ENVIRONMENTALLY NEUTRAL WIDEBAND BIOMIMETIC SONAR SIGNALS

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Abstract: *There is an expanding requirement in the defence, offshore, renewable energy, research and leisure sectors to reduce the impact of man-made sound, including active sonar transmissions, on marine mammals. This driven partly by public interest, but mainly by legislation such as the US Marine Mammal Protection Act. Typically, such requirements are met using visual monitoring by Marine Mammal Observers (MMOs) or passive acoustic monitoring (PAM). If animals are detected within a specified range, some form of mitigating action such as shutting down the sound source is then necessary. However, some marine species do not vocalise so, therefore, it may be desirable to look for forms of active sonar transmission that are potentially less harmful to marine life without having to shut down completely. One way this might be achieved is to use signal waveforms derived from naturally occurring sounds, such as the vocalisations of the animals themselves: biomimetic waveforms. It might be expected that such sounds would appear less threatening, or at least more familiar, thus reducing possible abnormal behavioural impacts. Marine mammals produce a variety of vocalisations, but this paper focuses on the echolocation clicks produced by odontocetes (toothed whales) such as sperm whales and dolphins. These signals are aimed at both detecting and classifying small, low target strength objects at very long ranges – characteristics that are all desirable in man-made sonar systems.*

Keywords: *Biomimetic, Sonar, Wideband, Environmental Impact,*

1. INTRODUCTION

There is a rapidly expanding requirement to reduce the impact of man-made sound, including active sonar transmissions, on marine mammals in the defence, offshore, renewable energy, academic research and leisure sectors. This is driven partly by increased public interest in these animals, but mainly by legislation such as the US Marine Mammal Protection Act [1], JNCC (Joint Nature Conservation Committee) Regulations applying to seismic survey in the UK [2], the UK Offshore Marine Conservation Regulations [3], and similar regulatory and licensing requirements elsewhere throughout the world.

Typically, such requirements are met using visual monitoring by Marine Mammal Observers (MMOs) or Passive Acoustic Monitoring (PAM) [4], based on listening for the vocalisations produced by marine mammals, such as the echolocation clicks of dolphins [5] or the low frequency calls of baleen whales [6]. Having detected animals, some form of mitigating action such as shutting down the sound source is then necessary.

However, some marine species do not vocalise and in general it may not be possible to ensure the absence of such marine mammals before commencing transmission. Therefore it is desirable to look for forms of sonar transmission that are potentially less harmful to marine life without needing to reduce the Source Level (SL) or shut down completely.

One way this might be achieved is to use signal waveforms derived from naturally occurring sounds such as the vocalisations of the animals themselves – biomimetic waveforms. It might be expected that such sounds would appear less threatening (or at least more familiar), thus reducing possible abnormal behavioural impacts.

2. ENVIRONMENTAL IMPACT

The interaction of marine mammals and man-made or anthropogenic sound is a subject of some contention. Our understanding of detailed interactions is relatively poor and largely restricted to a few species. However, there are instances where man-made sounds have been demonstrated to have adverse effects on marine mammals, and this includes sonar transmissions [7].

There are widely accepted guidelines relating to exposure criteria for injury in the form of Temporary or Permanent Threshold Shift (TTS or PTS) [8]. However, behavioural impacts are difficult to measure or predict. The challenge is to distinguish a significant behavioural response from an insignificant momentary alteration in behaviour. For the purposes of this paper, we are assuming that the biomimetic waveforms under consideration are likely to minimise behavioural reactions, but this assumption would need to be verified before any such waveforms could be used in service.

Given a specified waveform, SL, and other sonar parameters, the Sound Pressure Level (SPL) in the water around the sonar can be computed, as in the example shown in Fig. 1. Comparison between the SPLs and the exposure criteria can then be used to assess the likelihood of physical impact, either TTS or PTS, for a variety of mammals with different hearing ranges. This assessment can be based both on the instantaneous SPL and the cumulative exposure of an animal to the sound field for an extended period as it moves around, referred to as the Sound Exposure Level (SEL) [9].

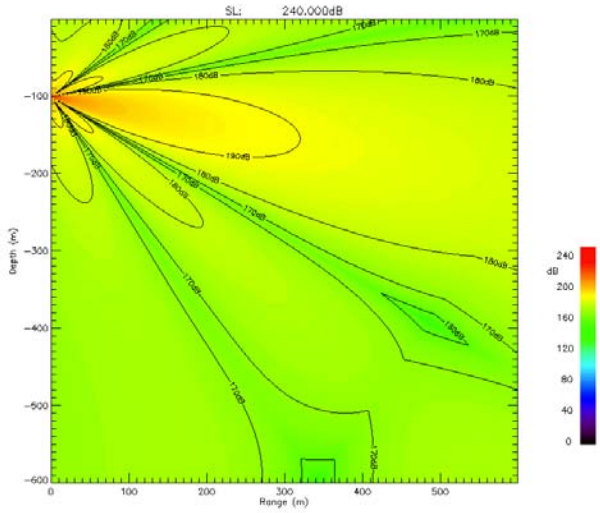

Fig.1: Example SPL contours plotted against range and depth.

In order to weigh the performance of conventional sonar signals against the biomimetic waveforms (to be described in §3 below), a simple metric will be applied (see §4): the potential detection performance will be compared for signals adjusted to obtain the same SEL for a given marine mammal target in a specified environment. This equates to both waveforms having the same ambient noise limited detection performance.

3. BIOMIMETIC WAVEFORMS

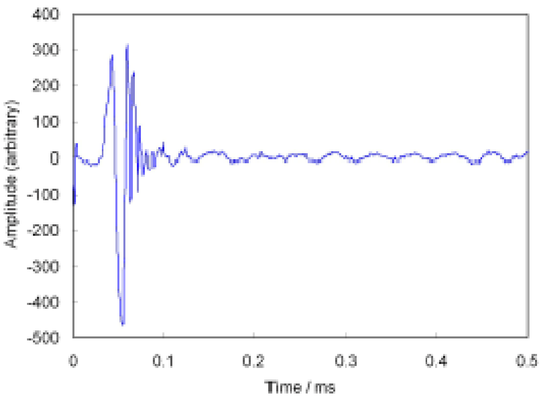

Fig.2: Typical dolphin echolocation waveform.

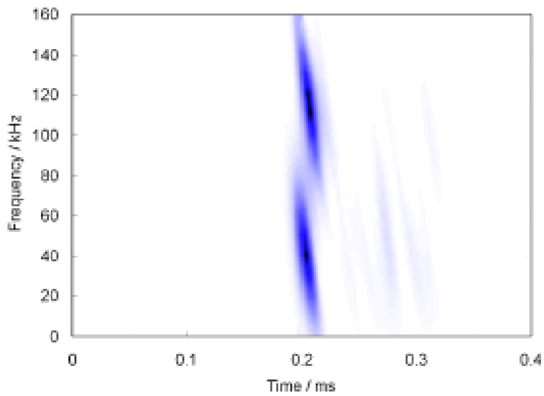

Fig.3: Spectrogram of dolphin click shown in Fig. 2, computed using a Short Time Fractional Fourier Transform.

Marine mammals produce a variety of vocalisations, but this article focuses on the echolocation clicks produced by dolphins and other odontocetes (toothed whales), mainly because these are active sonar signals, whereas many of the other vocalisations associated with these animals are for communications. However, this does not preclude the possibility of using biomimetic communication signals for sonar.

The inspiration for these novel signals came from the analysis of bottlenose dolphin (*Tursiops truncatus*) clicks [10]. The pulses are of very short duration, between 50 and 80 microseconds, and Fig.2 shows a typical dolphin echolocation click. A spectrogram computed using a Short Time Fractional Fourier Transform [11] is shown in Fig.3, and it is clear that the signal comprises of two short downward chirps.

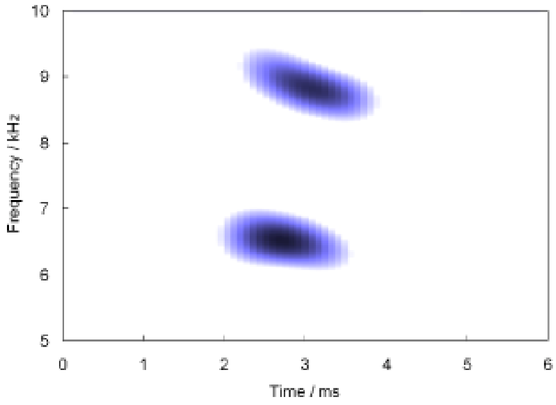

Fig.4: Spectrogram of sperm whale click , computed using a Short Time Fractional Fourier Transform.

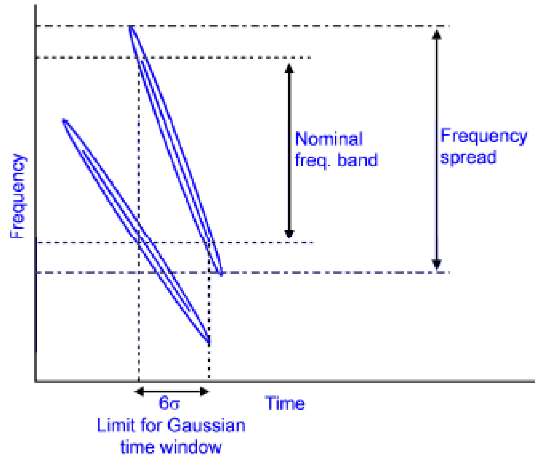

Fig.5: Chirp components for the biomimetic waveforms (after [10]).

The analysis presented in [10] shows that a double chirp structure is typical of bottlenose waveforms, but few other species have been studied. However, the present author has conducted a similar analysis with sperm whale (*Physeter macrocephalus*) clicks and an example result is shown in Fig.4. Once again, the double chirp structure is evident, although this signal is much lower in frequency and extended in duration.

Although not proven, it seems that the double chirp structure may be in widespread use for odontocete echolocation waveforms. Also not proven, but quite feasible, a signal structure that is likely to be heard frequently might appear less threatening to most mammals and so have a lower behavioural impact. Therefore, a biomimetic signal model was implemented, following the techniques used in [10], based on two linear frequency modulated chirps and shown schematically in Fig. 5.

In this implementation, the two chirps are defined by duration and frequency band and are amplitude weighted by a Gaussian time window. The nominal frequency bands indicate the frequencies at the start and end of the 6σ time window for the underlying chirp in each signal component. In practice, the Gaussian time window applied to the chirps does not fall to zero at these limits, so the bandwidth of the pulses is increased beyond the nominal band as illustrated in Fig. 5.

A waveform is fully defined by the frequency range and duration of the two chirps, along with the delay between the first and second. The chirps are generated using a method described in [12] and for the performance analysis presented here, a waveform has been chosen as representative of a sperm whale click.

4. SONAR PERFORMANCE

For comparison with the synthesised sperm whale click, a typical Anti-Submarine Warfare (ASW) Mid Frequency (MF) Sonar waveform, operating at a centre frequency of 7 kHz with a 500 ms 100 Hz bandwidth chirp will be used as an example.

Following the method described in [9], the SEL can be calculated for a single pulse by integrating the square of the pressure waveform over the duration of the pulse. For the two pulses of interest, this leads to SEL values of (SPL – 9.0) dB re 1μPa^2.s for the MF sonar and (SPL – 34.7) re 1μPa^2.s for the biomimetic waveform. The cumulative SEL can be computed from these values for a mammal swimming over a specified path simply by summing the relevant SELs for the duration of interest.

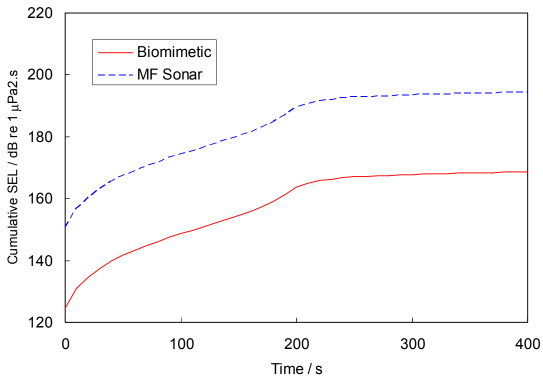

Fig.6: Calculated SEL for an MF cetacean swimming towards sonar..

Fig.6 gives an example for an MF cetacean such as a dolphin [8] swimming at a constant 10 kt (5.1 m/s) in a straight line towards the sonar from a distance of 1 km, passing the sonar at a Closest Point of Approach (CPA) of 50 m after 200 s, then continuing in a straight line out to a distance of 1 km beyond the sonar. For this simple example, the sonar SL is 220 dB re 1μPa @ 1 m for both waveforms, the sonar projector is assumed omnidirectional, and the Pulse Repetition Frequency (PRF) is one pulse per ten seconds. The cumulative SEL after the animal passes the sonar converges on 168 dB re 1μPa^2 for the biomimetic waveform and 194 dB re 1 μPa^2 for the MF Sonar signal.

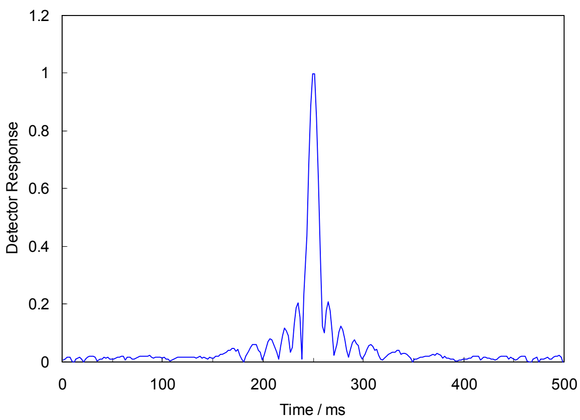

Fig.7: Matched filter response to the MF Sonar waveform at -12 dB SNR

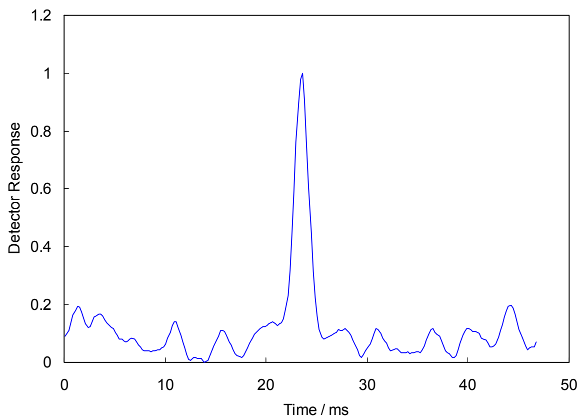

Fig.8: Spectrogram correlator response of the biomimetic waveform at -12dB SNR

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The criterion for injury suggested by [8] is 198 dB re 1 μPa^{2}s for multiple pulse sources. Clearly, both signals are below this level and would not lead to injury in the situation as described. In reality, although the ASW sonar PRF would be set to match the maximum display range, most echolocating animals tend to lock on to a target and trigger a pulse transmission on receiving an echo, at least at short range when locked on to a prey target. This gives rise to a PRF that increases rapidly as the animal approaches the prey, commonly referred to as a "feeding buzz" [13]. However, assuming a constant PRF, the biomimetic SL could be increased by 26 dB to produce the same SEL as the HF sonar.

This is unrealistic, but it makes the point that, at the same SL, the energy in the MF sonar pulse is considerably greater than that in the biomimetic signal. By adjusting the SLs to achieve the same cumulative SEL, the energy in the pulses is equalised and, other factors being equal, the detection performance for both waveforms will be the same.

What may be more important is how the waveforms perform in reverberation and clutter. Fig. 7 shows the response of a matched filter detector to the MF Sonar signal, buried in noise at -12 dB Signal to Noise Ratio (SNR). The result is a clear peak, well above the noise, and compressed in width to about 10 ms. This response, however, would be the same whether the echo came from a valid target, a rock on the sea bed, or scattering from particles in the water.

The biomimetic waveform, on the other hand, does not have a structure that gives such a clear response from a matched filter. There are other detectors, however, that are more appropriate and spectrogram correlation is commonly employed for detecting marine mammal vocalisations [14], and Fig. 8 shows the strong peak obtained when this process is applied to the biomimetic waveform, again at -12 dB SNR. Closer inspection reveals that the biomometic waveform/spectrogram correlator combination achieves a response peak in the time domain narrower than that achieved with the conventional MF sonar signal/matched filter setup. All this suggests that the biomimetic approach is potentially capable of a ten-fold enhancement in resolution.

4.1. Biomimetic Processing

The signal processing used by dolphins and other cetaceans is not well understood. Bats, however, are easier to study and there is evidence to suggest that, among other representations of received signals, some bats possess computational maps in the auditory cortex of frequency against time [15], allowing the possibility that they employ some form of spectrogram correlation processing. Additionally, it is believed that in order to carry out this processing with just a single spectrogram replica when, for example, the returning echo is Doppler shifted, these animals adapt their transmitted signals to compensate for Doppler and other transmission effects.

This means that if the transmitted waveform is shifted in frequency to compensate for the Doppler in the echo from a moving target, such as a moth, echoes from the background clutter such as foliage would have a different Doppler shift and would correlate less well, giving a degree of clutter rejection.

Another feature of bat neural processing depends on the wide bandwidth of their transmissions, so should be equally applicable to the wideband multiple chirp waveforms considered above. Big brown bats (*Eptesicus fucus*), in particular, can recognise echoes containing the full harmonic spectrum of their transmissions and associate these with close, on-axis targets. Echoes from greater distances will have suffered increased absorption at higher frequencies, so will have lost some harmonics. Likewise, off-axis echoes will have lost high-frequency content because of the frequency dependent directivity of transmitting and receiving beampatterns. Thus, the bat can track a nearby target at high PRF, while still maintaining general long-range and off-axis surveillance [17].

Finally, dolphins demonstrate a remarkable ability to recognise very fine differences in the geometry or materials of man made signals [18]. It is also known that dolphins and other cetaceans adapt the spectral characteristics of their transmitted waveforms for different tasks and when interrogating different targets. [19]. Biomimetic waveforms as described in [20] and similar to that used in this paper have been used in experiments to determine if adapting the biomimetic waveform parameters can highlight key spectral features in the echoes received from different targets.

It was found that the strongest features in the echoes were spectral notches, and such features can be extracted by applying a threshold on the second derivative of the echo spectrum to generate a signature characteristic of a particular target. The most robust signatures were obtained by adapting the waveform parameters to concentrate energy in the spectral areas of interest for that target.

5. DISCUSSION AND CONCLUSIONS

In this paper, the possibility of using biomimetic waveforms for active sonar has been revived. The main driver for this was the idea that signals similar to those used by marine mammals might appear less threatening than conventional sonar signals and so reduce the potential behavioural impact. A second consideration was that the waveforms used by these mammals may have performance advantages over conventional signals.

A brief analysis was presented, based on a synthesised waveform derived from a sperm whale echolocation click. It was noted that the model used tom generate the sperm whale click was also applicable to dolphin clicks and, possibly, a variety of other echolocating toothed whales. This biomimetic waveform was compared with a conventional signal representative of an MF ASW sonar.

As yet, it is not known whether or not such naturally occurring signals have a lower behavioural impact, but if biomimetic techniques can possibly improve sonar performance in reverberation and clutter without degrading noise limited performance, the additional advantage of reduced environmental impact is certainly worth exploring further.

6. ACKNOWLEDGEMENT

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