Who should be afraid of a tidal turbine – the good the bad or the ugly?

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***Abstract*— Advances in tidal power development indicate that many coastal straits and bends with rapid currents will be equipped with in-stream turbines in the future. Considering the variety among turbine designs it is reasonable to assume both large and small rotors will be utilized. Each design implies a different way of interfering with local environment. However, there are very few available reports on fish behaviour in the presence of in-stream turbines. In this paper fish swimming behaviour is investigated in relation to the risk of colliding with different tidal turbine rotors. Based on an existing model and Monte-Carlo simulations with biological data from a field survey the blade-strike probability is calculated for three different and widespread fish taxa (damselfishes, requiem sharks, and barracudas). The results indicate that small turbines carry higher risks, as long as fish are assumed not to detect and actively avoid the rotor. However, the following paper indicates that improvements to the model may alter these results. Furthermore, it is shown that the potential hazard of tidal turbines varies strongly between different fish taxa and individuals. And seemingly it is 'the bad' that has the most reasons to be afraid.**

***Keywords*— Tidal power, fish, environmental impact, blade-strike modelling, ecological risk**

I. INTRODUCTION

A rich diversity of tidal power systems are currently under development [1, 2]. According to projections of a substantial contribution of ocean energy to the world energy supply [3, 4] in-stream tidal turbines will be installed in narrow straits and coastal bends in many parts of the world. Although tidal power is an environmentally benign alternative to non-renewable energy sources from a climate change perspective, it is important to consider its possible local impact to fish and other fauna [5, 6]. Many, if not most, marine ecosystems are under heavy pressure from multiple human activities, most evidently fisheries [7-9]. Given the critical state of many fish stocks and species even minor additive stressors can generate significant ecological effects. Proactive thinking is therefore important when designing and implementing new technologies in the marine environment [10]. Hitherto, very little is known about the collision risk for fish passing tidal turbine rotors. Published reports from field surveys indicate that fish avoid spending time close to some tidal power systems (the relatively solid Open Hydro turbine) when currents increase [11], while fish seem to swim close to other turbines [12, 13], particularly during low light conditions. Despite the scientific value of field data on turbine effects on fish, monitoring studies are still few. To the knowledge of the authors, no data on fish-rotor interactions have been reported from the largest deployed in-stream tidal turbine SeaGen S, although the full-scale turbine has been operational since 2008. Hence, collision risks for fish passing through tidal turbines so far have had to be assessed through basic probabilistic modelling [14-16], indicating that potential risks vary between taxa. Non-validated modelling always carries uncertainties which are additionally escalated by the inherent natural variability of biological parameters. In the necessary step-wise improvement of this collision risk modelling even limited quantities of field data can be valuable.

With the aim of identifying particularly risk-relevant technical and biological parameters, collision risks for three different fish taxa and two different tidal turbines are compared in this paper. Parameter uncertainties are addressed by incorporating probabilistic distributions of fish size and behaviour based on video analysis of fish movements in combination with database acquired data. The three investigated fish are the damselfish, the bullshark, and the barracuda – or 'the good' 'the bad' and 'the ugly'.

II. METHODS

A. Blade-Strike Model

The collision model used (Eq. 1) was slightly modified from Schweizer *et al.* [14], originally adopted from fish collision risk modelling of conventional hydropower systems. The model calculates the probability of collision P (blade-strike) based on the number of turbine blades n, the rotation speed R (rpm), the angle α formed by the water flow and the axial direction of the rotor blade, the fish total length L (m), the angle β formed by the fish body and the rotor, the current speed v_w (m s^{-1}), and the fish swimming speed v_f (m s^{-1}):

$$P = (n \times (R/60) \times cos(\alpha) \times L \times cos(\beta)) / (v_w+v_f) \qquad \text{Eq. 1}$$

Modifications to the model by Schweizer *et al.* [14] include the β angle and the option of allowing v_f to take negative values (fish swimming against the current). These modifications were justified by field survey observations (section *E* below). It should be noted that the collision model assumes that fish are passive with respect to the incoming rotor blade, that is, fish behave naturally without detecting, or responding to, the potential hazard. This assumption is a rather important model setback [14, 16] and will be further discussed.

B. Tested Turbines and Assumptions

The two compared tidal turbines A and B are based on two existing devices: the SeaGen S turbine by Marine Current Turbines and the kinetic hydropower system (KHPS) by Verdant Power, respectively. The SeaGen S turbine is a 1.2 MW system with two large diameter rotors currently deployed in Strangford Lough, Northern Ireland. The KHPS is a smaller 35 kW turbine which has been deployed in the East River, New York. Both systems are among the forerunners of horizontal axis tidal turbines and have been operating for extended periods. The technical parameters used are provided in Table I.

Model sensitivity to the technical parameters and water current speed were analysed by altering the values of each parameter by ±20%. Since α is a fixed (0º) parameter for modern tidal turbines it was not included in the sensitivity analysis.

TABLE I
TECHNICAL ASSUMPTIONS

Assumptions and parameters	**Turbine A**	**Turbine B**
Raw model	SeaGen S	KHPS
Installed capacity per device	1200 kW (two rotors)	35 kW (one rotor)
Rotor diameter	16 m	5 m
Swept area	402 m^2	20 m^2
Technical model parameters		
Number of rotor blades (n)	2	3
Blade attack angle (α)	0º	0º
Rotation speed (R)	14 rpm	40 rpm
Environmental model parameter		
Water current speed (v_w)	2.4 m s^{-1}	2.4 m s^{-1}

C. Fish Parameters

The world's oceans contain more than 15 000 fish species [17], representing a great variety of size, shape, and physical performance. Considering the collision probability for fish passively moving through (not actively avoiding) a tidal turbine rotor the most important characteristics are the individual total length and the swimming speed [14, 16]. Fish length depends both on taxa and life stage (e.g. age, maturity). The swimming speed is related to physical traits and to the behaviour at the time of approaching the rotor. Some species cruise through the water at a fairly high average speed while others tend to hold a position or move slowly in relation to natural water movements [18, 19] but the actual swimming behaviour at the time of approaching a turbine is also bound to differ between individuals. Previous modelling studies have assumed fixed values for these biological parameters [12, 14, 16]. However, in this paper the biological parameters are incorporated as probabilistic distributions based on a field survey and the FishBase database [20], running the model as a Monte-Carlo simulation. In addition to fish lengths and swimming speeds, fish swimming direction (up-current/down-current) and body orientation (β) in relation to the current direction were also incorporated.

Histograms were used to identify suitable parameter distributions based on field and literature data. Normal distributions were assigned where applicable and triangular distributions were used for data not normally distributed but with acquired minimum, maximum, and peak (most common) values. Uniform distributions were used for parameters where only minimum and maximum values could be established. Because swimming speed is more or less related to body length [21] swimming speed was given as body lengths per second (instead of m s^{-1}), thus avoiding correlation associated inaccuracies when randomly combining parameter values in the Monte-Carle simulation.

Model sensitivity to the biological parameters were analysed by rank correlation analysis.

D. Investigated Fish Parameters

Tidal turbines target fast-flowing currents generally found at mid-water depth or closer to the surface [1, 22]. Pelagic and semi-pelagic fish should, therefore, be more exposed to risk than strictly benthic fish. The three tested fish taxa in this study represent three very different 'kinds of fish', all widely distributed and occurring in, although not restricted to, turbulent water at mid-water depth [20].

1) Damselfish – 'the good': Damselfish (*Pomacentridae*) form a large family of small and innocent-looking reef associated species, many of which use the current to efficiently forage on algae and crustaceans that drift by. In this study, damselfishes of the *Abudefduf* genera have been considered. They inhabit areas with rocky bottoms and frequently forage in the water column several meters above bottom, in shoals or smaller groups. Their body shape is ventrally compressed and length rarely exceeds 20 cm. Damselfish are common throughout the tropics and subtropics and their characteristics may represent other fish taxa of similar size and behaviour.

2) Bullshark – 'the bad': Requiem sharks (*Carcharhinidae*) are the most widely distributed shark family including most of the pelagic/oceanic species, and most of the species treacherous to humans. Given that they have a slow reproduction rate and are exposed to high fishing pressure, several requiem shark species are currently endangered. The bullshark (*Carcharhinus leucas*), having a particularly bad reputation for its potential aggressiveness, is a common shark with a wide distribution throughout most tropical and subtropical coastal areas and also ventures deep into fresh water river systems. The bullshark is commonly associated with turbid and turbulent water where it forages on fish and a variety of other animals. It prefers depths from the surface down to 30 m. The body is sturdy with a typical length of 2-3 m but it can reach up to 4 m. The biological parameters assigned for the bullshark in this study represent most of the species in the requiem shark family well.

3) Barracuda – 'the ugly': Barracudas (*Sphyraenidae*) are vicious predatory fish with elongated bodies. A large mouth with a forward projecting lower jaw equipped with large fanglike teeth gives the fish a rather sordid appearance. Barracudas are common throughout tropical and subtropical seas, feeding on large prey (fish and squid) above reefs and in open coastal waters. In this study field data was sampled for barracudas of the *Sphyraena* genus, including species particularly associated with turbid and turbulent water. Barracudas may exceed 1.5 m body length.

E. Field Data Collection

The field survey was carried out in 2012 in a subtropical tidal channel in southern Mozambique (Ponta Torres, Inhaca Island). Stereo-video boards (two cameras simultaneously recording the same object) were deployed for 45-120 minutes on 4 different occasions at sites with up to 18 m depth and current speeds between 0.3 and 1.5 m s^{-1}. Stereo-video technique implies that the 3-dimensional position of recorded objects can be determined with high accuracy [23, 24], allowing for length and speed measurements. The video recordings were analysed using EventMeasure (www.seagis.com.au). Total length, swimming speed and direction, and body orientation were extracted for targeted taxa. For this paper 20 randomly selected individuals of damselfish and barracuda were included (additional data will be extracted for a forthcoming paper on a related scope). FishBase [20] was used for data validation and for assigning values to bullshark parameters as no sharks were recorded.

III. RESULTS

A. Field Survey Results and Assigned Biological Parameters

The field survey generated continuous data distributions on fish body length, body orientation, and swimming speed relative to current direction for damselfish and barracuda. The natural variation was low for damselfish parameters but high for barracudas, therefore normal distributions were not found applicable to the latter and triangular distributions were instead applied. Both fish taxa preferably swam in up-current direction, making ground speed direction dependent on current speed (in strong currents even up-current swimmers moved down-current). Importantly, this tendency to reduce the ground speed implies extended time for passing a potential turbine rotor, and that fish often would move tail first towards a turbine, reducing the field of vision.

Table II-IV present the generated statistics and literature values for these parameters, including the applied probabilistic distributions (generating continuous data for the model input).

TABLE II
DAMSELFISH

Parameter	**Data**	**Distribution**
Length, *L* (m)	Field survey $\mu = 0.16$ $\sigma = 0.01$ min = 0.14 max = 0.19	Normal $\mu = 0.16$ $\sigma = 0.01$
Body orientation, β (degrees, relative to current direction)	Field survey $\mu = 45$ $\sigma = 40$ min = 0 max = 90	Uniform min = 0 max = 90
Swimming speed, v_f (body lengths per second, relative to current direction)	Field survey $\mu = -1.99$ $\sigma = 1.26$ min = -4.49 max = 1.79	Normal $\mu = -1.99$ $\sigma = 1.26$

TABLE III
BULLSHARK

Parameter	**Data**	**Distribution**
Length, *L* (m)	FishBase -using reported sizes for juveniles, common catch, and max records	Triangular min = 0.8 peak = 2.6 max = 4.0
Body orientation, β (degrees, relative to current direction)	Field data -assuming same as barracuda	Triangular min = 0 peak = 6 max = 45
Swimming speed (v_f), in body lengths per second relative to current direction	FishBase -reported cruising speed	Uniform min = -0.75 max = 0.75

TABLE VI
BARRACUDA

Parameter	**Data**	**Distribution**
Length, *L* (m)	Field survey $\mu = 1.26$ $\sigma = 0.22$ min = 0.83 max = 1.57	Triangular min = 0.8 peak = 1.3 max = 1.6
Body orientation, β (degrees, relative to current direction)	Field survey $\mu = 6$ $\sigma = 15$ min = 0 max = 45	Triangular min = 0 peak = 6 max = 45
Swimming speed, v_f (body lengths per second, relative to current direction)	Field survey $\mu = -0.37$ $\sigma = 0.42$ min = -0.91 max = 0.32	Triangular min = -0.9 peak = -0.5 max = 0.3

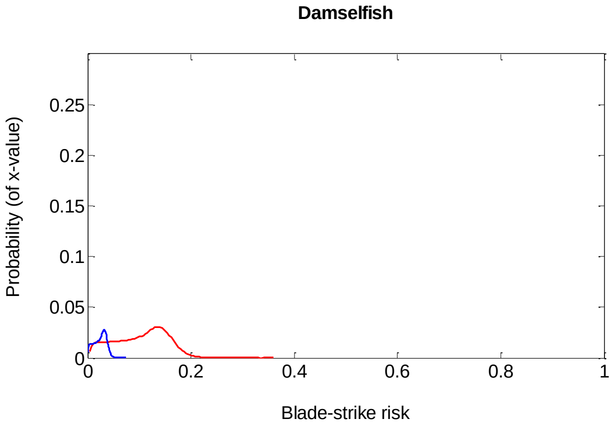

Fig. 1 Probability distributions for collision (blade-strike risk) given damselfish characteristics and passive movement through the rotor of turbine A (blue, peaks to the left) and turbine B (red, peaks to the right).

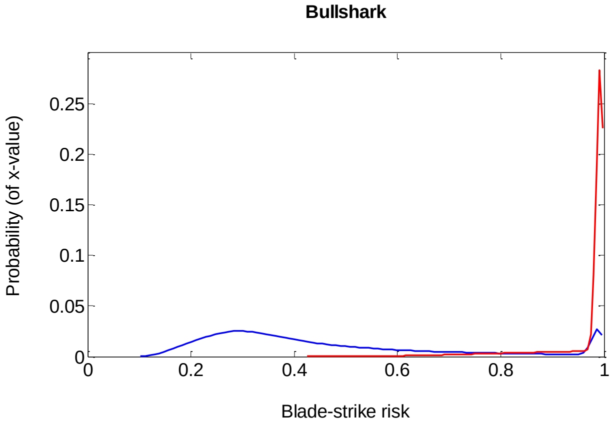

Fig. 2 Probability distributions for collision (blade-strike risk) given bullshark characteristics and passive movement through the rotor of turbine A (blue, peaks to the left) and turbine B (red, peaks to the right).

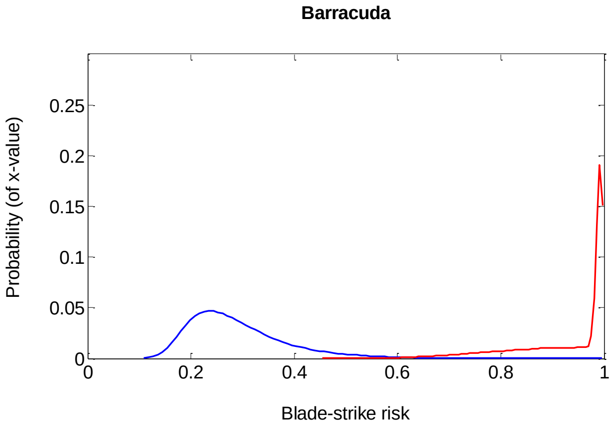

Fig. 3 Probability distributions for collision (blade-strike risk) given barracuda characteristics and passive movement through the rotor of turbine A (blue, peaks to the left) and turbine B (red, peaks to the right).

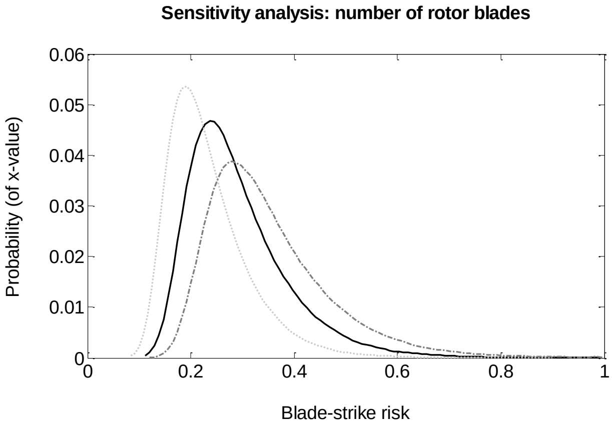

Fig. 4 Sensitivity analyses for number of turbine rotor blades, using barracuda characteristics and turbine A as baseline. Solid lines indicate no change in parameter value; light dotted line indicates -20%; broken line indicates +20%.

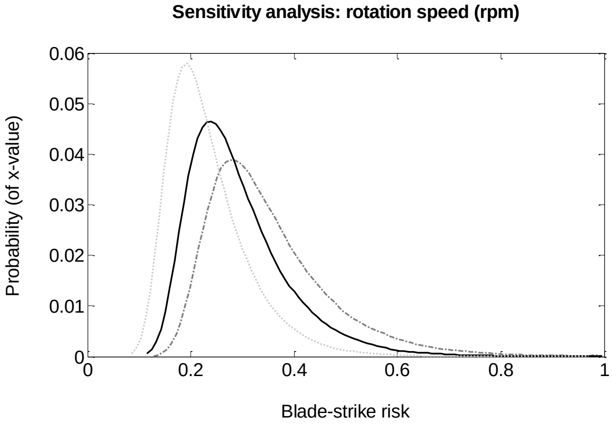

Fig. 5 Sensitivity analyses for rotor rotation speed, using barracuda characteristics and turbine A as baseline. Solid lines indicate no change in parameter value; light dotted line indicates -20%; broken line indicates +20%.

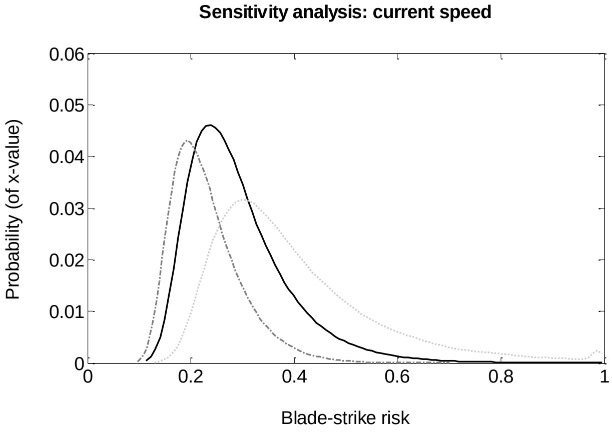

Fig. 6 Sensitivity analyses for current speed, using barracuda characteristics and turbine A as baseline. Solid lines indicate no change in parameter value; light dotted line indicates -20%; broken line indicates +20%.

B. *Model Results*

The resulting probability distributions over blade-strike risk for the three investigated fish and the two tested tidal turbines are given in Fig. 1-3. The probability distributions should be interpreted as the individual blade-strike risk for a specimen with characteristics (parameter values) randomly drawn from taxa-specific natural variation given by the probability distributions (Table II-IV). The results show that bullsharks and barracudas, as characterized by the assigned parameter distributions, are generally exposed to substantially higher risks than damselfish when passively approaching a tidal current turbine rotor. The difference between turbine A and B is large. The probability distribution for bullsharks and barracudas encountering turbine B indicates a collision probability close to 1. Here, the lower tails of the probability distributions (Fig. 2 and 3) can be interpreted as describing risks for small or cross-current oriented individuals moving down-current at high speed. For damselfish, however, the probability distribution (Fig. 1) shows that the blade-strike risk is very low at turbine A and well below 0.2 at turbine B.

C. *Sensitivity Analysis*

Rank correlation analyses, indicating the sensitivity of each biological parameter, showed that length and swimming speed were the (equally) most critical parameters for bullshark and barracuda, while body orientation was the most critical parameter for damselfish.

Among parameters possible to adjust technically the probability of collision increases with increased number of rotor blades (Fig. 4) and rotation speed (Fig. 5) while it decreases with enhanced current speed (Fig. 6). As illustrated, current speed is a somewhat more sensitive parameter than the two technical parameters.

IV. DISCUSSION

The use of Monte-Carlo simulations based on field data distributions complements previous modelling [14-16] and nuances the understanding of risks to organisms moving passively through turbine rotors. But the results of this study should not be interpreted as the actual probabilities of blade-strike risk for the assessed fishes and turbines. Rather, results should be used for orientation among influential technical and biological parameters and as guidance for further research and development.

Regarding the technical parameters it is shown that different turbines imply very different collision risks to approaching animals, where the turbine with more rotor blades and higher rotation speed is a greater hazard for organisms passively moving through the turbine rotor. When considering the swept area (increasing the probability of fish encountering the rotor) and the installed capacity of the two tested turbines, the smaller turbine (B) still imposes a higher (~60%) risk per installed kW.

However, the model assumes that fish do not notice or react to the rotor. Possibly, such a scenario would be realistic for some species during low-light conditions (e.g. turbid water during the night). However, most fish have well developed visual senses, particularly nocturnal species and species active in deep water. During the day and most conditions at night fish are likely to detect the turbine and attempt to escape the rotor, as has been observed at field surveys around deployed turbines [12, 13, 25]. When accounting for light conditions and organism sensing capabilities the results may be altered so that a smaller turbine (e.g. turbine B) with a shorter diameter imposes a lower probability of collision because fish are more likely to manage to avoid the rotor. Having detected the rotor, a fish is likely to alter its swimming behaviour and accelerate into burst speed. While startle acceleration and swimming speed per body length is often faster for small fish, large fish have a higher actual burst speed [26]. The required distance to swim, *i.e.* the rotor diameter and the detection distance, will consequently influence whether small or large fish will be exposed to the highest blade-strike risk. The existing model thus has to be extended.

Nevertheless, the basic results of the study, that indicate that very large fish, such as sharks, will collide with tidal turbines unless they manage to completely avoid encountering the rotor, is important. Bullsharks for instance inhabit murky waters and are active at night using hearing and electric sensor organs more than vision. As sharks are attracted rather than repelled by noise and vibrations it is not unlikely that the shark under these conditions would be very close to the rotor before differentiating it from prey. Perhaps there is a good reason for ‘the bad’ to be afraid of tidal current turbines.

A. *Limitations*

Apart from the limited model assumptions on passively swimming fish (as discussed above) this study carries limitations associated with the probabilistic distributions of biological parameters. The field survey was conducted at a specific site and covered few specimens. Extrapolations to other populations of the investigated fish taxa, and to other species, must thus be considered with care. However, assigning probabilities is an effective way of reducing the sensitivity to slight data errors. The data was collected at current speeds lower than at ordinary tidal power sites (fish behaviour at actual turbine sites may differ) and for bullshark the probabilistic distributions were based on database values. Lastly, it should be noted that the density of fish – although not considered in this study – is likely to be low where currents are particularly strong [11].

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