ANGULAR LOCALISATION IN DOLPHIN HEARING DERIVED FROM TRANSMISSION LINE MATRIX MODELLING OF THE LOWER JAW AND TEETH.

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1 INTRODUCTION

Dolphin echolocation, like any sonar, is a system consisting of many components, but essentially a transmitter, a receiver and a processor. This paper is mainly concerned with the receiving mechanism, along with the processing involved in beam forming and target localization. A wider discussion of dolphin echolocation and hearing will be found in the book by Au [1] or a more recent collection of articles covering all aspects of echolocation [2].

There is evidence that the dolphin's lower jaw is a component in the echolocation receiver, and Goodson and Klinowska [3] have proposed a model suggesting the equally spaced rows of teeth form receiving arrays. Various processing schemes for these 'tooth arrays' have been suggested (e.g. [4]) but, whatever the details, such arrays in an end-fire mode, unlike broadside arrays, should maintain directivity in the near field [5]. In addition, combining the rows of teeth in a monopulse configuration would give fine angular resolution but with wide beams for rapid area searching [6,7].

This model is based on the sea-going odontocetes (toothed whales) in general, and the Atlantic bottlenose dolphin, *Tursiops truncatus* in particular [3,6,7].

More recently, receiving beampatterns have been published [8,9] for a bottlenose dolphin, computed by applying transmission line matrix modelling (TLM) to a model of the lower jaw and teeth, obtained from CT scan data. This paper describes further analysis of the resulting patterns based on some of the concepts of the end-fire array model.

2 THE TLM MODEL

The TLM method is a time domain, differential numerical modelling technique ideally suited to the study of field problems [10]. It has found many applications including those within the field of bioacoustics [11, 12] and is broadly comparable with the finite difference method in the time domain [13]. 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.

2.1 2-D SIMULATION WITH REAL GEOMETRY

A 2D slice from a CT scan of an adult male bottlenose dolphin was utilized to construct the TLM mesh. The data of Racicot and Colbert [14] was first imported and rescaled in order that one voxel in the CT data represented one TLM node. In order to isolate the hard bones and teeth from the soft tissues in the slice, the data were then intensity thresholded and modelled with two node types. The first type modelled the free space with a sound velocity of 1500 m s^{-1} and the remainder (the hard bones and teeth) were modelled as reflecting nodes with a pressure wave reflection coefficient of +1. The model data subsequent to the pre-processing steps are depicted in Figure 1. Note that not all 22 teeth are evident in this particular slice. This is indicative of how the teeth are sloped in their path, and also that some of the teeth are much smaller. The two measurement points representing the hearing organs are placed within the model at the ends of the jaw channels. An assumption made in this model is that the hearing organs are acoustically isolated from each other internally and this is modelled by including an absorbing condition at the channel ends. A single broadband point source of pressure was used with a uniform frequency spectrum extending to the mesh limit.

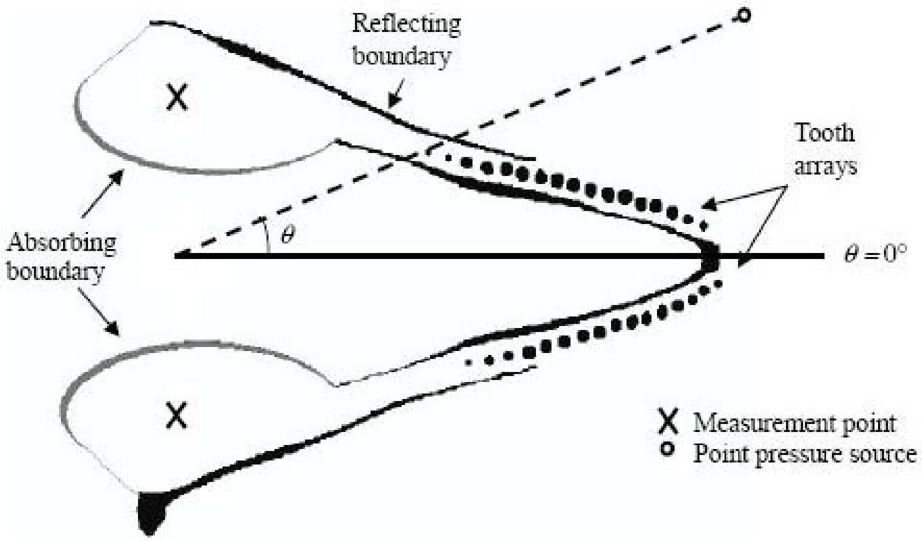

Figure 1: TLM set-up using real geometry.

2.2 BEAMPATTERNS

This model was used to simulate directivity patterns for the two measurement points, for the two cases of the jaw with and without teeth present, and several of these have been presented in [8] and [9]. Two examples will be given here for comparison with the patterns obtained if the teeth are treated as an end-fire array.

Figure 1 shows two sets of beampatterns for a frequency of 100 kHz. On the left is the result obtained with teeth present and on the right is the teeth absent case. The equivalent end-fire array patterns are shown in Figure 2.

A number of points are apparent. The first is that, in this case, the TLM patterns with teeth present are fairly erratic and quite narrow, whereas the teeth absent patterns are much broader and smoother. Neither has the sidelobe structure seen in the end-fire patterns. The teeth absent patterns are about the same width as the end-fire patterns, but spaced by a wider angle.

These comments are typical of the patterns presented in [8] and [9]. Most are erratic, rather than smooth, and none are very much like the end-fire patterns.

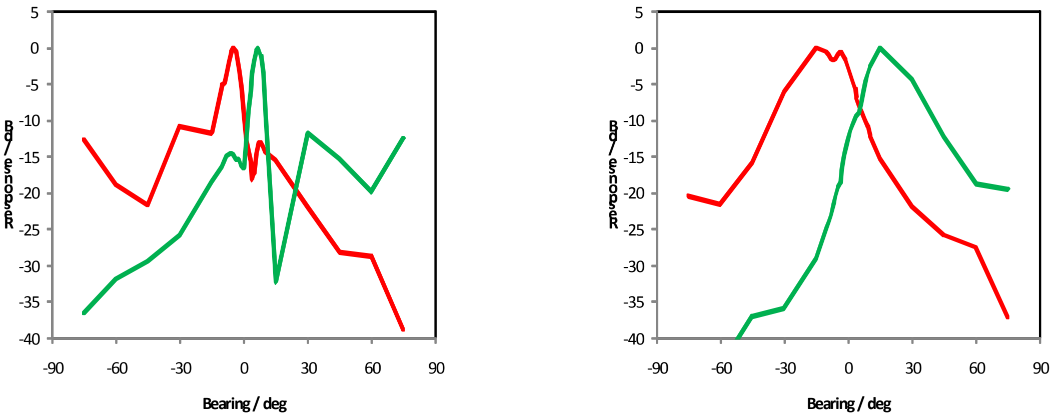

Figure 1: Pairs of beampatterns at left and right receivers generated by the TLM model for a frequency of 100kHz. Left: teeth present and right: teeth absent.

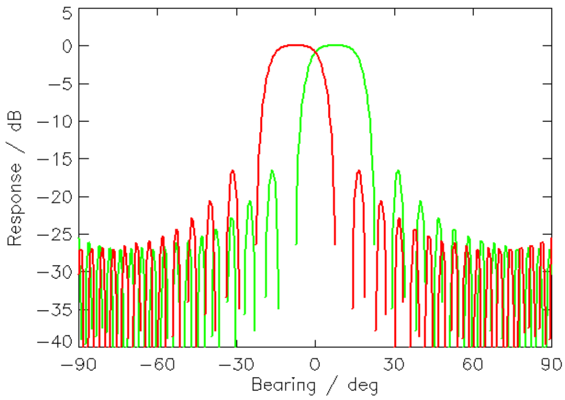

Figure 2: Beampattern pair for 100kHz obtained by modeling teeth as end-fire arrays.

2.3 DIFFERENCE PATTERNS

Both the TLM model and the end-fire array model generate pairs of beampatterns that point in different directions. It is suggested in [6] and [7] that the dolphin may use these two beams for angular localization, in the same way as monopulse radar. Monopulse systems combine pairs of beampatterns in a number of ways, but the most common is to take the difference in amplitude of the two beams and then normalize the result with the sum of the two beams. This produces an output that is nominally proportional to the target bearing over a range of angles roughly equivalent to the beamwidth.

For comparison purposes, just the difference pattern will be considered here, and Figure 3 shows differences for the end-fire array model at frequencies of 50, 60, 80, 100 and 120 kHz.

These patterns all produce an output more or less proportional to bearing over a range of roughly ±10°, although it is most linear at the higher frequencies. Outside this linear range, the bearing becomes ambiguous, but as this is outside of the receiving beamwidth, erroneous target bearings are not likely to occur. The slope of the response increases with frequency, but in a fairly smooth manner.

The TLM model equivalents are shown in Figure 4. Again, the results on the left are for teeth present, and on the right for teeth absent.

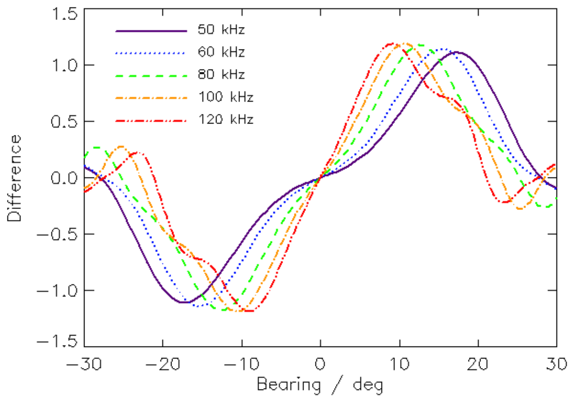

Figure 3: Difference patterns for the end-fire array model.

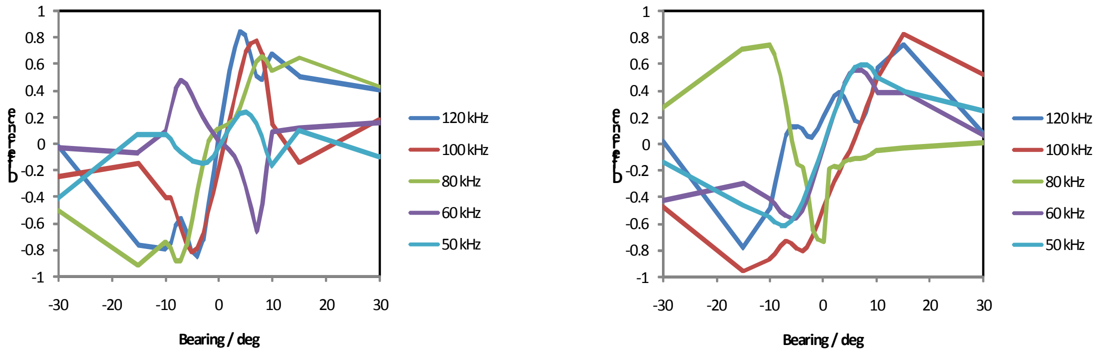

Figure 4: Difference patterns generated by the TLM model. Left: teeth present and right: teeth absent.

It is interesting that, in the TLM results, a number of curves in both teeth present and teeth absent cases are similar to the end-fire array model results. This is so for the higher frequencies with teeth present and for all but the 80 kHz and perhaps the 120 kHz case with teeth absent.

3 CONCLUSIONS

It is difficult to draw any firm conclusions from these results. Both the end-fire array model and the TLM model predict both that directional receiving beams are formed of roughly the same width as those measured in dolphins, and both suggest that a form of monopulse angular localisation is feasible. However, it should be noted that the TLM is modelling the teeth as scattering objects with two receivers, whilst the end-fire array is modeling them as receiving elements. It should also be noted that it is also possible that the dolphin uses completely different techniques for localization.

Patterns produced by the end-fire model are very precise, and this is because it is somewhat artificial. The results produced by the TLM model are more erratic, which might be expected in a natural system, but to what seems to be an excessive extent. Clearly, this model merits further investigation to find out if these erratic responses are really a feature of the system or whether they are an artifact of the model.

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