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Estimating the probability of fish encountering a marine hydrokinetic device

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ABSTRACT

Strong tidal currents in eastern Maine, USA, make that region attractive for tidal power development. Little is known about the effects of marine hydrokinetic (MHK) devices on fish, yet many fish species use tidal currents for movements. We used empirical data from stationary and mobile hydroacoustic surveys to examine the probability that fish would be at the depth of an MHK device and may therefore encounter it. The probability was estimated using three components: 1) probability of fish being at device-depth when the device was absent; 2) probability of fish behavior changing to avoid the device in the far-field; and 3) probability of fish being at device-depth in the near-field when the device was present. There were differences in probabilities of fish encountering the MHK device based on month, diel condition and tidal stage. The maximum probability of fish encountering the whole device was 0.432 (95% CI: [0.305, 0.553]), and the probability of fish encountering only device foils was 0.058 (95% CI: [0.043, 0.073]). Mobile hydroacoustics indicated that fish likely avoided the device with horizontal movement beginning 140 m away. We estimated the encounter probability for one device, but results can be applied to arrays, which may have bay-wide implications.

1. Introduction

Tidal power projects are being developed around the world in recent years to harness this predictable, regular and renewable energy from ocean currents [1–4]. Large, in-stream marine hydrokinetic (MHK) devices can be used to generate electricity from the kinetic energy of fast-flowing water using moving device foils [5–7]. Unlike barrage tidal power generation and tidal fences, which block off a channel, MHK devices are free-standing, open structures that are expected to be an environmentally sound tidal power option. The open configuration and relatively slow movement of MHK devices allow fish, water, and sediment to pass through the channel and provide opportunities for fish to avoid the areas of the device(s) [8–10].

Tidal currents play an important role in the life cycles of many fish species in estuaries and coastal ocean waters. By changing vertical position in the water column, migratory species can use tidal flow to access suitable foraging, spawning, and sheltering grounds [11–13]. The tidal currents provide an energetic advantage for directed movements between habitats [14–16]. Devices may sufficiently alter water flow patterns or other features to influence the behavior of fish using the tidal currents if there is spatial overlap between fish and MHK devices [6,8,17]. Effects on behavior may include interference with migration, habitat selection, and avoidance or evasion [4,17,18]. Concerns have been raised regarding the risk of foil strike to fish because some devices have tip velocities exceeding 10 m s^{-1} [19]. Although some studies have examined the survival of fish passing through tidal devices in laboratory flumes [9,10,18], little empirical data have been collected that directly document interactions between fish and MHK devices [4,19,20]. Thus, different quantitative models have been explored to model fish interactions with MHK devices [6,10,19,21,22]. Wilson et al. [21] used predator-prey interaction to predict the encounter rate of herring with MHK devices. A mark-recapture model was used to assess the survival rate for three riverine species [10]. More complicated models have been developed to cover different aspects of fish interactions with MHK devices [19,22], including interactions of certain species (e.g., sturgeon [22]) and interactions of different assemblages with a device [19]. Romero-Gomez and Richmond [6] first modeled the flow and turbulence characteristics around an MHK device and then simulated flow conditions in a Lagrangian particle model and estimated fish survival at

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96.7–99.1%. They determined that fish collision with a foil was dependent on fish size and turbulence resolution in the model.

It is difficult to accurately predict the effects and impacts of MHK devices on fish because relatively few commercial-scale devices have been deployed. In the USA, few MHK projects have been developed, tested, and deployed. To date, two devices have been tested in Cobscook Bay, Maine, the eastern-most bay of the USA, which opens into the Bay of Fundy. The mean tidal range is 5.7 m in Cobscook Bay [23] and current speed can exceed 2 m s^{-1} in the channel of the outer bay. Ocean Renewable Power Company, LLC (ORPC) has taken a sequential approach to developing tidal power in this region and conducted initial test deployment of two MHK devices: TidGen® and OCGen® prototype. Deployment of these test devices provided the opportunity to investigate fish responses to MHK devices and to estimate the probability of fish encountering a single MHK device.

The dynamic environment at tidal power sites presents challenges for monitoring the physical and biological characteristics around MHK devices. The extreme turbulence and sediment-laden water impair optical visibility, which reduces the effective use of camera or video monitoring techniques [20,24,25]. The strong tidal flows make the use of standard biological sampling tools such as nets and trawls difficult and dangerous. Passive acoustic telemetry has been used in such environments to monitor behavior of individuals of certain species such as striped bass (*Morone saxatilis*) [26] and Atlantic sturgeon (*Acipenser oxyrinchus oxyrinchus*) [22]. However, most tidal power sites have high levels of background noise from high flows, which limit detection due to the reduced efficiency of acoustic telemetry systems [26]. Hydroacoustic techniques have been successfully used to sample these high-velocity areas [7,27–29]. Nearly the entire water column can be sampled continuously using hydroacoustics, and the technique is less invasive to animals than other methods, such as trawling and tagging [30].

The probability that fish will encounter an MHK device located at a fixed depth depends on the natural distribution of fish in the water column. Fish vertical distribution has rarely been examined in strong tidal regions [7], and more typically investigated in regions with little or moderate currents [31–33], lakes [34], and rivers [35]. These studies demonstrated that the vertical distribution of fish depends on natural variations, e.g., year, month, tidal stage, diel condition, and location. Significant diel or tidal differences in fish vertical distribution have been documented by several studies [7,32,35], with additional variation related to time of year, location, and species [7,32]. Fish may detect changing hydrodynamics based on device presence and operation, sense device noise from the moving foils, or visually identify the structure, and thereby initiate an avoidance or attraction response to the MHK device [17]. Due to the complex nature of fish behavior, previous studies have not modeled avoidance in detail or included avoidance in modeled estimates of fish collision with MHK devices [6,21]. Although Hammar et al. [19] included fish behavior in their probabilistic model, there are no available empirical data for model validation. The lack of empirical data makes it difficult to quantify fish avoidance of devices in an open marine environment.

In this study, we aimed to estimate the probability of fish being at the same depth as (i.e., potentially encountering) an MHK device. Empirical data were collected using hydroacoustic techniques before, during, and after ORPC deployed two devices at the Cobscook Bay Tidal Energy Project (CBTEP) area during 2011–2014. Mobile hydroacoustic surveys were conducted to explicitly estimate the avoidance by fish as they approach a device. Stationary hydroacoustic surveys were carried out to estimate the vertical distributions of fish at the project area. Empirical data collected from these two hydroacoustic survey types were combined to estimate the probability of fish encountering an MHK device.

2. Methods

2.1. MHK devices

Two MHK devices were deployed by ORPC during different periods: TidGen® power system from March 2012 to July 2013, and prototype OCGen® module from July 2014 to August 2014 (Fig. 1). Hereafter each device is referred to generally as the TidGen® and OCGen® unless referencing specific components. The entire TidGen® (bottom support structure and device foils) was 31.2 m long, 15.2 m wide, and 9.5 m high, and was bottom-mounted using a solid steel frame. The foils of the TidGen® were 6.7–9.5 m above the seafloor (Fig. 1). Unlike the TidGen®, the OCGen® was moored to the seafloor with gravity anchors and cable (Fig. 1). The entire OCGen® (the float and foils) was 19.7 m long and 5.1 m high. The foils were located 8.0–10.5 m above the seafloor at slack tide. The depth of the OCGen® changed slightly with the current flow due to horizontal displacement, and foils were 5.9–7.4 m above the seafloor during maximum flow. The OCGen® can be displaced horizontally approximately 6.8 m from its neutral position during maximum flow. The two MHK devices had similar device foil designs (Gorlov helical design). The TidGen® had four sets of foils, while the OCGen® had two (Fig. 1).

2.2. Study region

From 2011 to 2013, stationary down-looking hydroacoustic surveys were conducted to monitor relative fish density and vertical distribution over time at the site of the TidGen® in outer Cobscook Bay (44°54.60′ N, 67°2.74′ W), and at a control site (44°54.04′ N, 67°1.71′ W) about 1.6 km seaward from the project site (Fig. 2; also, [7]). The control site allowed the differentiation of effects of the MHK devices from natural variation [7]. The water depth at the project site averaged 24.5 m at low tide and 32.3 m at high tide. At the control site, the water depth averaged 33.8 m at low tide and 41.3 m at high tide. The current speeds were generally less than 2 m s^{-1}, with a maximum speed of 2.5 m s^{-1}. The TidGen® stopped functioning in April 2013 and ORPC removed the foils and generator, leaving the bottom support frame. As such, mobile hydroacoustic surveys were carried out over and around the OCGen® in August 2014. The center location of the OCGen® (44°54.58′ N, 67°2.68′ W) was about 100 m seaward from the center location of the TidGen® bottom support frame.

2.3. Stationary down-looking hydroacoustics

From 2011 to 2013, stationary down-looking hydroacoustic surveys were conducted at the project and control sites on or near neap tides during multiple months (March, May, June, August, September, and November). After March 2013, ORPC operations around the TidGen® prevented hydroacoustic surveys at the project site, so following surveys were only conducted at the control site. In each month, 24-h surveys were conducted to cover diel and tidal variation in fish abundance and vertical distribution. Before and during the time that the first device (TidGen®) was deployed at the project site, stationary down-looking surveys were carried out from a boat moored approximately 100 m from the device location. The boat moved approximately 50–100 m around the mooring point. Hydroacoustic data were collected with a single-beam Simrad ES60 echosounder mounted 1 m below the surface, facing downward. The echosounder had a circular transducer (Simrad 38/200 CombiW) with a half-power beam angle of 31°, operating at 200 kHz and 38 kHz simultaneously at a rate of 2 pings s^{-1} and pulse