Environmentally Neutral Biomimetic Waveforms for ASW Sonar

Signals Derived from Waveforms that Exist in Nature Could Reduce Environmental Impact and Improve Performance

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There is a rapidly expanding requirement in the defense, offshore, renewable energy, research and leisure sectors to reduce the impact of man-made sound, including active sonar transmissions, on marine mammals. This is driven partly by public interest in these animals, but mainly by legislation such as the U.S. Marine Mammal Protection Act, the U.K. Offshore Marine Conservation Regulations, and similar regulatory and licensing requirements throughout the world.

Typically, such requirements are met using visual monitoring by marine mammal observers or passive acoustic monitoring based on listening for vocalizations such as the echolocation clicks of dolphins and porpoises or the low-frequency calls of baleen whales. If animals are detected within a specified range, some form of mitigating action such as shutting down the sound source is then necessary.

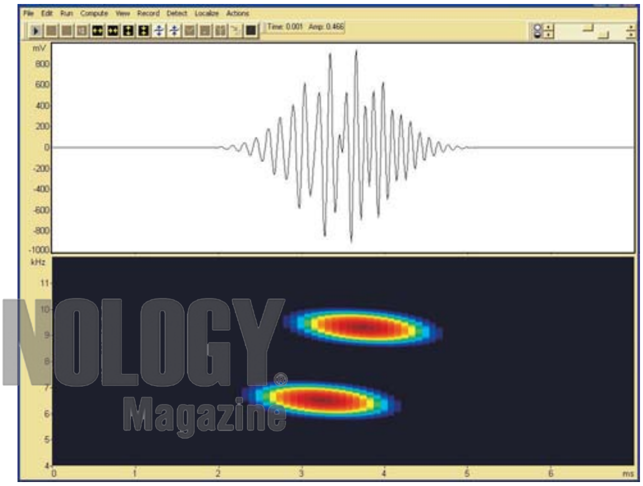
However, some marine species do not vocalize, and in general, it may not be possible to ensure the absence of marine mammals before commencing transmission. Therefore it is desirable to look for forms of sonar transmission that are potentially less harmful to marine life without needing to reduce the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

One way this might be achieved is to use signal waveforms derived from naturally occurring sounds, such as the vocalizations 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 behavioral impacts.

Environmental Impact

The interaction of marine mammals and man-made or anthropogenic sound is a subject of some contention. The 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.

There are widely accepted guidelines relating to exposure criteria for injury in the form of temporary or permanent threshold shift. However, behavioral impacts are difficult to measure or predict. The challenge is to distinguish a significant behavioral response from an insignificant momentary alteration in behavior. It is reasonable to assume that the biomimetic waveforms under consideration are likely to minimize behavioral reactions, but this assumption would need to be verified before any such waveforms could be used in service.



Example of a recorded natural sperm whale click waveform (top image) and its spectrogram (bottom image). The whale click is composed of two down chirps that fall in frequency by 500 hertz within a 1.8 milliseconds duration.

For physical impacts, given a specified waveform, transmission level and other sonar parameters, the sound pressure level in the water around an active sonar can be computed. Comparison between the sound pressure levels and the exposure criteria can then be used to assess the likelihood of physical impact, either temporary or permanent threshold shift, for a variety of mammals with different hearing ranges. This assessment can be based on the instantaneous sound pressure level or, possibly more realistically, 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).

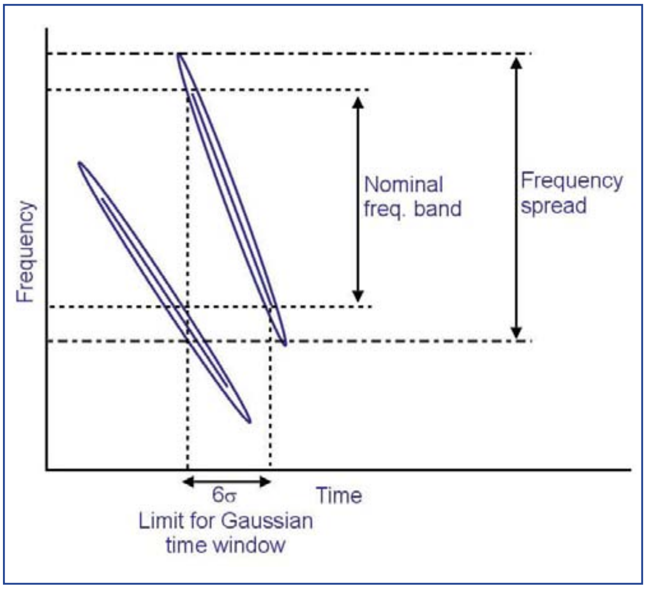
In order to weigh the performance of conventional sonar signals against the biomimetic waveforms, a simple metric may be applied: The potential detection performance can be compared for signals adjusted to obtain the same SEL for a given marine mammal target in a specified environment. This equates to both waveforms having the same ambient noise limited detection performance.

Biomimetic Waveforms

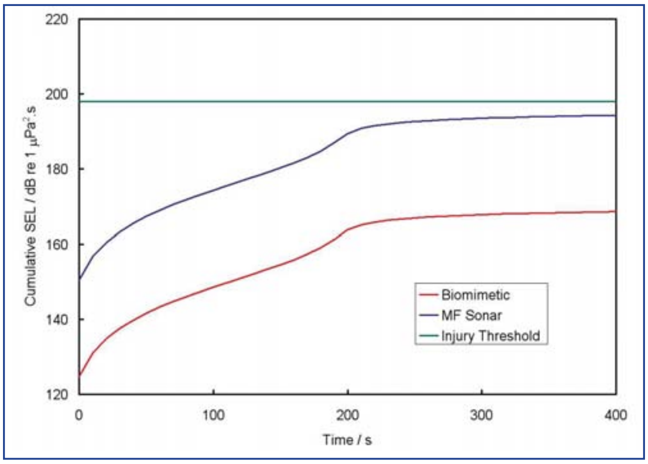
Marine mammals produce a variety of vocalizations, but this article focuses on the echolocation clicks produced by dolphins and other odontocetes (toothed whales), mainly because these are active sonar signals, whereas many of the vocalizations associated with these animals are for communications. However,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

The original inspiration for these novel signals came from the analysis of clicks from bottlenose dolphins (*Tursiops truncatus*). The pulses are of very short duration, between 50 and 80 microseconds, and spectrograms computed using short-time fractional Fourier transforms clearly show that the signal comprises two short downward chirps. However, although the double chirp structure seems typical of bottlenose waveforms, few other species have been studied, except for sperm whale (*Physeter macrocephalus*) clicks in which, once again, the double chirp structure is evident, although 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 and scalable in both time and frequency. This signal structure might appear less threatening to most mammals and thus have a lower behavioral impact. Therefore, a biomimetic signal model was implemented based on two linear-frequency-modulated chirps. In this implementation, a waveform is fully defined by the frequency range and duration of the two chirps, along with the delay between the first and second. A waveform representative of sperm whale clicks has been chosen for the sonar performance analysis presented in this article.



A schematic of the biomimetic waveform model showing how the two chirp components are defined.



Cumulative sound exposure levels for a cetacean swimming past the sonar for biomimetic (red) and the high-frequency (blue) sonar waveforms compared with the injury threshold (green).

Sonar Performance

For comparison with the synthesized echolocation click, a typical anti-submarine warfare (ASW), mid-frequency sonar waveform operating at a center frequency of seven kilohertz with a 500-millisecond, 100-hertz bandwidth chirp pulse was used as an example. For this simple illustration, the same typical sonar source level is used for both conventional and biomimetic waveforms, the sonar projector is assumed omnidirectional, and the pulse repetition frequency is one pulse per 10 seconds.

The instantaneous SEL can be calculated for a single pulse by integrating the square of the pressure waveform over the duration of the pulse, having determined the sound pressure level received by a mammal at a specified position relative to the sonar. The cumulative SEL can then be obtained from these values for a mammal swimming over a specified path simply by summing the resultant SELs for each ping transmitted for the duration of interest.

For instance, a cetacean such as a dolphin may swim at 10 knots in a straight line toward the sonar, passing at a closest point of approach of 50 meters and then continuing in a straight line beyond the sonar. After the animal passes the sonar, the cumulative SEL for the mid-frequency sonar signal converges on a value some four decibels below the criterion for injury suggested by the guidelines, and the cumulative SEL for the biomimetic waveform is 26 decibels below that.

Clearly, both signals are below the level that would lead to injury in the situation as described and, in addition, the biomimetic source level could be increased by 26 decibels to produce the same SEL as the high-frequency sonar.

This would be unrealistic, but it makes the point that, at the same source level, the energy in the mid-frequency sonar pulse is considerably greater than that in the biomimetic signal. By adjusting the source levels to achieve the same cumulative SEL, the energy in the pulses is equalized 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. The mid-frequency sonar signal is a conventional chirp, and the conventional detector would be a matched filter. The response of such a matched filter detector to the mid-frequency sonar signal, even buried in noise, would be a clear peak, well above the noise, and compressed in width to about 10 milliseconds. This response, however, would be the same whether the echo came from a valid target, a rock on the seabed 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 vocalizations. Again, a strong peak is obtained when this process is applied to the biomimetic waveform.

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. This allows 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 propagation 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 this should be equally applicable to the wideband multiple chirp waveforms considered above. Big brown bats (*Eptesicus fuscus*), in particular, can recognize echoes containing the full harmonic spectrum of their transmissions and associate these with close, on-axis targets. Echoes from greater distances will have suffered greater absorption at higher frequencies, resulting in losing some harmonics. Likewise, off-axis echoes will have lost high-frequency content because of the frequency-dependent directivity of transmitting and receiving beam patterns. Thus, the bat can track a nearby target at a high pulse-repetition frequency, while still maintaining general long-range and off-axis surveillance.

Finally, dolphins demonstrate a remarkable ability to recognize very fine differences in the geometry or materials of man-made targets. 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. Biomimetic waveforms similar to that described in this article have been used in experiments to determine if adapting the biomimetic waveform parameters can highlight key spectral features in the echoes returned 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.

A classification algorithm has been implemented based on this concept, and applying this algorithm to experimental data has demonstrated that the technique can distinguish different targets with a low rate of false positives. This finding confirms the view that a biomimetic waveform combined with biomimetic processing has the potential to enhance sonar performance.

Discussion and Conclusions

The main driver for using biomimetic waveforms was the idea that the waveforms used by these mammals may have performance advantages over more conventional signals. A second consideration was that signals similar to those used by marine mammals might appear less threatening than conventional sonar signals, reducing the potential behavioral impact.

A brief analysis was described, based on a synthesized waveform derived from a sperm whale echolocation click. It was noted that the model used to 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 mid-frequency ASW sonar.

To make the comparison meaningful with respect to minimizing physical impact on marine mammals, the cumulative SEL was estimated for both signals for the simple case of a mammal swimming past the sonar at 10 knots with a closest point of approach of 50 meters. The results of this comparison, along with a consideration of potential biomimetic processing techniques, may be summarized as follows:

The biomimetic waveform could be transmitted with a higher source level than the ASW signal for the same cumulative SEL. However, adjusting the transmitted source levels (and possibly pulse repetition frequencies) to achieve the same cumulative SEL for each waveform equalizes the energy in both waveforms, leading to similar detection performance when the primary limitation is ambient noise. Nevertheless, consideration of potential biomimetic processing techniques suggests the combination of biomimetic waveform and biomimetic processing could lead to improvements in areas such as clutter rejection and target classification.

As yet, it is unknown whether naturally occurring signals have a lower behavioral 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.

References

For a full list of references, contact Peter Dobbins at peter.dobbins@ultra-sonar.com. ■

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