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Hydroacoustic Assessment of Behavioral Responses by Fish Passing Near an Operating Tidal Turbine in the East River, New York

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Abstract
An important environmental issue facing the marine and hydrokinetic energy industry is whether fish that encounter underwater energy devices are likely to be struck and injured by moving components, primarily rotating turbine blades. The automated analysis of nearly 3 weeks of multibeam hydroacoustics data identified about 35,000 tracks of fish passing a tidal turbine in the East River, New York. These tracks included both individual fish and schools during periods with the turbine absent, the turbine present and operating, and the turbine present but not operating. The density of fish in the sampled area when the turbine was absent was roughly twice the density observed when the turbine was in place, particularly when the turbine was operating. This suggests that some avoidance occurred before fish were close enough to the turbine to be observed by the hydroacoustics system.

Various measures of swimming behavior (direction, velocity, and linearity) were calculated for each track and evaluated for indication of behavioral responses to turbine presence and operation. Fish tracks were grouped based on tidal cycle, current velocity, and swimming direction and were evaluated with respect to turbine presence and operation and with respect to distance from the turbine. Nonparametric tests (Kolmogorov–Smirnov test) and multivariate analysis (canonical discriminant analysis) found significant differences among groups with respect to turbine presence and operation, suggesting that some fish responded to the turbine by adjusting swimming behavior, such as making small adjustments to swimming direction and velocity as they passed near the turbine. We found no evidence that fish were being struck by rotating blades, but there did appear to be large-scale avoidance initiated out of the range of the hydroacoustics detection system. More study is needed to determine whether such avoidance behavior has significant ramifications for normal fish movement patterns, bioenergetics, seasonal migrations, and predator exposure.

Recent interest in the development of devices that can efficiently capture energy from flowing water and ocean waves raises many environmental concerns (Čada 2007; DOE 2009; VanZwieten et al. 2014). One of the most important environmental issues facing the marine and hydrokinetic energy industry is whether fish and marine mammals that encounter these devices are likely to be struck and possibly injured by moving components, primarily rotating turbine blades. For hydrokinetic devices (e.g., tidal turbines) that generate energy from flowing water, this concern is greatest for large organisms because their increased length increases the probability that they will be struck as they pass through the blade-swept area (Schweizer et al. 2011; Hammar et al. 2015) and because their increased mass means that the force absorbed if they are struck is greater and potentially more damaging (Amaral et al. 2015). Key to addressing this issue

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is understanding whether aquatic organisms encountering a hydrokinetic device change their swimming behavior in a way that decreases their likelihood of being struck and possibly injured by the device. Whether near-field or far-field behavior results in general avoidance of or attraction to hydrokinetic devices is a significant factor in the possible risk of physical contact with rotating turbine blades (Čada and Bevelhimer 2011).

Although numerous hydrokinetic device designs are under development (Waters and Aaggidis 2016), the ultimate goal for most developers is to deploy multiple devices in a large array positioned in high-velocity (high-energy) zones of rivers or tidal channels. Because this technology is so new and because so few devices have been in the water for extended periods of time, there are few field studies on fish interactions with hydrokinetic turbines. Balloon tag studies performed with fish released into a ducted axial-flow turbine in Hastings, Minnesota, found that survival rates for many species were 99% or greater (NAI 2009). Investigations of both barge-mounted and bottom-deployed horizontal-axis turbines in Cobscook Bay, Maine, using hydroacoustics found that (1) fish seemed to avoid operating a turbine more than a still turbine, (2) avoidance increased during the day and with fish size, and (3) avoidance of an operating turbine was detectable up to 140 m upstream of the turbine (Viehman and Zydlewski 2015; Viehman et al. 2015; Shen et al. 2016). Video evaluations of a vertical-axis turbine off the coast of Mozambique identified near-field avoidance by most fish; for the few fish that passed through the rotors, there was no evidence of blade strike (Hammar et al. 2013). Broadhurst et al. (2014) also used a video system to monitor fish abundance around a test turbine in the Orkney Isles, Scotland, and reported that schools often gathered around the operating device, perhaps for protection or feeding. Analysis of a horizontal-axis turbine in the East River, New York, by using a split-beam hydroacoustics system concluded that fish abundance in the deployment zone varied significantly with seasonal migrations, was greatest during slack tide, was equivalent between day and night periods, and was lower than the abundance in nearshore areas (Verdant Power 2010).

Although prior studies have provided sufficient evidence for developers to obtain permits and licenses for testing and some limited deployment, there is still great uncertainty about the possibility that tidal and large-river turbines might harm fish or modify their behavior in a substantial way. Recent federal licensing requirements (e.g., see projects by Verdant Power in New York and Ocean Renewable Power Company in Maine) have included evaluation of the possible interactions of fish and marine mammals with devices and additional monitoring as pilot arrays are deployed. Until it is demonstrated that these devices provide little risk of injury to aquatic organisms, this concern will likely persist for all device types and aquatic environments. These concerns are officially addressed by regulators under several regulatory statutes. For example, Section 7(a)(2) of the Endangered Species Act requires federal agencies to ensure that their actions are not likely to jeopardize the continued existence of federally listed threatened and endangered species or to result in the destruction or adverse modification of their designated critical habitat. Section 10(j) of the Federal Power Act requires the Federal Energy Regulatory Commission, when issuing a license, to include conditions based on recommendations by federal and state fish and wildlife agencies (submitted pursuant to the Fish and Wildlife Coordination Act) to “adequately and equitably protect, mitigate damages to, and enhance fish and wildlife (including related spawning grounds and habitat)” affected by the project.

In 2012, while testing a new generation of the Kinetic Hydropower System (KHPS) turbine at their Roosevelt Island Tidal Energy (RITE) site, Verdant Power deployed a dual-frequency identification sonar (DIDSON; Sound Metrics Corporation, Bellevue, Washington), also known as an acoustic camera, to collect continuous data on fish interactions with the turbine over a 3-week period in August–September. In this paper, we present a systematic analysis of the behavior and fate of fish as they passed through the acoustic beam relative to turbine presence and operation. The primary objective of this study was to systematically analyze the multibeam hydroacoustics data to quantify near-field fish behaviors, such as changes in water column position, swimming direction, and swimming velocity, in response to encountering an operating full-scale hydrokinetic turbine. Specifically, we wanted to determine whether fish actively avoided the operating turbine and, if not, to evaluate whether there was any indication of actual contact with the rotating blades. We also sought to characterize the relationship between flow dynamics of the tidal system and changes in fish behavior and distribution in the vicinity of the turbine.

**METHODS**

_Study area._—The hydroacoustics data were collected at Verdant Power’s RITE site in the east channel of the East River, New York City, New York. The east channel is approximately 240 m wide and 10 m deep; the west channel has similar cross-sectional dimensions. Maximum velocity during peak ebb and flood tides is roughly 2.0–2.5 m/s. The KHPS turbine (a bottom-mounted horizontal-axis turbine) was positioned about 40 m from the west shore of the east channel (i.e., near Roosevelt Island). The turbine rotor has three fixed blades and rotates at a constant speed of approximately 40 revolutions/min with a tip speed of 10 m/s. The rotor-swept area is 5 m in diameter, which represented about 2% by width of the east channel and about 0.8% of the cross-sectional area. The rotor hub was centered about middepth in an area with a total depth of 10–12 m depending on the tide, meaning that the swept area was between about 3 m above the bottom and 2–4 m below the surface. The blade movement self-starts and stops.
at a river velocity of approximately 1.0 m/s. When the turbine is in the flood tide position, a passive yaw mechanism allows the turbine to self-yaw into the prevailing current flow like a weather vane so that the blades are optimally aligned to generate energy. In the 180° opposite direction (i.e., the ebb tide position), a yaw stop holds the turbine in a stationary position, preventing it from self-seeking a variable flow orientation. For the effort completed in 2012, a modified Generation 5 KHPS turbine was used on an existing in-river monopile from August 29 through September 10.

Data collection.—A remotely aimed DIDSON (RAD) system consisted of a DIDSON transducer, a Remote Ocean Systems PT25 two-axis servo (Remote Ocean Systems, San Diego, California), a Remote Ocean Systems underwater cable, a river-bottom gravity mount, and a custom execution program that integrated the DIDSON aim and data collection. Data were collected continuously for 20 d (August 29–September 18, 2012) through multiple tidal cycles, including periods with and without the turbine in place and periods when the turbine rotor was rotating and when it was stationary. From August 29 through September 3, the RAD was subjected to various tests to ensure proper data collection and operation of the remote-control aiming system. During this period, data were collected, and the turbine was allowed to operate only during flood tides. Turbine operation began during ebb tides as well as flood tides on September 4 and continued through September 7. On September 8, the turbine testing was terminated, but data collection continued; on September 11, turbine removal was completed. The DIDSON continued to collect data aimed at the turbine’s former location through September 18; however, because the DIDSON aim was frequently changed near the end of deployment, we only analyzed data that were collected through September 14.

The DIDSON unit comprised 96 individual transducers lined up side to side (Figure 1a); each transducer sent out an acoustic ping at a frequency of 8 pings/s. The effective sampling range from the DIDSON was 5–15 m from the unit. The turbine was mounted on a base approximately 13 m from the DIDSON. Given the angles of projection of the DIDSON beam (12° vertical and 29° horizontal), the coverage window at the center of the turbine (i.e., 13 m from the DIDSON) was approximately 2.7 high × 6.7 m wide. Thus, the height of the beam only covered about half the 5-m height of the swept area.

The DIDSON data could be viewed as individual snapshots in time (Figure 1b) or in the form of a video. It is possible to analyze the videos manually, but because every ping from each transducer provided information on the location and reflectivity (i.e., signal strength) of any object encountered, the amount of data collected in this study made it impractical to conduct manual analysis. Therefore, we chose to analyze the data in an automated fashion by using commercial software (Echoview version 5; Myriax Software, Hobart, Tasmania, Australia).
An echo that returns to any of the 96 transducers after bouncing off a fish (also referred to as a target) includes information on the location of the target within a particular transducer’s field of view. A single fish is typically picked up by two or more transducers depending on the individual’s size and orientation; through data processing, pings returned to adjacent transducers can be joined together as a single target based on predefined time and distance thresholds for categorization as the same fish. The Echoview analysis assigns the joined target an estimate of target strength and an xyz location within the DIDSON field. Targets identified in successive pings within a predefined distance of each other can be linked to create a track of an individual fish as it passes through the DIDSON sampling area (Figure 1a). Analysis of individual tracks can provide information on direction of travel and swimming velocity.

We hypothesized that active avoidance might be detected in one or more metrics that measure direction and speed of travel, and we structured our automated analysis so that we could compare changes in fish behavior resulting from turbine presence or operation. We analyzed the data to provide (1) comparisons of the metrics among the three modes of turbine operation (turbine absent, turbine present but not rotating [i.e., stationary], and turbine rotating) during periods of the same tidal cycle (i.e., ebb or flood) and (2) comparisons of differences in metrics based on nearness to the turbine within each of the same operation modes individually.

Data coverage.—The data sets were filtered to address normal operating conditions of a tidal turbine, including the signature associated with rotating blades, self-seeking flow orientation in the opposite direction (flood) instead of the firm position at the yaw stop (ebb), and the normal change of turbine orientation four times daily with tidal flow. Not all periods of data collection provided useful data for analysis; some periods included turbine maintenance or removal, and the RAD was aimed away from the turbine during other periods. Of the 20 d of DIDSON deployment, we analyzed 202 h of data distributed across ebb and flood tides and operation modes: 77 h when the turbine was absent, 83 h when the turbine was present but not rotating, and 42 h when the turbine was present and rotating. Although data were collected during periods of extremely low velocity or slack tide, each data point was identified as occurring at either ebb tide or flood tide and was further categorized as occurring at low, medium, or high velocity within either of those tide qualifiers.

Echoview analysis.—The raw DIDSON data files were divided into subsets by RAD aim and turbine position and operation mode. Each subset was processed with a series of filtering techniques to remove noise, interference, and the echo from stationary objects (e.g., the nonrotating turbine); thus, all that remained were echoes of a signal strength greater than the smallest fish of interest. These data were then processed as described earlier to first identify fish targets at each point in time and then to identify fish tracks from individual targets that were joined based on signal strength and distance.

Stationary objects, such as the locked turbine in the ebb position, were relatively easy to filter from the analysis, leaving the rest of the field open for analysis of fish targets. However, the moving rotor was difficult to filter from the DIDSON field, especially when the turbine was in the flood position and not locked in place but was allowed to reposition itself to seek the optimal position for rotor rotation. Therefore, when the turbine was operating, we had to set an exclusion line across the DIDSON field at the point where the turbine was closest to the DIDSON unit. The exclusion zone for the different data subsets ranged from 9.7 to 12.1 m from the DIDSON depending on turbine rotor location, which in turn depended on operation mode and tide direction. Fish movements in the area beyond the exclusion zone were analyzed manually for a subset of the period when the turbine was operating to gain insight into the relative number of targets that were being missed by the exclusion line. We considered options for estimating the number of targets missed at the farthest extent of the DIDSON beam due to exclusion, but we concluded that extrapolation of values based on volume or cross-sectional area sampled and the volume or area sampled closer to the DIDSON would be inappropriate given the obvious decline in numbers of tracks with distance from the DIDSON (see Results).

We used Echoview to generate two types of output file. The first type was a comma-delimited text file (comma-separated value [csv]) of every fish track along with associated information for over 20 descriptive variables. The second type was a csv file of individual targets that included information on each fish each time it was identified, including an estimate of body length based on the distance between the two echoes most distant from each other that comprised the fish. For the best estimate of the body length of a fish in a track, we searched the individual target data set and extracted the maximum length of those individual targets with a ping number that corresponded to the range of pings defined for a fish track.

Echoview validation.—Correct identification of fish targets is primarily based on establishing a signal strength threshold that captures fish of the size of interest while at the same time excluding fish smaller than the size of interest. Because the fish’s orientation, its distance from the transducer, and other factors affect the strength of a returned signal, the range of signal strengths for fish of a given size can be quite variable. In other words, it is nearly impossible for automated analysis to capture every fish of a desired size that passes through the acoustic field. Therefore, we performed a validation exercise to determine the efficiency of our calibrated analysis.

We observed 112 min of DIDSON data in video form from September 1 and 5; without knowledge of the automated processing results, we noted the time, ping numbers, minimum and maximum range (i.e., distance from the DIDSON unit), and length of each fish target that appeared to be roughly over
10 cm. These data were compared with the automated results for the same periods. Of the 181 unique tracks (individual and schools) observed by the two methods, 74% were captured via the automated analysis. Of those targets that were not captured by the automated analysis, nearly all were small in size (based on visual observation) and likely just below the signal strength threshold established for inclusion; a few were larger but were seen only for two consecutive pings. Based on our validation, we believe that the automated method provided an accurate accounting of fish within the size range of interest that passed through the DIDSON beam during the sampling period.

During validation of the Echoview analysis and while performing other visual assessments of the data, we used the measuring tool in Echoview to hand-measure more than 100 individual fish of all sizes. These measurements were made on the clearest image of a track sequence and should have been accurate within 10–20% in most cases. The manual measurements were compared with the estimated maximum size for the same individual generated through analysis of the Echoview output. Unfortunately, we found poor agreement between the two estimates. Therefore, we did not include size as a variable in further analysis of the automated data collection. We did, however, use the signal strength to identify likely large fish for our manual analysis of fish passing near the rotating turbine blades.

*Direct observation of fish–turbine interactions.*—To minimize false detections caused by the moving rotor, for many analyses we established an exclusion depth at the tips of the rotor blades (typically 10–11 m from the DIDSON during ebb tides and 11–12 m from the DIDSON during flood tides) beyond which signals were excluded from automated analysis. Therefore, since we were unable to automatically assess fish that might encounter the rotor directly, we used the output data to identify fish tracks that were most likely to cross the exclusion line and encounter the rotor, and we evaluated those tracks manually. Such occurrences were most likely during ebb tides, when the direction of the flow, which was not perpendicular to the DIDSON beam, was at an angle that would take fish across the exclusion zone if they were within 1 m of the excluded area near the turbine. We filtered the identified fish tracks based on tide (ebb), turbine operation (rotating), fish length (Echoview-estimated lengths >15 cm), and maximum target depth (>9 m). Individually, these criteria were met by 69, 10, 16, and 18% of the tracks, respectively, but only approximately 0.1% of the tracks (36 tracks) met all four criteria. Each of these tracks was evaluated manually to determine whether any culminated in turbine interaction or active avoidance.

During the previously described validation exercise that included 112 min of data, we also noted every fish that passed near the turbine but was not captured by the automated analysis. Additionally, during the processing of other subsets of the data, fish targets that had close encounters with the turbine were noted anecdotally.

*Metrics evaluated.*—Output from the Echoview analysis included location, heading, and velocity of each fish as it passed through the multibeam field. Each track included information about the beginning and ending xyz locations in the beam, time in the beam, and returned signal strength, from which direction of movement, velocity, track linearity, and fish size could be estimated. Fish avoiding the turbine might be expected to change depth, swim faster, swim in a direction away from the turbine, or deviate from a straight course. Dependent variables that were evaluated to assess possible avoidance behavior included swimming velocity, vertical direction, change in range, and tortuosity. Swimming velocity (m/s) was calculated as the total distance covered by a track divided by the duration of the track. Vertical direction (degrees) was the direction of a fish track in the vertical plane (i.e., depth) as it passed through the DIDSON field, with +90° being straight up and −90° being straight down. Change in range (m) described the amount of change in position of a fish track relative to a straight line between the DIDSON and the turbine, ranging from 0 to 10 m within the 5–15-m range of DIDSON data collection. Tortuosity (unitless) was used as a measure of the linearity of a track based on the xyz position at each point in time that made up a track; it was calculated as the sum of the distances between adjacent targets in a track (that is, the total distance traveled) divided by the straight-line distance between the first and last targets in a track (Johnson and Moursund 2000). A tortuosity value of 1 (the smallest value possible) refers to a straight line, whereas the tortuosity value of a crooked line is theoretically boundless.

These behavioral responses were evaluated as functions of six variables: turbine presence or absence; turbine operation; tide; current velocity; relative direction; and distance from the DIDSON. The turbine was present from August 29 to September 10 and was absent from September 11 to September 14. Turbine operation was categorized as either stationary or rotating; when in place, the turbine rotor generally rotated at water velocities in excess of 1 m/s except from August 29 through September 3, when the rotor was allowed to rotate only during flood tides for testing purposes. Tide was classified as ebb or flood. Based on river flow data, a complete tidal cycle in the East River during the period of analysis was calculated at 12.4 h (i.e., 12 h, 24 min): a flood tide leading up to a high tide averaged about 6.4 h in duration, and an ebb tide leading up to a low tide averaged about 6 h. Therefore, the entire record of DIDSON data was characterized in alternating 6-h and 6.4-h periods.

Current velocity was categorized as low, medium, or high. Each fish track observation was associated with one of the three current velocity classes based on the tidal cycle time. The first sixth of a tide (1 h for ebb; 1.0667 h [i.e., 1 h, 4 min] for flood) was classified as low velocity; the second sixth was classified as medium velocity; the third and fourth sixths were designated as high velocity; the fifth sixth was classified as medium velocity; and the last sixth was designated as low...
velocity. Although this did not provide a specific velocity cutoff for each category, it did provide bins of equal duration, which we believe allowed for a better analysis given that velocities varied a little from day to day. On average, this meant that velocities in the low-velocity class were approximately 0.0–1.5 m/s, those in the medium-velocity class were approximately 1.5–2.1 m/s, and those in the high-velocity class were approximately 2.1–2.5 m/s.

Relative direction described whether a fish was swimming with the current or against the current and was determined by comparing the horizontal direction output from Echoview with the direction of the tide for each fish track observation. Based on the distribution of horizontal direction data for two different RAD aims, directions between 145° and 325° were considered to represent travel in the flood direction, and directions between 0° and 145° and those over 325° were considered as travel in the ebb direction. A fish swimming in the ebb direction during a flood tide was considered to be traveling against the current, and so forth. Distance (m) from the DIDSON (or, conversely, distance from the turbine) reflected the collection of data within a range of 5–15 m from the DIDSON unit. The mean distance from the DIDSON for each track as it passed through the field was included in the analysis. For reference, the turbine body was located at about 11.5 m from the DIDSON, and the turbine rotor, when present, was located 10–15 m from the DIDSON.

Statistical analysis.—Frequency distributions for each of the four primary behavioral metrics (swimming velocity, change in vertical direction, change in range relative to the turbine, and tortuosity) were first evaluated separately for differences among the three turbine conditions (i.e., absent, present and rotating, or present but stationary) by tide direction (i.e., ebb or flood) using the nonparametric Kolmogorov–Smirnov (K–S) two-sample test (Sokal and Rohlf 1981). Differences among turbine conditions were evaluated in three pairs (absent versus stationary; absent versus rotating; and stationary versus rotating) at an α value of 0.05 (two-tailed).

We used canonical discriminant analysis (CDA), a multivariate dimension-reduction technique, to evaluate the effect of turbine encounter on fish behavior among six groups of fish tracks defined by tidal direction (i.e., ebb or flood) and turbine condition (i.e., absent, present, rotating, or stationary). To minimize the number of external variables confounding the interpretation of results, this analysis was also limited to the RAD aim that included the highest percentage of tracks (aim 1; 64% of total tracks) and to tracks moving with the flow (84% of the total). We also limited the data to those collected when current velocity was in the medium or high category (i.e., >1.5 m/s) and was sufficient to turn the turbine blades if the turbine was in place and free to rotate.

Input variables included lateral movement in terms of distance from the turbine, change in vertical direction, swimming velocity, and tortuosity. The CDA generates canonical variables from the original quantitative variables to produce the maximum distances among the central tendencies of predefined groups. The greatest difference among groups is captured in the first canonical variable (Can1), with additional but lessening discriminatory ability provided by subsequent canonical variables. The CDA was performed by using the CANDISC procedure in SAS (SAS Institute 2011). Prior to analysis, the data were standardized and centered by subtracting each metric’s mean and then dividing by the SD. Because the DIDSON’s aim was neither perpendicular to the flow nor parallel with the surface, there was bias associated with the direction of flow (i.e., ebb versus flood tide). Therefore, the vertical direction and the change in range were standardized with means for each flow direction and with pooled variances. As part of the CDA, multidimensional Mahalanobis distances were calculated between each pair of group means, with shorter distances implying greater similarity between groups. The CDA output also included sample correlations between canonical variables and original variables, allowing identification of the original variables that were most responsible for group differences.

RESULTS

Counts of Fish Tracks

Our analysis identified 34,705 fish tracks, distributed as 11,641 during ebb tides and 4,049 during flood tides without a turbine in place; 10,490 during ebb tides and 5,076 during flood tides with a nonrotating turbine; and 1,734 during ebb tides and 1,715 during flood tides with a rotating turbine. Subsequent manual review of a subset of the tracks indicated that many actually represented schools of tens to hundreds of small fish instead of individual fish. On a per-hour basis, more tracks were observed when the turbine was not in place than when the turbine was present (Table 1).

Parsing the count of fish tracks by turbine operation mode, tide, and velocity revealed differences associated with each category (Table 2). The number of tracks per hour observed was generally higher during ebb tides than during flood tides and generally increased with increasing current velocity. The count per hour was highest when the turbine was absent; the count per hour was lowest when the turbine was present and rotating.

Spatial Distribution

In addition to consideration of operation mode, tide, and current velocity, the number of fish tracks—specifically the number of tracks per hour—can also be viewed relative to the nearness to the turbine (or distance from the DIDSON unit; Figure 2). In all cases, the greatest number of tracks occurred in the nearshore region—that is, the region farthest from the turbine. For the different categories (e.g., high
velocity with turbine absent), 65–80% of the tracks were in the region of 5–8 m from the DIDSON unit even though this portion of the beam had the smallest cross-sectional area and sampling volume. Regardless of distance from the turbine, the number of tracks observed when the turbine was absent exceeded the number observed in association with the stationary turbine, which in turn was greater than the number observed when the turbine was rotating, as noted earlier.

General Swimming Direction

An evaluation of fish swimming direction relative to current direction revealed that during periods when the river current was at operational velocities (i.e., medium- and high-velocity categories), about 12.5% of the fish tracks were moving in a direction against the current. In comparison, during the third of the time when current speed was below that necessary for turbine operation (i.e., low-velocity category, which included slack tide), about 26.9% of the fish tracks were against the current. Within those two velocity groupings, differences among the three turbine operation modes were small. During medium and high velocities, 13.6% of the tracks were moving against the current when the turbine was absent and 25.4% were moving against the current when the turbine was present (note that the turbine did not rotate during low velocities, so there was no differentiation between rotating and nonrotating modes).

Direct Observation of Fish–Turbine Interactions

The analysis of 36 tracks in which there was a possibility of a close encounter with the turbine based on the fish’s proximity to the turbine and the direction of the flow revealed that fish exhibited three different behaviors: (1) they showed no change in direction (two schools and two individuals), (2) they avoided the turbine by angling away from it (two schools and eight individuals), or (3) they swam at the moving blades and then disappeared from the DIDSON view either just before encountering the turbine or as they encountered the turbine (four schools and two individuals). Some of the tracks were multiple tracks of fish associated with the same school; therefore, the total did not sum to the original 36 tracks. There was no evidence that any fish was struck by the rotor.

During the validation exercise described earlier, we observed 38 schools and 82 individual fish during 112 min of video when the turbine was rotating. Only five (4%) of these had what appeared to be direct encounters with the rotor blade. One individual and one school avoided the rotor by angling away from it; two individuals disappeared

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<th>Date</th>
<th>Turbine absent</th>
<th>Turbine stationary</th>
<th>Turbine rotating</th>
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<td>Sep 11</td>
<td>216.7 (0.5)</td>
<td>80.0 (0.1)</td>
<td>69.8 (5.8)</td>
<td>–</td>
</tr>
<tr>
<td>Sep 12</td>
<td>589.5 (12.0)</td>
<td>173.6 (12.0)</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Sep 13</td>
<td>302.9 (12.0)</td>
<td>145.8 (11.3)</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Sep 14</td>
<td>138.0 (6.0)</td>
<td>53.5 (6.0)</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>
as they encountered the rotor (probably leaving the DIDSON beam by diving or surfacing out of view); and one individual (~20 cm in length) might have contacted the rotor. The fish that possibly came in contact with the rotor originated at the blade tip and swam in a direction that was rarely seen (i.e., directly toward the DIDSON and perpendicular to the flow). However, the swimming direction prior to its appearance could not be determined, and actual contact with the blade was not observed.

Swimming Velocity

For swimming velocity (and each of the other three metrics of interest), we first evaluated the distribution of values by turbine operation mode and tide, and we then evaluated the mean value as a function of distance from the DIDSON unit, which corresponded directly to distance from the turbine or the turbine location in the turbine-absent case. Pairwise comparisons of the frequency distributions found that swimming velocities with the turbine absent differed from those observed when the turbine was stationary during ebb and flood tides (K–S test: $P = 0.030$ and <0.001, respectively) and when the turbine was rotating during an ebb tide ($P < 0.001$) but not when the turbine was rotating during a flood tide ($P = 0.436$). The distributions of swimming velocity for the stationary turbine compared to the rotating turbine differed during both tides ($P < 0.001$ for both). During ebb tides, the swimming velocities of fish in the presence of a rotating turbine was skewed lower than when the turbine was absent or stationary (Figure 3, upper panels). This was also apparent in the plot of means as a function of distance (Figure 3, lower panels). During flood tides, this difference was not apparent until fish were within a few meters of the turbine. During a flood tide, velocities of fish near the turbine were also lower than those observed when the turbine was absent.

Vertical Direction

Pairwise comparisons of the frequency distributions for vertical direction indicated that vertical direction when the turbine was absent differed from that observed when the turbine was stationary during ebb and flood tides and also from that observed with the rotating turbine during both tides (K–S test: $P < 0.001$ for all four comparisons). The distributions of vertical direction for the stationary turbine compared to the rotating turbine differed during ebb tides ($P < 0.001$) but not during flood tides ($P = 0.054$). Because the DIDSON beam was not perpendicular to the

<table>
<thead>
<tr>
<th>Velocity</th>
<th>Turbine absent Ebb</th>
<th>Turbine stationary Ebb</th>
<th>Turbine rotating Ebb</th>
<th>Turbine absent Flood</th>
<th>Turbine stationary Flood</th>
<th>Turbine rotating Flood</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>217</td>
<td>79</td>
<td>78</td>
<td>104</td>
<td>93</td>
<td>83</td>
</tr>
<tr>
<td>Medium</td>
<td>350</td>
<td>166</td>
<td>100</td>
<td>116</td>
<td>100</td>
<td>40</td>
</tr>
<tr>
<td>High</td>
<td>589</td>
<td>223</td>
<td>88</td>
<td>194</td>
<td>98</td>
<td>52</td>
</tr>
<tr>
<td>Mean</td>
<td>382</td>
<td>146</td>
<td>79</td>
<td>138</td>
<td>96</td>
<td>49</td>
</tr>
</tbody>
</table>
flow and because it aimed up at the turbine from the bottom, fish moving with the current during ebb flow appeared to be moving downward more than they actually were. Likewise, during flood flow, vertical direction was biased in the upward direction. For this reason, neither ebb tide nor flood tide distributions were centered on zero, but the relative differences were still accurate (Figure 4, upper panels). (Note that for the CDA, this systemic bias was removed by data standardization prior to the analysis.) During ebb tides, fish that passed a rotating turbine responded with a little more downward movement than when the turbine was absent or stationary. Analysis of vertical direction as a function of nearness to the turbine produced mixed results (Figure 4, lower panels). During flood tides, there was a large increase in downward movement near the stationary turbine and the rotating turbine at the 10–12-m range.

**Change in Range**

Change in range refers to whether a fish moved closer to the turbine (positive values) or farther from it (negative values) during the time when the fish crossed through the DIDSON beam. Because the DIDSON’s position relative to the turbine was not perpendicular to the flow, fish passing through the DIDSON field in the direction of the current could appear to also be moving either toward or away from the RAD depending on the direction of flow. The general direction of flow during ebb tides was angled slightly away from the DIDSON and toward the turbine, and vice versa for flow during the flood tides. For this reason, the modes of the distributions for ebb and flood tides were not centered around zero (Figure 5, upper panels). (Note again that this bias related to flow direction was accounted for in the CDA via value standardization.) Pairwise comparisons of the frequency distributions determined that the change in range when the turbine was absent differed from the distributions for the stationary turbine during ebb and flood tides (K–S test: $P < 0.001$ for both) and for the rotating turbine during ebb tide ($P < 0.001$) but not during flood tide ($P = 0.894$). The distributions of change in range for the stationary turbine compared to the rotating turbine differed during both ebb tides ($P < 0.001$) and flood tides ($P = 0.044$). During ebb tides, fish encountering the rotating turbine seemed to move toward the turbine location (more-positive values) as they passed at a greater frequency than when the turbine was absent or stationary. During flood tides, there was little difference in frequency distributions among the three operation modes. However, as a function of nearness to the turbine, fish that were exposed to the turbine (either stationary or rotating) during flood tides seemed to maintain a heading alongside the turbine or toward it as they got closer to the turbine instead of moving away, as when the turbine was absent (Figure 5,
During ebb tides, this difference among the operating modes was not apparent.

**Tortuosity**

Tortuosity describes the linearity of a fish track, with a perfectly straight line having a value of 1; the larger the tortuosity value, the more crooked the path. Most (>70%) of the tracks were relatively straight, regardless of turbine mode or tide. Pairwise comparisons of the frequency distributions revealed that tortuosity with the turbine absent did not differ from tortuosity with the stationary turbine during ebb and flood tides (K-S test: \( P = 0.999 \) and 0.826, respectively). The distribution of tortuosity when the turbine was absent differed from that observed in association with the rotating turbine during ebb tides (\( P < 0.001 \)) but not during flood tides (\( P = 0.070 \)). The distribution of tortuosity when the turbine was absent differed from that observed in association with the rotating turbine during ebb tides (\( P < 0.001 \)) but not during flood tides (\( P = 0.456 \)). Frequency distribution plots suggested that fish passing a rotating turbine had, on average, straighter tracks (i.e., lowest tortuosity), particularly during ebb tides (Figure 6, upper panels). The turbine-absent and turbine-stationary groups demonstrated a consistent decline in tortuosity as the fish got closer to the turbine location during ebb tides (Figure 6, lower panels). In contrast, tortuosity increased with proximity to a rotating turbine during ebb tides. For the flood tide groups, a similar effect of the rotating turbine was not apparent.

**Multivariate Analysis**

The subset of data used for the CDA consisted of 14,837 fish tracks (43% of the total) and included only tracks that (1) were moving in the direction of the current, (2) were obtained during RAD aim 1, and (3) belonged to the medium- and high-velocity classes. The multivariate ANOVA conducted as part of the CDA determined that the group mean vectors were not equal and that the differences among the centroids were significant (Wilks’ lambda: \( P < 0.0001 \)). The CDA produced a Can1 that explained 19% of the sample variation and was weighted most heavily by the velocity variable (Table 3). The second canonical variable (Can2) explained 6% of the variation and was most influenced by vertical direction and range change. The third canonical variable (Can3) explained 3% of the variation and was most influenced by tortuosity. The loading of each canonical variable explained the spacing of the group centroids as plotted based on the canonical coordinates for each of the six tide × turbine operation groups (Figure 7). For example, Can1 separated the flood–turbine stationary and ebb–turbine rotating groups from the other four groups; Can2 separated the ebb groups from the flood groups; and Can3 separated the flood–turbine rotating and flood–turbine stationary groups from the other four groups and from each other. Other than the separation of the ebb and flood groups by Can2, there was little obvious logical explanation for the group separation provided by the CDA. The most obvious finding from the plots depicted in Figure 7 was the low degree of separation between the two turbine-absent groups. The Mahalanobis distances, which quantified...
FIGURE 5. The upper two panels depict the distribution (normalized to the total tracks for any turbine operating mode × tide combination) of the change in range (m; i.e., distance from the DIDSON unit; toward [+] or away from [−] the turbine) for three turbine operation modes (absent, stationary, and rotating) during ebb and flood tides. Each x-axis value represents the midpoint of a 0.5-m bin. The lower two panels show the mean (±SE) change in range for each fish track as a function of the mean distance from the DIDSON unit. Note that the DIDSON was located at 0 m and the turbine was between 11 and 15 m from the DIDSON unit, depending on turbine orientation and operation.

FIGURE 6. The upper two panels depict the distribution (normalized to the total tracks for each turbine operating mode × tide combination) of the tortuosity of fish tracks for the three turbine operation modes (absent, stationary, and rotating) during ebb and flood tides. Each x-axis value represents the midpoint for a bin of unitless tortuosity values (1.0–1.5, 1.5–2.0, 2.0–2.5, etc.). The lower two panels present the mean (±SE) tortuosity for each fish track during the three turbine operation modes as a function of the mean distance from the DIDSON unit. Note that the DIDSON was located at 0 m and the turbine was between 11 and 15 m from the DIDSON unit, depending on turbine orientation and operation.
the multidimensional distances among the six group centroids, also confirmed that the two turbine-absent groups were the most similar (Table 4). All group centroids were significantly different from each other, with the ebb–turbine rotating group being the most different from the others. The results were generally mixed, however, as there was little similarity within turbine operation types except for the two turbine-absent groups.

DISCUSSION

Summary of DIDSON Results

Our automated data analysis identified 34,708 fish tracks, which included both individual fish and schools. The number of tracks per hour of observation was generally higher during ebb tides than during flood tides and generally increased with increasing current velocity (Table 1). The count of tracks per hour was highest when the turbine was absent and lowest when the turbine was installed and rotating. The increase in rate with current velocity was probably a function of the fact that more water passed by the DIDSON during increased flow, carrying with it more fish, rather than being due to the presence of more fish in the water column during higher velocity. However, the latter is a possibility during some seasons for some migratory species that might be taking advantage of the currents to move in a particular direction. The most likely

<table>
<thead>
<tr>
<th>Variable</th>
<th>Can1</th>
<th>Can2</th>
<th>Can3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity</td>
<td>0.887</td>
<td>-0.358</td>
<td>-0.216</td>
</tr>
<tr>
<td>Vertical direction</td>
<td>0.409</td>
<td>0.891</td>
<td>-0.137</td>
</tr>
<tr>
<td>Range change</td>
<td>-0.307</td>
<td>-0.629</td>
<td>0.293</td>
</tr>
<tr>
<td>Tortuosity</td>
<td>0.297</td>
<td>0.011</td>
<td>0.890</td>
</tr>
<tr>
<td>Canonical correlation</td>
<td>0.192</td>
<td>0.064</td>
<td>0.031</td>
</tr>
<tr>
<td>F-value</td>
<td>31.89</td>
<td>6.37</td>
<td>2.46</td>
</tr>
<tr>
<td>P-value</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>0.0221</td>
</tr>
</tbody>
</table>

TABLE 3. Summary of canonical discriminant analysis results (Can = canonical variable) with four input variables used to evaluate similarities among six groups (two tidal conditions [ebb and flood] × three turbine operation modes [absent, stationary, and rotating]; n = 14,837 tracks).

FIGURE 7. Mean canonical scores of six groups (two tidal conditions [ebb and flood] × three turbine operating modes [absent, stationary, and rotating]) for canonical variable 1 (Can 1) versus Can 2 (upper panel) and for Can 2 versus Can 3 (lower panel). The canonical discriminant analysis was conducted with four input variables describing fish behavior (swimming velocity, vertical direction, change in range, and tortuosity) for 14,837 observations.

TABLE 4. Squared Mahalanobis distances between group means (below diagonal) and corresponding significance probabilities (above diagonal) from canonical discriminant analysis (groups represent combinations of two tidal conditions [ebb and flood] × three turbine operation modes [absent, stationary, and rotating]).

<table>
<thead>
<tr>
<th>Group</th>
<th>Ebb-absent</th>
<th>Ebb-stationary</th>
<th>Ebb-rotating</th>
<th>Flood-absent</th>
<th>Flood-stationary</th>
<th>Flood-rotating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ebb-absent</td>
<td>–</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>0.074</td>
</tr>
<tr>
<td>Ebb-stationary</td>
<td>0.034</td>
<td>–</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Ebb-rotating</td>
<td>0.330</td>
<td>0.424</td>
<td>–</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Flood-absent</td>
<td>0.020</td>
<td>0.039</td>
<td>0.510</td>
<td>–</td>
<td>&lt;0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>Flood-stationary</td>
<td>0.148</td>
<td>0.277</td>
<td>0.135</td>
<td>0.260</td>
<td>–</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Flood-rotating</td>
<td>0.019</td>
<td>0.079</td>
<td>0.294</td>
<td>0.047</td>
<td>0.154</td>
<td>–</td>
</tr>
</tbody>
</table>
explanation for why more fish were observed during ebb tides than flood tides is that the seasonal migration patterns of many species is outward bound or southward during the fall. We could not alternate days of turbine presence and turbine absence, so the increased number of fish seen when the turbine was absent may have been the result of a natural change in abundance in the system; however, the change was by a factor of 3 or 4 and occurred in a single day (from September 11 to September 12), suggesting that it was most likely a response to absence of the turbine after its removal on September 11 (Table 1).

In the near-field within the 10-m window viewed by the DIDSON, the number of fish observed decreased with nearness to the turbine location regardless of whether the turbine was absent, stationary, or rotating (Figure 2). Due to the fan shape of the volume sampled by the DIDSON unit (see Figure 1), a correction by either volume sampled or vertical cross-sectional area sampled would make this difference between nearshore and offshore densities even larger. Given that the offshore decline was similar with and without a turbine in place, turbine avoidance did not seem to be the primary cause of this particular behavior.

From our direct observations of small subsets of the DIDSON videos, we found that individual fish and schools that were headed toward rotating blades usually avoided the blades by adjusting their horizontal swimming direction slightly and angling away. Others disappeared just before encountering the rotor (i.e., within 1 m), which we assume to have happened because the fish changed vertical direction, swimming either above or below the turbine and therefore out of view of the DIDSON beam. The automated analysis did not detect this change in vertical direction, but that analysis was not able to assess movements by fish that approached the swept area directly because of the interference created by the moving blades. A direct contact with the rotor by a large fish (>50 cm) would likely have been apparent if it had occurred, but the DIDSON resolution made it difficult to observe actual contact for fish smaller than 50 cm. We occasionally saw some abrupt changes in direction, but we never confirmed contact with a rotor blade or observed fish swimming directly through the swept area and out the back side.

The best indications of near-field avoidance came from tracking the direction that fish moved as they approached the turbine. The results we presented were specifically designed to compare the tracks of fish (1) in different turbine environments—absent, stationary, and rotating—to evaluate whether turbine presence had an effect; and (2) at different distances from the turbine to determine whether turbine proximity had an effect. Fish tracks passing near the turbine were evaluated for changes in both velocity and direction; direction was assessed laterally and vertically as well as in three-dimensional space via path tortuosity.

Evaluation of the four behavioral metrics individually revealed some differences when the turbine was present versus when it was absent, especially during flood conditions and particularly in near proximity to the turbine (see Figures 3–6). When an apparent effect was observed, turbine presence resulted in reduced swimming velocity, increased downward trajectories, and movement toward the turbine.

One might expect that if fish were responding to the turbine, the case of the stationary turbine would fall somewhere between observations for the turbine-absent and turbine-rotating conditions. However, when there were differences between either turbine group and the corresponding turbine-absent group, it was just as likely to be in response to the stationary turbine as to the rotating turbine. The nonrotating turbine could have a greater effect on the local hydrodynamics, as it produces greater resistance than the rotating turbine. Additionally, because of movement or noise, fish may react at a greater distance to a rotating turbine than to a stationary turbine, which might partly explain the differences in responses to stationary and rotating turbines (e.g., tortuosity; see Figure 6).

The CDA multivariate analysis identified differences among the groups that were significant but not easily explained. The two turbine-absent groups (ebb and flood) were more similar than any other pair, suggesting that the differences among groups did not result from natural conditions but instead were likely in response to the turbine. However, such differences could have been a response to hydrodynamic conditions—created by a combination of tide direction and turbine presence—and not necessarily a response to a perceived threat.

In addition to the intended analysis of near-field effects, the DIDSON data also provided some information about possible far-field avoidance. For example, the density of fish in the DIDSON sample area when the turbine was absent was roughly two times the density observed when the turbine was in place for both turbine-rotating and turbine-stationary cases (see Figure 2). This suggests that some avoidance occurred before fish were close enough to the turbine to be observed by the DIDSON. This response is similar to that reported by Shen et al. (2016), who found evidence for general fish avoidance of a tidal energy device in Cobscook Bay at up to 140 m from the device.

Multibeam acoustics proved to be a useful tool for evaluating the near-field interactions of fish with an operating KHPS turbine. However, because of the DIDSON’s limited range and the size of the turbine, the position and aim of the DIDSON unit were critical for capturing the most useful information. This poses a particular challenge in tidal environments with turbines that change orientation depending on the direction of flow. The movement of the turbine (nacelle and rotor) also presented a challenge in automating data analysis, which was necessary because weeks of continuous data were required to adequately capture fish interactions under all conditions of flow and turbine operation. Future advances in data analysis techniques should make dealing with rotating and oscillating
turbines more feasible. Although multibeam hydroacoustics provide the best opportunity to “visually” assess fish interactions with turbines in low-visibility systems, the limited range of this technique and the postprocessing requirements make the technique less than ideal. For example, the diameter of the KHPS rotor was about twice the vertical range of the DIDSON field, preventing us from capturing the entire swept area. Precise positioning and strategic aiming of the RAD are crucial to capturing fish interactions with the turbine. Given the current range and width of field for the DIDSON unit, it would be better to position two DIDSON units in tandem to fully capture fish that enter and leave the blade-swept zone.

Although some investigators have begun to find success in employing multibeam systems to identify fish by species, doing so was not practical in this study. However, from previous fish sampling of the East River in the vicinity of the RITE site, we know that common species include the Winter Flounder Pseudopleuronectes americanus, Atlantic Tomcod Microgadus tomcod, Striped Bass Morone saxatilis, Grubby Myoxocephalus aeneus, Bay Anchovy Anchoa mitchilli, Atlantic Silverside Menidia menidia, Blueback Herring Alosa aestivalis, Northern Pipefish Syngnathus fuscus, and Atlantic Menhaden Brevoortia tyrannus (Verdant Power 2011). Atlantic Silversides and Northern Pipefish are regular residents of the area, while the other species are seasonally abundant depending on species-specific migratory patterns. Other, less-common species that likely migrate through the area on the way to and from their spawning grounds include the American Eel Anguilla rostrata, Alewife Alosa pseudoharengus, American Shad Alosa sapidissima, Atlantic Sturgeon Acipenser oxyrinchus, Rainbow Smelt Osmerus mordax, and Shortnose Sturgeon Acipenser brevirostrum. As multibeam system hardware and software continue to improve, the capability for species identification is likely to become more accurate.

Multiple investigators have used various models to predict the probability and risk of interactions between aquatic organisms and hydrokinetic turbines based on river and turbine dimensions, river hydraulics, and a series of probabilities of encounter at different scales (Wilson et al. 2007; Schweizer et al. 2011; Romero-Gomez and Richmond 2014). Efforts to include behavioral components that account for avoidance, evasion, and fish swimming ability are less common (Hammar et al. 2015; Shen et al. 2016), and real-world data to parameterize these features of the model are limited.

As part of the federal licensing process for testing and deployment of turbines in the East River, a fish interaction model was developed to address the probabilities that endangered species would interact with a pilot project array of up to 30 bottom-mounted turbines (FERC 2012). Although the model was developed for sturgeon species, it is applicable to other species simply by changing the species-specific input parameter values. Results from the present study, such as the angle of incidence approaching the turbine and the proportion of fish swimming with or against the current, will be incorporated into future revisions of that model.

Conclusions

In conclusion, we found no evidence that fish were regularly struck by turbine blades at the RITE site, and we believe that the likelihood is quite low based on several lines of evidence: the low probability that fish would directly encounter a turbine (Wilson et al. 2007), the apparent long-range avoidance seen in this study and another study (Viehman and Zydlowski 2015), the apparent ability of most fish to avoid rotor blades when they are encountered at close range (Amaral et al. 2010, 2015), and the paucity of evidence for direct blade strikes. However, based on the relative number of fish tracks identified under the different turbine conditions, the results of this study do suggest that avoidance might be occurring at a distance beyond the 10–15-m range of the DIDSON system.

Whether this avoidance has any ecological relevance could not be assessed here, but we can consider the possibilities. Detours of up to 10–20 m to avoid a single turbine are unlikely to produce any significant energetic or feeding disadvantage to resident or migratory fish or any significant delay in migration. However, it is possible that moving offshore, inshore, deeper, or shallower could, for a short time, subject fish to additional predators that they might not otherwise encounter. In addition, multiplying the seemingly insignificant effect of a single turbine by an array 20–50 such turbines could produce significant ecological ramifications. If the affected area expands to include a majority of the river width, the possibility for increased risk of physical interactions with turbines and exposure to predators could become more likely, and access to prey and feeding grounds could become more difficult. Barriers to normal migration routes, even if avoidable, could result in migration delays and additional energetic burden. To evaluate the cumulative effects of turbine arrays, additional studies on a larger scale than the present work will be needed to confirm that tidal turbines representing a variety of designs and configurations do not present a significant hazard to migratory and resident fish.

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REFERENCES


