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Marine Renewable Energy MRE2

Annual Report

Individual Consequences of Tidal Turbine Impacts

Sea Mammal Research Unit
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V5

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Executive Summary

In the absence of any field data, collision risk models currently assume that all collisions between marine mammals and tidal turbines will be fatal. This precautionary assumption is not likely to be true and could lead to over-estimation of mortality rates. This has the potential to be a serious constraint on the development of the tidal energy industry.

This issue was initially addressed in MMSS/001/11 - MR 7.2.3 through a series of collision trials using grey seal carcasses and a simulated turbine blade fixed to the keel of a jet drive boat. The model turbine blade ran along the curved keel of the boat. This curved deployment angle was likely to have reduced the energy transferred from the boat to the carcass when compared with a collision with a perpendicular blade, so the results of these initial trials were treated with caution. Refinements were made to the experimental set-up for the second set of trials, outlined in this report. Three lengths of aluminium box-section were welded to the keel of the boat to act as bolt-points for rigid support beams. These support beams were bolted to the turbine blade model to secure its deployment angle. The resulting deployment angle was close to perpendicular to the surface water at the point of impact, as confirmed by photographs.

Five juvenile grey seal carcasses were subjected to collision trials at a range of speeds between 9.26 $m.s^{-1}$ and 10.29 $m.s^{-1}$. Four carcasses were struck twice and the final carcass was struck three times, each time at a different location. Pre and post-trial x-rays as well as post-trial computerised tomography scans and post-mortems were carried out to establish trauma associated with the collisions. No skull damage was observed in the trials but all cases showed varying degrees of spinal fracture and three out of five cases showed signs of damage to the rib-cage. Massive diaphragmatic rupture was found in all cases. Other injuries noted were herniation and maceration of the liver, and lung congestion. However, soft-tissue damage was not considered a reliable indicator of collision consequences given the reduced integrity of the organs as a result of the freeze-thaw process. All of these pathological features were considered to have been likely to be lethal to a seal.

These results indicate that collisions with the tip of a tidal turbine blade travelling at >10.29 $m.s^{-1}$ would be lethal to a juvenile grey seal. When compared to the results from MMSS/001/11 - MR 7.2.3 it would appear a threshold exists (above 5.32 $m.s^{-1}$ and below 10.29 $m.s^{-1}$) below which a significant proportion of turbine blade collisions would not produce lethal, skeletal damage. Further trials, using the same experimental set-up and a combination of previously frozen and un-frozen seals is planned to a) establish a mortality threshold, and b) assess soft-tissue damage.

Contents

1 Introduction

The potential for renewable energy installations to directly and indirectly affect marine mammal populations has been studied from many different perspectives (Wilson *et al*,. 2007; Merchant *et al.*, 2014; Russell *et al.*, 2014). Short and long term effects of distribution changes and population trajectories directly related to offshore devices can be monitored through acoustic and visual observations, as well as telemetry based studies. However, to understand the results of physical impact between marine mammals and turbine blades, the likelihood of interactions (taking movement overlap and probability of avoidance into consideration, akin to a simple predator-prey model) must be coupled with some measure of the severity of these interactions on individuals (Thompson *et al.*, 2015). This can only be achieved by combining observational and experimental data.

Tidal turbines pose a potential risk to marine mammals. The speed of movement of these devices is controlled by the ambient flow of the system. However, existing turbine systems are designed so that the rotational tip-speed is held at around 4.5 times the speed of the current and limited by manufacturers to an approximate maximum of 12 $m.s^{-1}$.

Information on the ability of marine mammals to evade turbine blades is not yet available. Results of telemetry studies with harbour seals in and around the MCT SeaGen device in Strangford Narrows suggest that there may be a small but significant avoidance effect (Royal Haskoning, 2011). However, because of the mitigation requirement to stop the turbine whenever marine mammals approached the device there was no avoidance information and little understanding of how distribution and movement patterns might change as a result of the operation of this installation (Hastie, 2013). Collision risk modelling has therefore been adopted as the primary means of assessing the potential for impact. An implicit assumption that any contact is effectively fatal means that the models produce high take estimates. This can be moderated by applying avoidance factors, but the lack of relevant data means that these have to be based on data from other taxa, primarily birds evading wind turbines (Wilson *et al.,* 2007). The lack of relevant data on avoidance and the assumption of fatality in all collisions results in these models being highly conservative and highly sensitive to avoidance assumptions. There is a clear requirement for data gaps to be filled to better inform the environmental impact assessments of renewable energy devices.

A collision in these models is defined as any interaction which may result in physical damage to the organism. However, these species-specific models are largely based on spatial usage patterns and abundance data and assume mortality in the event of a collision. If the worst-case scenarios are determined to be non-fatal (i.e. at a tip-speed of $12m.s^{-1}$ an impact does not immediately kill, remove the ability to successfully forage and reproduce or render the animal unconscious), direct collisions between renewable energy devices and marine mammals are of little concern. This seems unlikely; such high speed collisions are likely to be damaging. However, lower speeds may not be, and excluding such low speed collisions from the estimated mortality may produce lower and more realistic assessments of impact. Previous investigations into the severity of interactions between seals and tidal turbines suggested that impact speeds below 5.6 $m.s^{-1}$ would not result in skeletal damage (Thompson *et al.*, 2015). Although these results were based on a speed correction factor which adjusted the blade speed to account for the curved keel impact angle, it does appear that there is a lower boundary to the range of collision speeds that would result in fatal injuries. Further investigation is required to determine this range to ensure uncertainty is minimised when modelling the potential removal from a population as a result of turbine interactions.

The absence of any information on the effects of collisions was identified as a clear and important data gap. It is not ethical to subject live seals to such impacts so the physical damage incurred by grey seal carcasses at various impact speeds was tested. An initial experimental set-up is described below that, with appropriate modifications, could be applied to different species to inform the damage aspect for future collision risk models.

The overall aims of this section of the project are:

- To describe the physical effects of collisions between tidal turbine blades and seals.
- To estimate the likely mortality rate from such collisions.
- To refine the experimental set-up to produce reliable estimates of trial impact speeds

2 Methods

2.1 Refinements to the simulated turbine blade

To assess the physical damage inflicted upon a seal when struck by a turbine blade a series of collision impact tests was carried out on seal carcasses using a simulated turbine blade attached to the keel of a jet drive boat, driven into the carcasses at known speeds.

The turbine blade was moulded using polyethylene to simulate the leading edge blade profile of the tip of a hypothetical/typical tidal turbine blade. This was bonded to a 6 mm thick, 850 mm long aluminium U-section. The U-section had two 6 mm aluminium U-sections of length 760 mm and 350 mm bolted to it at the base and at the mid-point respectively. These U-sections were bolted to two shorter U-sections which were welded to the keel of a jet-drive boat. The gap in the U-sections were lined with aluminium plates to ensure the supports were flush before bolting. The top of the blade was bolted directly to a final U-section which was also welded to the keel. The different lengths of the supports allowed the blade to remain perpendicular to the water when attached to the keel. Figure 1 shows the profile of the blade and its supports.

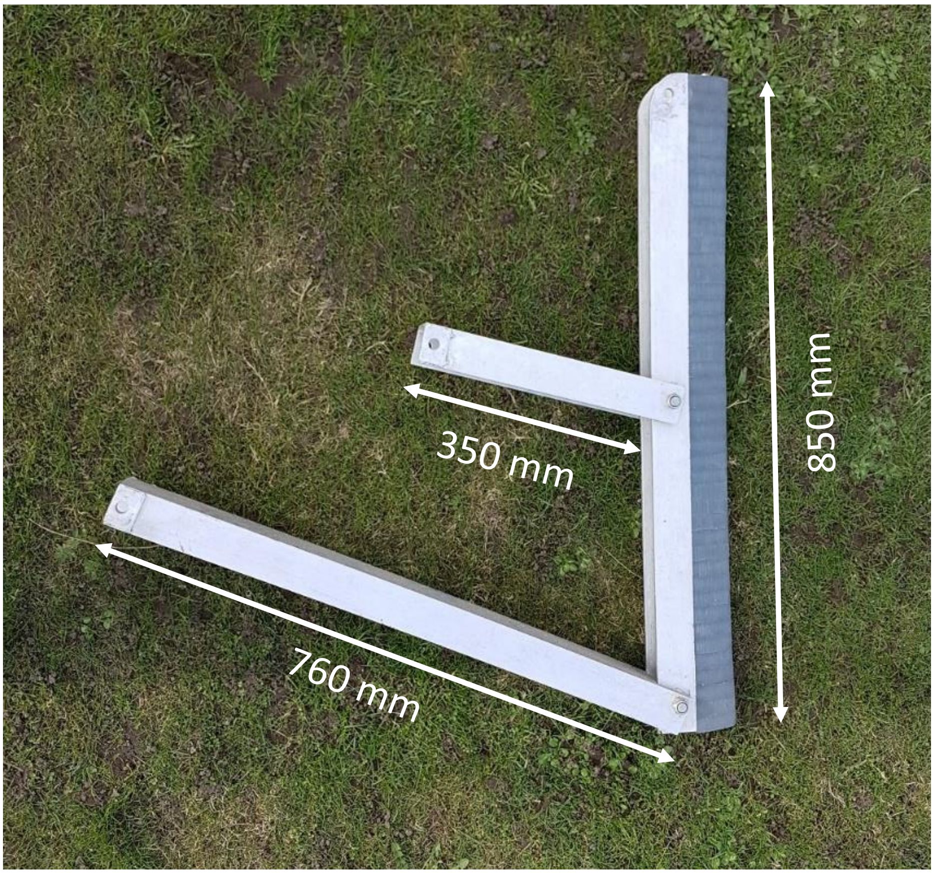

Figure 1. Profile of the turbine blade and its supports which were bolted to the keel of a jet-drive boat. The aluminium U-sections are 6 mm thick.

The blade tip was used for the model as it has the “sharpest” leading edge profile and the smallest frontal surface area, it therefore represents the most potentially dangerous part of the blade due to the narrower and therefore smaller area impact zone. For example, a typical 9 m turbine blade displays a 2 m chord at its widest point, 3 m from the blade root at a twist angle of 10.8° compared to a 0.75 m chord at a twist angle of 4° at the tip (Figure 2). Furthermore, the tip speed of a rotating object represents the fastest moving part and therefore will always represent the most potentially damaging area for a collision to occur.

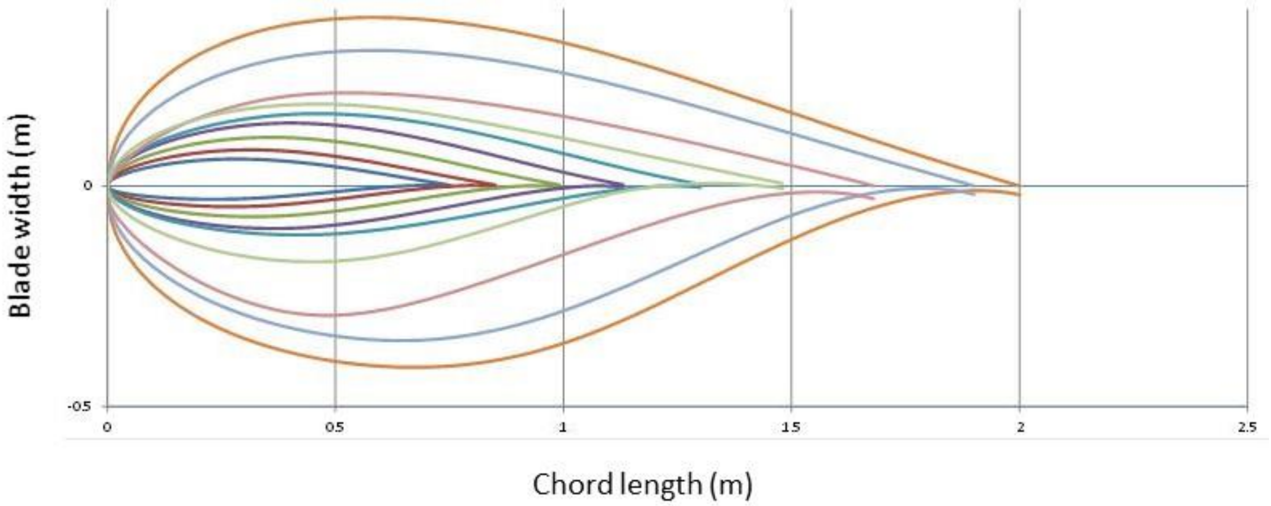

Figure 2. *S*cale drawings of the profiles of a typical tidal turbine blade at different distances from the centre. Widest profile is at 3m from the centre and profile becomes progressively narrower towards the tip. In reality, the profiles are progressively twisted but this has been removed to make it easier to compare profiles.

2.2 Study subjects and collision set-up

The carcasses of five grey seal juveniles were subjected to collisions. All carcasses were stored frozen at -20ºC and defrosted over 4-5 days at ambient temperature. Four of the seals had been by-caught in trawl nets and one was stranded dead. All the juvenile seals were radiographed prior to the trial to rule out the presence of any pre-existing fractures.

Seal carcasses were suspended semi-submerged just below the surface, using of buoys to secure them in place and prevent them from sinking (Figure 3). The carcasses were enclosed in a coarse, mesh, nylon net which was held at each end by anchored buoys. The net ensured the carcasses did not rotate prior to impact. Sash weights suspended from the anchor lines pulled the buoys apart and maintained the horizontal line under tension. The attachments were flexible, so the carcass was able to move in response to the collisions, but the tension in the horizontal line and the nylon net provided some resistance to horizontal rotation (pivoting) and to horizontal displacement. Increased drag at the apex of the carcass was also an assumed factor when the net was under tension; friction acting on the carcass when the net stretched may cause an unrealistic pull away from the animal’s centre of mass at both ends when the boat slowed down after impact.

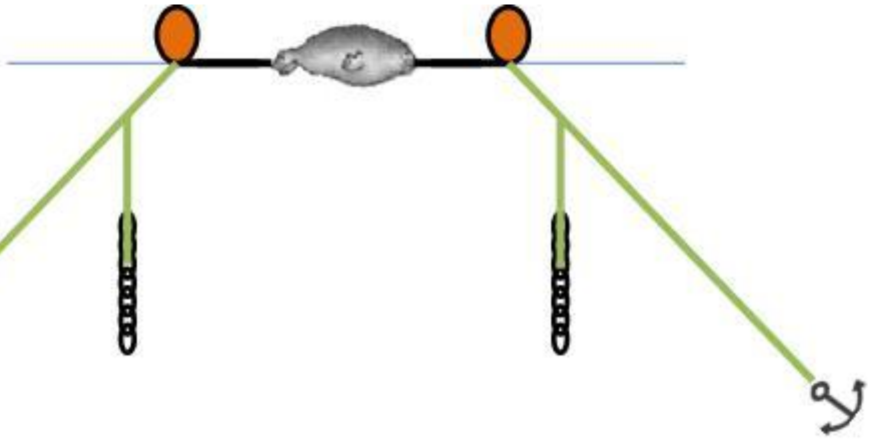

Figure 3. Diagram of the experimental set-up. Two buoys, weighted with chain and fixed in position at the surface with support anchors are connected by a 3 m length of rope. The carcass under test is attached to this rope with further flotation buoys attached if the carcass displayed negative buoyancy.

Collisions were inflicted to the torso of all the carcasses. A collision with the pelvis was undertaken for two of the cases and a collision with the skull was undertaken for a further two cases. Trials were carried out in St Andrews Bay, Fife: a sheltered bay off the coast of east Scotland. The trials were conducted on a day with light winds and at slack tide to minimise the effects of sea-state on the accuracy of the collisions and the drift of the carcasses.

The location of the point of collision was assessed by a vertically mounted video camera (30 frames per second) attached to the bow along the centre line. A frame grab from the video is shown in Figure 4 immediately before impact with the seal carcass. This allowed an accurate identification of the impact point in each collision. In practice, it was relatively straightforward to hit the carcasses at pre-determined spots. An additional underwater video camera attached to one of the anchored buoys was oriented to face along the carcass to observe the point of impact and movement of the carcass. Only the point of impact was consistently observable as turbulence in the water caused by the wake of the boat significantly reduced visibility immediately after impact in many trials.

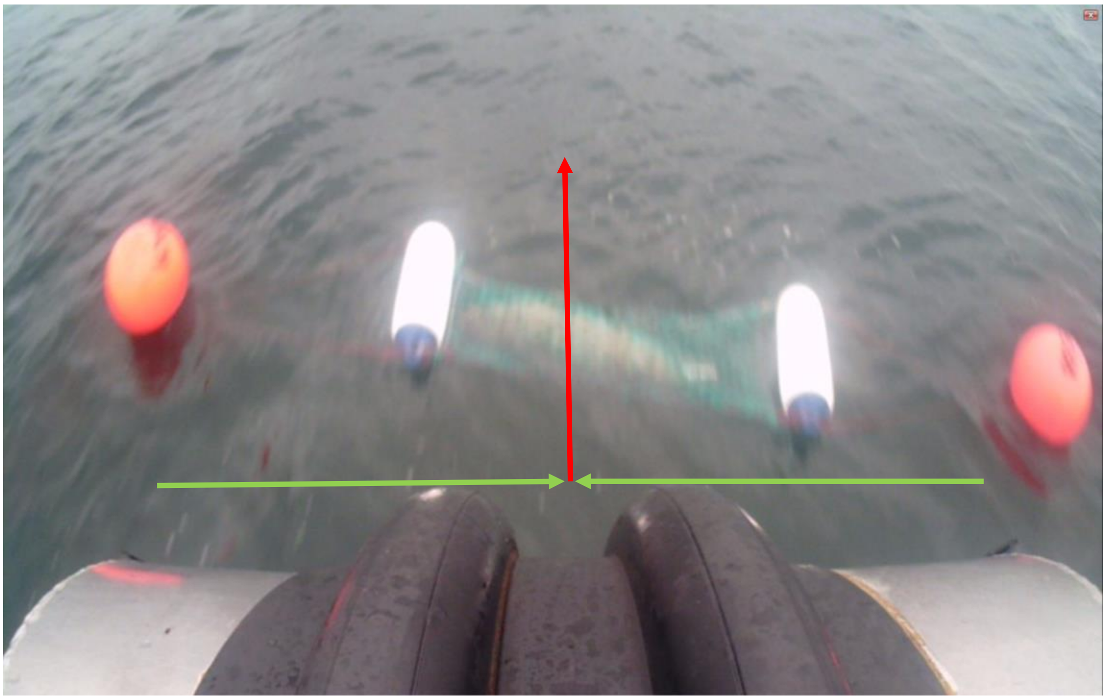

Figure 4. View from bow mounted camera indicating direction of movement and line of impact during an abdomen impact trial. The green arrows indicate the centre point of the boat given the position of the nose piece and the red arrow indicates direction of movement. The point at which the green arrows converge indicates the point of impact on the animal.

The development of the new blade mounting design allowed a perpendicular deployment angle so no additional corrections in the observed collision speeds were necessary. The speed of the collisions was taken as the GPS derived speed of the boat at the moment of impact. Figure 5 shows the deployment angle of the blade while the boat was in motion. Table 1 details the locations and speeds of each trial.

Figure 5. A collision trial immediately prior to impact. Note the orientation of the blade on the keel of the boat as being almost exactly perpendicular to the water line.

Table 1. Trial speeds and strike locations for each carcass.

Seal ID	Seal Trial #	Collision Speed	Collision location
HJ05	1	18 Kn (9.26 m.s^{-1})	Lower Jaw
	2	18 Kn (9.26 m.s^{-1})	Thoracic Spine
HJ08	1	19.8 Kn (10.19 m.s^{-1})	Cranium
	2	19.7 Kn (10.13 m.s^{-1})	Ventral Thorax
JG10	1	19.6 Kn (10.08 m.s^{-1})	Thoracic Spine
	2	19.5 Kn (10.03 m.s^{-1})	Dorsal pelvic region
HJ07	1	19.5 Kn (10.03 m.s^{-1})	Upper Ventral Thorax
	2	20.1 Kn (10.34 m.s^{-1})	Cervical spine
	3	20 Kn (10.29 m.s^{-1})	Cranium
HJ09	1	19.8 (10.19 m.s^{-1})	Thoracic Spine
	2	19.4 Kn (9.98 m.s^{-1})	Dorsal Pelvic Region

After the trials in Table 1 were completed, the carcasses were transported to the Computerised Tomography (CT) scanning unit at Scottish Rural and Agricultural College, Edinburgh. Each seal was radiographically assessed and a series of CT scans were taken for every 5 mm cross-section of the carcass. Each carcass was then necropsied by a veterinary pathologist with extensive experience of marine mammal necropsies. The radiographic images, CT scans and the necropsy analysis were used to assess skeletal damage only, because the freeze-thaw process is known to produce pseudo-bruising and renal haemorrhaging in pinnipeds (Roe *et al*., 2012). As a consequence, any observed internal damage to the muscle tissue or organs could not be confidently attributed to the collision trial impacts. It was not possible to perform any internal examination before the trials as the structural integrity of the skin and blubber layer could not be ensured if incisions had been made; in such cases carcasses could have displayed signs of trauma that otherwise would not have been present if the skin and blubber layer was left intact.

3 Results

3.1 Pre-collision examinations.

Pre-collision radiographs of the entire axial skeleton were taken using standard dorso-ventral or cranial oblique views. Special attention was paid to cranial, abdominal and pelvic regions due to the sensitivity of these areas to serious injury; these areas are most likely to cause death if significantly damaged and were also the areas targeted during the trials. No skeletal irregularities or signs of pre-existing injuries were identified on the carcasses pre-collision.

3.2 Post-trial radiography, CT scans and necropsies

Post-trial radiography and CT scans revealed the extent of skeletal damage as a result of the collision trials. The skull and pelvis remained intact in all cases, however, spinal injury was apparent to various degrees in all cases. Fractures resulting from blunt force trauma as well as complete spinal displacement was observed. Vertebral separation was observed along three axes and fractured ribs were most commonly observed close to the spinal join (Figure 6).

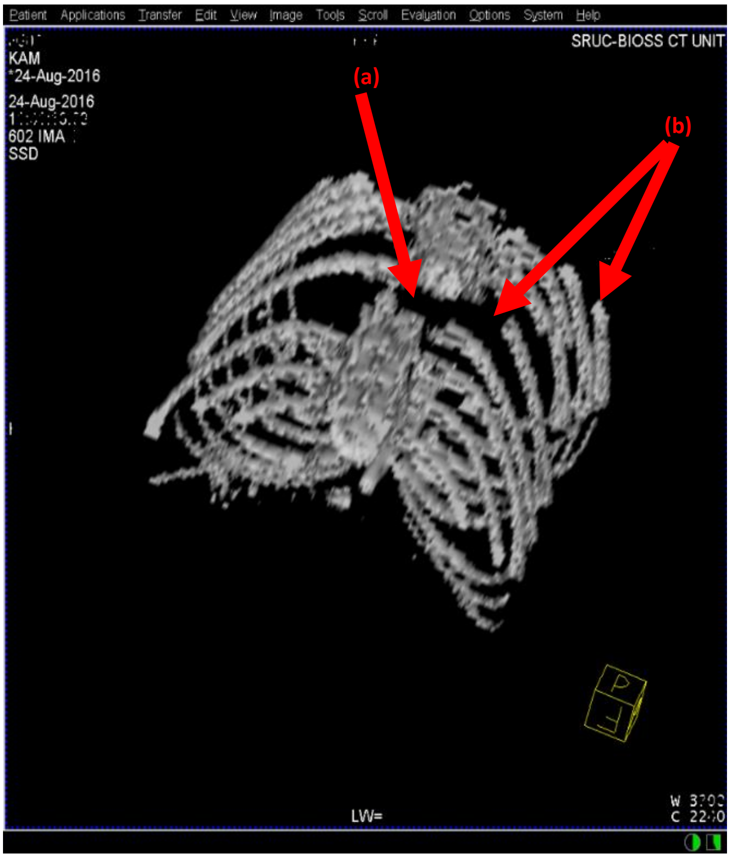

Figure 6. Post-trial, 3-dimensional radiographic image of seal JG10. (a) Spinal displacement along the dorso-ventral and anterior-posterior axes; (b) fracture and separation of ribs at the mid-point and near the spinal joint.

Necropsy analysis provided confirmation of the skeletal damage observed in the radiography and CT scans as well as an assessment of soft-tissue damage. It must again be noted that the soft-tissue damage observed in this experiment cannot be considered reliable due to the reduced integrity of the organs and musculature during the freeze-thaw process. Diaphragmatic rupture was observed in four of the five cases. Interestingly, seal JG10 did not show diaphragmatic rupture regardless of a strike to the thoracic spine, however, this was the only individual which showed significant lung congestion. Maceration and herniation of the liver was also noted in three cases. A summary of the injuries noted for each carcass is given in Table 2.

Table 2. Summary of pathological features. A red cell indicates the presence of the associated injury.

Seal ID	**Injury**						
	Diaphragmatic Rupture	**Spinal Fracture(s)**	**Spinal Displacement**	**Fractured Rib(s)**	**Ruptured Liver**	**Herniated Liver**	**Congested Lung**
HJ05	🟥	🟥		🟥	🟥		
HJ07	🟥	🟥			🟥	🟥	
HJ08	🟥	🟥		🟥		🟥	
HJ09	🟥	🟥		🟥	🟥	🟥	
JG10		🟥	🟥				🟥

4 Discussion

The results of the trials suggest that fast speed collisions with the tips of tidal turbines are likely to produce fatal injuries in juvenile grey seals. This does not assess the effects of other interactions, such as blunt cranial trauma leading to unconsciousness, which would also be likely fatal, however, it is likely that these injuries would occur at the speeds trialled and at lower speeds, given the severity of the skeletal trauma observed. Although death due to blows to the skull does occur without the presence of a skull fracture in humans, this is unusual and a skull fracture can be regarded as an indirect indicator of severity of the resulting trauma (Chattopadhyay & Tripathi, 2010; Sulaiman *et al*., 2014) so further investigation into cranial collisions is necessary. No skull damage was observed in the trials. However, even a minor head injury leading to concussion or severe short-term disorientation could be potentially lethal to a submerged seal which needs to be able to return to the surface to breathe. The soft-tissue damage observed highlights the need to further examine the types of injuries caused. The extent of damage to the liver and diaphragm in all cases suggests that, at these speeds, they would be vulnerable to some degree of soft-tissue injury, the severity if which remains unknown.

When compared with the trials from MMSS/001/11 - MR 7.2.3 these results suggest that a threshold exists between 5.6 $m.s^{-1}$ and 10.34 $m.s^{-1}$ below which fatal injury would be unlikely. A correct interpretation of the effects of collisions with blades will require collisions with fresh seal carcasses. These will be carried out in the near future. However, the results presented do provide critical information required to assess the likely injuries from collisions with turbine blades.

The impact speed will be a function of both the rotation rate of the turbine and the distance of the impact point from the centre of rotation. The rotation rate of the blade through the water will be a nonlinear function of the current speed; being stationary below some device specific stall speed and reaching a maximum at some intermediate current speed set by the specific design of the turbine and the local flow conditions. In addition, the speed of any particular point on a blade will be linearly related to the distance from the centre of rotation, being close to zero near the centre even at high rotation rates.

In the absence of other information, available collision risk models assume that marine mammals will not react to the presence of a turbine. Therefore, it is assumed that the impact point will be at some random point on the blade. The probability that a collision occurs on any particular section of blade will be equal to the proportion of the total area that is swept by that section and will be a related to the distances from the centre (e.g. the outer 10% of the blade sweeps 19% of the total area, while the inner 10% sweeps only 1%).

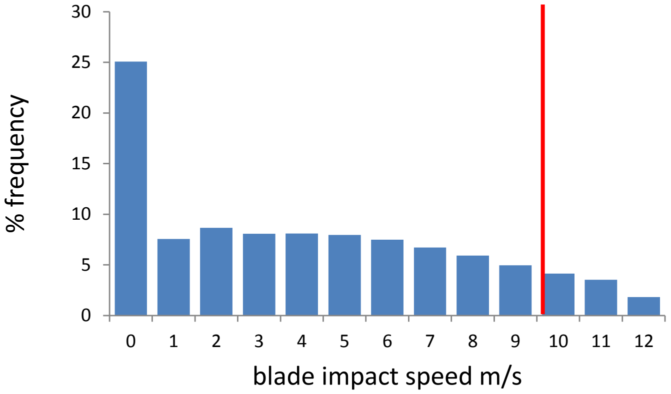

Figure 7. Frequency distribution of estimated blade speeds during collisions with randomly moving seals (Data provided by EWTEC). The red line indicates the minimum collision speed in these trials. All collisions above this value produced fatal injuries.

To illustrate the combined effects of the temporal patterns of flow and the position on the blade a frequency histogram of expected collision speeds was generated (Figure 7). The POLPRED package was used to generate estimates of the current speeds at 10-minute intervals over the period from the 4th of March to the 1st of April, 2014, for a site in the Sound of Islay. These current data were used to generate estimates of the blade speed, assuming that the turbine stalls at a current speed of 0.8 $m.s^{-1}$ and reaches a maximum tip speed of 12 $m.s^{-1}$ for current speeds of 2.5 $m.s^{-1}$ and higher. This is broadly similar to the pattern for the SeaGen device in Strangford. Figure 7 shows the frequency histogram of estimated blade speeds for collisions with seals swimming randomly with respect to the turbine position. It is apparent that most collisions would be with relatively slowly moving blades. Under these assumptions, the blade speed in the majority (>90 %) of collisions would be less than 10 $m.s^{-1}$.

These results suggest that the majority or perhaps all collisions at high blade speeds would be fatal. The severity of the skeletal damage in each of the collision trials with blade speeds >10$m.s^{-1}$ indicates that collisions at substantially lower speeds may cause serious and potentially fatal injuries. Further research, involving a series of collision trials at lower collision speeds, will be required to identify threshold speeds below which collisions with turbine blades can be regarded as safe.

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