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Performance characterization of a cross-flow hydrokinetic turbine in sheared inflow

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ABSTRACT

A method for constructing a non-dimensional performance curve for a cross-flow hydrokinetic turbine in sheared flow is developed for a natural river site. The river flow characteristics are quasi-steady, with negligible vertical shear, persistent lateral shear, and synoptic changes dominated by long time scales (days to weeks). Performance curves developed from inflow velocities measured at individual points (randomly sampled) yield inconclusive turbine performance characteristics because of the spatial variation in mean flow. Performance curves using temporally- and spatially-averaged inflow velocities are more conclusive. The implications of sheared inflow are considered in terms of resource assessment and turbine control.

1. Introduction

Hydrokinetic energy conversion involves the extraction of kinetic energy from moving water and its conversion to electricity, analogous to the operation of wind turbines. Naturally-occurring high energy flows, such as river, tidal, or ocean currents, can be harnessed without incurring the environmental costs associated with impoundment behind a dam. Hydrokinetic energy converters are also modular and scalable [1]. This makes such systems potentially attractive to markets ranging from instrumentation (10^1 W) to small communities (10^4 W) to regional utilities (10^8 W).

Hydrokinetic turbines can be broadly categorized as axial-flow and cross-flow systems, though novel approaches are also being explored [1]. For axial-flow turbines, the axis of rotation is parallel to the flow direction, while in cross-flow turbines it is perpendicular. Cross-flow turbines may be oriented horizontally, with their axis of rotation parallel to the water surface, or vertically, with the axis perpendicular to the surface [1]. This research focuses on the performance of a horizontally-oriented cross-flow turbine. Like wind turbines, hydrokinetic turbines may be characterized by a non-dimensional power performance curve relating the performance coefficient (C_P) to the tip-speed ratio (λ), a ratio of turbine blade velocity to free-stream velocity [2]. In general, the performance curve has a global maxima corresponding to optimal conversion efficiency from kinetic to mechanical power at an associated tip-speed ratio. If the turbine's mechanical power output is known, the performance coefficient is given as

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$$C_P = \frac{P}{\frac{1}{2}\rho A U_\infty^3} \quad (1)$$

where ρ is density of the working fluid (1000 kg/m^3 in riverine environments), A is turbine projected area (m^2), P is the mechanical power produced (W), and U_∞ is the free-stream, or inflow, velocity upstream of the turbine (m/s). Standard practice is for U_∞ to be measured close enough to the turbine to be representative of the inflow, but far enough away for axial and angular induction to be negligible [2]. C_P represents the fraction of kinetic power incident over the turbine swept area that is converted to mechanical power. The water-to-wire efficiency (η) is the product of C_P and the balance of system efficiency (e.g., generator, gearbox, power electronics). For commercial systems, electrical current and voltage output are more commonly measured than mechanical power and η may be calculated as

$$\eta = \frac{IV}{\frac{1}{2}\rho A U_\infty^3} \quad (2)$$

where I and V are the output current and voltage, respectively. The tip-speed ratio is defined as

$$\lambda = \frac{R\omega}{U_\infty} \quad (3)$$

where ω is the angular velocity of the turbine rotor (rad/s), and R is the rotor radius (m).

A challenge in riverine environments is that variations in bathymetry may give rise to horizontal or vertical shear on the same length scales as a turbine rotor [4]. Because of this, there may not be an obvious choice of U_∞ for the non-dimensional representation of performance.

This paper describes field measurements around a hydrokinetic turbine, the Ocean Renewable Power Company (ORPC) RivGen® turbine, on the Kvichak River near Iguigig, Alaska (USA). The turbine and the deployment site are first described, followed by a description of measurements of stream velocity. The characterization of turbine performance in the presence of strong lateral (across-rotor) shear is then presented, and the paper closes with a discussion of the implications of these results for resource characterization, turbine control, and performance assessment.

2. Background

2.1. Turbine

The RivGen turbine is a cross-flow helical hydrokinetic turbine designed to provide community-scale power (10^4 W) as an alternative to diesel generation in remote communities [5]. The turbine consists of two 4.1 m long rotors situated symmetrically about a 2.8 m wide gap housing the generator (Fig. 1).

Prior to installation, preliminary characterization was performed with tow trials in Eastport, ME. The turbine was lowered below a barge being towed at a constant velocity which resulted in near-uniform flow across the turbine. Using this method, the maximum water-to-wire efficiency was found to be $\sim$ 19%. This performance was in agreement with computational fluid dynamic simulation and is in-line with experimental performance of turbines with similar geometry [6,7].

2.2. Site description

The turbine was deployed in August 2014 on the Kvichak River just downstream of the village of Igiugig, Alaska (USA). A local coordinate system is defined in Fig. 2, with $+x$ downstream (U component of velocity), $+y$ cross-river towards the village (V component of velocity), and $+z$ upwards (W component of velocity). The origin is at the nominal center of the turbine (59.3248° N, 155.9151° W) and the rotation from an east-north-up (true) coordinate system is 107° clockwise.

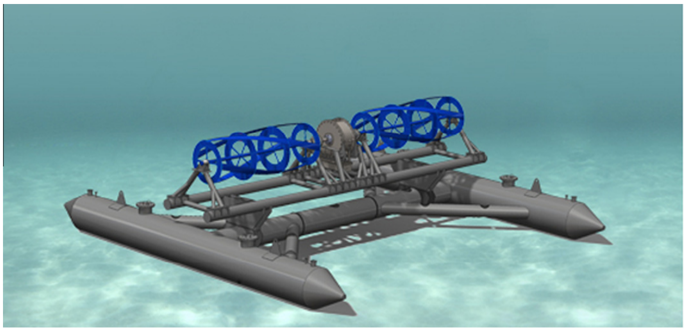

Fig. 1. Conceptual rendering of the RivGen turbine.