Noise Modelling of Tidal Turbine Arrays for Environmental Impact Assessment

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***Abstract* — A modelling methodology for assessing the noise impact of a tidal turbine array on marine animals is presented. The main noise sources, modelled semi-empirically, are inflow turbulence noise and mechanical noise. Underwater acoustic propagation is handled by the *AcTUP* software suite, utilising the *fast-field* method. The noise impact is then assessed based on a recommended 'dosage' criteria.**

A case study is presented based on the 'Sound of Islay' tidal energy project, concerned specifically with the low-frequency noise impact on fish (cod). This reveals that permanent threshold shift is not expected, whilst temporary hearing loss effects are possible if fish spend extensive periods close to the device (within 2 rotor diameters). Behavioural and masking effects might be expected, although these are hard to quantify from the literature. Improved noise source modelling is identified as a development required for the methodology.

***Keywords* — Tidal Turbines; Underwater Acoustics; Tidal arrays; Environmental Impact Assessment; Shallow-Water Acoustics**

I. Introduction

Interest in tidal energy extraction has increased in recent years since it provides a reliable and predictable source of renewable energy which can contribute towards reducing carbon emissions and reliance on finite energy resources. The UK has a significant tidal energy resource, estimated as up to 18 TWh/year [1], or 5% of the UK's 2003 energy demand. This has led to interest in the possible installation of numerous tidal turbines at multiple sites. Recently tidal energy extraction projects have been confirmed at the Skerries, Anglesey [2] and the Sound of Islay [3].

Pre-installation requirements call for an environmental impact assessment (EIA) study, which considers factors such as noise and habitat erosion. To the best of our knowledge, only one published study is available [4] which systematically treats the issue of turbine noise as part of a strategic environmental assessment. Despite this, there has been academic interest in modelling the noise emitted by renewable energy devices, its propagation underwater, and effect of marine animals [5-7]. A key limitation of these studies is the simple treatment of the noise source itself, often as a single representative overall sound pressure level value.

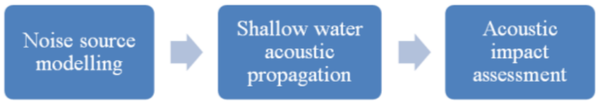
We propose a methodology incorporating semi-empirical noise source models for both hydrodynamic and mechanical noise, a 'standard' underwater acoustics propagation code, and impact assessment based on acoustic 'dosage' criteria (summarised in Table I), similar to that used by other authors [5-7]. Previous work by the authors [8] has shown that noise due to the interaction of the turbine blades with ocean turbulence is the dominant hydrodynamic noise source. However, this source alone was not expected to cause significant impact on marine animals. The development of this work into a more comprehensive methodology is the focus of this work. This is then applied to a proposed tidal array, which utilises designs similar to those depicted in Fig. 1.

An additional advantage of a numerical acoustic model is the ability to efficiently assess the sound field at multiple receiver locations which is not trivial when making underwater acoustic measurements. Patricio *et al.* [7] note that this benefit can be further utilised in the optimisation of renewable energy device layouts, so as to minimise acoustic environmental impact. Here we consider not only the acoustic field due to multiple devices, but also the increase in noise due to hydrodynamic interactions between turbines [9].

Fig. 1 Artist's impression of tidal turbine array, depicting Hammerfest Strøm design, as proposed for installation at the Sound of Islay site (Obtained from: http://www.hammerfeststrom.com/, accessed 13/05/2011)

This paper has the following structure. First, we introduce the turbine noise source model (Section. II). Next, the concepts of underwater acoustic modelling (Section. III) and the impact assessment criteria (Section. IV) adopted by this study are outlined. In Section. V a case study is presented based on the proposed Islay tidal energy installation site. A sensitivity analysis is also included, investigating the effect of numerous simulation parameters on the predictions of acoustic dosage. The limitations of the methodology are also discussed. Finally, conclusions and further work are described.

TABLE I
THREE-STAGE ACOUSTIC IMPACT ASSESSMENT MODEL, WITH ASSOCIATED CONSIDERATIONS



Considerations		
Nature of sources	Ambient noise	Species audiogram
Dominant sources	Sea bed effects	Received dosage
Modelling methodology	Depth & range effects	Physiological & behavioural effects

II. TIDAL TURBINE NOISE SOURCE MODELLING

The following sections describe the modelling of the dominant noise sources associated with the tidal turbine. They are defined as point sources centred on the turbine hub height. This is justified assuming the minimum observer distance to be more than twice the blade length away [10]. This corresponds approximately to the near/far field boundary identified in [8].

A. Hydrodynamic noise sources

Lloyd *et al*. [8] identified the dominant hydrodynamic noise sources for a tidal turbine, and modelled these semi-empirically based on the formulation presented by Blake [11] derived for ship propellers. It is worth noting that such approaches are commonly applied to wind turbines [12, 13], where considerable work has been carried out to assess noise impact in relation to human comfort. The relative contributions of the various noise flow induced noise sources to the sound pressure are quite different from that of a tidal turbine, due to differences in device size, rotational speed and flow conditions.

The main contribution to the total sound pressure was found to be that due to inflow turbulence interacting with the turbine blades. This is modelled assuming values for various parameters defining the incoming flow regime, including the axial turbulence length scale and root mean square (*rms*) fluctuating velocity, see [8] for full details. This source is expected to be dipolar, with its maximum value along an axis perpendicular to the turbine plane of rotation.

B. Mechanical noise sources

A component of the noise spectrum which is expected to be significant but was not previously considered by the authors is mechanical noise. Wind turbine noise models tend to ignore this component [12], but we expect it to be more important underwater due to the potentially more significant coupling into water.

A semi-empirical method for estimating the sound power level (SL_W) of industrial machinery [14, chap. 69] has been adapted for predicting tidal turbine mechanical noise. Based on measurements made in air, the SL_W for gearboxes can be estimated using:

$$SL_W = 79 + 3\log(n) + 4\log(P_{kW}) + 10\log(A) \quad (1)$$

where n is the number of revolutions per minute (rpm), P_{kW} is the rated power of the gearbox in kW, and A is a geometrical definition based on the assumed size of the unit (see *Appendix A* for full definition). The resulting SL_W is valid for octave bands. Equation (1) requires a 6 dB and 3 dB reduction in sound power level at frequencies of 31.5 and 63 Hz respectively, whilst the spectrum is flat for 125 Hz and above. Sound power source levels can be converted into sound pressures in free space using:

$$SL_P = SL_W - 10\log(4\pi r^2) + 10\log\left(\frac{\rho_w c_w W_{ref}}{p_{ref}^2}\right) \quad (2)$$

where r is the observation (receiver) range, and ρ_w and c_w are the fluid density and sound speed in water respectively. The reference values for sound power and mean square pressure are $1\text{x}10^{-12}$ W and $1\text{x}10^{-6}$ Pa. Here we have assumed that the sound power radiated into water is equal to that radiated in air. This is a large assumption; it is justified since the sound power radiated in water and air by a force excited vibrating acoustic shell can be considered approximately equal [15]. This source is considered to be monopole in nature. In practice the gearbox may be isolated from the outer turbine casing reducing the radiated power.

C. Combining noise sources

The octave band source levels calculated for the gearbox are converted to third-octave bands to provide consistency between the acoustic levels presented. This is achieved by correcting for the difference in bandwidths, such that, for an octave band source level (SL_1):

$$SL_{1/3} = SL_1 - 10\log(3) \quad (3)$$

where $SL_{1/3}$ is the source level in third-octave bands. In order to estimate the sound pressure level (SPL) experienced by a marine animal, the noise sources must be appropriately summed and the transmission loss accounted for. Since the highest possible SPL is desired, the directionality of the dipole is ignored, and SPL calculated on an axis perpendicular to the rotor plane. Assuming incoherent sources, the mean square pressure (MSP) values can be summed to give the overall source level. The MSP value of any source i can be calculated following:

$$\overline{p_i^2} = p_{ref}^2 10^{\frac{SL_i}{10}} . \quad (4)$$

The total MSP is then the summation:

$$\overline{p_{tot}^2} = \sum_i^n \overline{p_i^2} \qquad (5)$$

where the number of noise sources n in this case is 3 consisting of the hydrodynamic source, mechanical source and ambient noise. Converting the total mean square pressure back to a source level SL_{tot} allows the sound pressure level at the receiver to be calculated as:

$$SPL = SL_{tot} - TL \qquad (6)$$

where TL is the transmission loss determined from an underwater acoustic propagation model (discussed in the next section).

III. Shallow Water Acoustic Propagation Modelling

Modelling the propagation of noise sources using underwater acoustics models is important to provide a more accurate prediction of sound pressure levels seen by a receiver. Such models must account for the influences of temperature and salinity gradients, finite depth, water surface and sea bed roughness and seabed medium. Fig. 2 illustrates the acoustic propagation case for a tidal turbine. Of particular interest in shallow water are the cut-on and cut-off modes of the channel, which essentially behaves like an acoustic duct.

Underwater propagation modelling consists of solving the Helmholtz equation in a water column (and elastic sea bed media), accounting for appropriate boundary conditions at the free surface and sea bed. The sea surface is treated as a pressure-release boundary condition, whilst the sea bed is characterised as a fluid-fluid interface, requiring Neumann type continuity conditions between the two fluids. Variations of sea bed media and topography can also be accounted for through boundary conditions [16, chap. 31].

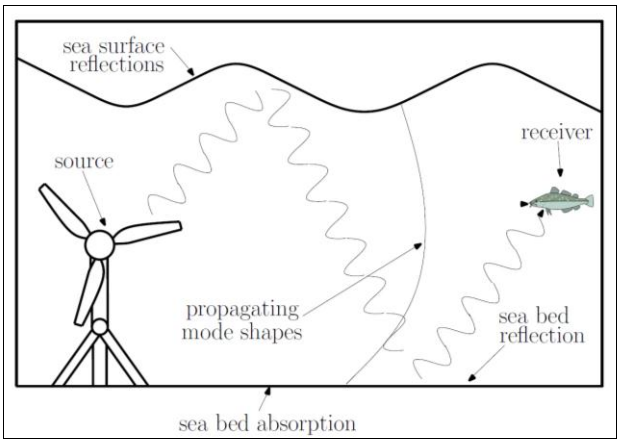


Fig. 2 Schematic illustration of the underwater acoustic propagation problem, relating to the sound pressure received by a marine animal from a tidal turbine.

The Green function solution to the problem can be found using four main techniques which fall into the categories of boundary value (BV) and initial value (IV) problems. These are summarised as:

- Ray (or beam) theory (IV)
- Spectral (fast-field) method (BV)
- Normal mode (BV)
- Parabolic equation method (IV)

Since the noise from tidal devices has been identified to be generally low-frequency (< 1 kHz), and assessments are required at relatively short distances (< 1 km), the most appropriate models are spectral and parabolic equations. [Curtin]. Ray theory is more suited to higher frequencies, whilst normal mode method is preferred for longer ranges.

All these techniques are coded into the AcTUP[1] v2.2l$^{\alpha}$ software, distributed by Curtin University [17]. This program is freely available, and provides a MATLAB® based graphical user interface for running and post-processing underwater acoustics transmission loss simulations. The simulations are carried out in 2D, assuming cylindrical symmetry. The effects of range-dependent water depth are not modelled, the acoustic propagation in range-dependant very shallow water would be expected to exhibit 3D behaviour.

D. Spectral method

The spectral method (also called *fast-field*) consists of defining a depth-dependent Green function and employing a fast Fourier transform (FFT) technique to find the original Green function solution to the Helmholtz equation. It is noted to be an efficient method, although no range-dependent sea bed data can be input.

The fast-field technique is implemented into AcTUP as the ‘Scooter & Fields’ model, where Scooter calculates the depth-dependent Green function, and Fields determines the transmission loss.

E. Parabolic equations model

This technique re-writes the solution to the Helmholtz equation in parabolic equation (PE) form including a function which accounts for range and depth effects. This is solved numerically using FFTs and a ‘split-step’ algorithm. Within AcTUP, the Range-dependent Acoustic Model (RAM) solves the PE formulation using higher-order Padé schemes. This method is noted for its ability to account for variations in sea bed topography and sea bed media with distance.

IV. Acoustic Impact Assessment Criteria

Acoustic impact assessment criteria represent the accumulated evidence from numerous marine ecology studies of marine animals’ responses to anthropogenic acoustic stimuli. A main deficiency in the application of the criteria is a lack of knowledge about animal movements over short time spans (of the order of hours) as these are the time scales over which acoustic dosage criteria are applied. Assumptions must be made as to the location of a receiver in proximity to a noise source over a 24 hour period, yet the received sound pressure varies considerably with range.

A. Zones of influence

A simple model widely used to assess noise impact is that proposed by Richardson *et al.* [18] termed the ‘zones of

[1] Acoustic Toolbox User-interface & Post-processor

influence' model. This is represented graphically in Fig. 3. The 'severity' of influence falls off with distance from the source, yet exposure duration will also contribute to the effects experienced by marine animals.

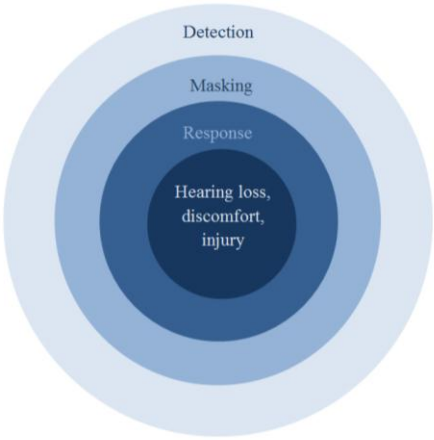


Fig. 3 Graphical representation of 'zones of influence' model, defined in [18].

It is important to note that the impacts considered cover a wide range of effects, which represent complex physiological and behavioural interactions of the receiver with the sound field. These are discussed briefly here.

B. Hearing threshold

A primary cause of injury and physiological damage to wildlife is permanent (PTS) or temporary threshold shift (TTS). It is generally accepted that these effects can occur if a marine animal is exposed to SPLs of 95 dB and 75 dB respectively above their hearing threshold (HT) level. Simple relationships can be used to estimate the occurrence of PTS and TTS, as carried out by Richards *et al*. [4]:

$$PTS = HT + 95 - 10\log_{10}\left(\frac{T}{28800}\right) \tag{7}$$

and

$$TTS = HT + 75 - 10\log_{10}\left(\frac{T}{28800}\right) \tag{8}$$

where T is the total exposure duration in seconds i.e. for a constant source, there is no contribution from the last term in either equation. To simplify the analysis, it is assumed here that the exposure duration corresponds to a 24 hour period i.e. constant exposure to acoustic signal. The frequency dependent HT for a cod (*Gadus Morhua*) is plotted in Fig. 4, along with an ambient noise spectrum, taken from [4], which is assumed typical in shallow water. Fish will be most susceptible to sounds in the frequency range 63 to 250 Hz. It will be shown in the next section that these are the frequencies that attenuate the least in shallow water.

C. Behavioural and physiological effects

These effects are hard to quantify and a lack of data on this subject is noted in the literature [19]. There is however a wider treatment of cetacean and other aquatic mammal species e.g. the comprehensive work of Southall *et al*. [20].

Studies into behavioural effects on fish have focussed on responses to air gun firings [21, 22] and are not directly applicable here. Extended duration exposure to broadband noise may cause stress in fish [23] although these effects have not been investigated fully.

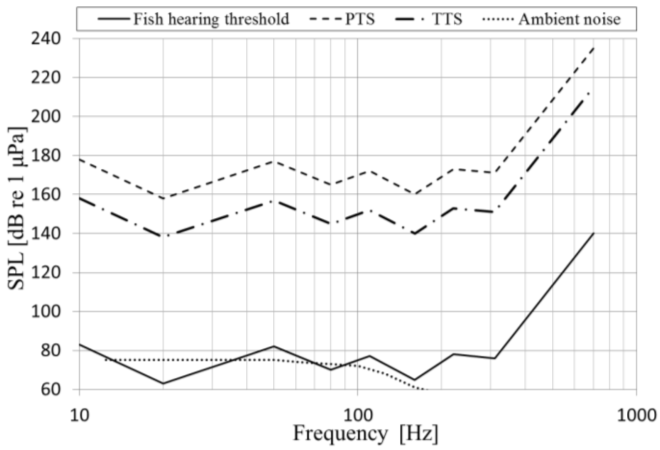


Fig. 4 Modelled fish (cod) hearing threshold with associated PTS and TTS levels as well as ambient noise spectrum.

V. THE CASE STUDY – SOUND OF ISLAY

The methodology outlined in previous sections is now applied to the proposed Sound of Islay tidal turbine site. It should be noted that the authors have chosen this site as indicative of proposed tidal array schemes and have no direct connections with proposers/opposers of such a scheme. The area is a known nursery ground for herring [24], with additional potential impact on fish stocks in the region. Whilst specific information on the design of the tidal devices is not available, Table II and Fig. 5 summarise the scenario.

TABLE II
GENERAL PARAMETERS FOR THE ISLAY TIDAL TURBINE PROJECT [24, 25]

Parameter	Value
Water depth / m	48
Max. spring tidal speed / ms^{-1}	3.6
Max. neap tidal speed / ms^{-1}	1.9
No. of turbines	10
Rated power per turbine / MW	1
Turbine diameter / m	23
Turbine hub height / m	22
No. of blades	3
Tip speed ratio	6
Ambient turbulence intensity / %	10
Turbulence axial length scale / m	15.4

Of primary concern is modelling the sound field due to multiple turbines, as well as investigating the influence of water depth, sea bed type and turbine layout on received sound pressure levels. This highlights the site-specific nature of this type of analysis.

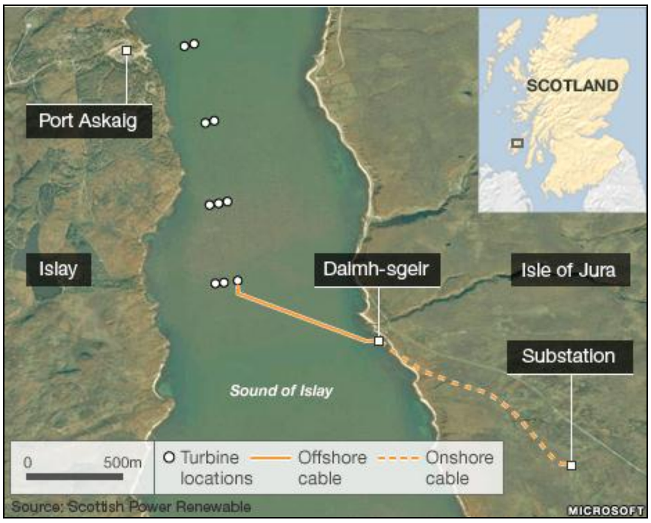


Fig. 5 Aerial view of proposed layout of Islay tidal turbine array. The streamwise and lateral separations of the devices are 20 and 1.5 diameters respectively [24]. Obtained from: http://www.bbc.co.uk/news/uk-scotland-glasgow-west-12767211, accessed 13/05/2011].

The acoustic simulation environment parameters are given in Table III. All values are taken from Jensen and Kuperman [26] except for sea bed roughness, which is from Soulsby [27].

TABLE III
SHALLOW WATER ACOUSTIC SIMULATION PARAMETERS

Medium	**Sea Water**	**Sea bed**
Type	Salt water	Coarse sand
Density / $kg.m^{-3}$	1026	2050
Compressional wave speed / ms^{-1}	1500	1800
Shear wave speed / ms^{-1}	-	600
Comp. wave attenuation / dB per wavelength	-	0.7
Shear wave attenuation / dB per wavelength	-	1.5
Surface roughness / m	-	0.015

Hydrodynamic interaction between turbines is accounted for by modifying the parameters input into the unsteady thrust loading spectrum which determines the dipolar sound spectrum. These are namely the inflow velocity and turbulence intensity.

Assessment of tidal turbine wake turbulence intensity has been made by Turnock *et al*. [9] using a semi-empirical method based on the work of Hassan [28] and Vermeulen [29] The increase in turbulence intensity in a turbine wake can be estimated as:

$$I_{+} = 5.7 C_T^{0.7} I_0^{0.68} \left(\frac{x}{x_n} \right)^{-0.57} \qquad (9)$$

where C_T is the thrust coefficient, I_0 is the ambient turbulence intensity, x is the distance downstream and x_n is the near wake length. A full description of the method is given in [30]. The thrust coefficient has been calculated using a blade element momentum theory (BEMT) code, originally developed by Barnsley & Wellicome [31]. The added turbulence intensity as a function of distance is depicted in Figure 6.

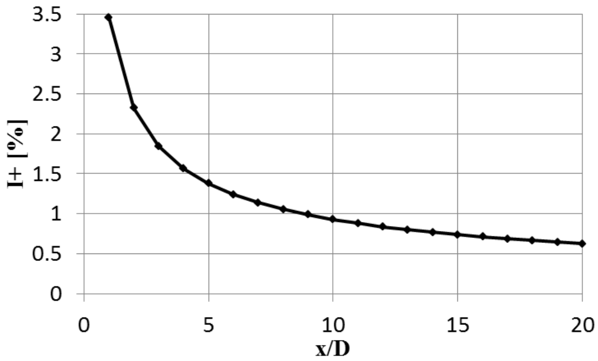


Fig. 6 Increase in turbulence intensity due to turbine wake flow, calculated using Equation (9). D is turbine diameter and x the distance downstream of the turbine.

The increase in turbulence intensity estimated here is small compared to the ambient turbulent intensity. Based on [4] the inflow velocity into a downstream turbine at ten diameters streamwise separation can be expected to recover to at least 90% of the free stream velocity. Assuming a constant tip speed ratio, the reduction in angular velocity (a key parameter in calculating the hydrodynamic noise spectrum) is expected to be minimal.

Thus it is assumed that any noise that could cause threshold shift or behavioural effects on marine animals consists of contributions from the three turbines placed alongside each other in the tidal array. Since the acoustic propagation simulation is two-dimensional, and assuming the receiver distance to be greater than the turbine spacing of 1.5 diameters, the combined SL for the three-turbine array is a MSP summation according to Equation (5). The resulting SLs are compared to the TTS data in Fig. 7. The data are *rms* SLs presented in dB re 1μPa. In general the contributions from the hydrodynamic and mechanical noise are similar, with the latter being typically 5 dB higher for the current, very simple model.

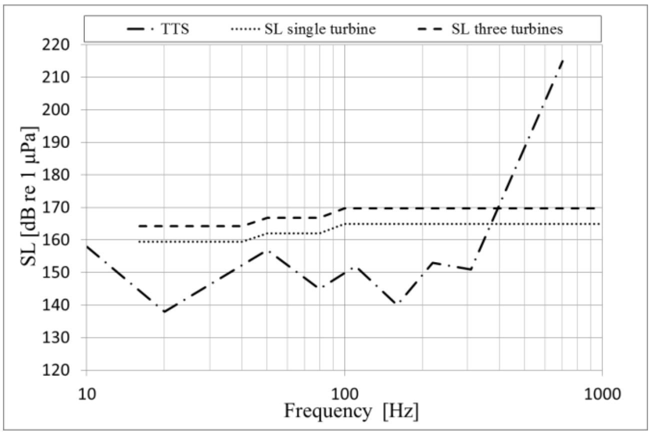


Fig. 7 The modelled third-octave frequency spectrum of source levels (at 1 metre) for single and three-turbine array, compared to temporary threshold shift data

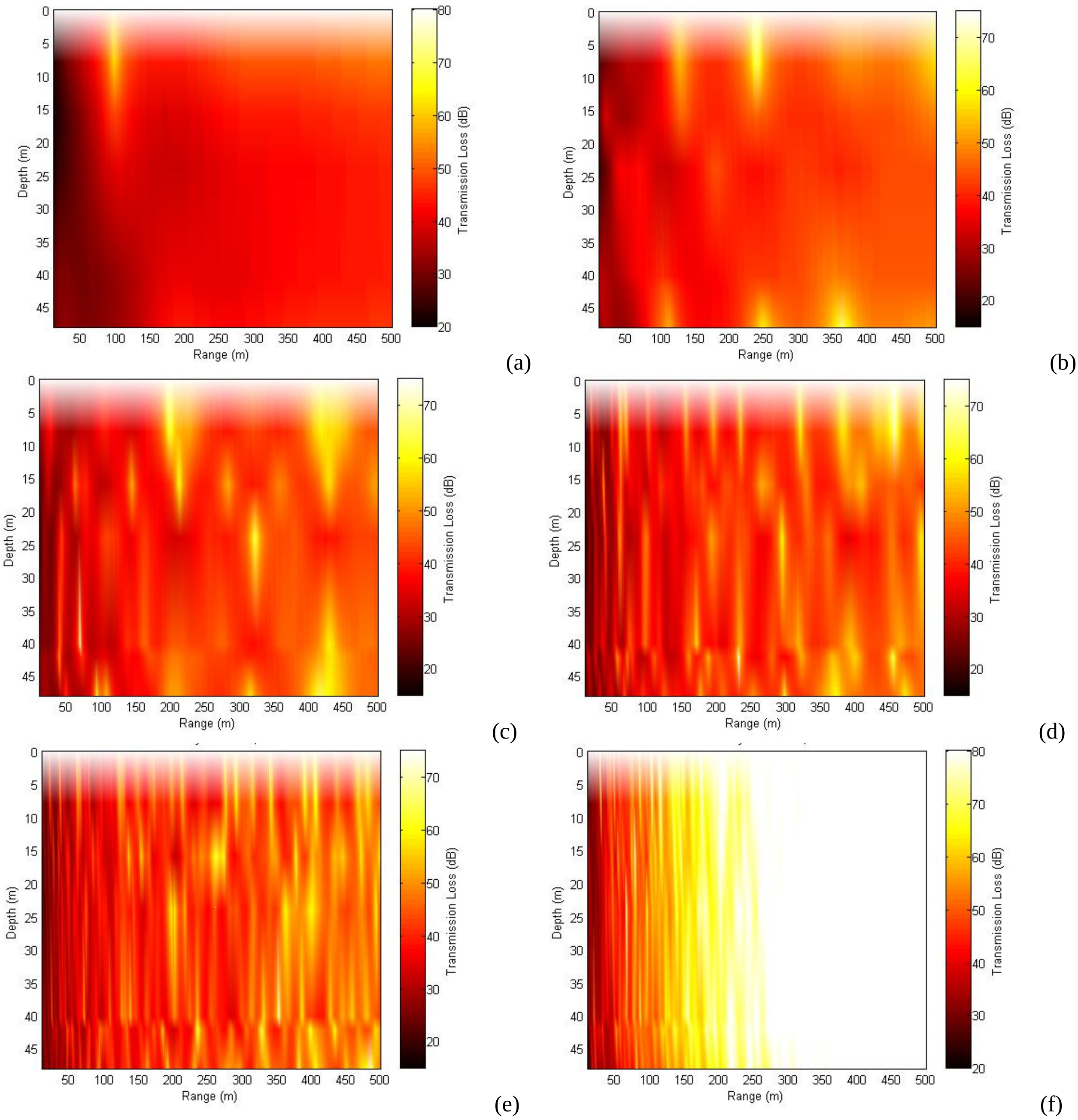


Fig. 8 Summary of transmission loss for the six frequencies of interest: (a) 31.5 Hz; (b) 63 Hz; (c) 125 Hz; (d) 250 Hz; (e) 500 Hz; (f) 1 kHz. The source depth is defined as 26 m below the sea surface, equivalent to the hub depth of the Hammerfest Strøm turbines.

Fig. 7 reveals that TTS might be possible close to the turbine array, but at a range of 10m the SPLs will have reduced by 20 dB. The PTS curve has not been included since fish would have to inhabit a region within one diameter of the turbines for a 24 hour period in order to experience any form of permanent physiological damage. This seems both unrealistic and is not supported under the current analysis, since near-field effects are not modelled.

The furthest distance at which TTS may occur is determined from the TL plots presented in Fig. 8. The plots reveal the complex nature of underwater acoustic propagation. In order to assess the noise impact, the difference between the TTS and SL has been calculated for each third-octave band. The maximum range at which this difference occurs provides an estimate of the TTS 'zone of influence' associated with the turbine. The impact assessment region is assumed to be close to the sea bed where fish are likely to spend the majority of time searching for food and the tidal current is much lower than the 3.6 ms^{-1} specified in Table II. The resulting ranges at which TTS could be expected are presented in Table IV. Comparison is made between the results from the *SCOOTER* model and a simple cylindrical spreading law (with additional loss in to the sediment), equal to 17 log (*r*). This model has been employed in [4] for the assessment of noise impact from renewable energy devices. TL plots as a function of range at selected frequencies are included in *Appendix B.*

TABLE IV

TEMPORARY THRESHOLD SHIFT 'ZONE OF INFLUENCE' ESTIMATION: COMPARISON BETWEEN ACTUP SCOOTER MODEL AND CYLINDRICAL SPREADING LAW

Frequency / Hz	**Maximum range at which TTS may occur / m**		
	AcTUP (1m above seabed)	**AcTUP (22m above seabed)**	**17 log (r) spreading**
16	10	12	18
20	28	20	35
25	2	14	18
31.5	-	6	10
40	-	4	5
50	-	3	4
63	-	6	10
80	2	12	19
100	4	7	14
125	13	11	14
160	39	28	55
200	-	12	16
250	-	7	13
315	-	8	13

Table IV reveals the large variation in expected noise impact with depth. For the location 1 metre above the sea bed, TTS is predicted within a range of two turbine diameters of the source for seven of the third octave bands. However, only two of the frequency bands correspond to locations outside of the turbine rotor diameter i.e. a meaningful position of a fish to inhabit. For the receiver location at hub depth, TTS may be expected for all bands, although the maximum ranges are slightly reduced. At most of the frequencies assessed, threshold shift is predicted at ranges within the near-field (turbine rotor radius), where the validity of this analysis is questionable.

The simplification of assuming a fish to spend a 24 hour period within a small distance of the turbines at a constant depth may be unrealistic, and thus these results are considered conservative. However, accurately predicting fish movement patterns and associated received acoustic dosage is a complex task, as the sound pressure level can vary considerably with range, depth and time. Although the physiological impact of this turbine array is expected to be minimal, further investigation into possible behavioural effects which may affect fish movement and breeding patterns is required.

VI. CONCLUSIONS

The modelling of underwater noise emitted by tidal turbine arrays and its environmental impact on marine animals is complex. A three-stage methodology has been developed expanding the source modeling work previously carried out by the authors [8]. The methodology has been applied to a realistic tidal turbine array representing a real life pre-installation project. It is seen that the major influence of tidal turbine noise will be at low frequencies (< 500 Hz); as such fish such as cod and herring are most likely to be affected. The use of underwater acoustic modelling has allowed a quantified estimate of shallow water acoustic transmission losses. This reveals that the influence of turbines in terms of temporary threshold shift is likely to be within approximately 2 diameters of the array in this case. However, the results are particularly case specific, and the impact will vary depending on numerous parameters such as number of turbines, their spacing and diameter, and water depth. Although the transmission loss has been estimated at each of the modelled frequencies, it is recommended that a frequency or range average be taken to account for the third-octave bandwidth averaging of the data [32] . A weakness of this work is the omission of this correction, which can smooth the transmission loss curve considerably [33].

Further work includes the development of the source model, particularly for the mechanical noise which should account for the mounting and isolation of the gearbox, and detailed structural vibration of the casing. Here, there is significant potential for radiated noise reduction. Discussions with turbine developers and manufacturers will be required to specify gearbox size and mounting arrangements more accurately. It is worth noting that a design based on the rim-driven concept of Sharkh *et al.* [34] or equivalent will avoid this noise source completely. The underwater acoustic propagation modelling could also be developed to introduce more complex effects, such as bathymetry variations. A lack of criteria for behavioural effects of noise on fish has also been identified.

APPENDIX A

DEFINITION OF GEARBOX NOISE PARAMETER 'A'

The parameter A is a definition relating to sound power level, which represents a surface surrounding the body of interest, through which acoustic pressure fluctuates. It is defined as:

$$A = 4\left(ab + bc + ca\right)\frac{a+b+c}{a+b+c+2d} \qquad (10)$$

with:

$$a = 0.5L + d;\ b = 0.5W + d;\ c = H + d \qquad (11)$$

where d is distance (prescribed as 1 metre in this case) and L, W and H are the body length, width and height respectively.

APPENDIX B

TRANSMISSION LOSS PLOTS

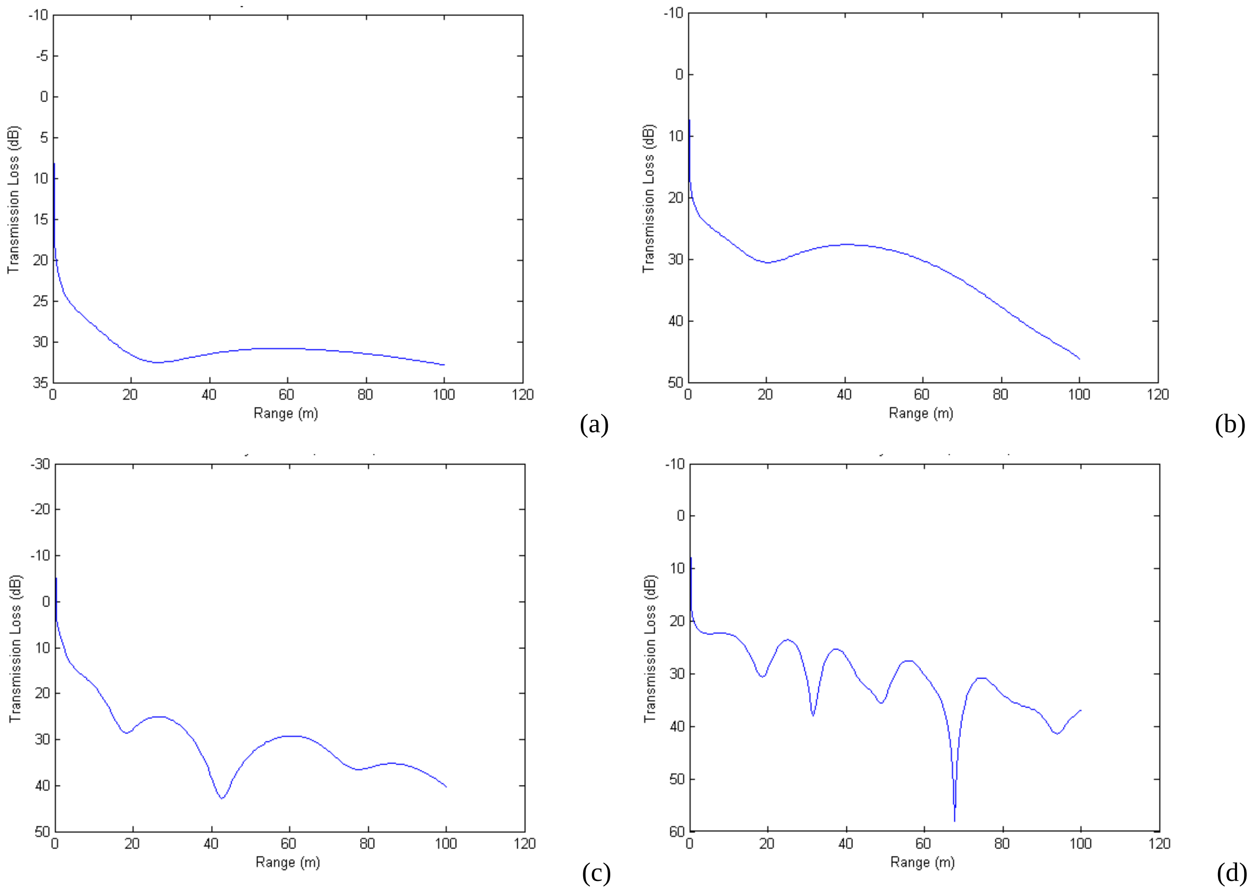


Fig. 9 Summary of transmission loss for the four frequencies of interest: (a) 31.5 Hz; (b) 63 Hz; (c) 125 Hz; (d) 250 Hz receiver depth is 1 metre above the seabed (estimate of typical fish location).

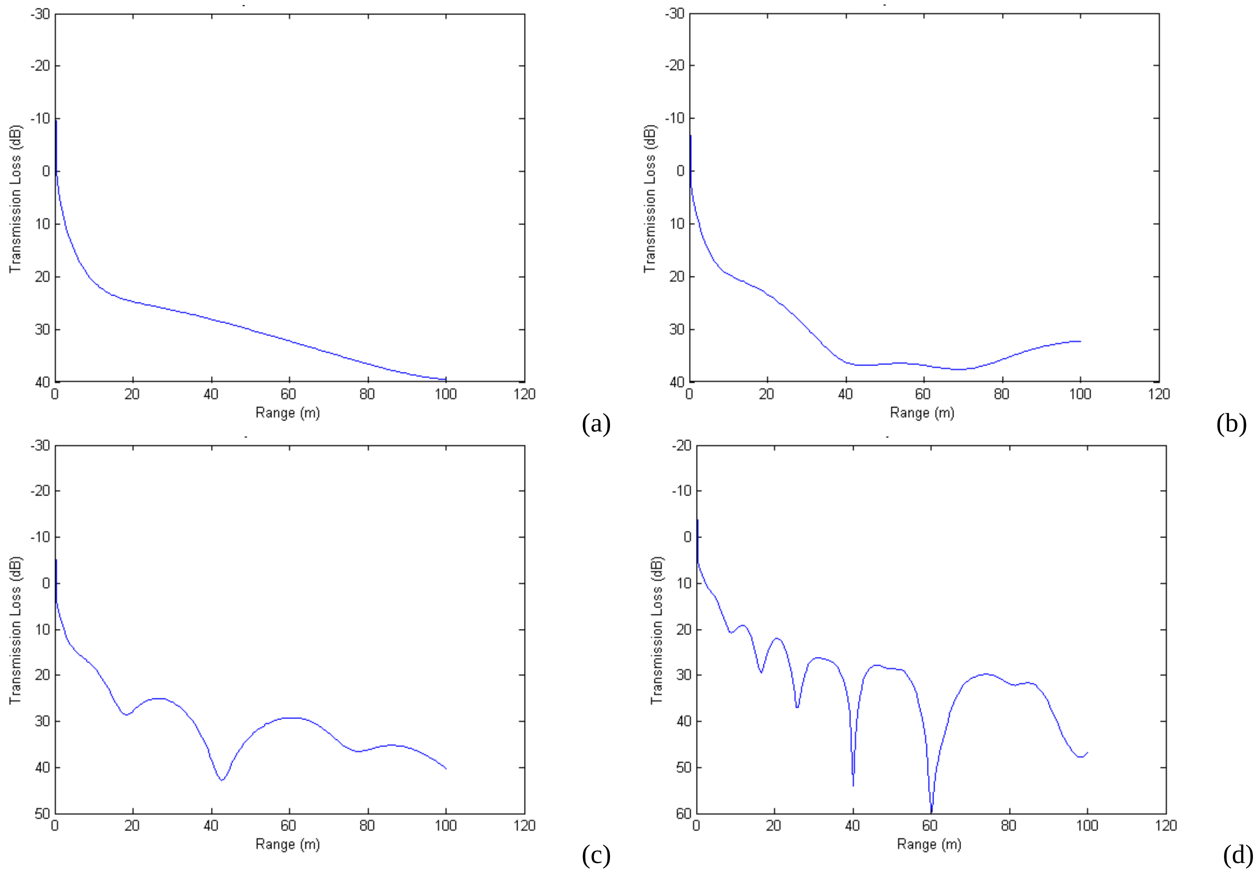


Fig. 10 Summary of transmission loss for the four frequencies of interest: (a) 31.5 Hz; (b) 63 Hz; (c) 125 Hz; (d) 250 Hz receiver depth is 22 metres above the seabed (turbine hub height).

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