Helical Turbine and Fish Safety

By Alexander Gorlov, August, 2010

Abstract

The objective of this paper is to describe research using the Helical Turbine for hydropower with particular focus on fish safety in the presence of a spinning mechanical rotor. Two possibilities of fish mortality are discussed, namely for the case of **free flow in kinetic scheme** (without dam), and **constrained flow** (with dam). Correspondingly, the following two conclusions are formulated. Probability of fish kill by kinetic turbines in free flow approaches zero since fish can easily detect and avoid the spinning rotor. The probability of fish kill in constrained flow is also very low because peripheral, helical blades of the turbine provide sufficient open space for fish passage. The latter conclusion leads to a recommendation of using a dam with helical turbines to generate much more and less expensive power than the plain kinetic scheme can provide at similar sites. Also, an inexpensive flexible barrier instead of conventional rigid dam is discussed.

1 Introduction

Electrification of all aspects of modern civilization has led to the development of various converters for transforming energy from natural power sources into electricity. However, power plants that use fossil and nuclear fuels create huge new environmental pollution problems and deplete limited natural resources at an exponential pace. Thus, clean renewable energy sources for generating electric power is a pressing problem in today's world. Energy from ocean and tidal currents is one of the best available renewable energy sources. In contrast to other clean energy sources, such as wind, solar, geothermal, etc., the kinetic and potential ocean energy can be predicted for centuries ahead. However, this energy, like wind and solar, is distributed over large areas that presents a problem of collecting it and making this industry economical. The helical turbine described below is an efficient, low cost and environmentally friendly apparatus for extracting power from free (kinetic) and ultra low head (potential) water streams. This is a relatively novel technology, but the turbine is already commercially used for hydropower. For example, two helical turbines of 1.0 Megawatt combined power have been in operation in free tidal flow of Uldolmok Strait (South Korea) since May, 2009. Meanwhile, helical turbines have been also used for wind power in many countries after the author's first publications in 1994.

The paper summarizes the author's experience in developing and implementing the helical turbine (sometimes called GHT – Gorlov Helical Turbine) for extracting power from free and ultra low head water flows. Fish safety is taken into particular consideration because of public concern about possibility of fish mortality during its passage through spinning hydraulic turbines. We will discuss the fish safety in view of using helical turbines for extracting power from rivers, ocean streams, and tides for free (kinetic without dam) and constrained (with dam) flows.

2. Fish mortality

2.1. *Conventional High Dam Turbines*

Let's point out that the public concern for fish safety results from high mortality rate of fish passing through turbines in **conventional, mostly river, high dam** structures, such as shown in Figure 1.
The design shown consists of two principal components, namely, the rigid dam (right part) and the powerhouse for hydraulic turbines (left part). The function of the dam is to concentrate dissipated power of the water stream and direct the entire flow through turbines of the powerhouse where mechanical energy of rotating turbines is transformed into electric current. In doing so, the dam builds up a water head between upper and down streams, creating conditions for optimal power output and turbine speed.

Figure 1. Conventional hydropower plant

The modern hydropower technology has developed turbines of extremely high efficiency (90% or even higher), such as shown in Figure 2 for high dam water heads. The turbine has to have a so-called high solidity to be efficient in extracting ***potential energy*** from elevated water and minimizing free space between blades to maintain high head between the basins. However, the fish often have no other way to get in downstream basin from the upstream except to pass through these tight turbines. The result of such passage sometimes leads to situation shown in Figure 3, which explains public concern for fish mortality in high and low dam power stations.

There are many well documented facts on the high mortality rate of fish passing through a turbine similar to that shown in Figure 2. Nevertheless, this is the classical and widely used scheme for river hydropower plants of high heads that use turbines of **big capacity and very high solidity** at the expense of high rate of fish mortality. Indeed, it’s hard imagining fish passing through such turbines without serious injury. Designers of dam hydropower systems anticipate installation of various devices, such as fish ladders, lifts or sluices to transport live fish through the dam from upstream to downstream, and reverse. Those systems are usually quite expensive and not always reliable, but unavoidable for both high and low head dams.

Figure 2. Kaplan turbine for high dam power plant

The high solidity turbines, such as the Kaplan turbine of Figure 2, are very efficient for high head dams. However, they become inefficient and cannot be used in free and ultra low head applications. This means that different turbines should be used for thousands of ultra low head dams, as well as for free ocean and tidal sites. The recent years of intensive experiments demonstrated that new ***cross flow turbines*** can be the rotors for extracting sufficient hydropower from water streams and remaining ***benign*** to fish.

The principal difference between high head propeller type turbines described above and cross flow ***reaction*** turbine is that the shaft and blades of the latter rotors are perpendicular to the flow. This allows distributing ***hydrofoil*** blades along the outer surface of the turbine, leaving sufficient space for fish passage. The **helical turbine,** in particular, is one of the most efficient of those cross flow machines.

Figure 3. Turbine clogged with eels. Note eel skin stretched across shaft. Photo: Alex Haro, S. O. Conte Anadromous Fish Restoration Center

2.2. Helical Turbine

The typical helical turbine for kinetic and ultra low head hydropower systems is shown in Figure 4. The turbine is the unidirectional rotation machine that makes it particularly valuable for application in reversible tidal or other open ocean streams. In rivers, it can be used for hydropower inside dams or in the downstream tailrace in cooling water flows of some thermal conventional plants, hydraulic canals, and tunnels, etc. The turbine needs no deep water for its horizontal installation, enabling usage in shallow sites.

The helical turbine, shown in Figure 4, was developed in 1993-1995 at Northeastern University in Boston, Massachusetts under R&D contracts from the US Department of Energy and the National Science Foundation. The turbine has been tested in laboratories at Northeastern University, as well as in the tidal currents of the Cape Cod Canal (Massachusetts), Vinalhaven Island (Maine), Long Island (N.Y.), Uldolmok Strait (South Korea). During these and other recent field tests, the triple-helix turbine demonstrated its reliability and up to 35% efficiency in free streams, which makes it one of the best hydraulic machines for such applications [2 – 8].

The turbine of Figure 4 has all blades located on the periphery of its rotation in contrast to propellers. Such design increases the open space for fish passage as opposed to other conventional propeller-type turbines.

The most dangerous space for fish, as can be seen in Figure 3, is the narrowing passage near the attachment of blades to the spinning shaft where fish mostly perish, since there is no free room for maneuvering and exiting from the tight blades' structure. In contrast, all three peripheral hydrofoil helical blades shown in Figure 4 can provide much more free space between them for safe fish passage through the turbine.

The turbine is a quite strong three dimensional frame that might be reliable in operation even without the shaft under low external loads. In this case, the solid long shaft might be replaced by short spindles at sites of bearings, transmitting the overall torque to the generator by means of the entire structure consisting of blades, spokes, hubs, and joints. In case or series of shaft-less turbines used in the system they can be jointed on adjacent spokes. Such modification might further increase the room for fish moving inside the turbine.

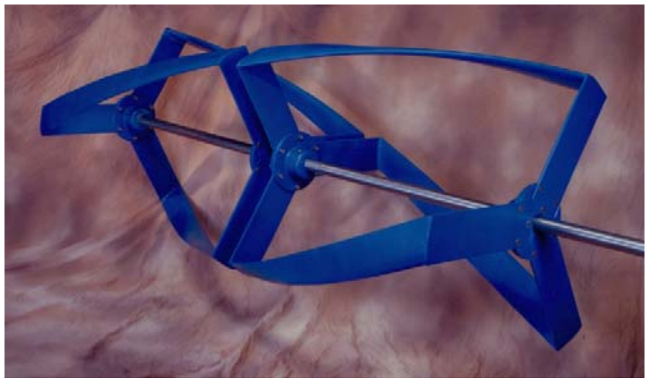


Fig. 4 Triple-helix twin turbine.
Diameter - 1m, Length (Height) - 2.5m.

Another modification of the helical turbine that opens even more space for fish passing is reducing the number of turbine blades. This would also simplify design and improve turbine performance in some free flows with kinetic mode of applications. We performed series of experiments with reduced number of helical blades that also lowers so-called turbine solidity and creates much better conditions for fish movement. In particular, the turbine with only one helical blade performed very well, generating power comparable to the triple helix machine in free streams. For example, the single helix turbine shown in Figure 5 is practically opened for fish swimming through it without interference from the moving blade.

Figure 5. Single Helix Turbine tested at Northeastern University
(Photo by B. Gorbaty, 2005)

Direction of the turbine rotation depends only on orientation of the blades, which move towards their leading edges. Thus, the turbine always rotates in the same direction independent of water flow direction. This makes the helical turbine a valuable machine in reversible tidal flows. Turbine axis can be set up vertically, horizontally or with any inclination in the vertical plane depending on the water depth and specific requirements of the project. Let's point out that this turbine is similar in its orientation to the well-known Darrieus wind turbine patented in 1931 in USA. The latter turbine has straight or curved-in plane airfoil blades. However, the Darrieus turbine has not received wide practical application mostly because of pulsation caused by instantaneous changing angles of attack of straight blades traveling along the circular path [1]. It is also not always self-starting in free water flow. In contrast, the helical arrangement of blades provides self-starting and uniform rotation of the turbine that is the principal advantage of this machine compared to the Darrieus turbine. Inclined helical blades are also advantageous for fish safety as shown below.

3. Probability of fish injury by helical turbine

Let us consider separately two hydropower systems that use helical cylindrical turbines with respect to their effect on fish safety, namely free flow kinetic system with no dam and constrained flow potential system with a dam.

Free flow kinetic

Dozens of tests were conducted by author's laboratory with various helical turbines assembled under raft and installed in the Cape Cod Canal tidal current in 1996 and again in 1998. The work was performed by the research team of Northeastern University with the help of the Army Corps of Engineers (New England Division), which mounted the turbines under the raft, transported the assembly to the site in the middle of the Canal, and arranged security during the test in the water.

The objective of the research was to define principal mechanical characteristics of the turbine, such as its torque, speed, power output, and efficiency depending on various water velocities, as well as its overall structural integrity and reliability in unstable natural conditions of the tidal current. The effect of turbine spinning on fish was not specifically anticipated in those testsg. Nevertheless, an assignment was given to draw attention to any alarming ecological changes in the area caused by turbine operation.

As a result, nothing unusual from the fish safety viewpoint was discovered during the two years of experiments, i.e., no signs of injury or mortality of fish was noticed. Moreover, neither Verdant Company, which tested the helical turbines in the Merrimack River (New Hampshire) in 2006, nor Korean Ocean R&D Institute (KORDI) in South Korea, which has used helical turbines in the Uldolmok Strait since 2002, ever observed or were alarmed by any harmful effect on fish caused by spinning helical turbines in free flows.

The above observations just confirm the fact that the helical turbine in free flow is probably not harmful to fish, which have sufficient space to avoid the rotating turbine instead of swimming through it. This is more understandable because the **spinning turbine** creates substantial additional hydrodynamic resistance to the water flow than it would if it stayed motionless. In the light of this phenomenon, let's call resistance to the water flow developed by motionless turbine in the stream **static** and resistance that appears when the turbine starts spinning **dynamic**. Static resistance remains constant for the given water velocity since it depends mostly on turbine geometry, i.e., its size, number of blades, and their shape, etc. However, the dynamic resistance increases dramatically with the appearance of angular velocity and acceleration of the turbine. It creates a noticeable additional physical obstacle to water flow, as well as, to a fish, preventing its free swimming through the turbine. Indeed, the incompressible fluid, such as water, transmits signal waves to the fish from this obstacle, allowing the fish to avoid it in free flow. Ichthyologists know this ability of fish to detect various obstacles in the stream long before they approach them.

We observed this resistance increasing with turbine speed in a series of experiments in the Hydro-Pneumatic Power Laboratory at Northeastern University by direct measuring of water elevation in front of the turbine, while gradually increasing its angular velocity from zero to a reasonably high value. The dynamic resistance increases almost proportionally to increasing the turbine speed in laminar flow. For example, we obtained the water elevation in front of spinning turbine up to 70% higher than for the initially motionless machine.

Thus, we have to conclude that the **resistance** of the spinning turbine to the water flow is a substantial factor that would force the fish to avoid direct interaction with the turbine, practically eliminating a possibility of its injury in rather wide and deep free water flow. It looks like a theoretical limit of this resistance might be close to the resistance of solid cylinder to water flow in the case of a very high speed of turbine rotation. We neglect a possibility of cavitations in this discussion since this phenomenon must be avoided, at best by reducing the turbine speed.

The static resistance depends on the geometry (structure) of a motionless turbine such as its size, number and dimensions of blades, their inclination, etc. The most commonly used geometrical characteristic of the turbine is its relative **solidity** defined as the ratio **σ = nb/D,** where **n** is the number of blades, **b** – chord of each blade cross section, and **D –** turbine diameter. The **σ** might be used for calculation of drag developed by the turbine in the water. However, for the thrust (drag) calculation it is more correct to use the following formulas for projection of all blades on the vertical (shaft) plane.

Denoting the solidity of the helical turbine by S (projection of blades on the shaft's plane), we can calculate it using the expression:

$$S = \tfrac{2nHr}{\pi}\left(d + \sum_{k=1}^{n} \sin\left(\tfrac{\pi k}{n} - d\right) - \sin\tfrac{\pi k}{n}\right) \qquad (1)$$

Where n is the number of blades, H and r are height and radius of the turbine, respectively, and d is half of the blade's chord in radians with respect to the axis of rotation.

Denote σ = S/2Hr as relative solidity of the turbine. Thus, it can be calculated as

$$\sigma = \tfrac{n}{\pi}\left[d + \sum_{k=1}^{n} \sin\left(\tfrac{\pi k}{n} - d\right) - \sin\tfrac{\pi k}{n}\right] \qquad (2)$$

For the two-blade turbine this value will be

$$\sigma = \frac{2}{\pi}\left[d - 1 + \sin d + \cos d\right] \qquad (3)$$

For the triple-helix turbine this value is

$$\sigma = \frac{3}{\pi}\left[d - \sqrt{3} + \sin d + \sqrt{3}\cos d\right] \qquad (4)$$

Dimensions of the triple-helix turbine of Figure 4 are H = 100 inches (2.5m), r = 20 inches (0.5m) and d = 0.15 radians. Substituting into (4) gives the following relative solidity for this turbine: σ = 0.267, or about 27% of the frontal area of the turbine.

Equations (1) – (4) are used, mostly, to obtain analytical values of the water pressure on the turbine or its thrust. Knowing turbine solidity, one can calculate the turbine thrust as

$$F = \frac{1}{2} C_d \rho \sigma A V^2 \qquad (5)$$

where C_d is drag coefficient, ρ is fluid density, A = 2Hr is turbine frontal area, V is water velocity. Force F is actually the water pressure on the turbine that contributes to external loads on the shaft, bearings and other parts of the supporting structure.

Equations (1) – (4) have been derived by M. Gavasheli (author's former graduate student) and included in his report "Gorlov Turbine Horizontal Projection", 2002.

Constrained flow potential

Turbines in dams combined with electric generators convert the accumulated energy potential behind the dam into mechanical and then into electrical power. In this case, without adequate barriers, migrating fish would unavoidably be forced to pass through the spinning turbines installed in the dam. The practices of high dam plants proved that substantial amount of fish perish in such passages either as a result of direct interaction with turbine parts (Fig. 3) or due to abrupt drop of water pressure between upstream and downstream water basins. Thus, fish mortality is quite common for high dam hydropower stations.

The case of **ultra low head** (under 3 meters) is different since it allows for successful use of helical turbines **in constrained flow** along with extracting part of the **kinetic energy** by the same turbines. Indeed, the helical turbine cannot tightly close the hydraulic channel as conventional turbines can do (Fig. 2). Thus, part of the water can flow freely through the turbine, providing higher speed to its rotation and adding corresponding **kinetic** energy to the total energy balance with **potential** energy part from the water head.

The point is that the constrained mode involves a water barrier (dam) across the stream to direct the entire water flow through the turbines producing much more power than any kinetic scheme. In other words, the **kinetic** mode described above generates power extracting it from **free** streams, while the **constrained** flow generates power extracting it from **potential energy** of the elevated upper basin behind the barrier. That elevation can be optimized by regulating the **water head** to increase the power output of the plant. In contrast, any energy optimization of **kinetic** mode is hardly possible because it depends on the natural velocity of the stream without any practical possibility of modifying it. Moreover, most of the water in kinetic scheme avoids turbines because of their resistance to the flow as described above. Naturally, the streams that avoid turbines generate no useful power.

Interaction of fish with blades (Physical Contact)

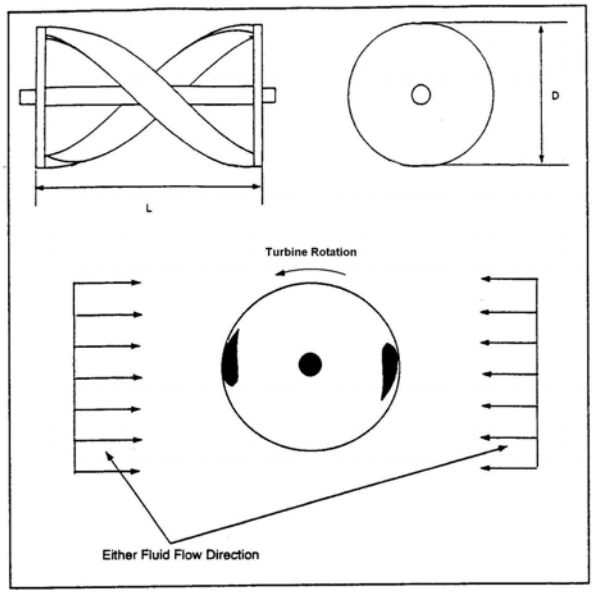
There is a common conclusion that the prime factor of fish mortality while it is forced to pass through the turbine is a shear strike from fast moving blades. Such conclusion mostly results from observation of fish harmed by fast rotating propeller-type turbines in high dams as discussed above.

This point of view cannot be automatically transferred to much slower helical turbine with its peripheral blades. Indeed, the helical turbine has the following three characteristics that make it different and more benign for fish in case of its direct interaction with the turbine, namely:

a. All blades have hydrofoil shape with quite thick well-rounded leading edge without sharp angles or abrasive surface. Turbine rotates in direction of blade movement, namely with leading edge first (Figure 6). This means that the fish can only contact the blade at its rounded leading edge, i.e. to be hit or simply pushed by this dull smooth frontal edge of the blade inside or out of the turbine.

b. Each helical blade (*EMA* in Figure 7) runs over cylindrical surface under angle of inclination δ. This is isometric projection of blade on the vertical plane as is shown. The inclined blade, being in contact with the fish body, would reduce the most dangerous shear load distributed over the larger inclined line of pressure. This inclination unavoidably softens the strike on the fish body.

c. Any two adjacent helical blades provide sufficient space in between them for fish safe passage, including their entrance and exit. In other words, the fish cannot be caught and held between blades, as shown in Figure 3. For example, the minimum distance between blades of the triple-helix turbine in Figure 4 is about one meter, which provides a rather wide opening for fish to swim inside the rotor. In case of large fish migrating, the larger turbine with smaller number of blades has to be selected. Or even single blade helical turbine of Figure 5 can be designed and tested for a specific project.



The helical turbine consists of long blades running along a cylindrical surface like a screw thread. The blades provide a reaction thrust from flows in either direction. The design of the turbine allows the engineer to reduce diameter D while increasing its length without power losses, providing important benefits in design.

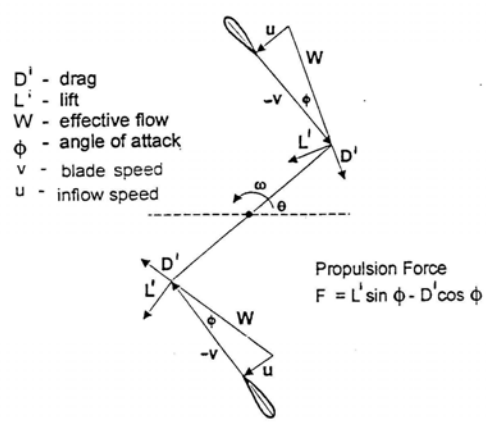


Figure 6. Double-Helix Turbine Diagram

Formula 5 above allows estimating the maximum shear force derived by moving blade that can strike the fish body sideward. This might be considered the same as drag from the water on fish body since there is no other rigid reaction from opposite side of the fish. Taking turbine speed as 90 *RPM*, $C_d = 0.5$, $\rho = 1{,}000$ kg/m^3 , blade linear velocity V = 5 m/s, one can obtain distributed normal load *p* over the fish body as *p* = 6.25 kPa or 0.9 psi.

It's hard to interpret the above 0.9 psi pressure from the viewpoint of immediate fish safety or how it might affect long-term competitive fitness or survival. Hypothetically, the worst scenario for fish is if the blade struck it close to the center of gravity of fish body that might cause its sharp bending. However, the probability of such particular impact is close to zero in free water space. In all other cases of direct contacts, fish most probably would be turned by the leading edge and pushed it sideward, away from the blade. Detailed testing of the Cylindrical Helical Turbine should be performed to find answers to the above hypothetical speculations.

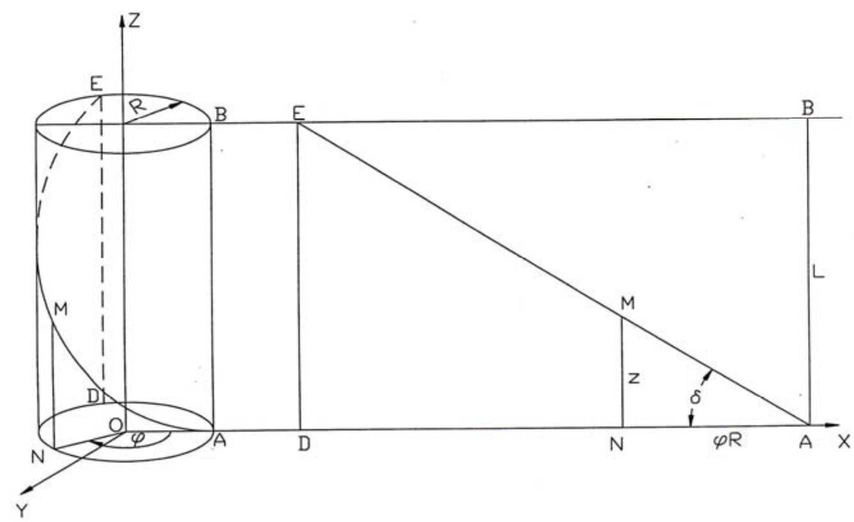


Figure 7. Isometric projection of blade line *EMA* on vertical plane

4. Fish Passage Test

The Alden Laboratory in Massachusetts is performing biological testing of fish passage through hydrokinetic turbines installed in Alden's large flume facility. The length of flume is about 80 ft, width of 20 ft and maximum water depth of about8 ft. Water velocity is about 3 ft/s. Maximum 10 ft/s can be obtained by constricting the flume for testing hydrokinetic turbines.

The photograph of Figure 8 below demonstrates the first testing with fish on July 22, 2010.

Fish was discharged through the duct in the flume (at left) in front of the spinning turbine (at right on the photo). A strong water jet directs the fish towards the turbine. The fish seen in the photo are captured by the water jet that forces them to pass through the turbine.

The spherical turbine used in this test is a modification of the helical turbine (Figure 4). It was built by the Lucid Energy Company in 2009 for particular applications in various hydraulic pipe systems (Figure 9).

One can see in the photograph quite remarkable behavior of the fish. All fish turned their tails towards the spinning turbine, swimming back against the strong water jet, and away from the turbine behind. This quite consistent fish behavior can be assumed as the fish's attempt to avoid the turbine, which was repeated by all fish released into the water flume at the day of testing.

This well documented test provides evidence, discussed above, that fish detect an obstacle such as spinning hydraulic turbine and try to avoid it if it can. In other words, the fish will act to avoid the turbine in a free flow kinetic scheme of operation.

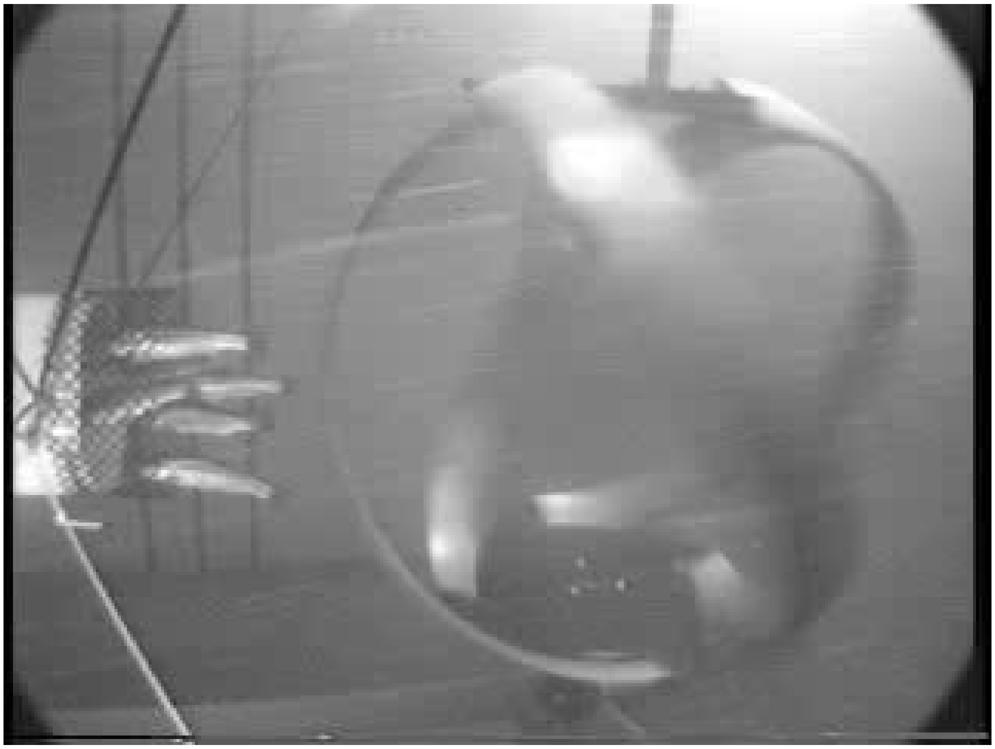


Figure 8. Test with Fish and Spherical Turbine.
Water jet direction - from left to right. Courtesy of Alden Lab, 2010

Figure 9. Lucid Spherical Turbine as tested

However, fish in constrained flow has no way of avoiding the turbine and must pass through it. In this case the helical turbine might be the one of the most benign machines available from the perspective of preventing turbine entrainment.

Unfortunately, we still have only qualitative but not quantitative information on the Alden Lab testing performed at the first day of their program. However, experimenting with cylindrical helical turbine of Figures 4 and 5 should show even better results from the viewpoint of fish safety because of their more open space for fish passage than the tested spherical turbine (Figure 9).

5. Power calculations

The following simple equations might be of help for estimation of turbine power for free (kinetic) and constrained (potential) water flows as function of water velocity and water head (SI units used)

Free flow (kinetic):

$$P_t = 0.5\,\eta\,\rho\,A\,V^3 \qquad (6)$$

Where P_t - turbine power,

η - turbine efficiency (power coefficient), $\eta = 0.35$ (max) from our lab tests

$\rho = m/L^3$, (kg/m^3) – water mass density, for $\rho = 1{,}000$ kg/m^3 equation (6) gives P_t in kW (instead of Watts)

A = HD (helical turbine cross flow area)

V – water velocity, m/sec

Also

$$P_t = T\,\omega \qquad (7)$$

Where T – torque is usually obtained from direct testing, (N-m).
ω – Angular velocity of the turbine, rad/sec

In terms of RPM = n, $\omega = 2\pi n/60$, and after substitution

$$P_t = 0.105\,Tn \qquad (8)$$

Manipulating by (6) – (8), one can get T, P_t or RPM as functions of water velocity V.

Important component for turbines in free flow is the blade/water velocities ratio. It is usually in limits of 2.0 – 2.6 to avoid possibility of cavitations.

The stream shear drag is approximately $F = 0.5\,\rho A V^2$ (9)

Constrained flow (potential):

Potential power component in case of a "barrage" effect on the cross flow turbines and supporting structures, including a semi-permeable dam with the head H (m)

$$P_H = \rho\,g\,Q\,H \text{ (Watts)} \qquad (10)$$

Where Q (m^3/sec) is a water flow rate through the turbine.

5. Concept of Flexible Barrier

The higher power of the constrained flow (potential) scheme is reflected in greater power efficiency of the helical turbines tested, as was mentioned above. For example, our experiments with vertical triple-helix turbine with 20"diameter by 28.5" height demonstrated up to 70% efficiency in constrained water channel with ultra low-head in contrast to 35% efficiency with the same turbine in free flow without the barrier. The testing was conducted in the Circulating Water Channel facility at the U.S. Coast Guard Academy (New London, Connecticut, 1996) by a research team from the Mechanical Engineering department of Northeastern University.

As to expressions (6) and (10), the constrained flow maintained by a low-head barrier, can provide substantially more power than the plain kinetic free flow system. However, from practical power generation viewpoint, one cannot do much for increasing water velocity of the free flow stream in kinetic scheme. At the same time, a designer has sufficient freedom in selecting a higher water head for more power in constrained flow. Nevertheless, the above mentioned concern for fish, which are forced through turbines, restricts attempts for using existing or newly designed low-head dams for power generation if migratory fish are to be safely and effectively passed downstream without the use of exclusionary devices. It is possible to use a fish friendly helical turbine for improving fish safety in constrained flow

To soften the conflict between higher water head with more power on the one hand, and fish safety concern, we suggest using kinetic helical turbines, such as shown in Figure 4, combined with a low-head hydraulic dam. As is shown, these turbines provide sufficient and rather safe space for fish, even for its swimming between moving blades.

Now we approach the possibility of using a **flexible barrier with helical turbines** (water sail, Figure 10). Such barriers for low-head hydropower have advantages in comparison to conventional dams. First of all, the barrier can be easily adjusted to develop any low-head without concerns with safe fish passage through turbines in the powerhouse. The point is that the upper edge of the flexible barrier in contrast to rigid conventional dams would fluctuate up and down correspondingly to such fluctuation of the water surface. The water head in this case might be adjusted and maintained on a constant level of, say, three meters or less depending on the requirements for the power plant operation. Thus, the flexible barrier with helical turbine might be especially advantageous for tidal power applications because this design allows generation of much more power from tides than the power from the same turbines in kinetic scheme.

The structural advantage of the water sail is its ability to resist tensile strains since it is always a stretched structure. All parts of this barrier are in tension, utilizing completely the tensile strength of the structural elements. One of the advantages of the barrier is its portability. This is the prefabricated structure that can be installed along any shallow shore location. It can also be easily removed for repair or for restoration of surrounding ecology and other environmental purposes, and then reinstalled again.

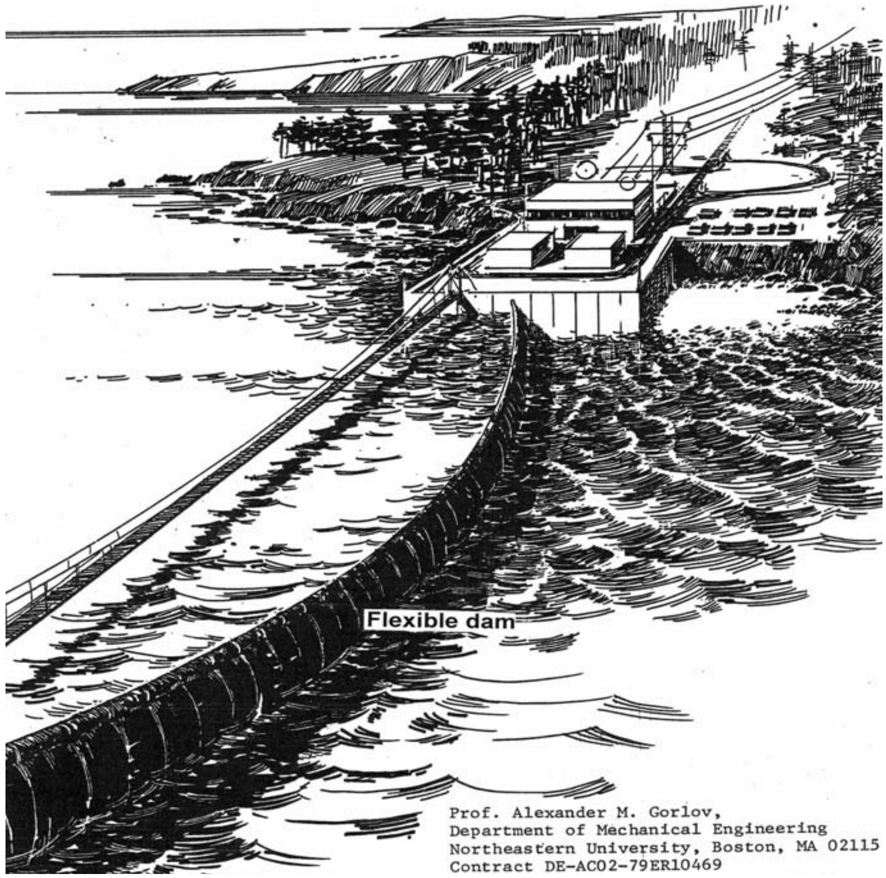


Figure 10. Flexible Barrier for Tidal Power Station (Artistic Rendering, 1981)

The floating supporting system should maintain the upper edge of the barrier on the upstream water level to build up a permanent water head designed for optimal turbine operation. This approach enables generating tidal power under ultra low head, and maintaining the natural ecological balance without distortion of surrounding environment. This method prolongs the time of turbine operation during each tidal cycle by shifting their start-up to the moment the designed water head has been reached.

Originally we suggested this idea in our research project funded by the DOE in 1981. Now with developing of the helical turbine the flexible barrier becomes even more justifiable in combination with the system "Flexible Barrier/Helical Turbine". The power generating components of the plant, namely the number of turbines assembled with generators and gear boxes for speed increasing, control apparatus, etc, to be located in the powerhouse on the background of Figure 10.

Our preliminary estimations show that the flexible plastic dam might be less expensive than conventional rigid structure both in construction and maintenance.

Conclusion

Based on the above discussion we can conclude:

- **Fish are safe in free water flow (kinetic mode) with respect to a possibility of its interaction with spinning turbine since fish can easily detect and avoid the turbine. Moreover, in case of the helical turbine used, fish can pass most probably through it harmlessly.**
- **A combined system of helical turbine with flexible adjustable barrier provides better chances for fish surviving in constrained flow passage than in case of any propeller-type high dam turbine is used.**
- **The system "helical turbine/flexible barrier" (constrained power scheme) is much more power efficient than system of plain kinetic turbines without dam. This is also because the helical turbine with dam uses both potential and kinetic energy in power balance.**
- **It is possible to assess with certain assurance whether the helical turbine is safe for fish passage in low head constrained flow (with barrier).**
- **The hydraulic barrier assembled with kinetic helical turbine allows optimizing its energy efficiency by adjusting the water head. Helical turbine in such assembly can generate twice as much power in contrast to fully kinetic mode.**
- **Plain kinetic mode might be recommended either for site where barrier isn't applicable or it is economically unjustifiable, such as in high sea or in site of a heavy maritime traffic. However, modern floatation systems can be of help in this case.**

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