ON THE BANDGAP THEORY OF HEARING IN THE ATLANTIC BOTTLENOSE DOLPHIN

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1 INTRODUCTION

Since the observation of sonar in bats in early 1912 by Maxim and then the discovery of sonar in cetaceans in by McBride in 1947, humans have been interested in the performance capabilities and mechanisms of these naturally evolved biosonar systems. This work has shown that dolphins, in particular the Atlantic bottlenose dolphin (*Tursiops truncatus*) have very versatile sonar systems with excellent target discrimination in shallow water, highly reverberant, environments. This sonar system is often quoted as outperforming man made systems [1]. Knowing that these capabilities are achievable has lead to extensive research into exactly how the dolphin system operates within the dolphin physiology and into the types of neurological signal processing being implemented. It is hoped that this research will help to improve man made systems and further humanities understanding of underwater acoustics.

This paper looks at the reception of sound via the lower jaw bone of the Atlantic bottlenose dolphin as there is currently a large body of research to support the role of the lower jaw bone in sound reception. In many odontocete species the lower jawbone is a hollow structure filled with fatty tissue which forms an acoustic path to the tympanic bulla of the middle ear. The reception of sound through the jaw was first suggested by Norris in (1964) [2] and was supported by electro-physiological studies conducted by Bullock (1968) [3] and McCormick in (1970) [4], where the Audio Brainstem Response was evoked from an animal when a sound source was placed upon the lower jawbone and tooth. This work was furthered by Brill (1988) [5] who demonstrated that the animal failed to echolocate when the lower jawbone was acoustically shielded even though the outgoing sonar signals remained mostly unchanged. The actual mechanism by which sound enters the lower jaw has been heavily debated including speculation by various researchers that the teeth may play a role in the receiving system. For this paper we will assume that sound enters the jaw at the front edge and travels along the hollow channel of the jawbone. We will examine the effect of the teeth within the lower jawbone as the sound propagates along the channel, using the Transmission Line Modelling Method (TLM). TLM has been used in acoustics for a number of years and has been verified to be an equitant to finite difference time domain modelling with the advantage of being quicker than other volume element methods [6], one advantage of time domain modelling is that a time domain wave form can be extracted from a single simulation run which contains a board band frequencies

2 BACKGROUND THEORY AND MODELLING

2.1 Acoustic band gaps and the applicability to dolphin teeth

When periodic arrays of elements are present in a structure it is well known that in certain frequency bands dispersive behaviour can be observed [7]. It is possible to design such a structure in order that for certain bands, wave propagation is heavy attenuated, and hence the term ‘band gap’ is often applied. Band gap structures are a familiar concept to solid state physicists and, more recently, to designers of electromagnetic band gap (EBG) materials. In acoustics the experimental observations of Robertson et al. [8], have demonstrated the existence of acoustic stop bands or band gaps within a periodic scattering array of long cylindrical metallic rods. It was demonstrated that if the rods are placed in a square or triangular lattice with a volume filling factor of greater than 0.3 then an acoustic band gap can be sustained. The filling factor, F, for a square lattice can be calculated by Equation 1, where a is the separation between centres of adjacent elements and d is the diameter of the cylindrical rods.

$$F = \frac{\pi d^2}{4a^2} \tag{1}$$

Furthermore this work shows that the centre frequency f_c of the acoustic band gap can be predicted from the periodicity of the lattice geometry by using Equation 2, where u is the speed of sound propagation in the medium surrounding the rods.

$$fc = \frac{u}{2a} \tag{2}$$

The observations by Goodson and Klinoska [9] that the teeth in the lower jaw form a periodic structure with an almost uniform separation of 11.4 mm, have lead us to consider the existence of acoustic stop bands within the dolphin hearing system. Previous work carried out [10] has revealed the speed of sound in the lower jaw bone of a deceased adult Tursiops truncatus with out any flesh or fatty materials present, is approximately 2600 m/s which is considerably higher than that of water. This would result in a boundary condition which could act as an acoustic wave guide to any sound trapped inside the hollow bone channel. This work was also able to show that the speed of sound within an individual tooth is between 2200 m/s and 3380 m/s, this would again give a considerable impedance boundary between and sound travelling in the hollow bone channel and the tooth. Once in this channel the sound would have to travel down the hollow channel that is made up from various fatty lipids as has been shown by Koopman *et. al* [11]. This work shows that the lower jaw is more complex than first thought, in that the jaw is not just made up from a single fatty material, but from many compounds which are known to have differing sound velocities in much the same way as the melon does. These different sound velocities might serve to direct the sound around the contours of the jaw bone. If this is the case then assuming that the sound is actually travelling in a straight line at uniform speed would not be far from the actual situation.

From this evidence we can hypothesise the sound transmission path to be one where sound enters the hollow cavity of the jaw bone near the rostrum of the animal, travels along the fatty sound channel, which is filled with teeth that are periodically spaced, and sat within a wave guide and is then projected towards the ear. Using CT data that has been made available to us by the US Navy, which was originally taken by Houser *et al*. [12], we have been able to examine how a tooth is sat in the gum and jawbone of a dolphin. A small cross-section of the left side of a lower jaw bone and the rooted section of a tooth can be seen in Figure 1. This picture shows the peg and socket nature of the dolphin tooth. The tooth is held in place by the gum and a soft bone structure that doesn't show up on this image due to its low density. From the header information in the CT images, it is possible

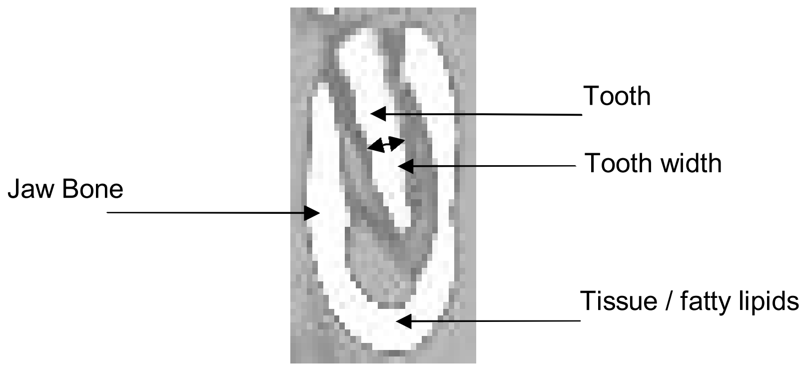


Figure 1. CT cross section of the lower jaw bone and tooth of a bottlenose dolphin.

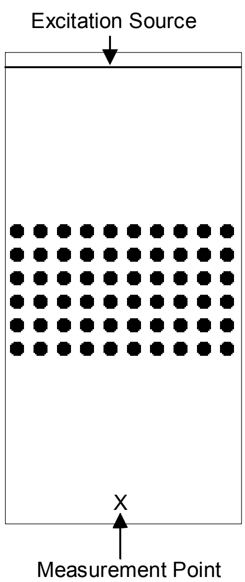
to convert the number of voxels into real measurements where each voxel represents 0.6836 mm of space in each coordinate direction. Using this we can estimate the internal width of the channel to be between 8.9 mm and 11.6 mm. Further to this the diameter of the tooth is approximately 4 mm, which is confirmed by measurements by with Vernier callipers on a tooth taken from the lower jaw of a bottlenose dolphin. With this information it is possible to construct a two dimensional model of the tooth structure within the jaw bone.

2.2 Numerical modelling technique

The Transmission Line Modeling (TLM) method is a time domain, differential numerical modelling technique ideally suited to the study of field problems [13]. It has found many applications including those within the field of bioacoustics [14, 15] and is broadly comparable with the finite difference method in the time domain [16]. TLM exploits the analogy between waves propagating in the acoustic field and pulses propagating on an orthogonal mesh of interconnected transmission lines. These transmission lines are governed by differential equations which are isomorphic to those that of the transmission medium and thus the network can model the propagating waves. The equivalence of the transmission line model with the linearised Euler equations in acoustics can be proved mathematically and consequently it is possible to conceptually manipulate just the transmission lines. An additional advantage of applying transmission line equivalents is that stability criteria are guaranteed to be met when the model includes only passive electrical components. Typically TLM is applied to a structured arrangement of cubic or parallelepipedic cells (‘the mesh’) which are individually termed nodes.

3 TWO-DIMENSIONAL NUMERICAL MODELS

3.1 Validation example: Infinite arrays



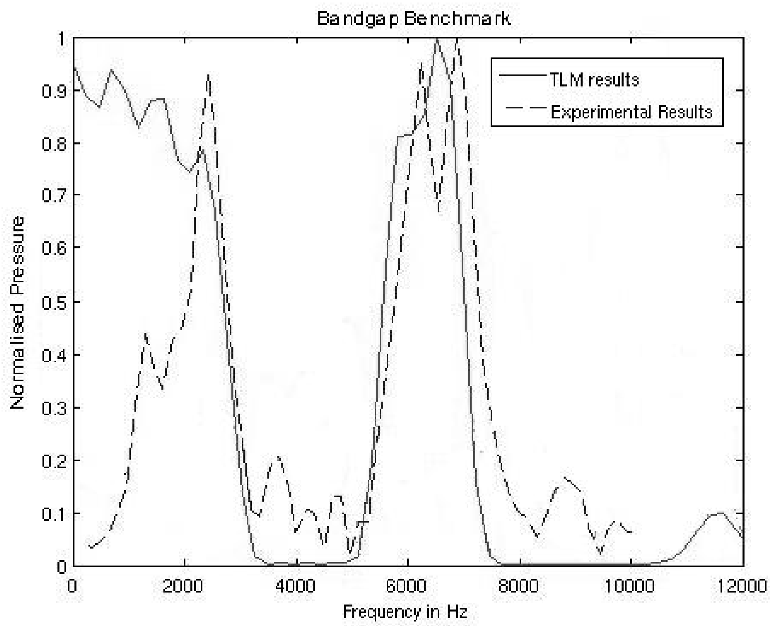


Figure 2. Benchmark TLM Geometry

Figure 3. TLM modelling results compaired with experiment performed by Robertson *et al*. [8]

Custom TLM software was produced and used to model the scenario described. Before the TLM software could be used on the main scenario it was first verified against a variety of benchmarks, in particular it was verified against the experiment performed by Robertson *et al*. [8], a series of rods were spaced to replicate the spacings and diameters used, this setup can be seen in Figure 2. The results for this bench mark can be seen in Figure 3. The source for the benchmark experiment was a Gaussian plane wave which excited frequencies from near dc up above 10 kHz. The scale of the experimental data has been normalised between 0 and 1 for easier comparison to the TLM results. All TLM results are normalised against a mesh of exactly the same size with source and measurement points kept constant, but with the rods removed. These results show very good correlation with the experimental evidence. The low frequency roll off below 2 kHz in the experimental results is due to the frequency response of the speaker used. The higher frequency band gaps appear to correlate well and the tail off above 8 kHz is very similar. This demonstrates that TLM is a useful modelling technique when looking for acoustic stop bands.

3.2 Finite waveguide models

3.2.1 Basic model set up

Figure 4 shows the experimental set up that was used for the hypothesised model.

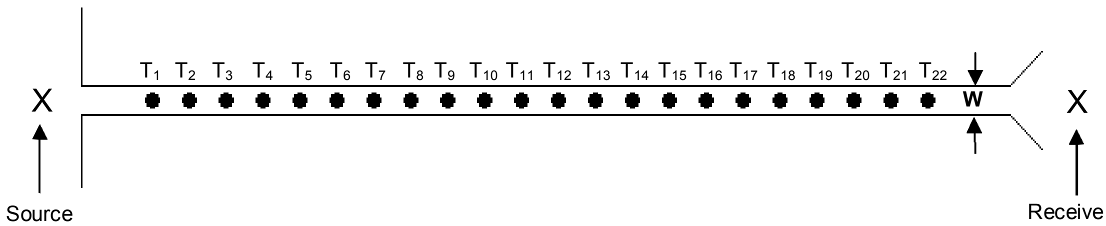


Figure 4. TLM Geometry

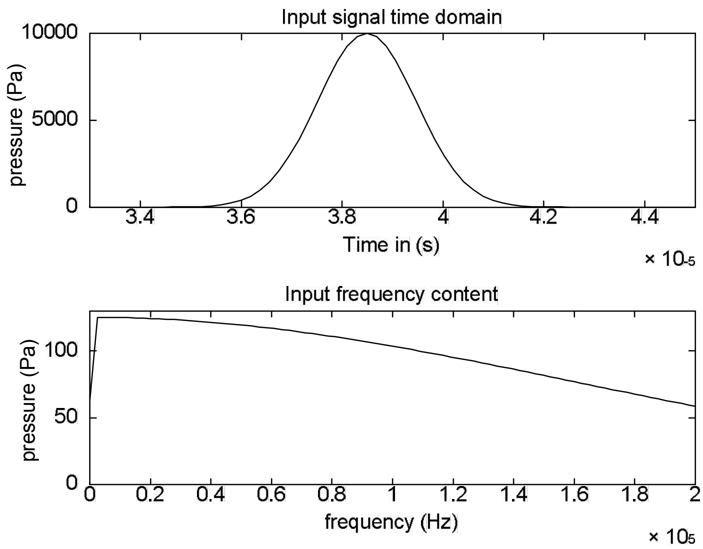


Figure 5. Time domain excitation signal and frequency spectrum

A Gaussian signal, which is shown in Figure 5 in both the time and frequency domain, was injected as a point source on the left hand side of the simulation mesh centred upon the centre of the jaw, and transmitted along the waveguide. The measurement point is at the far right of the mesh. The input sound signal was chosen as it allows a wide band of frequencies within the outgoing dolphin click to be simultaneously modelled. A horn with a 45^o angle was used at the exit end of the simulated jaw bone to increase directivity and to simulate how the sound might pass from the jaw into the ear in the actual dolphin. An absorbing boundary condition was applied to the outer surface of the mesh to simulate the wave propagating into free space without back reflections. The black objects that can be seen in Figure 4 represent a solid scattering surface in which the wave is reflected away while maintaining its phase. The mesh was constructed with a node size of 0.5 mm which given the assumed sound speed of 1500 m/s allowed a maximum modelling frequency of 300 kHz. This scaling factor was chosen in order to allow the teeth to be modelled as circular objects although a larger node size would have modelled the frequencies of interest but would have impacted the quantisation of the physical objects. In order to solely show the effect of the teeth on the model, a simulation was run with the teeth in place and was then re-run with T_1-T_{22} removed. The output signals were converted to the frequency domain using a 2048 point DFT and then normalised. To normalise the signals the magnitude of the signals with the teeth present was divided by those of the signal that did not have the teeth present. As the width of the hollow fatty channel is not constant we repeated the experiment for a range of channel widths (7.5 mm 9.0 mm 10.5 mm 13.5 mm 16.5 mm), in order to study the effects on the band gap structure.

Results

Figure 6 shows the normalised effect of the teeth upon the transmission of sound through the sound channel with a number of different widths.

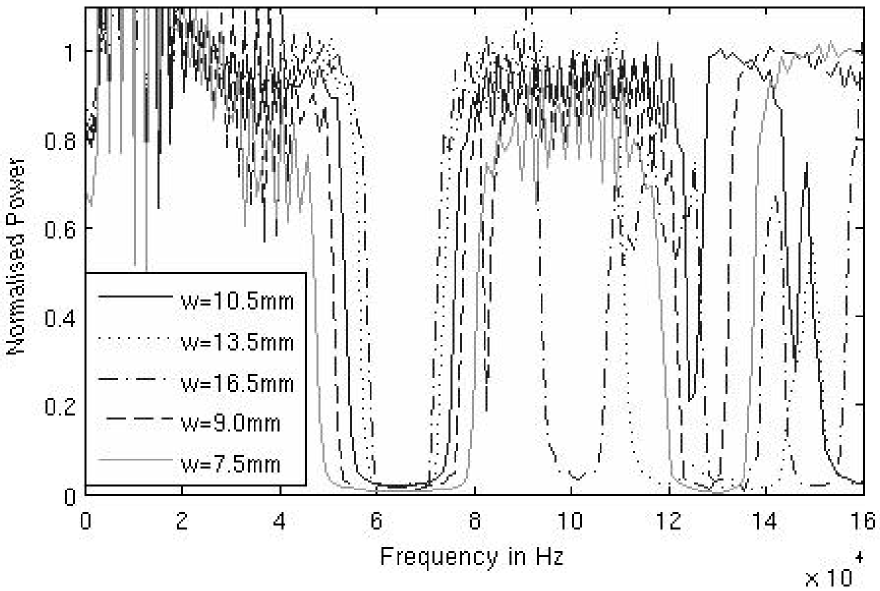


Figure 6. 2-D band gap structure for the hypothesised tooth model for a range of widths.

For all widths it can be seen that there is a stable band gap centred upon 65 kHz. This is close to the theoretical value that can be calculated by utilisation of Equation 2 which is 68 kHz. However less stability was observed in the secondary band gap that is formed at approximately 120 kHz. This band gap either continues for the rest of the hearing band or allows passage again at 135 kHz. This filter effect could serve to increase signal to noise ratio by filtering out unwanted lower frequencies whilst still allowing those of interest to propagate to the ear. The ringing that can be seen in the pass band on the graph is due to the simulation output being substantially in the near field of the scattering array and its proximity to the absorbing boundary.

3.3 Finite model with teeth removed

3.3.1 Model set up

One further effect that was examined was the effect of the band gap when some teeth are removed from the jaw. In order to model this effect, a new simulation was laid out as in Figure 4 but this time various combinations of teeth were removed. The same input signal was applied and the same analysis techniques were used as for the previous experiment. A typical result for the model where T_4, T_7, T_{10} T_{11} and T_{19} have been removed is shown in the following section.

3.3.2 Results

The results shown in Figure 7 demonstrate that the band gap is sustained and still centred about 65 kHz, however it shows attenuation in what was previously the pass band of the echolocation frequencies. This would imply that the dolphin would suffer a decrease in signal to noise as a result of loosening teeth. What is also apparent is that when all the teeth are removed a plane wave can pass directly down the channel without and filtering occurring, this would still allow the dolphin to echo locate however might impair the processing due to the increase in background noise.

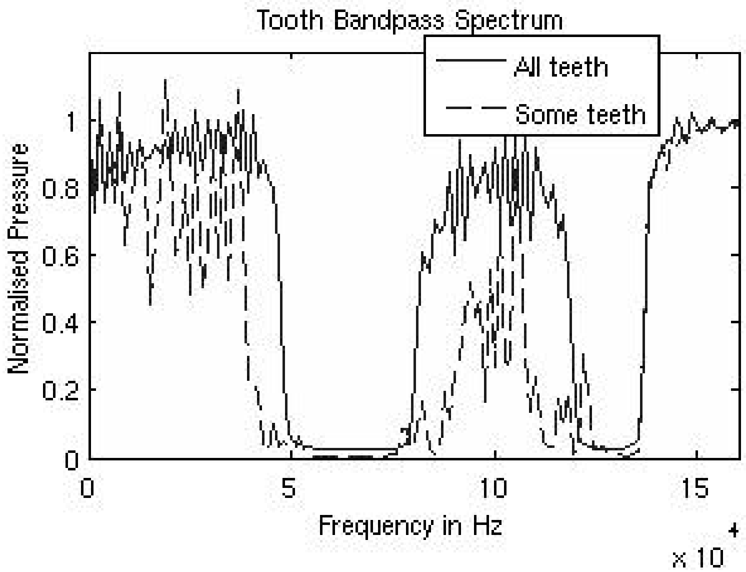


Figure 7. A typical result for removing some teeth from the jaw model. W=7.5mm

The 2-D results look reasonably convincing and well defined however it is clear from the CT slice shown in Figure 1 that the 2-D simulation is not applicable to the entire depth of the hollow channel, as the tooth is not present for the full depth of the channel, nor is it infinitely long as has been assumed in the 2-D case.

4 THREE-DIMENSIONAL MODELS

Further modeling was carried out using a 3-D version of the TLM software used in the previous simulation. The model depicted in Figure 8 shows the basic setup where rods of similar length to the tooth are contained within a solid channel. The height of the channel is 34 mm and the height of the rods was 25 mm. These dimensions were measured from the available CT data, however the depth of the channel and the depth of tooth penetration varies along the entire jawbone. The channel width was 9 mm, and the rod diameter was 4 mm as in the previous experiments. As before two measurements were taken and a normalised output showing the effect of the teeth was produced. The results can be seen in Figure 9.

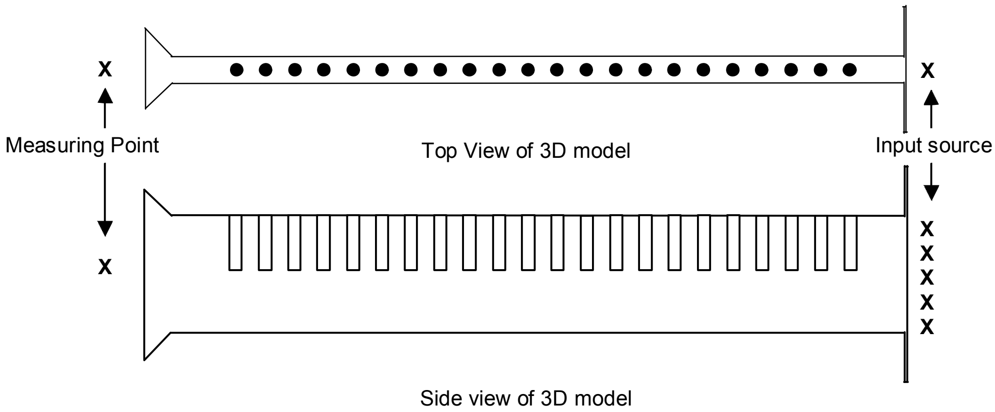


Figure 8. 3-D TLM model of a simplified dolphin lower jaw.

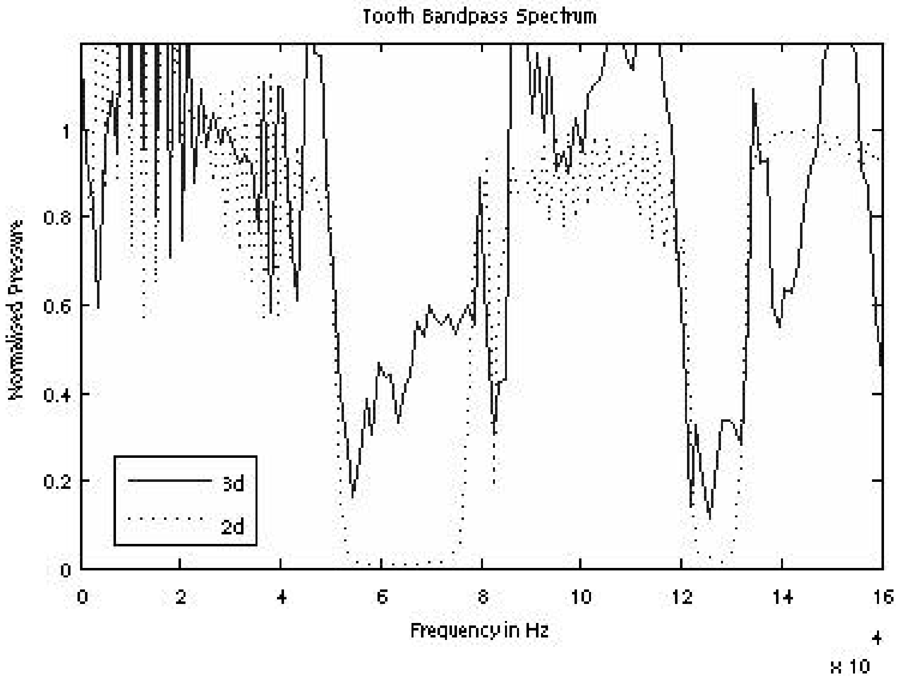


Figure 9. 3-D simulation results compared to 2-D results were channel width is 9 mm.

Although the band gap is less defined there is still a clear stop band between 55 kHz and 75 kHz. From this it can be seen that the band structure follows the 2-D version well, meaning the properties identified earlier are still applicable. The 3-D model still contains the same artefacts in the pass band that are due to the numerical modelling and the boundary conditions used.

5 CONCLUSIONS

If this hypothesis is correct then we have presented clear evidence of the existance of an acoustic band gap which could be used in further signal processing to aid target localisation and improve signal to noise. However this band gap may be further influenced by the presence of resonant frequencies within the rods (teeth) [10].

ACKNOWLEDGEMENTS

The authors would like to the Dorian Houser of Biometica for providing the CT data that aided in this paper.

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