Underwater Acoustic Impact of Marine Renewable Energy Devices: Modelling Approaches

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Abstract

This work aims to research, verify and validate an existing open-source sound propagation algorithm. For this purpose, KRAKEN, a normal mode program, has been chosen, and its capabilities when applied to the prediction of noise generated by offshore renewable energy devices will be determined. These devices are often deployed in shallow waters, giving rise to important near-field effects usually neglected in sound propagation algorithms. Verification of results has been performed through mesh sensitivity and refinement studies, estimation of the numerical uncertainty related to acoustic energy predictions, and comparison to benchmark test cases. For validation purposes, experimental measurements performed near a WaveRoller device on the coast of Peniche, Portugal, were used. While results matched experimental measurements for frequencies at which most of the domain is in the far-field, low frequency cases presented a challenge. Results have been found to qualitatively follow patterns observed experimentally, but some values fall outside the estimated error margins. While the work here presented gives a clear indication that KRAKEN can be used to fulfil the stated objectives, further research is needed to explain some of the encountered discrepancies both on the computational and on the experimental sides.

Keywords: ocean acoustics, verification, uncertainty, validation, KRAKEN

1. Introduction

Given the ongoing concerns regarding climate change and sustainability, efforts are being focused, throughout all industries, in reducing emissions and negative anthropogenic impacts on the environment and biodiversity. Among these an important area of study is the generation and propagation of noise in the environment. The deployment of renewable energy devices necessarily gives rise to noise being generated in their surroundings [16], resulting in a set of regulations from the European Union and the International Maritime Organization to which these devices are subjected, as well as further directives from the European Environment Agency regarding noise exposure and its potential health and environmental effects [10].

In order to verify compliance with the relevant regulations and reduce environmental impact, WavEC Offshore Renewables intends to combine CFD analysis of potential noise sources, based on the open source ReFRESCO CFD software [27], with propagation algorithms, to yield a complete noise analysis tool. In this work, the candidate model for the latter component of the framework will be studied and validated against experimental data from an offshore renewable energy device called WaveRoller.

While the methodologies and theory described in this work focus on ocean acoustics, the principles are nonetheless valid for any kind of medium. Moreover, the ocean environment represents a more complex challenge than the free atmosphere, given the particularly intricate interactions occurring at its top and bottom boundaries, the role played by water salinity and the different pressure and temperature dependencies with depth.

A final point motivating this work is the promotion and further development of Free and Open Source Software. Seeing as the first component of the WavEC tool is already based on some of these principles, it is fitting the second component follows suit.

While at air-water or air-ground boundaries, sound waves are essentially fully reflected [18][21], underwater the transition from the ocean medium into the sea-floor sediment is more gradual. This results in diffraction and refraction effects at the boundary, which add a secondary artificial source of sound to the problem [11][15][21]. How these effects are handled determines the accuracy and ap-
plicability of any given noise propagation method. The existing algorithms to model this phenomenon are further differentiated by their treatment of the underlying wave equation, and are described in various texts [6][7][13]. For the purposes of this work, it has been found that normal mode theory presents the best fit, hence the choice of KRAKEN.

An important package of existing tools is the one provided by Ocean Acoustics Library’s Acoustics Toolbox [1]. Collecting work developed since the 1980s by Michael B. Porter and others, this toolbox contains specialised programs that are open for anyone to use and modify [22][23]. This offers great flexibility and automation possibilities and, since the purpose of this research is to integrate these tools in a larger project, such raw software is an appropriate starting point.

The main components of the Acoustics Toolbox are BELLHOP, a ray tracing algorithm, and KRAKEN, a normal mode based program. Given the requirements to predict sound in relatively shallow water and at low frequencies, KRAKEN has been chosen as the candidate model to incorporate in the noise propagation tool. Its versatility and continued development further justify this choice. BELLHOP was also used in this work, when applicable, to provide benchmark qualitative results.

The main objectives of this work are to verify and validate KRAKEN, determining the model’s numerical convergence conditions and applicability. Verification is achieved by performing multiple mesh convergence studies on benchmark cases. On the other hand, validation of the KRAKEN output is achieved by comparing it to experimental data gathered in the field. If the main objectives are achieved, integration into the general sound analysis tool can begin.

2. Background

In this section, the theoretical basis for the work will be described, as presented by the various referenced authors. First, the linearised wave equation forming the basis of all acoustic problems will be given, along with its underlying assumptions. Following this, the manipulations of this equation that result in the normal mode model implemented in KRAKEN will be presented.

2.1. Wave Equation

Let us consider an arbitrary control volume in a fluid. The conservation of mass equation will read

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{U}) = 0 ,
\]

where \( \rho \) is the local total density, \( t \) is time, and \( \vec{U} \) is the local speed.

In acoustic media, the following assumptions will be made [21]:

- the involved Reynolds numbers are high enough that the problem may be considered inviscid;
- there are no external body forces acting on the control volume;
- the fluid is at rest;
- all processes are adiabatic; and
- all variables can be represented as a sum of some constant average value and a variable perturbation component.

Under these conditions, the momentum equation [14] can be simplified to

\[
\rho_0 \frac{\partial \vec{u}}{\partial t} = -\nabla p ,
\]

where \( \vec{u} \) and \( p \) are the perturbation velocity and pressure, respectively, and \( \rho_0 \) is the free-field density. Given the adiabatic assumption, the pressure field \( P \) can be taken as depending only on the state variable \( \rho \), with the derivative given by

\[
\frac{dP}{d\rho} = c^2 ,
\]

where \( c \) is the speed of sound in the medium. Taking a linear approximation to this and applying the above assumptions to (1)-(2), the final form of the linearised wave equation in an arbitrary coordinate system written in terms of the perturbation pressure field can be obtained as

\[
\nabla \cdot \left( \frac{1}{\rho_0} \nabla p \right) - \frac{1}{c^2 \rho_0} \frac{\partial^2 p}{\partial t^2} = 0 .
\]

In the context of noise propagation, far-field effects are the main area of interest. As such, sources will be modelled as points [21]. Moreover, given the cylindrical symmetry for the same depth (or altitude) exhibited by propagation environments, we can present (4) in a cylindrical system of coordinates as [15]:

\[
\frac{1}{\rho_0(z)} \frac{\partial}{\partial r} \left( r \frac{\partial p(r, z)}{\partial r} \right) + \frac{\partial}{\partial z} \left( \frac{1}{\rho_0(z)} \frac{\partial p(r, z)}{\partial z} \right) + \frac{(i\omega)^2}{\rho_0(z)c^2(z)} p(r, z) = - \frac{1}{\rho_0(z)} \frac{\delta(z - z_s)\delta r}{2\pi r} ,
\]

where the time dependency was suppressed through a Fourier transform, implying the pressure field \( p(r, z, t) \) will respond in phase with the source, which now appears on the right-hand side of the equation. \( \omega \) is the angular frequency, \( \delta \) is the Dirac delta function, \( z_s \) is the source depth, and its amplitude has been made unitary to simplify the derivation of the equations. Equation (5) is the Helmholtz equation on which various sound propagation models, including KRAKEN, will be developed.
2.2. Normal Modes
While sophisticated boundary conditions are of importance, some simplifications are first presented in order to derive some fundamental normal mode concepts [22]. As such, the top \( z = 0 \) and bottom \( z = D \) boundary conditions for (5) will be simplified as a perfect vacuum \( p(r,0) = 0 \) and a perfectly rigid surface, respectively. These assumptions are reasonable for deep ocean problems, where effects of the sea floor are negligible.

Away from the source, a pressure field does not unequivocally define what originated it [21]. As such, the unforced solution to (5) can be calculated to describe the far-field sound propagation. The problem to be solved is then a partial differential equation (PDE)

\[
\frac{1}{\rho_0(z)} \frac{\partial}{\partial r} \left( r \frac{\partial p(r, z)}{\partial r} \right) + \frac{\partial}{\partial z} \left( \frac{1}{\rho_0(z)} \frac{\partial p(r, z)}{\partial z} \right) + \frac{\omega^2}{\rho_0(z) c(z)^2} p(r, z) = 0, \quad (6)
\]

\[
p(r, 0) = 0, \quad (7)
\]

\[
\frac{\partial}{\partial z} p(r, D) = 0, \quad (8)
\]

with an additional condition that the solution must be outward travelling as \( r \lim_{r \to \infty} \) [22]. To solve (6)-(8), the normal mode approach separates the spatial variables \( r \) and \( z \) as

\[
p(r, z) = Z(z) R(r), \quad (9)
\]

where \( Z(z) \) and \( R(r) \) are functions of solely one spatial coordinate. From this, the eigenvalues of the new problem can be identified as

\[
\frac{\rho_0}{Z} \frac{\partial}{\partial z} \left( \frac{1}{\rho_0} \frac{\partial Z}{\partial z} \right) + \frac{\omega^2}{c^2} k^2 = 0. \quad (10)
\]

Given that \( Z(z) \) must obey the same boundary conditions as the original problem (6)-(8), the new ordinary differential equation (ODE) to solve is

\[
\frac{\partial}{\partial z} \left( \frac{1}{\rho_0} \frac{\partial Z}{\partial z} \right) + \frac{\omega^2}{\rho_0 c^2} Z - \frac{1}{\rho_0} k^2 Z = 0. \quad (11)
\]

\[
Z(0) = 0, \quad (12)
\]

\[
\frac{\partial}{\partial z} Z(D) = 0. \quad (13)
\]

Equations (11)-(13) represent a Sturm-Liouville problem, which has a set of well known properties [17], among them

- set of solutions is orthogonal; and
- \( k_m \) are the eigenvalues of the problem (and the horizontal wavenumbers).

The second Sturm-Liouville property listed allows the pressure field \( p(r, z) \) to be written as a sum of all solutions \( Z_m \). Taking the density to be constant, while still retaining its effects in the sound speed profile \( c(z) \), and normalising the modes so as to form an orthonormal set [22], the solution for the pressure field can be obtained as a function of only the normal modes:

\[
p(r, z) = \frac{i}{4\rho_0(z_s)} \sum_{m=1}^{\infty} Z_m(z_s) Z_m^*(z) H_0^{(1)}(k_m r), \quad (14)
\]

where \( H_0^{(1)} \) is the Hankel function of the first kind, chosen due to the outward travelling wave condition. The steps taken to solve \( R(r) \) as a function of \( Z(z) \) can be consulted in the referenced texts.

2.3. Shallow Water Boundary Conditions
For shallow water, the effects of sound interaction with the bottom play an important role. Consequently, the boundary condition becomes non-linear, introducing a singularity into the eigenvalue problem and breaking the Sturm-Liouville property regarding the completeness of the set of modes \( Z_m \).

As a solution, the spectral integral representation [25] of the pressure field is introduced:

\[
p(r, z) = \frac{1}{4\pi} \int_{-\infty}^{\infty} G(z, z_s; k) H_0^{(1)}(kr) dk, \quad (15)
\]

in which \( G \) represents a Green’s function satisfying an equation similar to (10). Given (15), the ODE now reads

\[
\rho_0 \frac{\partial}{\partial z} \left( \frac{1}{\rho_0} \frac{\partial G}{\partial z} \right) + \frac{\omega^2}{c^2} G - k^2 G = \delta(z - z_s), \quad (16)
\]

\[
f^{TOP}(k^2) G(0) + \frac{g^{TOP}(k^2)}{\rho_0(0)} \frac{dG}{dz}(0) = 0, \quad (17)
\]

\[
f^{BOT}(k^2) G(D) + \frac{g^{BOT}(k^2)}{\rho_0(D)} \frac{dG}{dz}(D) = 0, \quad (18)
\]

where, for completeness, both top and bottom boundaries are not simplified, with the \( f \) and \( g \) coefficients representing angle-dependent impedances [3]. Their calculation is obtained through the application of propagator matrices to the sea-floor elastic problem [20].

Due to the presence of a singularity, a contour integral in the complex plane must be solved. The associated branch-cut [25] determines the efficiency of the given normal mode method. Both the EJP [11]
and Pekeris cuts are used in KRAKEN [22], with varying levels of stability, mode calculation potential and computational cost.

The unforced solutions $Z_m$ obtained previously can be used in equation (15) and, as long as, together with the eigenvalues, they do not form a trivial solution, the final set of equations describing the pressure field is then given by

$$ p(r, z) = \frac{i}{4\rho_0(z)} \sum_{m=1}^{M} Z_m(z) Z_m(z) H_0^{(1)}(k_m r) k_m - \int_{cut} \cdots, \tag{19} $$

$$ \rho_0(z) \frac{\partial}{\partial z} \left( \frac{1}{\rho_0(z)} \frac{\partial Z}{\partial z} \right) + \frac{\omega^2}{c_s^2(z)} Z - k^2 Z = 0, \tag{20} $$

$$ f_{TOP}^{(k^2)} Z(0) + g_{TOP}^{(k^2)} \frac{dZ}{dz}(0) = 0, \tag{21} $$

$$ f_{BOT}^{(k^2)} Z(D) + g_{BOT}^{(k^2)} \frac{dZ}{dz}(D) = 0. \tag{22} $$

Here, the equations were simplified by appropriately scaling the normal modes $Z_m$ [22].

3. Implementation and Verification

In this section, the numerical setup of the normal mode model in KRAKEN will be described, followed by a discussion of the numerical methods employed to solve the resulting discrete system of equations. The procedures followed to verify convergence and the obtained results will also be discussed.

3.1. Numerical Model

The main problem to be solved numerically is described by (20)-(22). The first simplification is to consider density to be constant, while still allowing its effects on propagation to be felt through the sound speed profile $c(z)$. As such, equation (20) becomes

$$ \frac{d^2 Z}{dz^2} + \left( \frac{\omega^2}{c_s^2(z)} - k^2 \right) Z = 0. \tag{23} $$

The discretization of (23) will be done through the finite difference method and follows from the usual Taylor series expansion manipulation for the derivatives [12].

Given that equation (23) involves only $Z(z)$ and its second derivative, a second order finite differences approximation to the first derivative of $Z(z)$ can be found:

$$ \left( \frac{dZ(z)}{dz} \right)_i = \frac{Z(z) - Z(z_i)}{(z - z_i)} + \frac{z - z_i}{2} \left[ \left( \frac{\omega^2}{c_s^2(z)} - k^2 \right) Z(z) \right]_i + O ((z - z_i)^2). \tag{24} $$

To find an expression for the second derivative itself, the central differences approximation is employed. As such, the scheme as a whole represents a second order approximation.

Since the implemented numerical method in KRAKEN uses a regularly spaced Cartesian mesh to calculate the vertical modes $Z(z)$, we denote this spacing as $h$. Using subscript indexes to indicate where the function is being calculated, we obtain the discretized system of equations from (20)-(22)

$$ \frac{Z_{i+1} - 2Z_i + Z_{i-1}}{h^2} + \left( \frac{\omega^2}{c_s^2} - k^2 \right) Z_i = 0, \tag{25} $$

$$ f_{TOP}^{(k^2)} Z_0 + g_{TOP}^{(k^2)} \left[ \frac{Z_1 - Z_0}{h} + \frac{\rho}{2} \left( \frac{\omega^2}{c_s^2} - k^2 \right) Z_0 \right] = 0, \tag{26} $$

$$ f_{BOT}^{(k^2)} Z_N + g_{BOT}^{(k^2)} \left[ \frac{Z_N - Z_{N-1}}{h} - \frac{\rho}{2} \left( \frac{\omega^2}{c_N^2} - k^2 \right) Z_N \right] = 0, \tag{27} $$

where the forward differences approximation was used for the top boundary condition equation (26) given the lack of points before the surface $z = z_0$, and the backward differences approximation was used for the bottom boundary condition equation (27) at $z = z_N$ for analogous reasons.

To match the solutions of different media at the interface $z = D$, continuity of pressure and displacement (normal velocity) must be imposed [3]. The first is accomplished by simply using the same variable for each system of equations at the boundary $Z_{N_{medium1}} = Z_{0_{medium2}}$. The second arises from the definition of elastic displacement and we get

$$ \frac{Z_{N_{medium1}}'}{\rho_{medium1}} = \frac{Z_{0_{medium2}}'}{\rho_{medium2}}, \tag{28} $$

to which the backward and forward differences approximations may be applied.

Regarding the Hankel function present in (19), KRAKEN implements is using the asymptotic approximation [22]:

$$ H_0^{(1)}(k_m r) \approx \frac{\sqrt{2}}{\sqrt{\pi r}} e^{-ik_m r} e^{-ik_m r}, \tag{29} $$
where $k_m$ are the horizontal wavenumbers for the modes, as well as the eigenvalues of the problem.

Finally, the only term left to calculate is the branch-cut integral. In its standard form, KRAKEN neglects it, which is a valid approximation in the far-field. However, for very shallow water and for near-field cases, this simplification may result in errors that will propagate towards the far-field. As such, there is a version of the program, called KRAKENC, which computes the branch-cut integral [26], at the cost of increased run-times. This is the version used in this work.

3.2. Numerical Solution
To solve the discretized system of equations, the eigenvalues $k_m$ of the problem are iteratively calculated by setting the matrix determinant of the system to zero and applying a root finder to the resulting equation. Next, an inverse iteration method is applied to calculate the modes [28].

Given the difficulty in solving for these eigenvalues, two root finders of varying robustness are employed. The first method, Sturm Sequences [4], is a bisection algorithm which is fail-proof, as long as there are no elastic layers in the given problem, i.e. when the sea-floor effects are not required.

Unfortunately, for the cases relevant to this work, elastic bottom boundary conditions will play an important role. The alternative method implemented for these cases is Eigenvalue Deflation [28], which is a secant-based algorithm. This method may have issues converging when branch cut calculations are to be included, which is an important factor to keep in mind when using KRAKENC.

3.3. Verification
Numerical errors are made up of a round-off, an iterative, and a discretization error[8]. The first two are related to the finite precision offered by computers when storing values (double-precision in the case of KRAKEN) and the intrinsic non-linearity of the equations being solved, respectively. The third error is associated with the numerical discretization and the resulting mesh on which the computations are performed. This is the only aspect directly in control of the end-user.

In order to verify calculation convergence, total acoustic energy $e_{ac}$, as defined by equation (30), needs to be calculated, because its conservation across different numerical meshes is one of the main properties which can indicate whether or not a problem is well posed.

$$ e_{ac} = \frac{|p|^2}{\rho c} . \quad (30) $$

If conservation is checked, local energy convergence can then be investigated, which will give an indication of the numerical uncertainty associated with the local pressure, and hence sound level. For this purpose, average values are calculated at the centre of each cell whose nodes are made up of grid points. If convergence is verified, results can then be compared to experimental data.

Numerical uncertainty can be estimated by running the same case under different mesh sizes. For this purpose, the Numerical Uncertainty Analysis (NUA) program [9] is used. This tool is able to determine the relationship between obtained results and successively finer mesh sizes, allowing the order of convergence to be studied and ideal meshes to be selected.

Given that the obtained values for the acoustic energy variable do not represent the same property as the experimentally measured Sound Pressure Level, an estimation of the numerical uncertainty relating to the Transmission Loss must be obtained. Transmission Loss between two points, represented by the pressures $p_0$ and $p_1$, is defined as

$$ TL(p_1) = -20 \log_{10} \left( \frac{p_1}{p_0} \right) . \quad (31) $$

From equation (30), we can write that the converged value of the variable, $e_{conv}$, lies in the range of

$$ e_{conv} = e_{comp} (1 \pm u_e) = \frac{[p(1 \pm u_p)]^2}{\rho (1 \pm u_p) c (1 \pm u_c)} , \quad (32) $$

where $u_e$ and $u_p$ are the numerical uncertainty associated with the acoustic energy and pressure, $u_p$ and $u_c$ are the measurement uncertainty related to density $\rho$ and speed of sound $c$, respectively, and $e_{comp}$ and $p$ are computed values. From this equation, the upper and lower bounds for the numerical uncertainty associated with pressure can be found, which can then be used to calculate the upper and lower bounds of the Transmission Loss error as

$$ \epsilon_{TL}^e = \mp 20 \log_{10} \left( \sqrt{(1 \pm u_e)(1 \pm u_c)(1 \pm u_p)} \right) . \quad (33) $$

Verification was first studied for a simple, flat-bathymetry case, with a typical sound speed profile [2] using KRAKENC. The source is placed at the origin, with frequencies ranging from 60 to 400 Hz, and numerical meshes containing 12-70 points per wavelength. The environment and the three points to be studied are illustrated in figure 1.
First, pressure convergence was studied, with local values exhibiting good behaviour and very low uncertainty levels for low frequencies as shown in figure 2. Since the output pressure field is given as a ratio relative to the source pressure, the analysed values had to be amplified for proper analysis by NUA.

However, for higher frequencies, some points started exhibiting erratic behaviour, as in figures 3 and 4.

These results illustrate the need to calculate acoustic energy and its convergence, in order to compensate for local fluctuations at individual points. Upon calculation of the total acoustic energy following the previously described methodology, all frequencies exhibited the same behaviour, as shown in figures 5 and 6, confirming convergence.

Additionally, all results exhibit second order behaviour, as expected given the finite differences approximations used.

4. Validation
KRAKEN was validated against experimental results obtained off the coast of Peniche, Portugal,
for the noise field generated by a WaveRoller device [5].

4.1. Modelling the Experiment

The computational domain is illustrated in figure 7

Measurement points were divided into two groups, called Transect-1 and Transect-2. The first consists of four points following a downward slope, along a bearing of approximately 45° due north-west. The second set of points lies due north-east at a bearing of 60°, where the sea-floor depth remains approximately constant.

Given the shallow depths present, KRAKENC has been chosen to compute the modes, as complex eigenvalues are to be expected to play an important role. In fact, the regular version of KRAKEN fails to compute any modes for various frequencies in this case.

The first step in computing the pressure field due to the WaveRoller device is to discretize the horizontal domain into a number of triangles, by way of the Delaunay triangulation algorithm [14]. Figure 8 shows the resulting computational domain, along with the approximate directions of the transects.

Since no data were available on the characteristics of the sea-bottom at the WaveRoller location in Peniche, estimates had to be obtained from documentation [29] and [24]. Table 1 collects the used values.

\[
\begin{array}{cccc}
  c_p (\text{m/s}) & c_s (\text{m/s}) & \rho (\text{kg/m}^3) & Q_p & Q_s \\
  1885 & 290 & 2.1 & 34 & 25 \\
\end{array}
\]

Table 1: Estimated properties of the sandy bottom in the experiment surroundings. The quality factor \( Q \) is defined as \( Q = \frac{\pi f \alpha}{c_s} \), where \( \alpha \) is the attenuation.

The chosen frequencies to be run were 125, 500 and 1600 Hz. The first two are the most relevant for the WaveRoller device, while the third one represents a higher frequency at which some of the normal mode model assumptions should work better. This is because, at depths of less than 30 m, the sea-floor is still very well inside the distance classified as near-field for low frequencies. At the regular water speed of sound of 1500 m/s, a sound wave emitted at 125 Hz has a wavelength of about 12 m. This may affect the nature of the eigenvalues to be found by KRAKEN and may lead to diverging solutions.

Finally, proper validation is only possible by verifying convergence of the obtained solution. As such, various mesh sizes, ranging from 12 to 80 points per wavelength, were used initially, and energy analysis followed that described in section 3.3.

Following this, a second analysis was run with fixed mesh sizes across all frequencies, ranging from 50 to 500 points per meter in depth, in an attempt to improve the obtained results. For this new case, the 2500 Hz frequency level, representing the upper limit of noise emission by the WaveRoller, was also analysed.

The problem properties are summed up as:

- **Frequencies**: 125, 500, 1600 (+ 2500) [Hz];
• Top Boundary Condition: Vacuum;

• Bottom Boundary Condition: acousto-elastic halfspace, with properties described in table 1;

• Mesh Sizes: 32-80 points per wavelength;

• Mesh Sizes for second run: 50-500 points per wavelength;

• Results grid: \( \Delta r = 1m, \Delta z = 0.5m. \)

Some qualitative solutions, along with the approximate locations of the measurement points, are presented in figures 9 and 10.

Figure 9: Cross-sectional TL plot with range and depth for the approximate Transect 1 section at 500 Hz.

Figure 10: Cross-sectional TL plot with range and depth for the approximate Transect 2 section at 1600 Hz.

4.2. Initial Solution

For the 125 and 500 Hz cases, no consistent results were obtained. In the former, KRAKEN failed to calculate any modes, while in the latter case no energy convergence was checked, with very erratic results for different mesh sizes. On the other hand, the 1600 Hz runs showed exceptional stability, with numerical uncertainty values below 3%, as exemplified in figure 11.

Figure 11: Total acoustic energy numerical uncertainty study for the approximate Transect 1 bearing at 1600 Hz. The actual value of the acoustic energy was amplified by several orders of magnitude to improve the calculation.

Even though the two most relevant frequency runs for the WaveRoller model failed to yield proper results, data were still available for the 1600 Hz band. As such, a comparison to the measured experimental measurements is provided. Using (33) together with the NUA analysis to calculate the error of the computational results, and applying a standard deviation uncertainty to the WaveRoller data, figures 12 and 13 were generated comparing both sets of results.

Figure 12: Data validation for Transect 1. Transmission Loss predicted by KRAKEN at 1600 Hz shows good agreement with experimental measurements.

Figure 13: Data validation for Transect 2. Transmission Loss predicted by KRAKEN at 1600 Hz shows good agreement with experimental measurements.

Except for T1-1, which shows higher Transmis-
sion Loss than would be expected, all other points match the measurements well. At the furthest points of each transect, values tend to diverge, but this is due to the non-existing background noise in KRAKEN.

4.3. Enhanced Solution

During the elaboration of this work, erratic behaviour was identified to be caused when the numerical mesh does not contain all sound speed profile data given as input. As such, a new set of runs was computed to attempt to fix the issues observed previously, possibly caused by the frequency scaling when automatically generating the meshes.

However, as before, the 125 Hz case failed to calculate any relevant modes, confirming that it is too low a frequency for these depths using the current methods. Near-field models, such as Green’s function algorithms, are more appropriate for distances within 5 wavelengths, as is the case at this low frequency.

As for the higher frequency cases, the results are well-behaved and converging as expected. Consequently, the data can be compared to experimental results, and this is presented, for cases with relevant new behaviour, in figures 14-16.

As in the previous section, the 1600 Hz case seems to be in good agreement with the experimental data, except for T1-3. For this point, TL levels vary greatly with depth, and it is difficult to know exactly at what depth the hydrophone was placed. Depending on this, the computational solution may agree with the measurement.

At 2500 Hz, the solution agrees well for both Transects but an unexpected measurement at T2-1, where a higher SPL was detected than at the source, makes it more difficult to draw comparisons for that point.

4.4. Results Discussion

The erratic behaviour observed was shown not to be due to mesh/sound speed profile mismatch, as it persisted in both sets of solutions. It is possible the usage of very small elements in the domain discretization is preventing the field calculation algorithm from properly matching different cells, seeing as the mode calculation itself seemed to be mostly well behaved at 500 Hz. As such, the problem seems to be manifesting when assembling the solution for the entire domain.

On the experimental side, some limitations may be skewing a proper validation of results. First of all, the sampling of a single depth point makes it hard to directly compare experimental and computational results, given their sensitivity to depth. Secondly, the cyclical nature of the WaveRoller noise generation creates a difficulty in modelling it with KRAKEN, since the program acts in the frequency domain and computes a stationary, time-independent pressure field as a result of a continuous sound source.

5. Conclusions

KRAKEN has been concluded to work fairly well even under conditions that lie outside the scope of its underlying assumptions, as shallow depths in the near-field can be taken into account through the use of the KRAKENC version of the program. While this features longer run-times, modern day computing power has evolved to the point that complex problems with fine meshes can be obtained with
the current form of the software in under one day. However, there seems to be a limit at which mode computation is just not possible, regardless of the employed methods. This seems to happen up to about 5 wavelengths in depth. At closer ranges, a point-like source is no longer a valid model.

These limitations notwithstanding, the KRAKEN normal mode program has been shown to be capable of producing results qualitatively matching those measured near marine renewable energy devices.

5.1. Future Work
At lower frequencies, perhaps the usage of finer mode sampling in depth or of larger areas for acoustic energy calculation can improve results. Neglecting low bathymetry slopes and modelling the seafloor as flat may also help.

The coupling of KRAKEN computations with near-field solutions obtained from Green’s function or parabolic algorithms may yield better results for extreme cases, and is an area of interest for future research.

Experimental measurements at more depth points would also help better understand the correlation between computations and detected values in the field.

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