Modelling and Analyses of Underwater Acoustic Signals Emitted by Marine Energy Device

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Abstract
Assessment of the 'health' of marine based electro-mechanical devices where certain types of failure modes (e.g. damaged bearings, hydraulic faults, electrical arcs, vibrations) occur is essential for companies involved in the renewable ocean energy and marine technology sectors. This directly impacts on the operation and management costs of ocean based systems, specifically impacting on efficiency / yield, reliability, and maintenance costs. This paper presents the modelling and simulation of sound signals emitted by a point absorber WEC device. One third octave band centred frequency signals in a dominant 100 Hz - 1000 Hz range were used to estimate the propagation loss as a function of range. Estimated Sound pressure level (SPL) values from finite element (FE) models with different surface interfaces were compared to measured values from the WEC device. Rough surface interfaces of the FE models were seen to contribute significantly towards the propagation loss of the sound signals in an acoustic domain. It was also estimated that increase in the root mean square (rms) height of the rough surface led to significant increase attenuation and propagation loss. This study contributes to the knowledge of parameter effects in an acoustic environment, which is useful in the understanding and informed prediction and performance of idealized underwater acoustic models.

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1. Introduction

Assessment of the 'health' of marine based electro-mechanical devices where certain types of failure modes (e.g. damaged bearings, hydraulic faults, electrical arcs, vibrations) occur is essential for companies involved in the renewable ocean energy and marine technology sectors. This directly impacts on the operation and management costs of ocean based systems, specifically impacting on efficiency / yield, reliability, and maintenance costs.

In shallow water environments, attenuation/transmission loss by bottom surface, scattering, wave interactions and boundary effects are important factors in understanding acoustic signal propagation. Attenuation of underwater acoustic signals is caused mainly by their geometric spreading. Other factors causing attenuation include surface interactions and the absorption of sound in sea water. The absorption of sound in sea water with an absorption co-efficient (α) is dependent on temperature, frequency, depth, salinity and acidity (Fisher & Simmons, 1977). Underwater acoustic models are important when it comes to the understanding and estimation of both active and passive sound navigation and ranging.

An idealized predictive medium for modelling and simulation of underwater sound propagation incorporates the spreading, absorption, and scattering loss mechanisms exhibited by underwater acoustic signals during propagation. Ray theory, normal modes, parabolic equations and couple modes are all current methods used to simulate underwater acoustic propagation and loss. The aforementioned methods, however, neglect scattered energy from the interfaces at angles which are close to normal, thus making the finite element (FE) analysis method a benchmark for approximation as discretization density increases (Isakson & Chotiros, 2011).

In this paper, Comsol FE analysis package is used, this package is capable of coupling different physical domains such as the solid and fluid domains, and approaching the exact solution of the Helmholtz equation. This paper presents a FE model that simulates the emission and analyses of acoustic signals produced by a wave energy device to aid the diagnosis of any of the aforementioned failure modes. We model the propagation of the acoustic signals produced by this device taking into account its boundary conditions such as the bathymetry of the deployment site, properties of the propagation media, type of spreading of the acoustic signal and the interaction with the surface and bottom interfaces of the acoustic environment. The results show the effect of varying surface interface roughness on the sound signal emitted by the wave energy device and it's attenuation with respect to distance.

1.1. Wave Energy Converter and Noises

The acquisition of acoustic signatures for WEC devices from their associated primary operational components such as turbines, generators, hydraulic components (pumps and valves), moving parts such as hinges and actuators, without actual field measurements is not trivial. Secondary noise sources associated with these devices include noises from cable vibration, cavitation noises and noises from water impinging on these devices.

To quantify the noise radiated by WECs, ambient noise present at the site in the absence of any WEC is usually characterised in both ebb and flood conditions

(Broudic, Croft, Willis, Masters, & Sei-Him, 2014; Miles R Willis, 2011). One of the earliest noise measurements in the direct vicinity of an operational WEC was carried out in the Bristol Channel on marine current turbines. An SPL value of 166 dB re 1 µPa at 1 m from the source (using a simple spreading law) was measured. It is important however to take caution during the interpretation of this effective source level (using the spreading law), since there might be interference effectively leading to large fluctuations in sound pressure level at short distances from the source (Richards, Harland, & Jones, 2007). A full scale point absorber, the Danish Wavestar WEC, was measured to emit 106 - 109 dB re 1 µPa in the 125 Hz to 250 Hz frequency range, which was 1 - 2 dB above ambient levels in October of 2012. Highest sounds signal emitted by this device was at 150 Hz frequency with a corresponding SPL value of between 121 - 125 dB. This was present from the hydraulic pump of the device during start-up and shut-down of the converter (Paul Lepper, 2013). Harmonic acoustic components associated with rotational speed of turbine and impulsive noise associated with increased air pressure within the air chamber, was obtained from a wave energy oscillating water column device in Portugal in 2010. SPL values measured for the harmonics at different rotational speeds of the turbine blades were highest at 126 dB re 1µPa 10m from the device (Sofia Patricio, 2012).

The characteristic noises emitted by WECs differ between different WEC concepts. In the full scale point absorber type WEC which is represented by the point source in this study, noise types include transient noises originating from the activities of the translator and stator components as demonstrated by Haikonen *et al* (Haikonen, Sundberg, & Leijon, 2013). The amplitudes of the sound signals by these components are dominant in the frequencies below 1000 Hz ranging between 118 and 155 dB re 1µPa, with peak amplitudes at 100 Hz and 300 Hz.

2. Fe Modeling And Simulation

The FE analysis involves finding the solution to the Helmholtz eqn. (2) which stems from the reduction of the wave eqn. (1). In this document only a summary of the derivation of the equation is provided, however, an exhaustive method for the derivations can be gotten from reference (Ihlenburg, 1998).

$$\frac{1}{\rho_0 c^2}\frac{\partial^2 p}{\partial t^2} + \nabla \cdot \left(-\frac{1}{\rho_0}\nabla p + q\right) = 0 \qquad (1)$$

From eqn. 1 p is the acoustic pressure, ρ_0 the fluid density and q an optional dipole source. A time-harmonic wave $p = p_0 e^{iwt}$ is substituted into eqn. (1) to obtain the Helmholtz eqn. (2).

$$\Delta p + k^2 p = 0 \qquad (2)$$

Eqn. (2) describes a harmonic wave equation propagating in a medium with an assumption of no dissipation of energy. P is the sound pressure amplitude and k is the wave number which is related to angular frequency

$\omega = 2\pi f$ and speed of sound c_s as shown in eqn. (3)

$$k = \frac{\omega}{c_s} \tag{3}$$

The homogeneous Helmholtz equation is thus derived by substituting (3) into (2) to give eqn. (4).

$$\nabla \cdot \left(-\frac{1}{\rho_0}(\nabla p)\right) - \frac{\omega^2 p}{\rho_0 c_s^2} = 0 \tag{4}$$

Sound signals radiate from a point source with the energy emitted at a given time diffusing in all directions as described by eqn. (5)

$$\nabla \cdot \frac{1}{\rho_c}\left(\nabla p_t - q\right) - \frac{k^2 p_t}{\rho_c} = 2\sqrt{\frac{2\pi P_{ref}\, c_c}{\rho_c}} \tag{5}$$

From eqn. 5, P_{ref} the reference pressure and c is the speed of sound in the medium.

2.1.1 Mesh/Length scale/Timescale

To allow for adequate convergence of the solution, triangular mesh elements were used to resolve the wavelength of the smallest sound signal into fractions as shown in Fig 1. The maximum mesh size was given as thus: mesh $(h)_{max}[m] = \lambda/_8$ where $(\lambda)[m] = c/_f$, with time scale$[s] = 1/_s$. Where, $c\ [ms^{-1}]$ is speed of sound and $f[Hz]$ is frequency.

2.2 Pressure Release Surface & a Perfectly Matched Layer

The upper boundary for the acoustic domain was modelled as a pressure-release surface (Katsnelson, Petnikov, & Lynch, 2012). This pressure release surface is depicted in Fig. 1. This boundary surface assumes a Dirichlet boundary condition (Pierson/Moskowitz spectrum at 10.3 m/s). To reduce reflections at the boundaries, perfectly matched layers were used to truncate the infinite domain. These layers were at least twice the size of the biggest wave length.

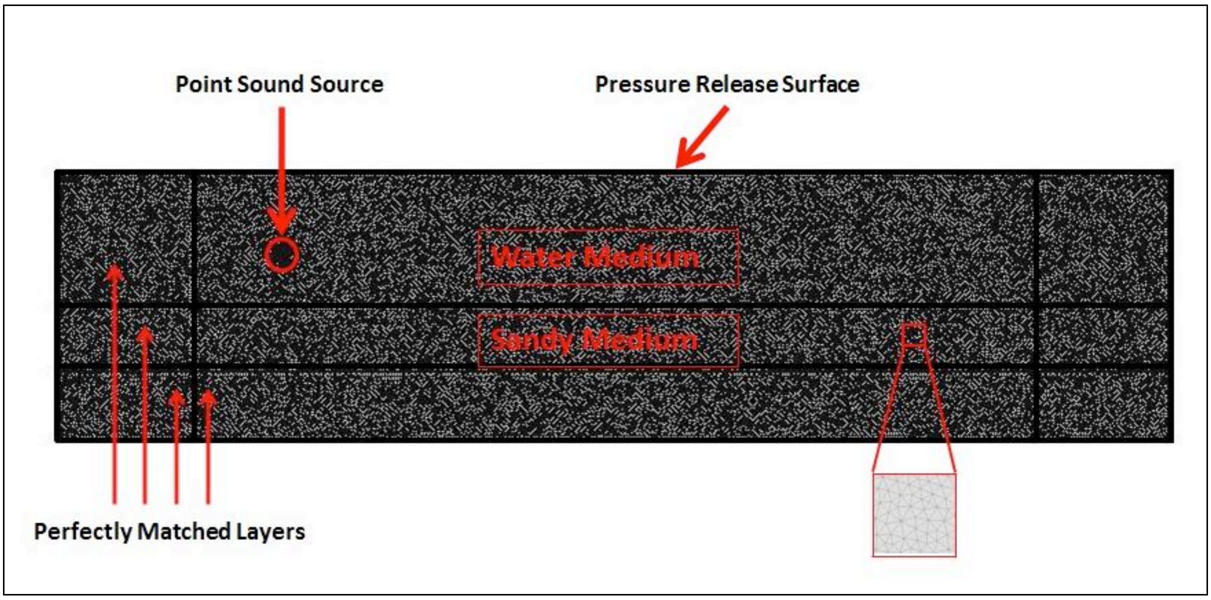

Fig. 1: Model geometry showing the different media, perfectly matched layers and pressure release surface. Zoomed in mesh shown (inset)

3. Problem Description

Sound is assumed to propagate spherically in a homogeneous acoustic medium from a point source. The mix winter Pekeris water sound speed profile is used together with other parameter values shown in Table 1.

Table 1: Acoustic parameters and properties used in the models

Parameter/Material	**Value**
Water	Density (ρ), 1029 [kg/m^3] Sound speed (c), 1500 [m/s]
Soil	Density (ρ), 2500 [kg/m^3] Sound speed (c), 1000 [m/s]
Source depth	24 [m]

Theoretical plots of frequencies against range are shown in Fig. 2 for the Spherical spreading and attenuation loss of sound signals in an acoustic medium using the simple propagation loss (PL) eqn. (6). This formula is widely used to evaluate the performance of underwater acoustic systems (Katsnelson, et al., 2012).

$$- PL = - 20 \log R - \alpha R \quad (6)$$

From eqn. 6, R is the range from the sound source and α is the attenuation coefficient which is calculated using the temperature, depth, and salinity and acidity parameters.

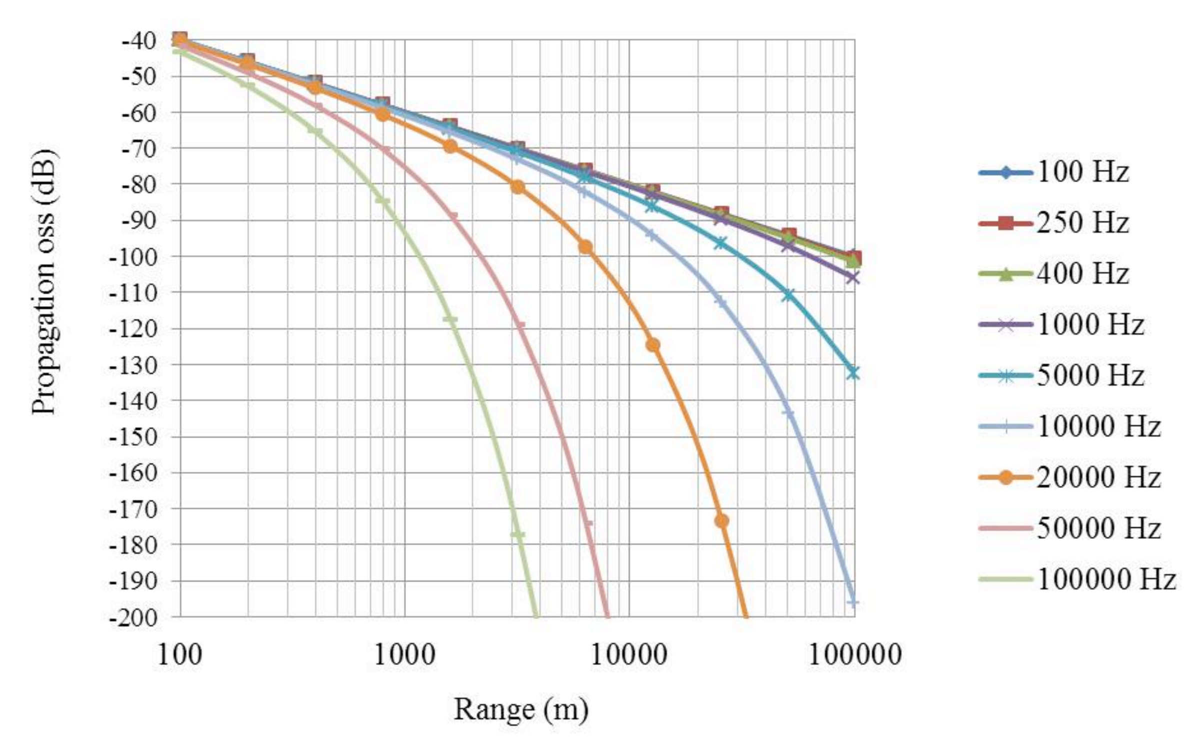

Fig. 2: Theoretical propagation loss - PL = - 20 log R – αR of frequencies as a function of range. Using Francois and Garrison absorption coefficient (α) with conditions: Temperature = 10^0C, Salinity = 35 p.s.u. and depth = 24 m.

Fig. 2 depicts the theoretical propagation loss of the amplitude of signals with respect to range and frequency components. Higher frequencies attenuate faster in an exponential manner, with very low frequencies having the capacity to travel further. However, more idealised propagation models require the incorporation of other propagation parameters including interfaces generating multiple concurrent paths and scattering. The models in this study therefore incorporate this other parameters and their estimates towards the propagation of sound. Table 2 details the different parameters of the models considered for analyses.

Table 2: Models used for simulation

Type	Water/Air Interface	Sand/Water Interface
Model 1 (Control)	Flat	Flat
Model 2	Rough	Rough
Model 3	Rough(Smaller)	Rough

4. Results

Analyses were carried out amongst the 3 different models. Model 1 is assumed to be the control model with no surface interface roughness, model 2 has a bigger surface interface roughness corresponding to approximately the root mean squared (rms) height of the acoustic wavelength (λ_{rms}), and model 3 a smaller surface interface roughness (0.13m λ_{rms}). One third Octave band centred frequencies 125 Hz and 1000 Hz were used. These give the limits for the frequencies range for which the amplitudes of the sound signals normally emitted by the WEC device under study are most dominant.

4.1 Analysis of Fe Models

Analyses on the FE models show a general decrease in sound pressure levels (SPL) as the sound signals propagate away from the source. Fig. 3 shows the SPL values for the three different models for an approximate range of 3000 m at 125 Hz and 1000 Hz frequency values. It is observed that as frequency values increases, the rate of attenuation of SPL increases. And this is consistent with the theoretical analysis (See Fig. 2).

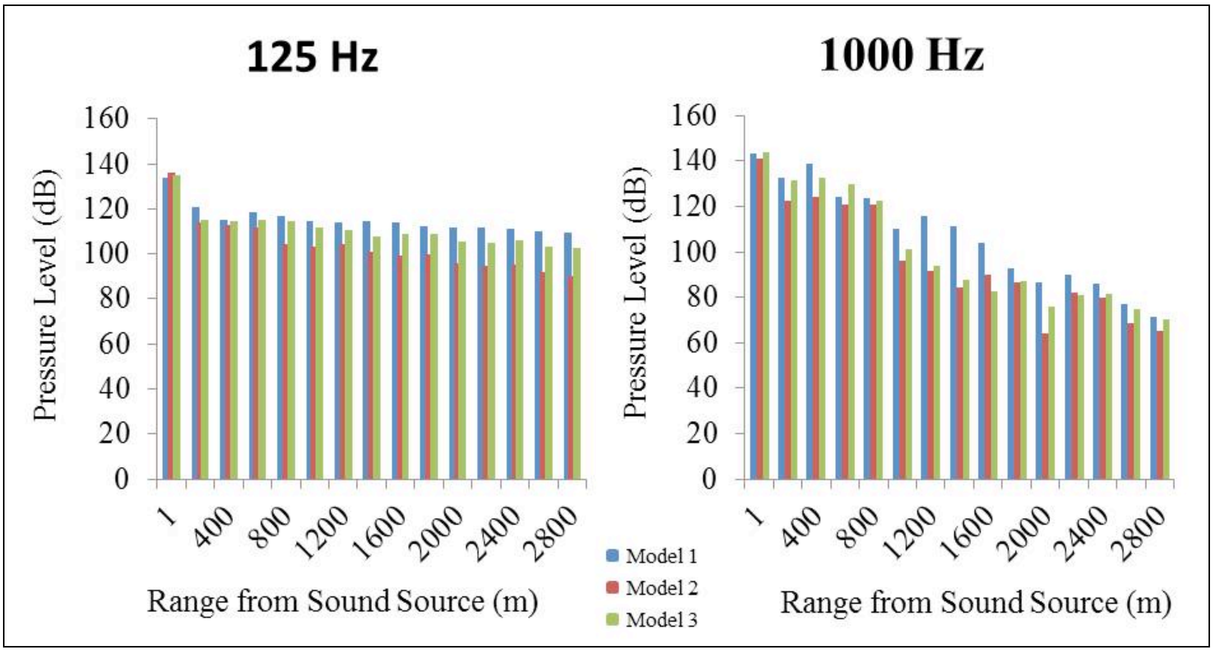

Fig. 3: Attenuation of sound as a function of frequency and range for the different models. Models exhibit the same characteristics as theoretical models with respect to frequency against range.

It is also observed that the models (2 & 3) with the rough surface interfaces attenuate more sound signals than the model (1) with the flat surface interfaces. Model 2 with bigger surface roughness attenuates more sound signals than model 3 with smaller surface roughness.

4.2. Analyses of Experimental Values

Evaluation of sound propagation loss of 1/3 octave centred frequency sound signals emitted from a point absorber device was estimation at 100 m and 1000 m from the sound source, in the 100 Hz to 1000 Hz range. The acquisition of this acoustic data from the WEC device was part of a study by Haikonen *et al* (Haikonen, et al., 2013). The parameters such as depth of the device for the acquisition of the data from the WEC are similar to those incorporated into the models in this study. Fig. 4 shows attenuation of sound signals emitted by the WEC in the 100 Hz to 1000 Hz frequency range. The signals in this range have the greatest amplitude.

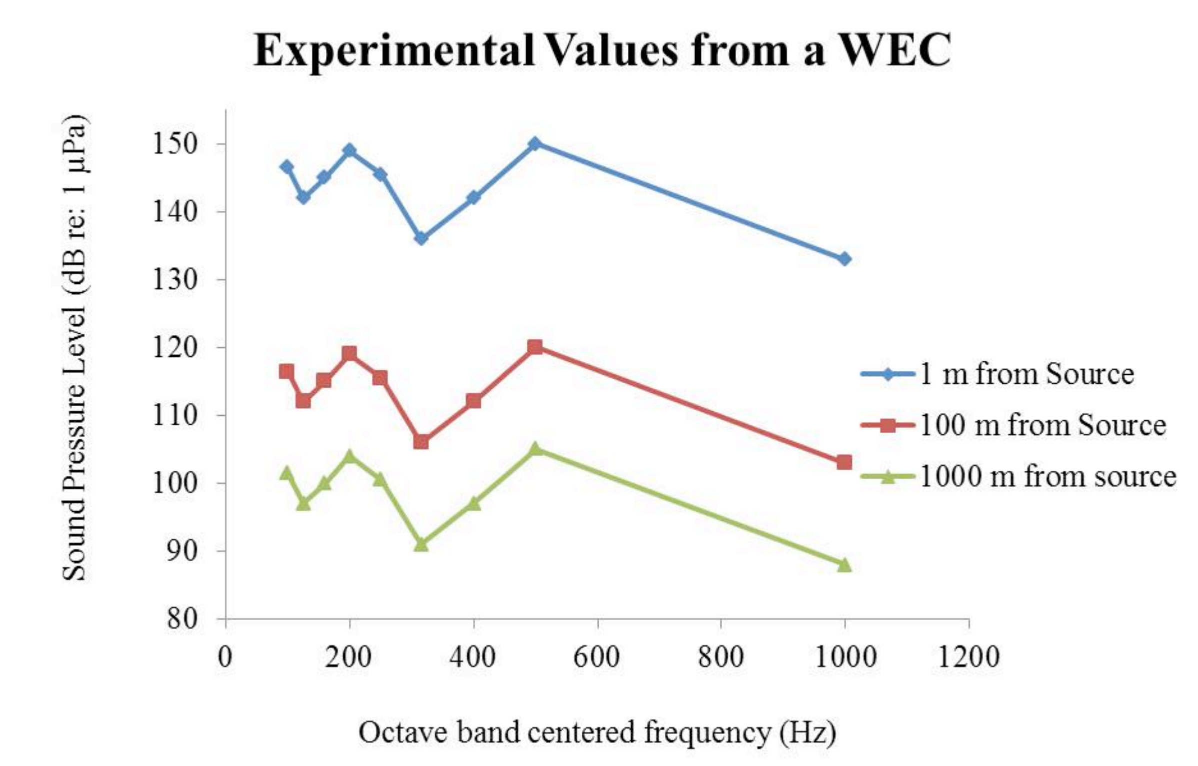

Fig. 4: Propagation loss of 1/3 Octave band centred frequency from a point absorber WEC. Sound source is at a depth of 24 m and the dominant frequency amplitudes are in the 100 Hz to 1000 Hz frequency range.

It can be seen from Fig. 4 that the overall SPL values decrease as the sound signals propagate away from the source. The propagation loss eqn. (6) was used in the estimation of the values at the different point. However, it is important to note that the attenuation loss coefficient was not accounted for during extrapolation due to lack of availability of the attenuation loss factors from the site during measurement.

Comparative analysis of values obtained from models 1 & 2 was carried out against estimated experimental values from the device. Fig. 5 depicts the values estimated at 100 m and 1000 m distances from the sound source. Model 2 provides a closer fit to the estimated measured values from the WEC device in terms of attenuation. This indicates that the increased roughness of the interface of model 2 contributes significantly to the propagation loss of the sound signals.

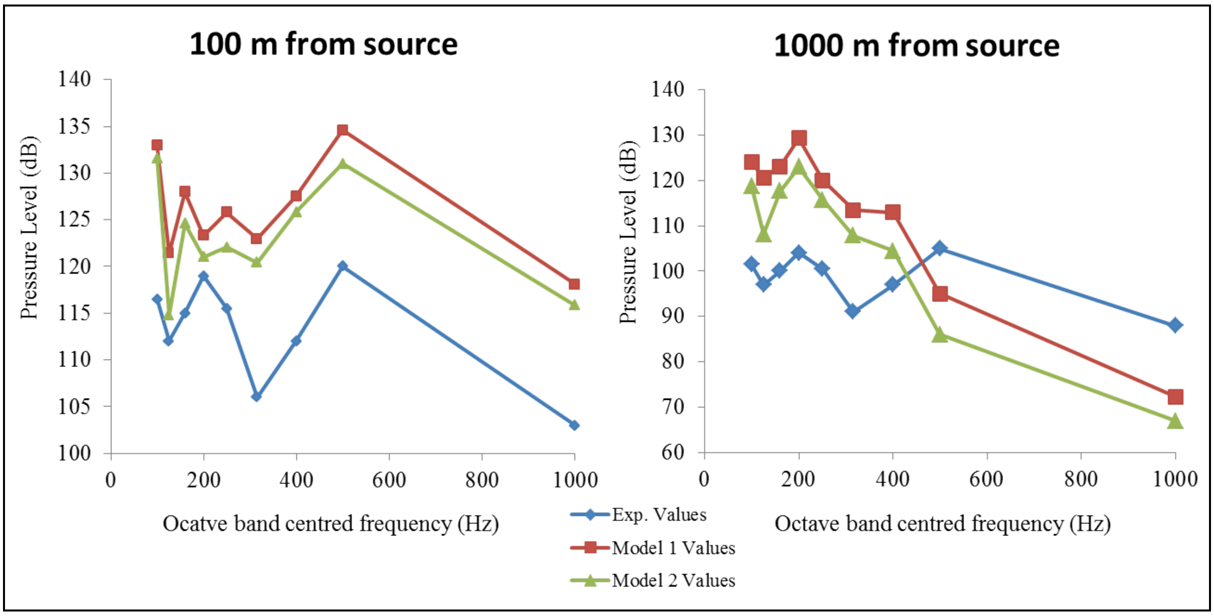

Fig. 5: Propagation loss of models 1 & 2 against estimated experimental values. Model 2 with rough surface interface exhibits more attenuation of sound signals and gives closer results to experimental values.

5. Summary

The modelling and simulation of acoustic wave propagation in an acoustic environment with different surface interfaces was carried out in this study. Spreading loss, attenuation loss due to domain properties such as temperature and density, together with losses due to scattering and interaction of waves were incorporated into the 2-D models. Results showed an increase in attenuation of sound signals as frequencies increased in all models, which is consistent with theoretical calculation of attenuation as a function of distance and frequency components. Models with roughness on the surfaces exhibited more.

5.1 Limitations

Most modelling and simulations are carried out in a 2-D domain due to computational power constraints. Implementation of a 3-D domain for simulation suggests a more idealistic representation. Sound directionality is an important factor for the modelling of sound. Sound sources are generally represented by sources which radiate signals in an omnidirectional pattern. However, this is not the case with most sound emitting sources. Incorporation of different sound speed profiles in underwater acoustics models also has an effect towards the analyses of sound propagation and loss. Lastly, single WECs do not emit a high level of noise. The deployment of an array may generate a concerning level and this should be considered in future modelling (Patrício, Moura, & Simas, 2009).

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