.5 m below the water surface (Fig. 3) for the 190-kW operating condition. This location was also used for the first five releases at the 380-kW operating condition, but the high flow in the intake was imparting large forces on the



Fig. 1. Map showing the location of Hurley Dam (35.286691° , -79.894578°) located ~ 8 km south of Troy, North Carolina.

release pipe that could have caused the pipe to break away from the structure it was mounted to. For this reason, the release pipe was moved back to the original location for the remainder of the testing at 380 kW. A total of 11, 17, and 19 valid data sets were collected for the 90-, 190-, and 380-kW operating conditions respectively. The Sensor Fish were recaptured ~ 150 m downstream from the dam using long-handled dip nets.

2.4. Data acquisition and analysis

The data sets collected by Sensor Fish are typically large and require substantial data processing. To improve the ease and efficiency of processing Sensor Fish data sets, a set of software tools known as the Hydropower Biological Toolset (HBET) [38] were developed. HBET includes software tools to store Sensor Fish data in a centralized database, use previously collected data sets to design new Sensor Fish studies to test a hypothesis, process the raw Sensor Fish data to obtain quantitative measurements of parameters that describe the hydraulic conditions, to apply species-specific dose-response relationships developed from controlled laboratory experiments to estimate the biological response of fish being exposed to the same conditions as the Sensor Fish, and to make comparisons between different studies or

treatments.

As a Sensor Fish passes through a hydraulic structure, such as a turbine, the time histories of pressure, 3D linear acceleration, 3D rotational velocity, 3D magnetic field strength, and temperature are collected. Passage through the hydraulic structure results in consistent characteristics in the time histories of the different sensors that can be used to divide the data set into different passage regions. Sensor Fish data processing begins by using the data analysis portion of HBET to generate plots of pressure, acceleration magnitude, and rotational velocity magnitude. Once plotted, the HBET user manually creates timing marks corresponding to the locations in the data set that represent the beginning or end of a specific passage region. Events of interest, such as the rapid decrease in pressure that occurs during runner passage and the occurrence of severe acceleration events, are calculated after dividing the data into individual passage regions.

2.5. Pressure analysis

As a fish passes through a reaction turbine there is typically a large, rapid decrease in pressure as the fish passes from the high-pressure side of the runner to the low-pressure side. Once the data from the Sensor Fish has been divided into the different passage regions, the nadir

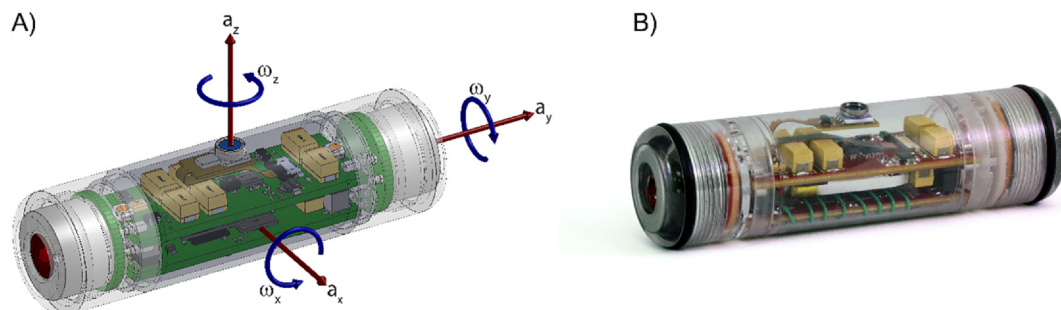


Fig. 2. Images of the Sensor Fish Gen 2: (A) Computer aided design showing coordinate system; (B) Photograph.

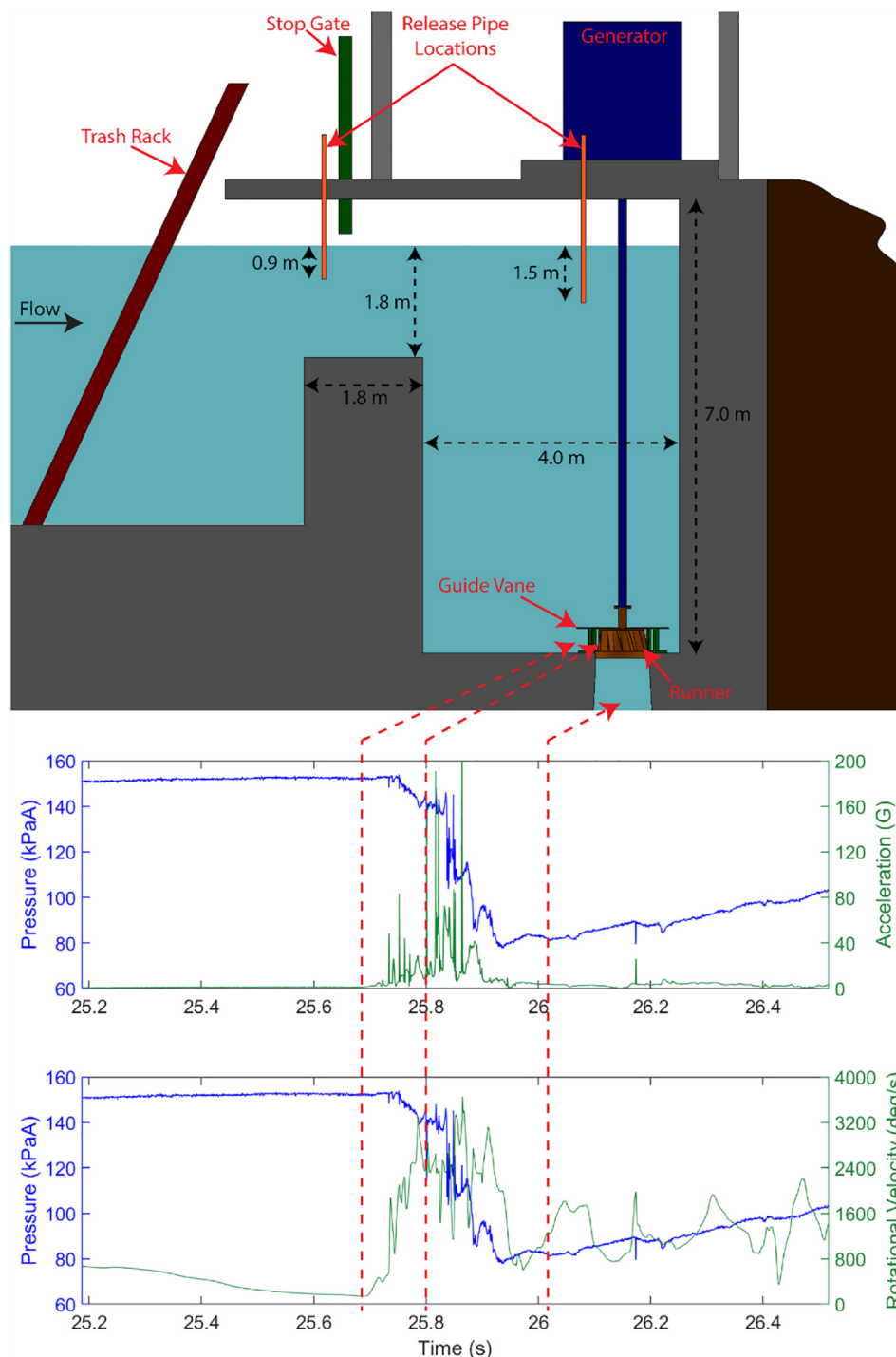


Fig. 3. Example of Sensor Fish passage through the Francis turbine at Hurley Dam. The approximate locations in the data relative to the physical locations are shown.

pressure is determined by extracting the minimum pressure in the runner region. Another pressure parameter that can be calculated from the Sensor Fish data during runner passage is the maximum pressure rate-of-change. The maximum rate-of-change is calculated by first using a zero-phase filter [39] with a window size of 10 samples to smooth the pressure data to avoid noise in the pressure data from affecting the results of the numerical differentiation. Once the pressure data are filtered, the maximum pressure rate-of-change is calculated by taking the derivative of the smoothed pressure data numerically using a five-point stencil [40].

2.6. Acceleration event analysis

Fish passing through a turbine can be exposed to high levels of acceleration resulting from shearing flows, collision with a stationary structure, or being struck by the turbine runner. After the Sensor Fish data is divided into the different passage regions the occurrences of severe acceleration events are identified by finding spikes in the acceleration magnitude that exceed a threshold of 95 G. This threshold of 95 G was determined from controlled laboratory experiments where juvenile Chinook salmon and Sensor Fish were exposed to shearing flows in a flume [29]. After identifying the severe acceleration events they are further classified as being attributed to shear or collision/

strike. A shear event is defined as a spike in the acceleration magnitude where the duration, as defined by the point on each side of the acceleration spike corresponding to 70% of the maximum value, is larger than 0.0075 s, and a collision/strike is defined by a duration less than 0.0075 s [25]. Once the severe acceleration events have been identified and classified, the proportion of Sensor Fish releases that experienced at least one severe acceleration event related to either shear or collision/strike is computed for each treatment.

3. Results and discussion

3.1. Turbine passage example

Analysis of data collected using Sensor Fish begins by manually dividing the data into different passage regions by carefully examining the pressure, acceleration, and rotational velocity time histories. Plots are generated using the data analysis portion of the HBET and timing marks are placed at the boundary of the different regions by identifying repeatable characteristics of the data. The specific regions of the passage and the characteristics that are used to identify them are listed below and shown in Fig. 3:

1. **Turbine Intake Region:** Region spanning from the release of Sensor Fish into the turbine intake to the upstream side of the guide vane. The beginning of this region is determined by identifying an increase in acceleration as the Sensor Fish is placed into the release pipe. Passage through this region is characterized by very low levels of acceleration and rotational velocity. The end of this region is determined by finding the moment just before the levels of acceleration and rotational velocity begin to increase.
2. **Guide Vane Region:** Region spanning from just upstream to just downstream of the guide vane. The beginning of this region is identified by the increase in acceleration and rotational velocity, as well as typically occurring near the maximum pressure. Passage through this region is characterized by occasional acceleration spikes from collision with the guide vane as well as the beginning of a gradual decrease in pressure. The end of this region is primarily identified by the beginning of the rapid pressure drop that occurs as the Sensor Fish passes the turbine runner blades. In addition, there is often a very short period of reduced acceleration activity prior to the runner passage.
3. **Runner Region:** Region spanning from just upstream to just downstream of the turbine runner. Passage through this region is characterized by the rapid decrease in pressure that occurs as the Sensor Fish passes the high-pressure side of the runner blades to the low-pressure side, as well as frequent acceleration spikes from blade-strike and occasionally shearing flows. The end of this region is identified by the pressure beginning to increase from the nadir pressure.
4. **Draft Tube Region:** Region spanning from the downstream side of the turbine runner to exiting into the tailrace. Passage through this region is characterized by lower levels of acceleration with infrequent occurrences of acceleration spikes resulting from collision with the draft tube walls and a moderate level of rotational velocity. The exact moment when the Sensor Fish enters the tailrace is not easily identified but is considered the point where the pressure has increased to a plateau which includes any severe acceleration events that may have occurred in the draft tube.

3.2. Pressure analysis

There was an inverse relationship between the level of power generation and the nadir pressure; as power generation increased the nadir pressure decreased (Fig. 4A). The median nadir pressures were 74.7, 66.6, and 56.6 kPaA for the 90-, 190-, and 380-kW operating conditions, respectively. In addition to the nadir pressure, the pressure rate-

of-change during runner passage was computed for each release and the distributions were plotted for each operating condition (Fig. 4B). The median pressure rate-of-changes were 1781, 1279, and 2238 kPa/s for the 90-, 190-, and 380-kW operating conditions respectively.

During passage through a reaction turbine, the rapid decrease in pressure that occurs during runner passage can potentially result in barotrauma injuries. The probability of a fish with a swim bladder experiencing a mortal injury, which is defined as an immediate mortality or an injury that could lead to mortality (e.g., exophthalmia (eye-pop); hemorrhaging in the pericardium, liver, or kidney; ruptured swim bladder; blood or bile secretions from the vent; and emboli in the gills or pelvic fins), is dependent on the ratio between the nadir pressure and the acclimation pressure (i.e., depth) that a fish was acclimated to prior to turbine passage. If the nadir pressure is above atmospheric pressure it is unlikely that a fish will experience barotrauma. However, if the nadir pressure is below atmospheric pressure, as is the case for the results at Hurley Dam, every fish will have a non-zero probability of experiencing a mortal injury. Surface pressure and the pressure at the maximum possible depth prior to entering the turbine (5.2 m) were used to calculate the distribution for the probability of mortal injury for each operating condition using the dose-response relationship for juvenile Chinook salmon [23] (Fig. 5A and B). For fish assumed to be acclimated to surface pressure, the median probabilities of barotrauma mortal injury were 1.3, 2.0, and 3.7% for the 90-, 190-, and 380-kW operating conditions, respectively. For fish assumed to be acclimated to the pressure at the maximum depth prior to entering the turbine (5.2 m), the median probabilities of barotrauma mortal injury were 5.9, 8.9, and 15.4% for the 90-, 190-, and 380-kW operating conditions, respectively.

The distributions for the probability of mortal injury using the dose-response relationship for juvenile walleye (*Sander vitreus*) [41], which are less susceptible to barotrauma than juvenile Chinook salmon, were also calculated (Fig. 5C and 5D). For walleye assumed to be acclimated to surface pressure, the median probabilities of barotrauma mortal injury were 1.7, 2.4, and 3.7% for the 90-, 190-, and 380-kW operating conditions, respectively. For walleye assumed to be acclimated to the pressure at the maximum depth prior to entering the turbine (5.2 m), the median probabilities of barotrauma mortal injury were 5.2, 7.1, and 10.8% for the 90-, 190-, and 380-kW operating conditions, respectively.

To provide additional context to the pressure results from Hurley Dam, comparisons were made with other dams featuring Francis turbines [42] and a low-head siphon turbine with a Kaplan runner [43] in the US Pacific Northwest and a dam featuring a Francis turbine in Laos [44]. Comparing the nadir pressures (Table 1), the low-head siphon turbine studied at the Head of the U Dam and all of the other Francis turbines, except for those at Nam Ngum Dam in Laos, were substantially below atmospheric pressure. The worst conditions for fish passage at Hurley Dam with respect to nadir pressure were at the operating condition of 380 kW, which was near the generator limit. The median nadir pressure of 57 kPaA was slightly better than all the Francis turbines except those at Nam Ngum Dam, and was much better than the siphon turbine at the Head of the U Dam which was also a low-head hydropower site. The median nadir pressure for each of the turbines utilized in the comparison was used to estimate the probability of barotrauma mortal injury (Table 2). When Hurley Dam is operating at 380 kW, the estimate of mortal injury related to barotrauma was 4 and 15% for fish acclimated to the water surface and to a depth of 5.2 m, respectively. For comparison, Cougar Dam at the maximum opening operating condition had much higher estimates for mortal injury at 51 and 83% for fish acclimated to the surface and to a depth of 5.2 m, respectively. Head of the U Dam also had much higher estimates for barotrauma mortal injury at 60 and 87% for fish acclimated to the surface and to a depth of 5.2 m, respectively. For the pressure rate-of-change values at Hurley Dam, they were generally higher than the Head of the U Dam, similar to Nam Ngum Dam, and much lower than the other dams with Francis turbines studied with Sensor Fish.

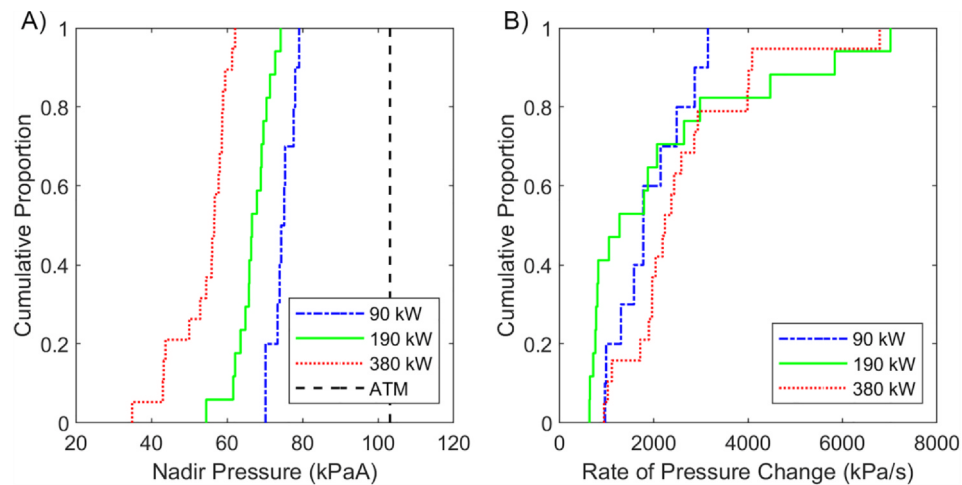


Fig. 4. Pressure results from Sensor Fish measurements at Hurley Dam: (A) Nadir pressure distribution during runner passage (dotted vertical line represents atmospheric pressure); (B) Rate of pressure change distribution during runner passage.

3.3. Acceleration event analysis

For each Sensor Fish release, the occurrence of severe acceleration events (> 95 G) were identified and classified as resulting from collision/strike or shear (Table 3). The distribution of maximum acceleration in the guide vane and runner region for each release was also

computed (Fig. 6). Collisions and/or strike occurred in the guide vane, runner, and draft tube regions for all operating conditions. The proportion of Sensor Fish releases with at least one severe acceleration event were highest in the runner region at between 73 and 78% of releases, where the proportion increased with power generation. The next highest region was the guide vane region with 50 to 64% of

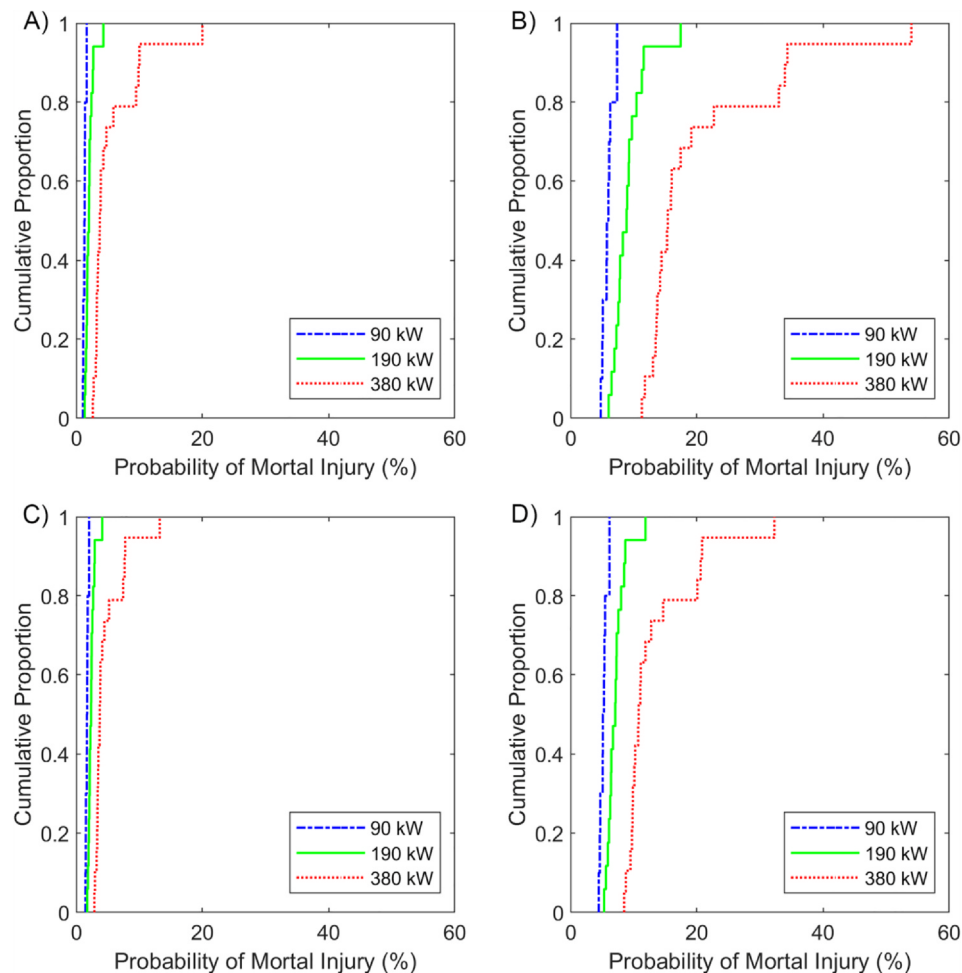


Fig. 5. Probability of barotrauma mortal injury for each operating condition based on the ratio between the nadir pressure and: (A) Surface pressure – juvenile Chinook salmon; (B) Pressure corresponding to maximum depth prior to entering the turbine (5.2 m) – juvenile Chinook salmon; (C) Surface pressure – juvenile walleye; (D) Pressure corresponding to maximum depth prior to entering the turbine (5.2 m) – juvenile walleye.

Table 1
Comparison of median nadir pressure, pressure change, and pressure rate-of-change (ROC) Between the Francis turbine at Hurley Dam, other Francis turbines [42] and a low-head siphon turbine (Head of the U Dam) in the US Pacific Northwest [43], and a Francis turbine in Laos [44].

	Hurley Dam			Nam Ngum Dam		Arrowrock Dam	Detroit Dam	Cougar Dam		Head of the U Dam	
	90 kW	190 kW	380 kW	Unit 1	Unit 4			Minimum Opening	Maximum Opening	Peak Efficiency	
Nadir Pressure (kPaA)	75	67	57	99	126	54	48	56	24	56	22
Pressure Change (kPa)	78	84	89	365	366	283	860	787	848	784	85
Pressure ROC (kPa/s)	1781	1279	2238	2729	1907	4661	7670	7769	13,215	9300	1277

releases, with no clear trend related to the power generation. The draft tube region had the lowest proportion at 9 to 28% of releases, again with no clear trend related to the power generation. The only occurrence of severe acceleration events related to shear occurred in the runner region at the 380-kW operating condition, with 10% of releases.

Comparing the acceleration results in the runner regions to the same dams that were used in the comparison of the pressure results (Table 4) indicates that while the total severe acceleration events, for shear and strike combined, in the runner region at Hurley Dam are high, they are lower than those at Detroit and Cougar Dams. Most of the severe acceleration events in the runner region at Hurley Dam are attributed to strike, with shear severe acceleration events only occurring infrequently at the treatment with the highest generating power. If the comparison is only between strike severe events, the proportion of Sensor Fish releases that experienced severe strike acceleration events at Hurley Dam were high but not the highest of the dams compared. Comparing the acceleration results for the low-head siphon turbine at the Head of the U Dam, the percentage of severe events was higher at Hurley Dam. Comparing the results in the guide vane region, the percentage of severe acceleration events at Hurley Dam is higher than several of the other dams with Francis turbines but is not the highest. The percentage of severe acceleration events in the guide vane region at Hurley Dam is much higher than at the low-head siphon turbine at the Head of the U Dam. One potential reason there were more severe acceleration events in the guide vane region at Hurley Dam could be that the other dams with Francis runners have scroll cases that may have provided a straighter path through the guide vane compared to Hurley Dam where the Sensor Fish may have been approaching the guide vane from a steeper angle (refer to Fig. 3). Although the siphon turbine at the Head of the U Dam did not have a scroll case, the release pipe used in that study released the Sensor Fish very close to the guide vane.

The Sensor Fish was developed to understand the physical conditions that a fish would encounter as it passes through hydraulic structures or complex flow fields. Unlike the Sensor Fish, a live fish may be capable of manipulating its body to avoid contacting structures in its path under certain hydraulic conditions. However, under more severe conditions a live fish may be unable to respond to fast moving turbulent flows, and under these conditions treating the live fish as a neutrally buoyant particle, like the Sensor Fish, is more appropriate. When live fish are exposed to shear and collision, the details of the injury mechanism has a major effect on the injury rates. For example, when fish are exposed to a simulated shear environment headfirst the injuries are more severe than for those exposed tailfirst [28], and if a collision occurs to the head of a fish there is a higher probability of injury than if the collision is on its tail [34]. As a result, Sensor Fish often experience severe acceleration events at a rate higher than live fish injury rates. However, Sensor Fish data can be used to evaluate the relative biological performance of a hydraulic structure. For example, in an evaluation of a surface spillway weir conducted by Duncan et al. [45], the live fish injury estimates were highly correlated ($r = 0.978$; $p\text{-value} = 0.0007$) with the percentage of the Sensor Fish severe acceleration events attributed to collision in the spillway-deflector region, which was correctly identified as the likely location of fish injuries based on a second study conducted after this region was structurally modified. The results of this study conducted on the Francis turbine with the modular guide vane at Hurley Dam could be used to make useful comparisons to the performance of the PROPEL-Turbine that is planned to be installed at Hurley Dam in the near future.

The objective of this study was to investigate the hydraulic characteristics that can impact the biological performance of a Francis turbine that was retrofitted with modular guide vane that is utilized by the modular PROPEL-Turbine. Francis turbines are the most common type of turbine both worldwide and in the US. In the US, Francis turbines account for 43% of all turbines currently deployed with a total capacity of 53.7 GW [46]. There are many dams in the US, like Hurley Dam, that were built several decades ago. These dams have turbine

Table 2

Comparison of estimated probability of mortal injury for juvenile Chinook salmon based on median nadir pressure between the Francis turbine at Hurley Dam, other Francis turbines [42] and a low-head siphon turbine (Head of the U Dam) in the US Pacific Northwest [43], and a Francis turbine in Laos [44].

	Hurley Dam			Nam Ngum Dam		Arrowrock Dam	Detroit Dam	Cougar Dam			Head of the U Dam
	90 kW	190 kW	380 kW	Unit 1	Unit 4			Minimum Opening	Maximum Opening	Peak Efficiency	
Mortal Injury - Surface	1%	2%	4%	0%	0%	4%	7%	4%	51%	4%	60%
Mortal Injury – 5.2 m	6%	9%	15%	2%	1%	18%	26%	16%	83%	16%	87%

Table 3

Proportion of Sensor Fish releases that experienced at least one severe acceleration event (> 95 G) from collision/strike or shear during passage through each region.

Passage Region	Event Type	Percent Severe Events			
		90 kW	190 kW	380 kW	All
Guide vane	Strike	64%	50%	55%	55%
	Shear	0%	0%	0%	0%
Runner	Strike	73%	78%	80%	78%
	Shear	0%	0%	10%	4%
Draft tube	Strike	9%	28%	10%	16%
	Shear	0%	0%	0%	0%
All regions	Strike	100%	89%	95%	94%
	Shear	0%	0%	10%	4%
	Combined	100%	89%	95%	94%

components, such as the guide vane, that will need to be repaired or replaced at some point in the future. This study determined that although over 50% of Sensor Fish releases experienced severe acceleration events passing through the guide vane region, the results are still within the range of results from other dams with Francis turbines. In addition, if Hurley Dam featured a scroll case, as opposed to the existing radial open flume configuration, it is possible that the proportion of Sensor Fish that experienced severe acceleration events could have been reduced, since the approach of the Sensor Fish may have had a straighter path through the guide vane. The advantage of using this guide vane is that the modular nature reduces the time and effort required to manufacture a traditional guide vane. Rather than using complicated castings to create the guide vane, this modular guide vane uses sub-assemblies that fit together. By having a range of standardized modular parts available, like this guide vane, hydropower operators can save time and effort required to manufacture replacement parts and can

reduce revenue lost due to a turbine outage.

4. Conclusion

Sensor Fish were used to evaluate a Francis turbine that was retrofitted with a modular guide vane at Hurley Dam. Testing was conducted at three operating conditions: 90, 190, and 380 kW. The nadir pressures measured during runner passage at each of the operating conditions were below atmospheric pressure, with median values of 74.7, 66.6, and 56.6 kPaA for the 90-, 190-, and 380-kW operating conditions respectively. These nadir pressures were compared to other Francis turbines as well as a low head siphon turbine. The other turbines used in the comparison had nadir pressures that ranged from 22 kPaA for the low head siphon turbine at the Head of the U Dam to 122 kPaA at the Francis turbine of Unit 4 at Nam Ngum Dam. In this comparison the results from Hurley Dam were near the middle of the range for the turbines compared against. The proportion of Sensor Fish releases with at least one severe acceleration event for the different operating conditions at Hurley Dam ranged from 73 to 80% in the runner region, 50 to 64% in the guide vane region, and 9 to 28% in the draft tube region. Comparing these percentages with those from the dams used for comparisons, the percentage of releases with severe acceleration events at Hurley Dam were high but were not the highest.

Hurley Dam serves as both an operating asset and a test ground for testing new turbines, like the modular PROPEL-Turbine that is planned to be deployed in the adjacent turbine bay of the powerhouse. Traditional turbine evaluation methods have previously been used to validate performance aspects of the PROPEL-Turbine but assessing if a turbine is “fish friendly” has been a more difficult assessment to make. Using a tool like the Sensor Fish to assist in the assessment of a turbine’s biological performance allows turbine designers and operators to go beyond the assessment of, and optimizing for, power production by also considering how different aspects of the design and operation may

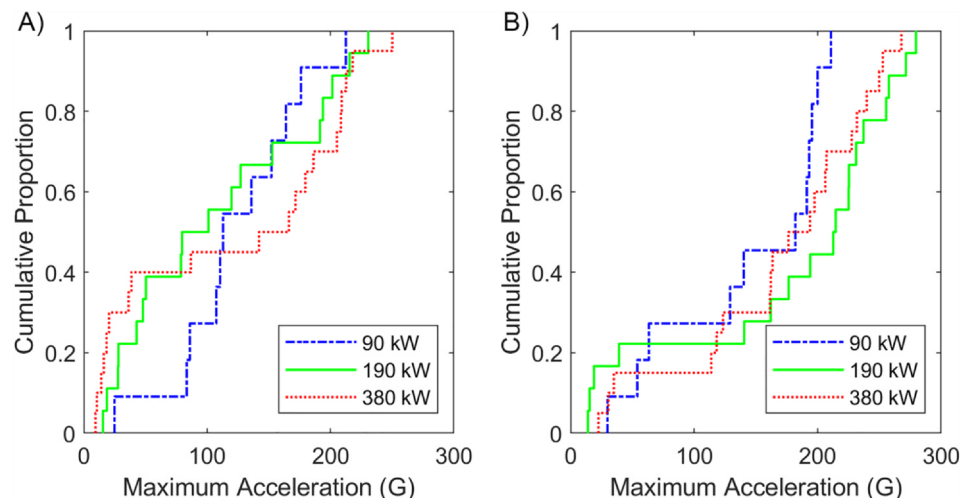


Fig. 6. Distribution of maximum acceleration during passage through the: (A) Guide vane region; (B) Runner region.

Table 4

Comparison of proportion of Sensor Fish releases with severe acceleration events ($> 95G$) from strike/collision or shear during passage through each region between the Francis turbine at Hurley Dam, other Francis turbines [42] and a low-head siphon turbine (Head of the U Dam) in the US Pacific Northwest [43], and a Francis turbine in Laos [44].

Passage Region	Event Type	Hurley Dam			Nam Ngum Dam		Arrowrock Dam	Detroit Dam	Cougar Dam			Head of the U Dam
		90 kW	190 kW	380 kW	Unit 1	Unit 4			Minimum Opening	Maximum Opening	Peak Efficiency	
Guide vane	Strike	64%	50%	55%	60%	32%	80%	32%	25%	33%	25%	12%
	Shear	0%	0%	0%	3%	0%	20%	5%	0%	0%	0%	0%
Runner	Strike	73%	78%	80%	37%	32%	60%	42%	75%	100%	25%	47%
	Shear	0%	0%	10%	3%	16%	20%	100%	100%	100%	100%	2%
Draft tube	Strike	9%	28%	10%	0%	5%	0%	11%	25%	0%	0%	0%
	Shear	0%	0%	0%	0%	0%	0%	5%	0%	0%	0%	0%
All regions	Strike	100%	89%	95%	90%	58%	100%	84%	75%	100%	50%	52%
	Shear	0%	0%	10%	7%	16%	40%	100%	100%	100%	100%	2%

affect fish. The Sensor Fish dataset collected in the existing Francis turbine with the retrofitted modular guide vane can serve as a baseline that can be used to evaluate the relative biological performance of the new PROPEL-Turbine under identical physical conditions. Francis turbines are the most common type of turbine both worldwide and in the United States. As these turbines age many will need to be upgraded in the near future. The testing that was conducted at Hurley Dam demonstrates that the modular guide vane that was retrofitted to the existing Francis turbine is a suitable replacement that provides biological performance similar to the guide vane used with existing Francis turbines. This testing allows us to understand the passage of fish through their modular turbine designs in a stepwise manner. By having a range of standardized modular parts available, like this guide vane, hydropower operators can save time and effort required to manufacture replacement parts and can reduce revenue lost due to a turbine outage.

Declaration of Competing Interest

None.

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