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ESTIMATING THE PROBABILITY OF FISH ENCOUNTERING A MARINE HYDROKINETIC DEVICE

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INTRODUCTION

Cobscook Bay, Maine is well known for its strong tides. The mean tidal range is 5.7 meters and current speed can exceed 2 $m \cdot s^{-1}$ in the channel of the outer bay, which makes this area attractive for tidal power development [1]. Extracting energy using marine hydrokinetic (MHK) devices is receiving growing global interest because of the environmental friendliness of the technology and the predictability of the tides. The MHK devices extract energy with moving parts which can result in a collision risk for fish if they cannot avoid/escape the moving parts. Although some studies have examined the survival of fish passing through tidal turbines in laboratory flumes [2-3] and fish behavior in the near-field of a test turbine [4], the potential effects of MHK devices on fish remain unclear.

It is difficult to accurately predict the effects and impacts of MHK devices on fish because relatively few commercial-scale devices have been deployed. Ocean Renewable Power Company, LLC (ORPC) has taken a sequential approach to develop tidal power, beginning with the identification of potential development sites, establishment of a test site in Cobscook Bay, and the initial test deployment of two MHK devices. The two devices were deployed by ORPC during different periods: TidGen® from March 2012 to July 2013, and OCGen® from July 2014 to August 2014. The test turbines provided the opportunity to investigate fish reactions to MHK devices and estimate their encounter probability with the TidGen®.

The dynamic environment at tidal power sites precludes the use of most conventional biological monitoring tools. However, hydroacoustic techniques can work well in such environments [5-6]. To examine fish response to a single MHK device, we used two different hydroacoustic approaches: stationary down-looking surveys and mobile down-looking surveys. Stationary down-looking surveys were conducted at the site of the TidGen® device, and also at a control site about 1.75 km seaward from the project site (Figure 1). Mobile down-looking surveys were carried out at the project site only (Figure 1).

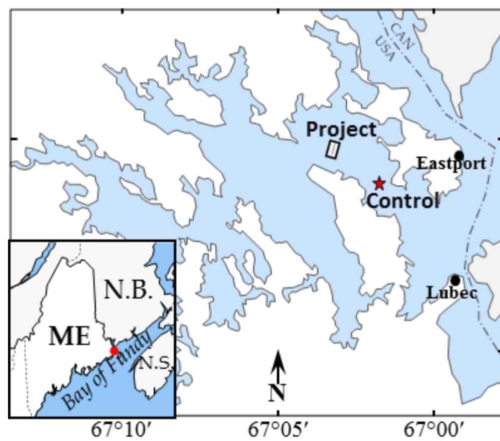

FIGURE 1. MAP OF COBSCOOK BAY WITH LOCATIONS OF THE PROJECT AND CONTROL SITES.

METHODOLOGY

Data Collection and Processing

From 2011 to 2013, we conducted stationary down-looking hydroacoustic surveys at the project and control sites on neap tides during different months (March, May, June, August, September, and November). In April 2013, ORPC operations around the TidGen® prevented hydroacoustic surveys at the project site, so after March 2013, surveys were only conducted at the control site. Each survey spanned 24 hours to cover all diel and tidal conditions. Before and during the time that the first device (TidGen®) was deployed at the project site in 2012-2013, stationary down-looking surveys were carried out from a boat moored approximately 100 m from the device location. Data were collected with a single beam Simrad ES60 echosounder operating at 200 kHz. The water depth at the project site was approximately 25 m at low tide and the TidGen® (bottom-mounted) occupied the water column from 0 to 9.5 m above the seafloor (the turbine blades were located 6.5 to 9.5 m above the seafloor).

Echoview® (6.1, Myriax, Hobart, Australia) software was used to process the down-looking hydroacoustic data. Calibration values were applied to the raw data and the upper 10 m of the water column were excluded because entrained air caused acoustic interference. The echogram was divided into cells spanning 30 min in time and 1 m in depth. For each cell, the area backscattering coefficient, s_a, was exported.

Fish may change behavior in the 100 m space between the stationary down-looking survey site and the TidGen®. Safety considerations prevented us from mooring closer to the device. Thus, mobile acoustics near the OCGen® were used to observe fish behavior when they approached and departed from the device (Figure 2). In summer 2014, a Simrad EK60 split beam echosounder operating at 200 kHz was used to conduct mobile hydroacoustic surveys around the OCGen®, which was moored to the seafloor and spanned the middle of the water column (turbine blades located 8 to 11 m above the seafloor). The mobile down-looking hydroacoustic surveys involved transects in which the boat drifted with the current from 200 m upstream to 200 m downstream of the OCGen® (Figure 2). Mobile surveys were conducted on a neap tide, carried out during 10 sequential flood tides over 5 continuous days, with more than 20 transects conducted during each tide.

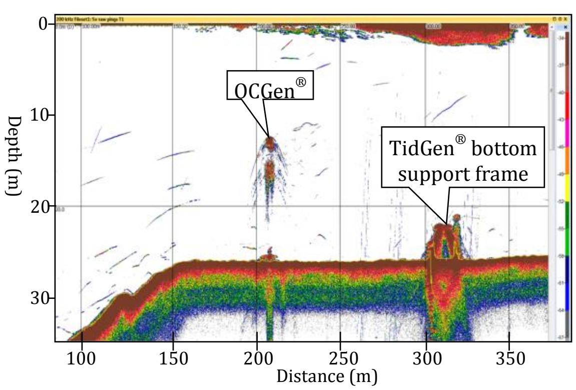

FIGURE 2. ONE MOBILE TRANSECT OVER THE OCGEN® AND THE TIDGEN® BOTTOM SUPPORT FRAME DURING A FLOOD TIDE.

Mobile hydroacoustic data were processed using Echoview® software. For each transect, single targets were detected. The target strength threshold was set to -70 dB to exclude small organisms (such as zooplankton and small fish without a swim-bladder). Echoview's fish tracking module was used to identify individual fish (i.e., groups of single targets showing a pattern of systematic movement).

Encounter Probability Model

The probability that fish would encounter the TidGen® was estimated from three components: 1) the probability of fish being at the device depth when the device was not present at the project site (p_1); 2) the probability of fish behavior changing to avoid the device before being detected by the stationary surveys at the project site when the TidGen® was present (p_2); and 3) the probability of fish behavior changing to avoid the device between the location of the stationary survey and the OCGen® (p_3). Because the turbine blades of the TidGen® and the OCGen® have a similar design and are located at similar depths, the probability of fish encountering the TidGen® can be calculated as

$$p = p_1 * (1 - p_2) * (1 - p_3) \quad (1)$$

Data from the stationary hydroacoustic surveys (from 2011 – 2013) carried out near the TidGen® were used to estimate the first two probability components (p_1 and p_2). Data collected from mobile hydroacoustic surveys near the OCGen® in 2014 were used to estimate the third probability component (p_3). Because the highest risk to fish would occur when the turbine is rotating, we focused analyses on data collected when the current velocity at the device (velocity data collected using a bottom mounted ADCP near the device) was greater than 1 m·s^{-1}, which is the velocity at which the turbine begins to rotate.

A Bayesian Generalized Linear Model (BGLM) was used to estimate the probability of fish at certain depths of interest in absence of the MHK device (p_1): 1) at the depth spanned by the entire TidGen® (0-9.5 m above the sea floor) and 2) the depth spanned by the moving components (turbine blades) of the TidGen® (6.5-9.5 m above the sea floor). Three factors were considered: month, diel condition, and tidal cycle. These factors have had significant influences on fish vertical distribution [6]. The model is given as

$$y = \beta_0 + \sum_{j=1}^{J_1} \beta_{1,j} x_{1,j} + \sum_{k=1}^{J_2} \beta_{2,k} x_{2,k} + \sum_{l=1}^{J_3} \beta_{3,l} x_{3,l} + \sum_{j=1}^{J_1} \sum_{k=1}^{J_2} \beta_{1\times2,j,k} x_{1\times2,j,k} \quad (2)$$

where y denotes the probability of fish being at the depth of interest, β_0 denotes the baseline which is the overall mean probability of fish at a certain depth of interest, β_1 denotes the deflection of diel condition (x_1) (i.e. how much y changes when x_1 changes from neutral to category j), β_2 denotes the deflection of the month (x_2), β_3 denotes the deflection of tidal cycle (x_3), and $\beta_{1\times2}$ denotes the interaction of diel condition and month.

To determine if fish behavior changed before being detected by the stationary surveys in the presence of the TidGen®, fish vertical distributions were compared between the survey locations at the project site and at the control site during months when the bottom support frame of the TidGen® was in the water (2012: March, May) or the entire device was in the water (2012: August, September and 2013: March). The Hotelling's T^2 test was used to determine if fish vertical distribution differed at the two sites. Because the device was fixed on the seafloor and the down-looking hydroacoustic surveys took place from a boat, the distance between the device and the boat was different for ebb and flood tides. Since there was no information about the distance at which the device may affect fish behavior, the datasets were separated by the tidal cycle for each month and then compared between sites.

Mobile hydroacoustic data were processed to estimate p_3. Since our focus was on the probability of fish encountering the MHK device, data collected upstream of the OCGen® were used to obtain the number of fish present in front of the device. To investigate how fish avoided the OCGen®, transects over the OCGen® were grouped by diel condition and fish tracks were grouped into distance bins of 10 m, with distance measured between the fish track and the OCGen®. If fish avoided the device, the number of fish tracks will decrease as fish approach to the device. Thus, a simple linear regression was fitted (number of fish tracks vs. distance to the OCGen®) to estimate fish avoidance. Fish avoidance was estimated as the predicted number of fish tracks between the distance when the number of fish tracks started to decrease and 10 m upstream of the device. We cannot investigate fish behavior closer due to the strong acoustic backscatter from the device. The confidence interval (CI) of p_3 was estimated using a bootstrap method. The total probability of fish encountering the TidGen® was estimated by combining the three probability components using Equation 1.

RESULTS

The data in 2011 were used to determine the probability of fish being at depths of interest in the absence of the MHK devices because no devices were deployed then. In 2011 at the project site, the overall mean probability of fish being at the depth of the entire TidGen® device (0-9.5 m above the seafloor) was 0.793 (Highest Density Interval, HDI: 0.748 to 0.835) (Figure 3), and the overall mean probability of fish at the depth of the turbine blades (6.5-9.5 m above the seafloor) was 0.083 (HDI: 0.064 to 0.103). At the control site in 2011, the probability of fish being at the depth of the entire device was 0.783 (HDI: 0.746 to 0.820), and the probability of fish being at depth of the turbine blades was 0.084 (HDI: 0.072 to 0.097).

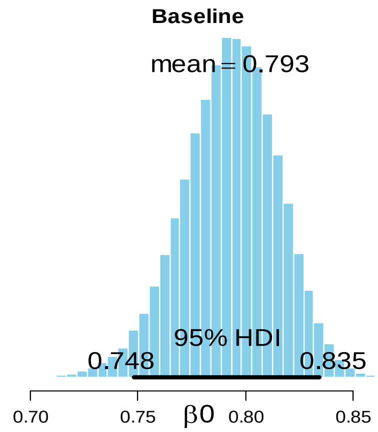

FIGURE 3. THE POSTERIOR DISTRIBUTION OF THE BASELINE WITH ITS HDI AT THE PROJECTED MHK DEPLOYMENT LOCATION IN 2011 (PRIOR TO DEPLOYMENT).

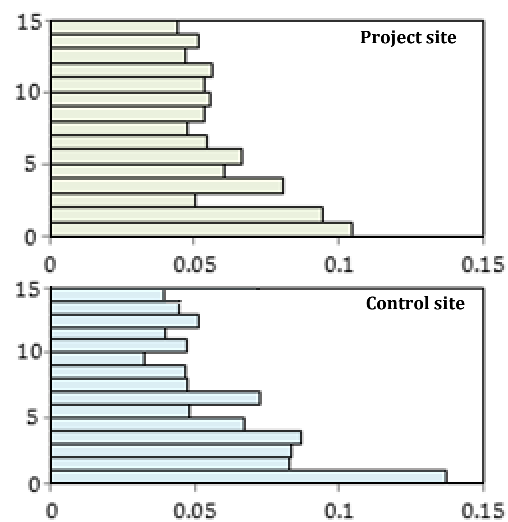

FIGURE 4. VERTICAL DISTRIBUTION OF FISH DURING EBB TIDE IN SEPTEMBER 2012 SURVEY. VERTICAL AXIS IS DISTANCE ABOVE BOTTOM (M). EACH HORIZONTAL BAR REPRESENTS THE PROPORTION OF AREA BACKSCATTER IN THAT LAYER OF THE WATER COLUMN.

The proportion of fish generally increased toward the sea floor at both the project and control sites (Figure 4). By comparing fish vertical distributions at stationary survey locations between the project site and the control site, we found that fish vertical distributions were not significantly different at the two sites when the TidGen® was in water (Hotelling's T^2 test: p values ranged from 0.145 to 0.594). In other words, fish behavior did not change before being detected by the stationary down-looking hydroacoustic equipment when the turbine was deployed (i.e. $p_2 = 0$).

Since the presence of the device did not affect fish vertical distribution at survey locations, the BGLM was also used to estimate p_1 in 2012 (when the device was present). In 2012, the probability of fish being at the depth of the entire device was 0.652 (HDI: 0.543 to 0.762) at the project site and 0.674 (HDI: 0.615 to 0.731) at control site. In 2012, the probability of fish being at the depth of the turbine blades was 0.090 (HDI: 0.069 to 0.113) at the project site and 0.086 (HDI: 0.067 to 0.106) at the control site. Similar probabilities between the two sites suggested that fish behavior did not change due to the presence of the device.

In 2013, the probability of fish being at the theoretical depth of the device was 0.658 (HDI: 0.614 to 0.701). The probability of fish being at the theoretical depth of the turbine blades was 0.093 (HDI: 0.081 to 0.105). Since the probabilities were very close at both sites in 2011 and 2012, the data at the control site in 2013 could be used to reflect the probability at the project site when data were not available in 2013.

Because fish quantity started to decrease 140 m upstream of the OCGen® in 2014, the simple linear regression was fitted with the data from 10 m to 140 m upstream of the OCGen®. Generally, fish avoided the device by horizontal movements, not vertical movements. The relationship between fish numbers and distance from the device was not significantly different between day and night (p=0.128), so all transects over the OCGen® were grouped together. The R^2 value was 0.86 for the linear regression of number of fish tracks vs. distance to the OCGen® (Figure 5). The proportion of fish avoiding the device was calculated as the predicted number of fish between 10 m and 140 m

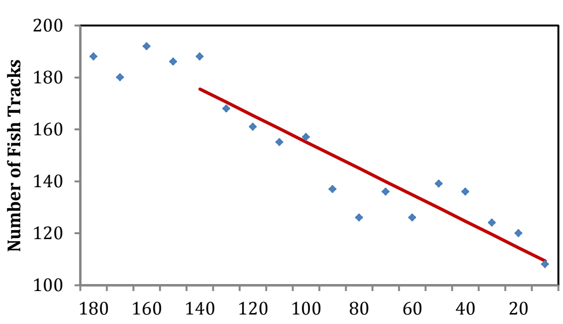

FIGURE 5. NUMBER OF FISH TRACKS UPSTREAM OF THE OCGEN® DEVICE.

upstream of the device. Over all transects, 37.2% (95% CI: [21.8%, 49.4%]) of fish avoided the device (i.e. p_3=0.372).

The probability of fish encountering the turbine was estimated by combining the three probability components using Equation 1. The maximum values for p_1 were used: 0.793 for the probability that fish would be at the depth of the entire TidGen®, 0.093 for the probability that fish would be at the depth of the turbine blades. Then, the probability of fish encountering the whole TidGen® would be 0.498 (95% CI: [0.371, 0.619]) and the probability of fish encountering the turbine blades would be 0.058 (95% CI: [0.043, 0.073]).

CONCLUSIONS

Our work has been the first opportunity to collect and apply empirical data to estimate the probability of fish encountering an MHK device under natural conditions. This, along with several laboratory experiments [2-3] is informing our understanding of fish interactions with tidal turbines.

Stationary down-looking hydroacoustic surveys provided valuable data to estimate the probability of fish being at depths of interest in the absence and presence of a single MHK device. The probability of fish being at the depth of the whole TidGen® (p_1) ranged from 0.652 to 0.793. The probability of fish being at the depth of the blades of the TidGen® (p_1) ranged from 0.083 to 0.093. By comparing fish vertical distribution at the stationary survey locations between two sites in the presence of an MHK device, we found that fish behavior did not change between the project and control sites over a 1.75 km distance (i.e. p_2=0). Mobile hydroacoustic surveys spanning 200 m upstream to 200 m downstream of an MHK device made it possible to monitor fish behavior from 200 m to 10 m upstream of the device. Fish started to avoid the device when they were about 140 m upstream of the device, and the estimated fish avoidance between the location of the stationary survey and the location of the OCGen® (p_3) was 0.372. By combining all three probability components, our preliminary results indicated that the probability of fish encountering the whole TidGen® was about 0.498 and the probability of fish encountering the turbine blades was 0.058. It was previously demonstrated that the probability of fish entering a similar turbine was approximately 0.5 when the turbine was rotating [4]. If we combine this probability (calculated from within 3 m of a turbine) with the probability calculated here (using data from 10-200 m from the device), the probability of fish encountering the turbine blades would be less than 0.029.

Cobscook Bay is a productive ecosystem with many pelagic fish species (such as Atlantic herring, alewife, and Atlantic mackerel) and benthic fish species (such as winter flounder, tomcod and hake) [7]. Because the turbine blades are approximately 10 m above the seafloor, pelagic species might have a higher probability of encountering the blades than benthic species. Overall, the risk of collision of fish with an MHK device was low (0.029) in Cobscook Bay. Our surveys were conducted with hydroacoustics, which limited our ability to isolate fish species within such a mixed fish community. However, physical sampling of fish by trawls during these hydroacoustic surveys [7] indicated the species likely detected. In August, the most abundant species captured by trawls were Atlantic herring, winter flounder, silver hake, haddock, and white hake [7]. Additionally, many Atlantic mackerel were caught using hook-and-line sampling during August hydroacoustic surveys. Atlantic herring and Atlantic mackerel were therefore the most likely to be interacting with the tidal energy devices.

Fish interactions with MHK devices have been characterized using other technologies which provided more species-specific information [4, 8], but they also have some limitations. Stereo-video underwater cameras, for example, were used to study MHK effects on fish swimming behavior of different species [8]. However, cameras cannot detect fish at night without artificial lighting, which could alter the natural behavior of fish [9]. Acoustic cameras such as DIDSON, is another method of observing fish during both day and night and can provide estimates of fish size and shape [4], but fish species can be difficult to discriminate. The detection range of a DIDSON unit is limited, and the ranges that may be viewed with video depend on water turbidity. Although our methods cannot separate species, we used the best of hydroacoustics to describe general behavior of fish under the limiting conditions of the available technology.

Although this study only estimated the probability of fish encountering one MHK device, the results allow a path to characterize fish responses to arrays of MHK devices and identified technological limitations that should be considered in future study. Our results characterized some effects of MHK devices on fish, which can aid commercial developers in identifying mitigation options as required by the National Environmental Policy Act.

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