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Simulating blade-strike on fish passing through marine hydrokinetic turbines

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ABSTRACT

The occurrence, frequency, and intensity of blade-strike of fish on an axial-flow marine hydrokinetic turbine was simulated using two modeling approaches: a novel scheme combining computational fluid dynamics (CFD) with Lagrangian particle tracking, and a conventional kinematic model. The kinematic model included simplifying assumptions of fish trajectories such as distribution and velocity. The proposed CFD and Lagrangian particle tracking methods provided a more realistic representation of blade-strike mechanisms by integrating the following components: (i) advanced unsteady turbulence simulation using detached eddy simulation (DES), (ii) generation of inflow turbulence based on field data, (iii) moving turbine blades in highly transient flows, and (iv) Lagrangian particles to mimic the potential fish pathways. The test conditions to evaluate the blade-strike probability and fish survival rate were: (i) the turbulence environment, (ii) the fish size, and (iii) the approaching flow velocity. The proposed Lagrangian method simulates potential fish trajectories and their interaction with the rotating turbine with the limitation that it does not include any volitional fish avoidance behavior. Depending upon the scenario, the percentage of particles that registered a collision event ranged from 6% to 19% of the released sample size. Next, by using a set of experimental correlations of the exposure-response for live fish colliding with moving blades, the simulated collision data were used as input variables to estimate the survival rate of fish passing through the operating turbine. The resulting survival rates were greater than 96% in all scenarios, which is comparable to or better than known survival rates for conventional hydropower turbines. The kinematic model predicted higher blade-strike probabilities and mortality rates than the Lagrangian particle-based method did. The Lagrangian method also offers the advantage of expanding the evaluation framework to include additional mechanisms of stress and injury on fish, or other aquatic biota, caused by hydrokinetic turbines and related devices.

1. Introduction

Hydrokinetic power production is an emerging renewable energy technology that has recently attracted the attention of the research community, industry, and governmental entities as an alternative clean energy source. A report by Schweizer et al. [1] provides the context of proposed and ongoing hydrokinetic projects in the USA based on information collected from the Federal Energy Regulatory Commission. Within the summary, they described the types of systems, geographical distributions, extent of the projects (single or "farm" units), the potential interactions with fish populations, etc. Commonly labeled as "underwater" power sources by early researchers [2,3], the main feature of hydrokinetic turbines is their operation at zero- or near zero-head hydraulic conditions, i.e., the device transforms the kinetic energy of flowing water into driving energy to activate an electric generator [4,5]. Hydrokinetic technology falls into two primary categories: units that use river flow energy and those that extract energy from tidal currents in estuaries and coastal oceans [4]. The present study focuses on the latter type, also known as marine hydrokinetic (MHK) turbines or tidal current energy converter turbines.

Hydrokinetic turbine technology is still at an early stage of development and testing at various laboratory and onsite pilot installations. Hydrokinetic technology is promising in that, compared to other renewables such as wind and solar, it is less dependent on variable weather conditions. In addition, MHK devices may likely have less impact on the aquatic biota in the proximity of the installation site as compared to conventional hydropower plants. Storage and transmission costs can be reduced because the units

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can potentially be installed near end user centers. On the other hand, MHK turbines will still interact with and alter the surrounding ecosystem, thereby giving rise to potential environmental effects such as changes in tidal flushing dynamics, accelerated sediment transport with altered erosion/deposition patterns, and negative interaction with aquatic biota by creating the probability of hazardous strikes on the blades [6].

From a technical standpoint, the MHK technology was developed based on two engineering fields: wind energy and marine propulsion. Although early reviews recognized that a rich knowledge base of hydrodynamic aspects can be transferred from these fields [3], research specialized in the environmental impact of MHK turbines is still scarce [7]. Previous computational fluid dynamics (CFD) studies described the altered flow conditions that arise near MHK turbines by modeling the device as a sink/source term of momentum and turbulence [6,8,9]. Such an approach is advantageous given its computational affordability to describe flow conditions over large domains, and to optimize the placement and arrangement of multiple units ("MHK turbine farms"). However, the coarse resolution of the sink/source momentum approach precludes the evaluation of the more extreme and adverse hydrodynamic conditions that are present very close to the unit (one-turbine diameter). Instead, more recent studies have addressed the flow description near the turbine by resolving the details of the flow physics [5,7]. Whereas the latter simulation approach (turbulence resolution) is more computationally demanding than the former (turbulence modeling), it allows us to develop predictive assessment capabilities for sediment transport dynamics and biological performance based on hazards present during fish passage through MHK turbines.

The evaluation of the biological performance of hydrokinetic turbines has been addressed in various field and laboratory studies with live fish interacting with reduced scale and prototype devices. In two associated reports, concepts from fish survival assessment in conventional hydroelectric turbines were reviewed in relation to hydrokinetic turbines to elucidate the potential similarities and differences between the two hydropower technologies [10]. The conclusions pointed to better biological performance of hydrokinetic turbines in comparison to the hydropower counterparts owing to the less abrupt changes in flow direction, lower approach velocities, lower pressure differential, and the limited number of engineered structures with collision potential for fish, such as the lack of wicket gates and stay vanes. The follow-up report determined injury and survival rates, as well as behavioral effects of live fish crossing hydrokinetic turbines [11]. The experimental design consisted of two types of turbines (spherical, cross-flow and axial-flow), two flow conditions, two fish species, and two fish size groups. The document also reported the application of a classic kinematic model to evaluate blade-strike probabilities, a method that was revisited and applied in the present study. Gorlov [12] described a tidal power project on the U.S. East Coast related to a proposed helical turbine design and its potential consequences on fish passage safety. The study suggested a very limited probability of fish mortality owing to the "sufficient open space for fish passage". Another study by Normandeau Associates [13] characterized field-based rates of survival, injury, and predation of living fish through an operating onsite hydrokinetic turbine (HGE hydrokinetic system, Hydro Green Energy, Houston, Texas) with three blades, a low rotation rate and a 3.66-m-diameter rotor. The turbine was located at the tailrace of the Mississippi Lock and Dam No. 2 near Hastings, Minnesota. Two fish size groups were released (sample ranges of 115–235 mm and 388–710 mm) at operating conditions that gave rise to stream-flow velocities ranging from 1.73 to 2.95 m/s. A high survival rate (>99%) was recorded with neither visible blade-strike injury nor increased rates of predation.

To reduce the need for laboratory and field tests, this work presents a design approach where the turbine flow is first described using computational fluid dynamics, and then, potential biological impacts of a design are evaluated based on known responses to simulation hydraulic conditions. The present work demonstrates this approach for blade-strike collisions on a horizontal axis MHK turbine. The evaluation is presented in terms of the estimated survival rates of fish passage, for which we followed three major steps. First, we simulated and described the flow characteristics and turbulence environment near an MHK turbine of a prescribed geometry (Section 3). We validated the simulation results against prescribed power and thrust force performance obtained from laboratory tests at various operation conditions [14,15]. Second, we evaluated the likelihood that fish will strike the rotating blade during passage through the turbine (Section 4). Finally, we assessed the survival rate of fish colliding with the operating turbine blades (Section 5). The outcomes of probability and survival rate were compared to those from a conventional kinematic model.

2. Marine hydrokinetic (MHK) turbine design

2.1. General features

The geometry of the MHK turbine was prescribed for this study (i.e., the blade design is not part of the present work), and was designed based on the blade element method (BEM). Historically, the BEM was carried over from wind turbine design concepts, and has usually been the chosen modeling approach for the blade design of MHK systems [3]. The following objectives were pursued as part of the design process of the MHK turbine [16]: (i) maximize hydraulic performance with respect to the lift/drag ratio, (ii) minimize sensitivity to debris accumulation to economize on maintenance cost, (iii) provide sufficient thickness for bending stiffness, (iv) incorporate adequate stall features, and (v) minimize cavitation and singing, the latter being a hydroacoustic/hydroelastic phenomenon of the trailing edges of the blades specific to operation in aqueous environments. The hydrofoil profiles were determined using XFOIL (MIT, Cambridge, Massachusetts) that contains routines for parameterizing geometries and flow condition distributions. The general dimensions of the MHK device are shown in Fig. 1.

2.2. Hydraulic performance: BEM and laboratory tests

Although BEM concepts are widely available in the literature, as summarized here BEM consists of equating the flow momentum and surface forces (friction and pressure) to define the performance of a section (lifting foil) of known characteristics from radius (R) to radius ($R + \Delta R$). Next, the local sectional forces are integrated over the entire blade to obtain the overall device performance. The technique is particularly successful for geometries with relatively high aspect ratios, such as those in most MHK turbine blades. Conventionally, a prescribed foil section (or a combination of a few sections) provides the starting geometry for the analysis.

The design optimization sought to maximize the percentage of power to be extracted from the free stream while minimizing the axial momentum imparted by the flow stream onto the device surface. To quantify the performance, the power coefficient (C_P) is defined in the following relationship:

$$C_P = \frac{P_{\mathrm{OUT}}}{\frac{1}{2}\rho U^3 A} \tag{1}$$