EXPERIMENTAL EVIDENCE OF BANDGAP STRUCTURES IN THE LOWER JAW OF THE BOTTLENOSE DOLPHIN (*TURSIOPS TRUNCATUS*).

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ABSTRACT

Previous studies using the TLM numerical modelling technique have demonstrated the potential existence of bandgap structures within the lower jawbone of the Atlantic Bottlenose dolphin (*Tursiops truncatus*) [1]. The study presented here shows experimental evidence of the existence of these bandgaps within a 2-D structure that mimics the principal dimensions of the lower teeth and jawbone of the Bottlenose dolphin. The bandgap present is due to the tooth structure in the lower jaw forming a periodic array of scattering elements, which results in the formation of an acoustic stop band that is angular dependent.

1 INTRODUCTION

For more than half a century sonar designers have been fascinated by the capabilities and the performance of the echolocation systems in marine mammals [2]. This work has shown that a number of dolphins have very versatile sonar systems with excellent target discrimination in shallow water, highly reverberant, environments. An animal that has been measured extensively is the Atlantic Bottlenose dolphin, *Tursiops truncatus*. This animal's sonar system is often quoted as outperforming man made systems [3]. There is an increasing body of work which suggests that the lower jaw of the Bottlenose dolphin is the main echolocation reception source [4]. However there has been some debate over the role of the lower jaw in the reception process, and more specifically whether or not the teeth have an impact on echolocation capability. This paper adds further support to the case for the teeth being involved as a passive beam forming structure. Specifically, the argument is made that the individual teeth form a periodic filter.

Acoustic band gaps or stop bands are formed when periodic arrays of scattering elements are present in a geometric space. It is well known that in certain frequency bands dispersive behaviour can be observed [5]. It is possible to design such a structure so that for certain frequency 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 [6] and acoustic engineers [7]. This band gap property is also highly dependent on the direction of the incident sound field.

Robertson *et al.* [7], demonstrated that if an array of rods is 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 using Equation 1, where a is the separation between centres of adjacent elements and d is the diameter of the cylindrical rods. Furthermore, it has been demonstrated experimentally in air 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.

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

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

Previous work [1] has demonstrated the existence of acoustic band gaps within the jaw geometry of the Bottlenose dolphin. These band gaps were observed within the frequency band in which dolphins are known to echolocate [2]. In the current paper the simplified model used for numerical simulations has been scaled and manufactured so that it can undergo acoustic testing in water. The experiment examines how sound propagates around the replica lower jaw of the bottlenose dolphin and the resultant sensitivity patterns. The experiments were carried out in the Loughborough University test tank, which is 10 m long 8 m wide and 1.8 m deep.

2 EXPERIMENTATION

The lower jawbone was simplified into a quasi 2-D structure and *all dimensions were scaled by a factor of 1.25* in order to simplify the manufacturing process. To further simplify the experiment, only one half of the lower jawbone was modelled. The experimental setup can be seen in Figure 1 and 2. M5 (5 mm diameter) steel rods measuring 300 mm in height were used to replicate the teeth of the dolphin. 1 mm thick aluminium plating was used to replicate the hard inner boundary of the jawbone. The steel rods where held in position at the top and bottom by wood, that had been drilled with a rod separation of 15 mm and a channel separation of 15 mm. The outside of the steel plating was covered with anechoic rubber tiles, to prevent sound from entering the centre channel from the broadside direction.

The receiving hydrophone was of type HS150 and was located at the rear of the structure in order to measure the sound transmission through the channel. A replica broadband dolphin click was transmitted using a Hameg function generator through a power amplifier with a HS70 omni-directional ball hydrophone at a repetition rate of 5 s^{-1}. The source was maintained at a fixed position whilst the test array was rotated through 180 degrees using a pan and tilt system in 1 degree steps. The receiving hydrophone was connected to a +60 dB Etec pre-amplifier with a high-pass filter of 10 kHz and a low-pass filter of 160 kHz. The signal was captured on a Techtronics digital storage scope having a sampling rate of 2.5 M samples/sec. The experiment was then repeated with the steel rods removed from the array but with the steel plates, source and receiver in identical positions.

The transmission after propagation was then analysed and subsequently transformed using a Discrete Fourier Transform (DFT). The peak signal for each source position was subsequently plotted at several frequencies for analysis. The results were normalised by dividing the amplitude obtained at each frequency from the array by that obtained in the reference case with the rods removed.

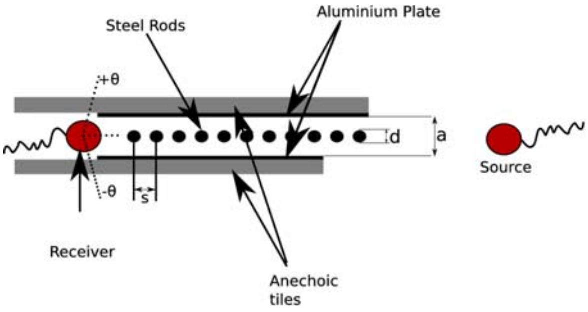

Figure 1. Cutaway diagram of the experimental setup viewed from above.

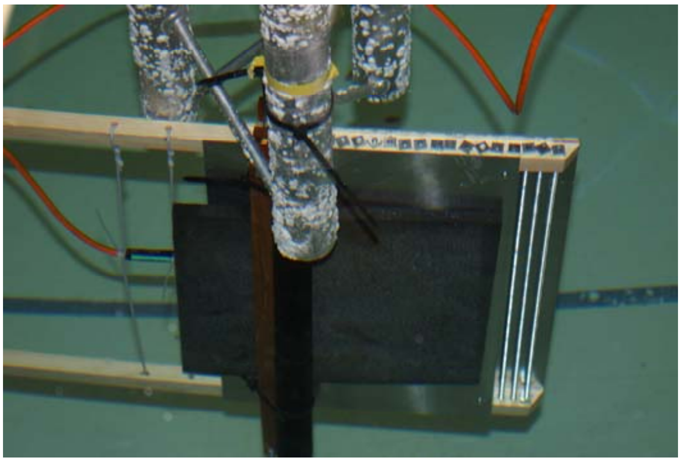

Figure 2. Photograph of the test array shown from the side.

3 RESULTS

Figure 3 shows an example result for the end fire response of the array. The first band gap is clearly visible at around 50 kHz, which closely matches the primary band-gap predicted by the array dimensions and the application of Equation 2.

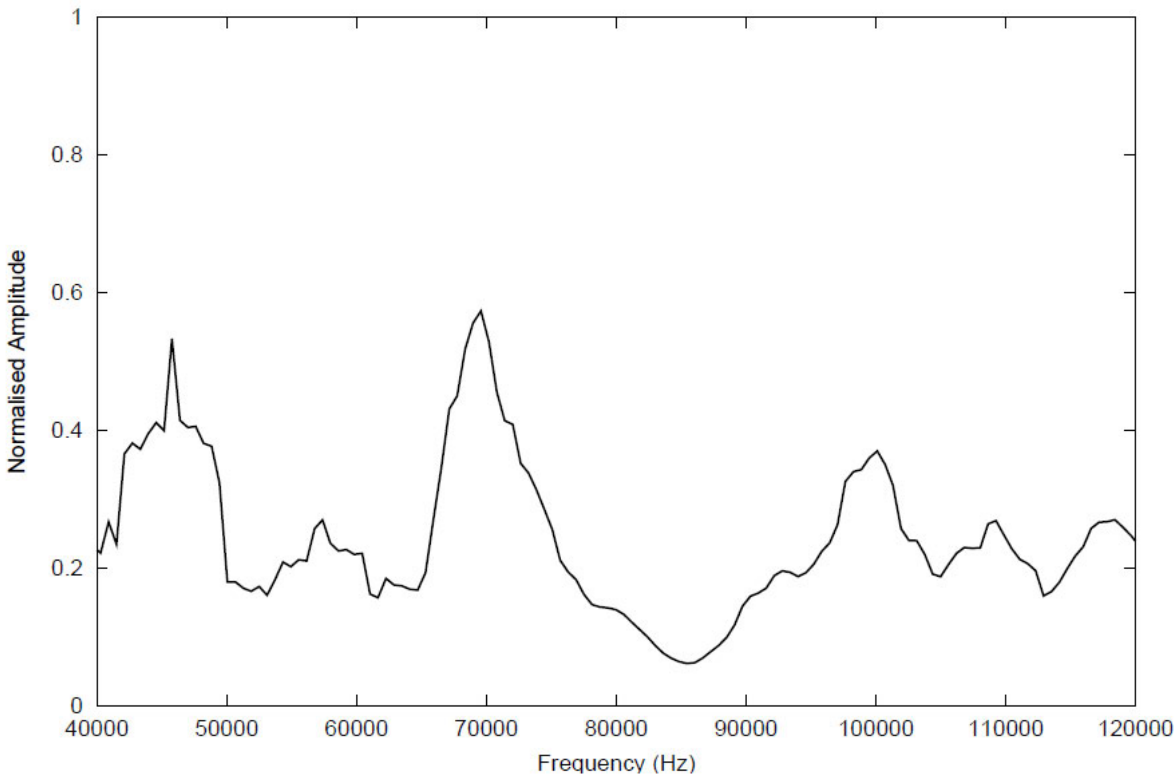

Figure 3: Normalised endfire response for the experimental array. The array consists of 15 uniformly spaced, 5 mm diameter, circular rods (steel) with a separation of 15 mm placed in a 15 mm wide hard boundary (aluminum) channel. The start of the first stop band can be seen at 50 kHz.

4 CONCLUSIONS

A band-gap filter effect has been demonstrated experimentally using a set of semi-infinite rods within a wave guide at normal incidence. These results are comparable to results previously reported, which were based on computer simulations only [1]. This provides further support for the hypothesis that band gaps could have an effect on the hearing mechanisms of dolphins, and presents the possibility of developing a practical biomimetic array that emulates the behavior of the tooth-jaw geometry.

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