How to Evaluate Hydrokinetic Turbine Performance and Loads

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INTRODUCTION

Turbines placed in a river or an ocean current (tidal or unidirectional) are called hydrokinetic turbines because they use the kinetic energy of the flowing water. These devices are considered advantageous in that they do not require impoundments that can cause fish passage concerns, habitat loss problems, and the resulting permitting challenges. As such, there is a potential to increase hydropower generation significantly. At this writing, numerous projects have been proposed and preliminary permits obtained for using these technologies. Developers and investors may not currently have the tools necessary to determine the economic feasibility of such projects, however.

This white paper describes how to estimate power extraction and fluid dynamic loads, as well as how to scale that power up to larger and more numerous units. In addition, this paper describes how to mitigate risk through laboratory performance testing and how to evaluate the suitability of an existing turbine design.

We begin with a short review of basic concepts of hydrokinetic turbine designs and how they are classified, then move to developing formulas for power extraction and foundation/anchoring loads. We conclude with a discussion of the conversion of mechanical shaft power to electricity.

BASIC PRINCIPLES

Although there are many sites where hydrokinetic turbines could be deployed, the requirement for strong currents to generate maximum practicable power narrows initial installations to a smaller number of sites.

Hydrokinetic turbines are, in principle, very much like wind turbines. The differences between the two include the greater density of water (approximately 900 times greater than air, leading to greater forces and greater power density), the need for waterproofing of the device, the need to avoid installations in navigation channels, and the need to consider wave forces at hydrokinetic turbine installation sites.

Both wind turbines and hydrokinetic turbines may be broadly classified based upon whether the axis of rotation is vertical or horizontal. Furthermore, the effective force driving the rotor may be primarily due to drag (pressure difference due to downstream flow separation and eddies) or lift forces (higher velocity on one side causing a net pressure difference). In all cases, the resulting differential pressure over the blade area produces a force and thus a moment (or torque) about the axis of rotation, which causes the rotor to turn a shaft generally connected to a generator.

The advantage of a vertical axis rotor is that it turns in one direction irrespective of the wind or water current direction. An example from everyday life is the cup anemometer used to measure wind speeds. An early vertical axis wind turbine with multiple cylindrical "cups" mounted adjacent to each other was invented in about 1925 by Savonius. Cylinders with their concave side facing the flow have a higher drag coefficient (1.33) than those with their convex side facing the flow (0.34), thus producing a net moment. These cylinders are easy to construct since they do not involve complex shapes and are fixed in geometry with varying current speeds. Conversion to electrical energy may be done at the base in the support structure. Also, the rotor starts once the wind speed is sufficient to overcome bearing friction irrespective of the initial position of the rotor.

An "advance" in vertical-axis rotor design occurred in about 1927 when Darrieus invented a rotor blade which relied on the "lift" produced on carefully shaped vertical blades or airfoils (wings). These blades operated more efficiently than the Savonius cylinders. The blades are similar to those used on hydrofoil boats. They are positioned so that a component of the lift force produces the desired torque on the shaft. An example, as applied to a hydrokinetic turbine, is shown in Figure 1. This type of vertical axis rotor may not be self starting, depending on the exact blade shaping and static orientation to the current. There may also be some pressure pulsations as each blade passes a particular flow angle.

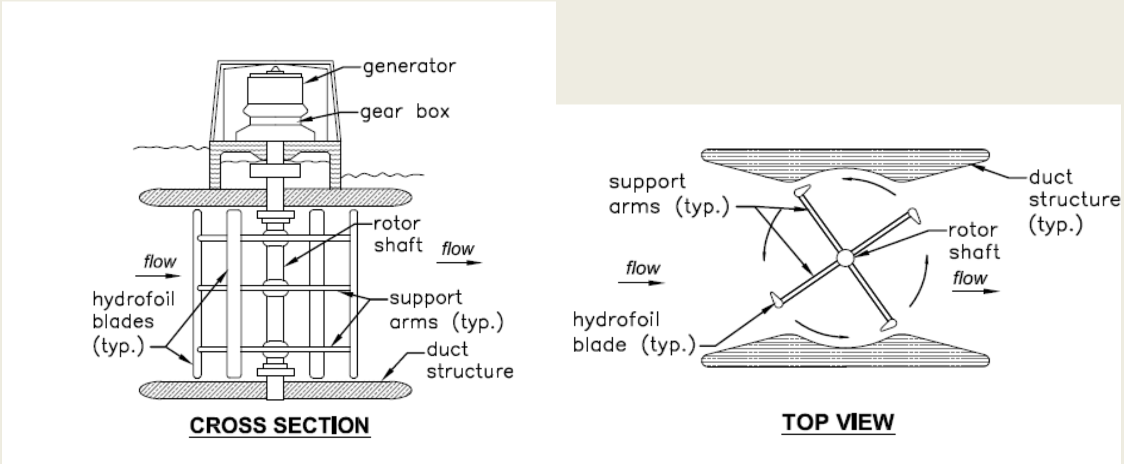

Figure 1- Darrieus style hydrokinetic turbine

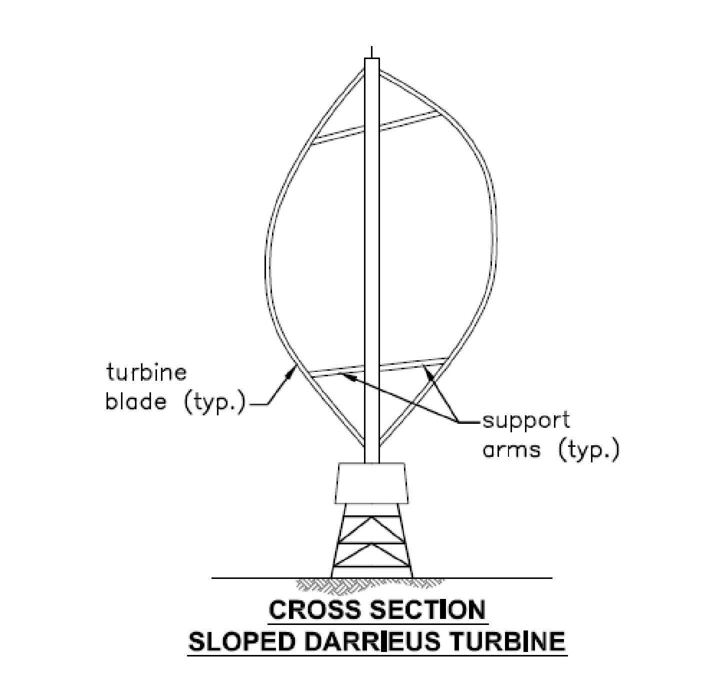

Figure 2- Sloped Darrieus turbine

Figure 3- Gorlov water turbine in the Alden test flume, tapered for possible use in a pipe. Courtesy of Lucid Energy Technologies, LLP

Figure 4- Free Flow Power turbine in the Alden test flume.

To minimize the size of the support arms, the Darrieus rotor may be shaped as shown in Figure 2, though this reduces the area of intercepted current and thus reduces the power output. To help overcome the potential start-up problem and avoid a secondary motor to start rotation, the Darrieus rotor may be shaped as shown in Figure 3, as some portion of the “wrapped” blade is always providing torque once the current is sufficient to overcome friction. This was patented by Professor Alexander Gorlov of Northeastern University in 2001. The Gorlov Turbine also minimizes pulsations due to periodic pressure changes on straight vertical blades. An interesting feature of the Darrieus type hydrokinetic rotors (e.g. Figures 2 and 3) is that the total torque is sufficient so that the blade speed may be considerably higher than the current speed.

Because power extraction depends directly on the area swept by the blades (see below), some designs focus on maximizing this parameter, which is more easily and economically achieved with a horizontal axis rotor. Resulting mechanical stresses notwithstanding, it is relatively easy to extend the length of the blade to create a greater swept area. The tip speed of such blades will generally exceed the free stream velocity. A ducted version of a horizontal axis hydrokinetic rotor is shown in Figure 4. The ducting acts to increase the velocity of the flow going past the blades. Other non-ducted designs look very similar to the common three bladed modern wind turbines. In general, blades on horizontal axis rotors may be fixed or have adjustable pitch to achieve maximum practicable efficiency and power output at various current speeds. In that case, speed sensing and control logic is needed to operate the extra variable pitch mechanism. Having the rotor downstream of the vertical support (pivot) allows the rotor to swivel and be "automatically" properly aligned with changes in current direction. There may also be cutoff logic to stop the rotor from turning should the current be too low to produce power or should the current be too high and cause an over-speed of the rotor with resultant excess forces on the blades, shaft and other turbine components.

Computing Power Extraction

At first glance, the maximum application of kinetic energy available to the turbine would seem to imply that the total approach velocity and mass flux is converted to mechanical energy by the turbine, leaving little or no kinetic energy downstream. The development of the power extraction equation will start on this premise, with coefficients added subsequently to account for actual limiting factors.

For any hydropower system, the power available by a flow with either kinetic or potential energy is given by

$$P = \rho\, g\, Q\, H \qquad (1)$$

where P = power (lb-ft/sec)

ρ = density of water (or air) (lb/ft^3)

g = 32.2 ft/s^2, the gravitational acceleration

Q= volumetric flow (ft^3/sec)

H= energy head (ft)

For power extraction from potential energy, H is the available difference in water level or pressure head. For power extraction from kinetic energy, H is the velocity head, or

$$H = V^2/2g \qquad (2)$$

where V = velocity (ft/sec)

Substituting $Q = AV$ (blade-swept area times velocity), equation 1 may be written as

$$P = 0.5\ \rho\ A\ V^3 \tag{3}$$

Although this is the power available, it is, by far, not the power that may actually be extracted from the flow. The primary issue is that the velocity cannot be reduced to zero at the outlet of the turbine, since that would imply no flow over the blades to create drag or lift; therefore, the total kinetic energy of the approach flow is not available. There is an optimum between this condition and no reduction in velocity through the turbine, and this optimization issue was analyzed by Betz in 1926. A quick summary of his analysis follows:

> To remove energy from the flow, there must be a decrease in velocity from upstream to downstream of the plane of rotor rotation. Since the mass flow is constant, this reduction implies an expansion in flow area from upstream of the rotor to downstream. By formulating the power extracted as a ratio to the flow power available, it is evident that this power ratio depends on the ratio of the downstream to the upstream velocities. The maximum possible power extraction of 59% occurs when the downstream velocity is 1/3 of the upstream approach velocity.

This value of 0.59 is the so-called Betz limit for power extraction from flowing air or water, and the goal for a turbine design is to reach this limit. Equation 3 therefore needs to include this multiplier.

Additionally, the rotor itself may only be about 60% efficient in extracting energy, depending on factors such as blade shaping. In addition, bearings and the gear box needed to increase the shaft speed to those compatible with generators typically have an efficiency of about 0.9 and a modern generator may have an efficiency of about 0.9, so equation 3 is also multiplied by these three additional coefficients. The result is

$$P = 0.5\ \rho\ A\ V^3\ C_P\ N_R\ N_B\ N_G \tag{4}$$ [i]

where C_P = the Betz limit (theoretically about 0.59)

N_R= rotor efficiency (about 0.6 for a good design)

N_B= bearing and gear friction (about 0.9)

N_G= generator efficiency (about 0.9)

Inserting these above mentioned numerical values for the constants and coefficients gives

$$P = 0.22\ D^2\ V^3 \tag{5}$$

Precision in the numerical values is neither possible nor warranted at this point because the coefficients will vary with the turbine design. However, equation 5 may be used to estimate the power that can be produced by a prototype turbine. It may also be used to calculate the power produced by turbines of different sizes. If multiple hydrokinetic turbines are arranged to avoid interference, the total power extracted would be equation 5 multiplied by the number of turbines.

Estimating Turbine Support or Anchor Forces

An estimate of the force required to hold a turbine in place, either by a fixed column or an anchor system, can be calculated assuming the velocity on the downstream side of the turbine is reduced to zero. This conservative (high) estimate is analogous to assuming the turbine is a solid disk in the path of the flow, which compensates for not considering the drag on other components such as columns, struts, the generator housing, and mooring lines. The drag force on a disk equal in diameter to the turbine is given by

$$F = C_D\, A\, \rho\, V^2/2 \qquad (6)$$

where F = the drag force (lbf)

C_D= a drag coefficient (dimensionless)

For a solid disk, C_D has a value of about 1.0, and using the value for ρ of about 2.0 lbm/ft^3 with A= ($\pi D^2/4$), equation 6 reduces to

$$F = 0.78\, D^2\, V^2 (1\text{bf}/32.2 \text{ lbm ft/s}^2) \qquad (7)$$

The location of this resultant force on the turbine system may produce an overturning moment for a rigidly mounted turbine or, for an anchored system, may result in a mooring line force with horizontal and vertical components (as in a boat anchor line).

Conversion of Shaft Power to Electricity

In most cases, the shaft output power of a hydrokinetic turbine is converted to electrical power within or close to the turbine mount. This is because it is much more convenient and efficient to transport electrical power over the relatively long distance from the turbine to the shore (electrical grid or local load) than to transport mechanical shaft power. Therefore, a waterproof generator is usually housed at the end of the shaft for submerged turbines or at the top of a column penetrating through the water surface. The latter design must also consider wave forces and navigational issues, indicating that a totally submerged design may be preferable.

Due to the relatively slow rotational speeds of hydrokinetic turbines (about 10 to 20 rpm depending on the rotor diameter and current speeds), a gear box is generally used to increase the shaft rotation rate to one that is compatible with generators. If a standard induction generator is used, it must be driven at a constant speed to produce 60-cycle AC current, a difficult task with varying current speeds. Alternatively, a more expensive variable frequency AC/DC/AC converter may be used to accommodate variability in the turbine shaft rotation rate due to varying current speeds.

EXAMPLE: A PILOT OCEAN DEMONSTRATION

To illustrate the application of a hydrokinetic turbine and the necessary considerations, consider a site with a depth of about 60 ft about one-half mile offshore, with currents basically in one direction at about 3 to 4 knots or an average of 6 ft/sec. To provide some bottom clearance for a support structure and to get the runner above the low bottom currents, as well as to provide for possible shipping, the runner diameter could be in the range of 20 to 30 ft. However, a prototype test turbine would likely be about 10 ft in diameter to allow for installation without large construction equipment.

The power which may be extracted from the prototype turbine would be based on Equation 5, $P = 0.22 D^2 V^3$. With the following input parameters, D=10 ft and V= 6 ft/sec, P= 4,750 lb-ft/sec, which is 8.6 hp or about 6.5 kW. Based on an average power draw of 1.3 kW per home, this output would power about five homes. Although clearly not commercially viable, given the cost to design, manufacture, install and provide for electrical connections, this could be considered a "demonstration of concept."

A larger unit would produce considerably more power; for example, if the runner diameter were increased to 20 ft (i.e., doubled), the power would be increased by a factor of 4 since the power varies with the square of the diameter. If the diameter were tripled to 30 ft, the power would be nine times higher. Additional turbines would produce more power proportional to the number of units added if they do not interfere with each other.

The relatively low power output for a 10-ft unit indicates why commercial turbines tend to be large in diameter and why many turbines are typically proposed for a given site.

In our example, Equation 7 would be used to estimate the total anchoring force. With D=10 ft and V=6 ft/sec, F=2,800 lbs, which is well within the limits of standard anchors such as the Danforth type (www.danforthanchor.com). However, note that the anchor forces also increase with the square of the runner diameter.

LABORATORY TESTING CONSIDERATIONS

Mechanical Performance

With the relatively early stage development of most hydrokinetic systems, there is a recognized need to test them in the field. The equations derived above, as well as much more complex mathematical and modeling analysis tools, make many assumptions which will not hold in the real world of varying flow currents, deep (possibly salt) water, debris, and so on. While many developers and their funding partners are usually in a hurry to get a device proven "in the water," much risk can be mitigated through laboratory flume testing prior to field pilot testing. System or component failures in a laboratory allow a developer to make necessary adjustments and design changes without the public scrutiny that goes along with a pilot project in the field. The cost and few months of extra time to perform laboratory tests may be well worth avoiding the financial and public relations expense of perceived failures in the water.

Figure 5- Alden large test flume

Performance characteristics that can be tested in laboratory flumes include:

- Torque and power extraction vs. flow velocity and rotation rate
- Component and full system loads
- Vibration modes and amplitudes
- Thermal characteristics
- Cut-in and cut-out water speeds

Environmental Performance

In addition to avoiding costly mechanical problems during site demonstration, laboratory tests can also be helpful in determining the fish friendliness of a turbine. A measurement of environmental performance is generally required by the responsible licensing agencies, and the approach taken is often to make field measurements of fish behavior and survival. These measurements can be extremely complex, expensive, and often inconclusive, however. There a number of flume facilities with the capability of injecting fish and recording their behavior and survival with very high accuracy and repeatability, which, when coordinated with the relevant licensing agencies, may be effective for demonstrating the potential for good environmental performance of the technology.

SUMMARY

This white paper has provided an introduction to the mechanics of hydrokinetic turbines and a method to estimate power generation potential and fluid dynamic loads. This basic information should prove useful to developers of hydrokinetic technologies and projects for the purposes of basic design and feasibility determination. Additionally, the paper has covered some considerations for laboratory testing of late stage turbine designs.

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[i] See also http://awea.org/faq/windpower.html