BIOINSPIRED ANTENNAS BASED ON ACOUSTIC ANIMALS

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1 INTRODUCTION

There has been recent interest in the acoustics of the hearing of echolocating animals such as bats and dolphins and how to improve human-made sensor performance by mimicking their functionality [1, 2]. The lower jaw bones, soft tissues and dentition of some dolphin species have attracted much attention and their role in echolocation has been a subject of much research interest and debate [3-7]. There are now numerous research papers which seem to suggest a significant role of the jaw and teeth in the auditory path. Mimicking the functionality of these teeth is therefore an interesting and potentially important research area. It is well known that many dolphin species have fairly evenly-spaced teeth and that these are seated within porous bones filled with fats. Furthermore the jaw bones themselves are filled with lipids and there is a growing body of evidence that these too are acoustically significant. The present paper considers this fatty structure and the possibilities for biomimicry in another domain and application - that of an electromagnetic antenna. The structure that will be considered is an antenna found in many households around the world - the Yagi-Uda. This device has been very highly optimised and the method of positioning of the parasitic elements within its structure is well established. The objective of the current paper is to examine the acoustic structure and to draw analogies with the intention of improving the design of the antenna.

The Yagi-Uda antenna is a travelling wave device and is an ideal candidate for bimimicry. No simple analytical formulation is provided for the element spacing, though in practice like in the dolphin they are approximately even-spaced. Another reason for selecting this device for this work is the postulation that the tooth spacing and hearing of a dolphin is based on similar principles [2, 7]. One limitation in the analogy thus far is a lack of consideration of a variably density structure around the individual elements. This paper goes some way towards addressing this limitation.

The wider aim of this paper is to present a general methodology for mimicking the functional elements of biological structures operating in the acoustic domain in electromagnetics. The paper begins by considering a general method for converting structures found in an acoustic mammal and converting them for use in an antenna. The paper also considers the problem of the different boundary conditions found in acoustic and electromagnetic problems and how this may potentially be overcome.

2 METHODOLOGY

The process for converting an acoustic structure into one that is useful in the electromagnetic domain is not as straightforward as it may immediately seem. The familiar wave equation governing pressure wave propagation in an acoustic material is given in Equation (1) and that of electromagnetic wave propagation (for the E-field) is given in Equation (2).

$$\nabla^2 p - \frac{1}{c_s^2}\frac{\partial^2 p}{dt^2} = 0 \qquad (1)$$

$$\nabla^2 \mathbf{E} - \mu_0\,\varepsilon_0\,\varepsilon_r\,\frac{\partial^2 \mathbf{E}}{dt^2} = 0 \qquad (2)$$

where $\mathbf{E}$ is the electric field vector, μ_0 is the permeability of free space, ε_0 is the permittivity of free space, p is the acoustic pressure, t is the time, and c_s is the propagation speed in the acoustic material. ε_r is the relative permittivity of the medium. It would appear that the two cases are directly analogous; however there are two important differences. Firstly the presence of a vector electric field in Equation 2 in place of the scalar pressure. Secondly, the boundary conditions have not been considered. There are significant differences between the usual conducting boundaries encountered in an antenna which have an electric field reflection coefficient of -1 and those found in in an acoustic radiating structure with rigid boundaries which have a (pressure) reflection coefficient of +1. Despite these differences there are some well-known and simple structures such as horns where the analogy is established. Most sonar transmission and reception organs found in marine and airborne mammals are however far more geometrically complex than horns and their precise functions are not so easy to immediately identify and mimic. A general approach that can be taken is therefore to take the complex structure and to model it using computational acoustics [5, 7-9]. Figure 1 illustrates a general process for deriving an antenna design using this method.

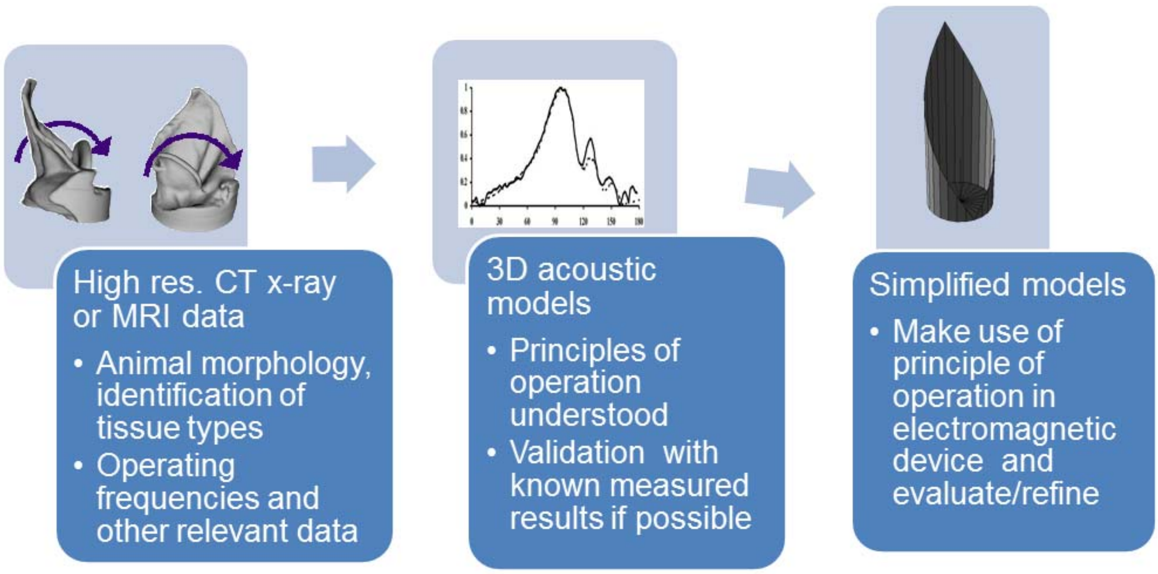


Figure 1: General process for taking an acoustic structure and producing an antenna. This example shows a bat's ear being used for bioinspiration.

The example given uses a bat's ear as the input to the process [1]. It can be seen that the successful final design on the right hand side is vastly simplified from the original, but also there have been significant changes in the feeding mechanism for the structure. The changes were necessary as the bat's auditory canal was of a diameter which would have been too small to support wave propagation in the electromagnetic equivalent due to the differing boundary conditions. The modelling method in both the acoustic and the electromagnetic simulations was Transmission Line Modelling (TLM) which is a type of finite difference, time-domain (FDTD) approach [8, 9].

The present paper attempts to adopt a similar methodology to the case of a dolphin jawbone, fatty channel and teeth. In the next section the geometry is considered in more detail.

3 CANDIDATE STRUCTURE AND APPROACH

Recent works have detailed how the jaw of the dolphin contains lipids of varying sound velocities which surround the teeth [10], though the presence of these materials was known previously. Exploiting the graded nature of these structures is the main focus of the current paper, however first we consider the dolphin's lower jaw bone in a more general sense. Figure 2 shows a two dimensional slice of the geometry of the lower jaw of the Atlantic Bottlenose Dolphin and shows how this was modelled in a previous paper [7].

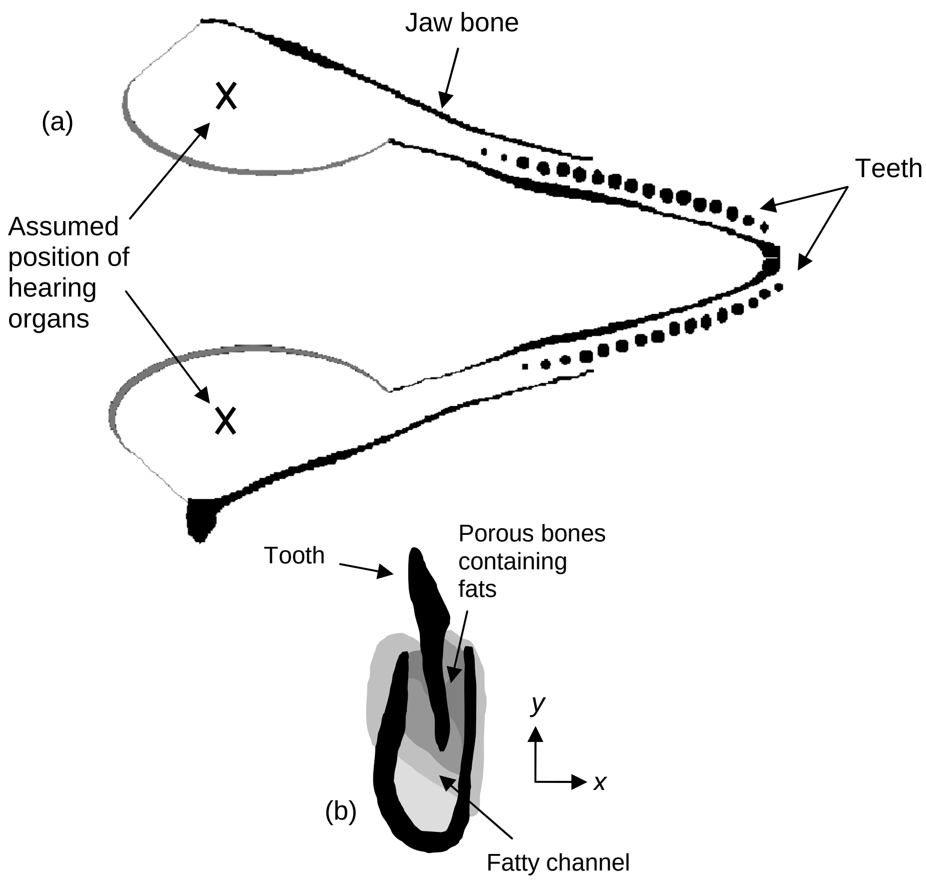


Figure 2: Diagram of the lower jaw and teeth of the Atlantic Bottlenose Dolphin (*Tursiops Truncatus*). (a) shows a two dimensional cross section of the teeth and jaw bones; (b) shows a cut through one of the teeth and illustrates the fatty channel which runs down the length of the jaw.

In the previous work the tooth array was considered in the context of an acoustic bandgap structure [11]. We have attempted to draw direct analogy from the bandgap theory and to produce a biomimetic antenna but with limited success. Figure 3 show such a device constructed using a periodic array of conducting posts within a waveguide having an oblique end truncation. Our attempts to optimise this device have so far not yielded satisfactory results. A major obstacle to success is the difference in propagation modes between a waveguide in the two different domains. In the present paper an alternative approach is taken which considers the teeth removed from the hard jaw bone but still surrounded by the graded sound velocity (fatty) channel.

Figure 3: First attempt to produce a bioinspired antenna using a waveguide. This device had limited success due to the differing fundamental modes of the acoustic and electromagnetic waveguide.

Here the analogy is considered from the arguably simpler viewpoint of a travelling wave antenna structure without a containing waveguide [6]. Figure 4 shows the basic antenna used as the focus of the modelling study.

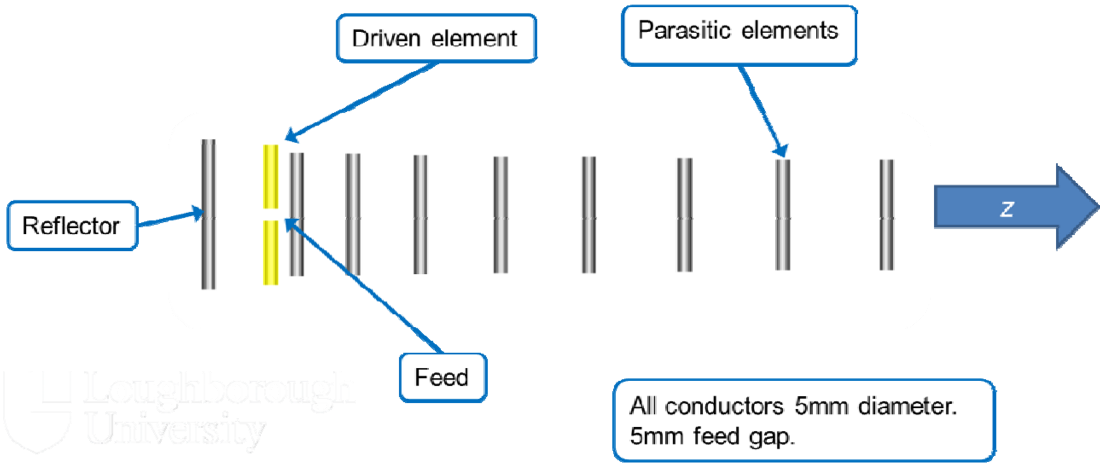


Figure 4: Optimised Yagi-Uda array used in the current paper. The element spacings are chosen to maximise directivity in the z-direction.

The device is a Yagi-Uda antenna [12] made from 8 parasitic elements, a driven element and a reflector. The design aspects of this device are omitted from the current paper as it is not important to the acoustics of the problem. The conductive elements acting as parasitics measure 5 mm in diameter and are assumed to be made of copper. The overall gain of the structure is greater than 13 dBi and this is considered optimal for the element thicknesses and number of elements chosen.

The present paper aims to take bioinspiration from the arrangement found in Figure 2(b) and to incorporate a graded structure in a dolphin-like way around the antenna.

4 BIOINSPIRED ANTENNA

4.1 Geometry and dimensions

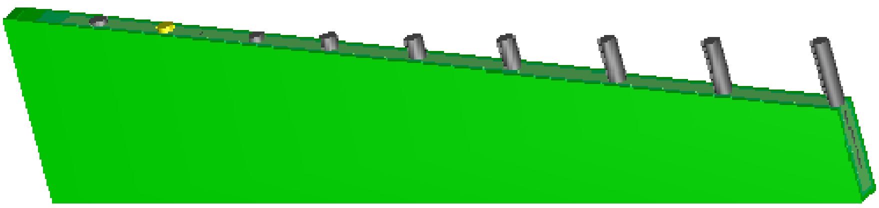
From Equations (1) and (2) it is clear that to form an analogy between the acoustic and the electromagnetic cases it is necessary for:

$$\frac{1}{c_s^2(x,y,z)} \to \mu_0\ \varepsilon_0\ \varepsilon_r(x,y,z) \qquad (3)$$

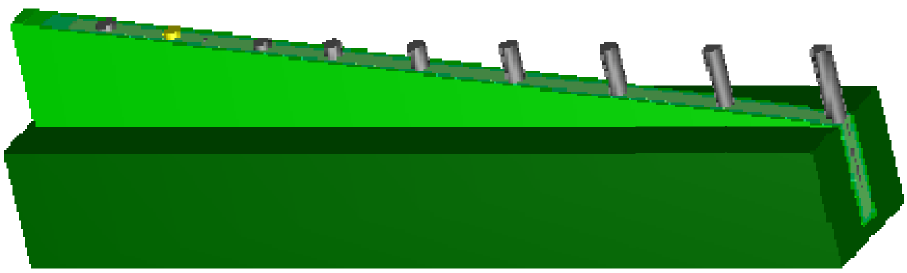
The (acoustic) background medium is salt water for the dolphin (c_s = 1560m.s^{-1}) and the (electromagnetic) background medium is air with:

$$c_{em} = \frac{1}{\sqrt{\mu_0\ \varepsilon_0}} = 3\times10^8\,\text{m.s}^{-1} \qquad (4)$$

If the problem is scaled to the background material in terms of frequency and dimensions in the background medium then this mapping (3) will be valid. To include the fatty channel in the models some typical measurements [10] have been used to estimate the relative sound velocity near to the teeth. The term $\varepsilon_r(x,y,z)$ can be chosen so that in the background material $\varepsilon_r(x,y,z)$ = 1.0 and elsewhere it takes a suitable value to represent $c_s(x,y,z)$ measured for the acoustic case.



(a)



` (b)

Figure 5: Yagi array shown embedded in dielectric material with (a) two; (b) three layers. Between the ‘teeth’ $\varepsilon_r(x,y,z)$ = 1.0, the first layer is 1 mm thick and is a rectangular envelope enclosing all the elements exactly with $\varepsilon_r(x,y,z)$ = 1.1. The second layer is also 1 mm thick with $\varepsilon_r(x,y,z)$ = 1.3. The last layer added in (b) is a 10 mm thick layer of $\varepsilon_r(x,y,z)$ = 2.2.

The end result of this scaling process is shown in Figure 5. Here the continuous nature of the graded structure has not been reproduced in detail in (a), instead a nominal value near to the 'teeth' and a second point has been used. Each layer is 1 mm thick. In (b) a third higher value dielectric layer has been incorporated.

4.2 Results

The results shown inset in Figure 6 show the directivity verses the reference design with and without the fatty channel present (as shown in Figure 5(a)). It shows clearly that directivity with the channel present is notably higher over a broader frequency range than the one without. It can also be seen that the impedance bandwidth of the device with the dielectric surround is also improved. Hence it can be concluded from these results that the performance antenna has been improved over the reference case.

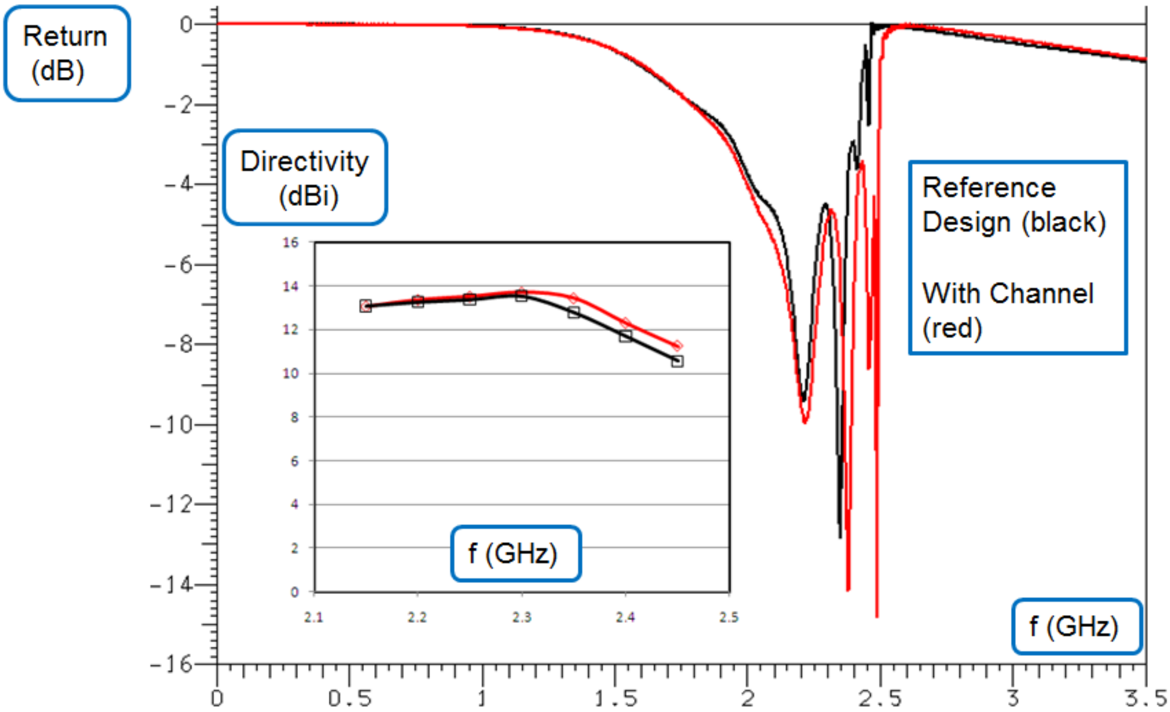


Figure 6: The electrical reflection coefficient referenced to 50Ω at the antenna terminals and directivity of the biomimetic antenna (inset).

By including the final layer (the dielectric 'mount') we see other results for the simulation. The results are summarised in Figure 7. It is important to note that the antenna's performance is worsened when this final layer is included. However in a practical sense this represents a device that can be physically mounted on a platform. Usually a Yagi would be mounted on a thin mast to avoid interaction with its elements. In this case the dielectric makes a much more substantial and practical option. The first and second layers go some way towards restoring the performance of this device relative to the original simulation where no mount was present.

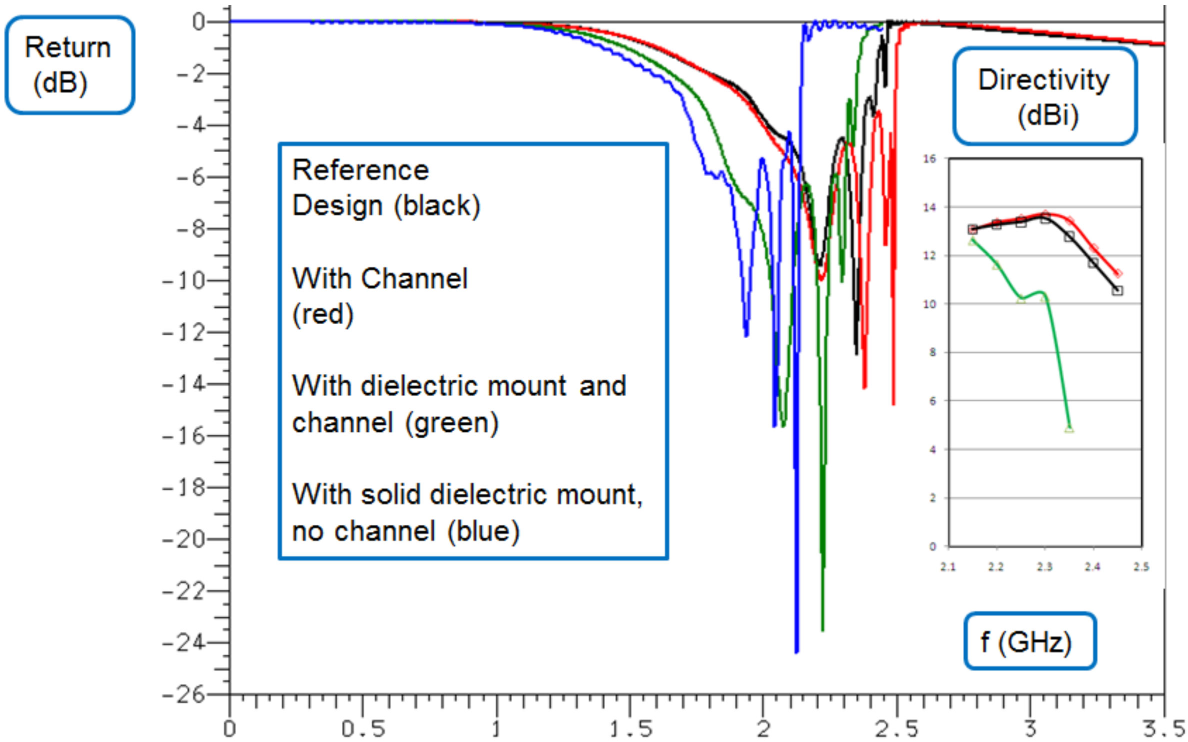


Figure 7: The electrical reflection coefficient referenced to 50Ω at the antenna terminals and directivity of the biomimetic antenna with the third dielectric layer (inset).

5 CONCLUSION

Sensors found in the animal kingdom have been shown to have performance benefits in a number of echo location tasks. In this paper a bioinspired modification to an already optimal antenna has been adopted. It has been shown that this can lead to further performance enhancements. In addition it has been shown that bioacoustics can offer some solutions to the practical problem of mounting a sensor. The main limitation found when drawing an analogy between the acoustic and electromagnetic domains is a lack of comparable boundary condition definition for some cases. However it may be possible that this can be overcome in narrow frequency bands by resorting to a class of electromagnetic metamaterials known as artificial magnetic conductors [13]. This offers a new avenue of research into analogies between acoustic and electromagnetic structures.

ACKNOWLEDGEMENTS

The author would like to thank the following people who contributed to this work: Dr Simon Dible, Mr Saagar Gajjar, and Dr Paul Lepper.

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