DOI: 10.61782/fa.2023.0920

A NOVEL MODULATION APPROACH BASED ON NONLINEAR ACOUSTIC SIGNALS FOR UNDERWATER COMMUNICATIONS

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ABSTRACT

Nonlinear acoustics is the catalyst of a new generation of applications that are being exploited in different fields. The parametric nonlinear effect, i.e. the appearance of extra harmonics in the spectrum besides the fundamental frequency is a particular feature in nonlinear acoustic and it can be used in the field of communications. In this sense, the study of modulation is an essential aspect that suits the needs of nonlinear acoustic communications. This paper presents a novel technique of nonlinear parametric modulation-induced harmonics. This type of modulation provides a narrow directivity using low transmission frequencies (2 to 50 kHz). Its feasibility and the parametric effect are demonstrated by analyzing a recorded 16-bit parametric signal and its spectrogram. Finally, detection performance is shown by applying cross-correlation to the received signal.

Keywords: *underwater acoustic communications, ultrasounds, nonlinear acoustics, parametric effect, signal processing, cross-correlation detection method*

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1. INTRODUCTION

Most of the applications for information transmission in water are based on acoustic systems because sound waves are better adapted to the marine environment, although their propagation in the underwater acoustic channel presents important limitations due to the limited bandwidth, multipath propagation, source refractive properties, among others [1–7].

In the field of communication systems using acoustic signals, there is special interest in the study of parametric effects since the propagation of underwater acoustic waves produces non-linear effects. In this sense, there are some proposals of systems that take advantage of parametric generation for the transmission of digital data [8–15]. Among them, it stands out the MAST project, PARACOM [8], implementing a type of modulation for parametric acoustic communications providing long-range communications.

This work presents a new nonlinear acoustic signal modulation scheme, more specifically wide band sine-sweep signals, that provides more accurate bit detection and discrimination than previous acoustic signal modulations.

This paper is organized as follows: Section 2 introduces the theoretical background governing the nonlinear acoustics to understand the parametric and its benefits. Section 3 describes our nonlinear (parametric) acoustic signal modulation. Section 4 presents the processing of acoustic signals for bit detection in recorded modulated signals. Finally, Section 5 concludes.

2. BACKGROUND

Parametric underwater acoustic communications use the nonlinear effects generated in the underwater channel for data transmission. To this end, a pressure bi-frequency signal, $p'(0,t)$, can be defined as:

$$p'(0,t) = A_a \sin(\omega_a\, t) + A_b \sin(\omega_b\, t), \tag{1}$$

where ω_a and ω_b are primary high frequencies, and very close to each other. A_a and A_b are the amplitudes of these primary frequencies.

Thus, a medium (water) excited by a bi-frequency signal (equation (1)) allows a mutual interaction between them due to the channel nonlinear effects, forming secondary waves of frequencies being the linear sum and difference combinations of the primary frequencies, also known as beat frequencies. Moreover, the dissipating effects of the medium attenuate higher frequency waves making them disappear. At large distances from the source, a single-frequency signal prevails, ω_d, which is the difference $\omega_d = \omega_a - \omega_b$. As ω_d is a low frequency, it suffers a lower attenuation effect and can propagate to further distances. This phenomenon, known as *parametric effect*, generates low frequency signals with narrow radiation patterns (a feature of the primary higher frequencies) [16, 17]. In addition, an important property of the parametric effect is that it enables reliable signal detection and demodulation. This will be discussed in the following sections.

Also, if $A_a = A_b = A_c/2$, equation (1) can be rewritten as:

$$\begin{aligned} p'(0,t) &= A_c \cos(\omega_m\, t) \sin(\omega_c\, t) \\ &= \frac{A_c}{2} \sin(\underbrace{(\omega_c + \omega_m)}_{\omega_a}\, t) + \frac{A_c}{2} \sin(\underbrace{(\omega_c - \omega_m)}_{\omega_b}\, t), \end{aligned} \tag{2}$$

where ω_m is the frequency of the modulating signal, ω_c is the frequency the carrier signal, and A_c the amplitude of the carrier signal. Thus, if the envelope $E(t)$ is a harmonic signal, $E(t) = \sin(\omega_m\, t)$, it will be reduced to a bi-frequency excitation and the difference frequency, $\omega_d = 2\,\omega_m$, will be twice the frequency of the modulating signal.

In this way, for any signal with an envelope, the demodulation is related to the second derivative of the time-squared envelope, $E^2(t)$, as shown in equation (3). This is defined as the parametric signal, p_{param}:

$$p_{param} \backsim \frac{\partial^2 E^2(t)}{\partial t^2} \tag{3}$$

3. MODULATION FOR NONLINEAR PARAMETRIC SIGNALS

3.1 Direct process

The process for obtaining parametric signals in underwater acoustic communications is based on the *direct process* [18]. Basically, departing from a signal given by a modulation (e.g., equation (2)), a parametric signal must be designed [19] in such a way that can be decoded even under the effects of nonlinear propagation.

This paper proposes the utilization of a known modulating signal $E(t)$ of type sine-sweep that represents bits as in (4).

$$E(t) = \sin\left(\left(\frac{|\omega_{m2} - \omega_{m1}|}{\tau}\, t + \omega_{m1}\right) t\right), \tag{4}$$

where ω_{m1} is the initial frequency of the sine-sweep, ω_{m2} is the final frequency of the sine-sweep, τ is the total duration of the sine-sweep, and t is the time.

Let us define $\omega_d = |\omega_{m2} - \omega_{m1}|$. The profile of the parametric signal of equation (3) can be obtained as:

$$\begin{aligned} p_{param} \backsim\ & 4\frac{\omega_d}{\tau} \sin\left(2\left(\frac{\omega_d}{\tau}\, t + \omega_{m1}\right)\right) \\ & + 2\left(\frac{2\,\omega_d}{\tau}\, t + \omega_{m1}\right)^2 \cos\left(2\left(\frac{\omega_d}{\tau}\, t + \omega_{m1}\right)\right) \end{aligned} \tag{5}$$

In equation (5), the parametric signal is a sine-sweep with a frequency twice the one of the modulating frequency, and an initial amplitude equal to zero growing proportional to t^2. This equation is derived following the theoretical parametric transmission model studied by Westervelt [20] and Bektay [21]. It is the result of the second derivative of envelope $E(t)$ (equation (4)) squared. Fig. 1 shows the effect of applying this process with a sine-sweep modulated signal ranging from $f_{m1} = 2\,\mathrm{kHz}$ to $f_{m2} = 20\,\mathrm{kHz}$ ($\omega_{m1} = 2\,\pi\, f_{m1}$, $\omega_{m2} = 2\,\pi\, f_{m2}$), and with a duration of $1\,\mathrm{ms}$. It can be observed that the parametric signal frequencies are twice the ones of the modulated signal, with a sine-sweep ranging from $4\,\mathrm{kHz}$ to $40\,\mathrm{kHz}$.

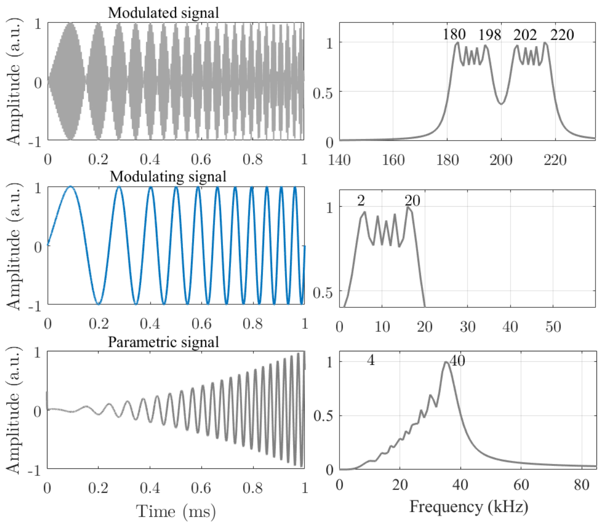

Figure 1. Direct process for a sine-sweep signal in the time and frequency domain. In the top, the sended modulated signal is represented; in the middle, the modulating signal (low frequency, 2 to 20 kHz) is showed; and in the bottom, it can be seen the received demodulated signal produced by the parametric effect (4 to 40 kHz).

3.2 Parametric sine-sweep

As previously stated, this work presents a novel modulation technique for underwater acoustic communications. It is based on the concatenation of several broadband sine-sweep signals (equation (4)). In this modulation, the bit '1' is defined by an upward sine-sweep as a modulated signal (f_{m1} to f_{m2}), and the bit '0' is defined by a downward sine-sweep (f_{m2} to f_{m1}).

Fig. 2 depicts the modulated signals for bits '1' and '0' for better visual comprehension. Nevertheless, these signals are transmitted concatenated to form the desired message.

In our experiments, the sine-sweep envelope for a bit '1' ranged from 2 kHz to 20 kHz, and for a bit '0' ranged from 20 kHz to 2 kHz. Both signals have a duration of 1 ms, modulated with a sine of frequency carrier $f_c = 200\,\text{kHz}$. This produces a parametric signal with a frequency twice the one of the emitted signal envelope as shown in Fig 1.

Fig. 3 shows the second derivative of the time-squared

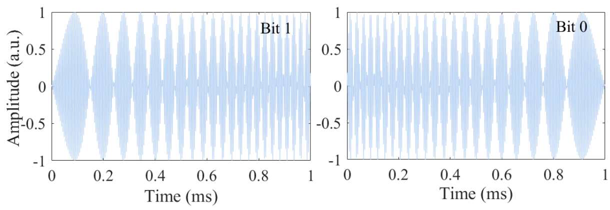

Figure 2. Modulated sine-sweep signal.

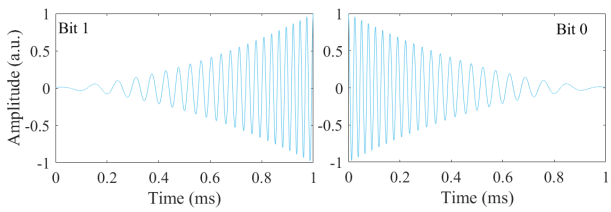

Figure 3. Expected parametric signals for bits '1' and '0'.

envelope (equation (4)). This is the combination of harmonic signals with variable frequency and increasing amplitude as a function of the modulating frequency Δf.

4. SIGNAL PROCESSING FOR BIT DETECTION

As mentioned in Section 3, the amplitude of the low-frequency signal due to the parametric effect is lower than the emitted signal, making it difficult to detect, or distinguish from background noise. To empirically demonstrate this, we recorded a parametric signal with a 16-bit string (1010 0101 1001 0110) at an emitter-receiver distance of one meter. The experiment setup is shown in Fig. 4. The transmitting and receiving system operates at a sampling frequency of 20 MHz and the bits are emitted continuously.

A good way to prove the occurrence of the parametric effect is to analyze the recorded signal spectrogram. Fig. 5 shows the emitted signal around 200 kHz, and low frequency rising and falling sine-sweeps ranging from 4 kHz and 40 kHz corresponding to the parametric bits, clearly distinguishable.

These experimental results show that, as predicted by theory, the parametric signal frequencies are twice the ones of the original signals.

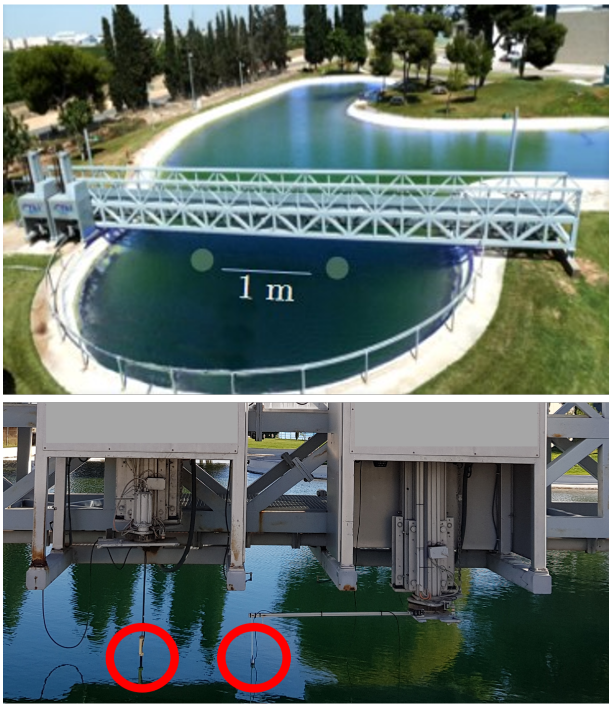

Figure 4. Experimental setup: Troncoconic pond with a 10 m depth, a diameter of 20 m, and positioning system. The hydrophone is placed on the left, and the projector on the right.

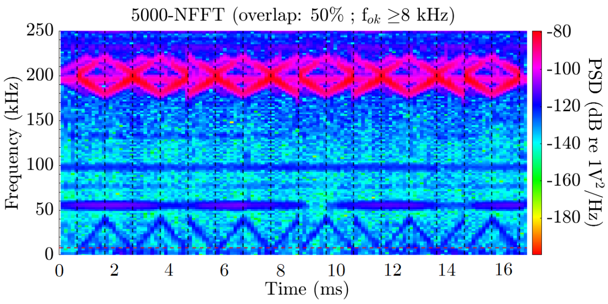

Figure 5. Zoom on the Y-axis of the spectrogram of the received signal. This transform uses 5000 samples for the Fast Fourier Transform with a 50% overlap, producing a time resolution of 125 µs, and a frequency resolution of 2 kHz.

4.1 Cross-Correlation decoding method

Cross-correlation can show the occurrence of specific signals in a recording with a matched filter. This method

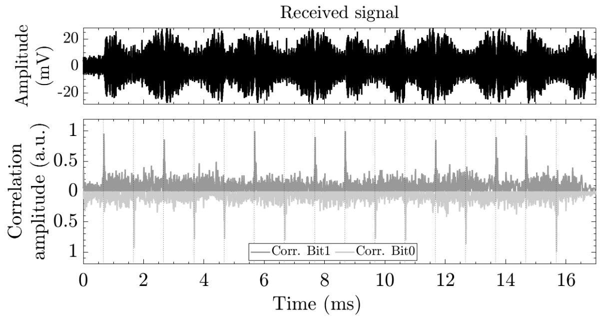

Figure 6. The received signal is placed at the top. At the bottom, the cross-correlations between the received signal and the expected parametric sine-sweep signal from 4 kHz to 40 kHz for each bit.

can also estimate the amplitude of the received signal [22]. It consists of correlating a filter with an impulse response matching the searched signal with the recorded signal. Thus, if a similarity occurs a peak will appear. In our particular case, the technique is applied by correlating the recorded signal with parametric bit signals '1' and '0' [23].

Fig. 6 shows the received signal and the resulting correlation (top) for both bits '1' and '0' (bottom). Both correlations have been normalized. Superimposing them for comparison demonstrates the distinction between the two bits and the ease of detection for this parametric effect.

These results show that the parametric sine-sweep modulation is a suitable alternative to be used in nonlinear underwater acoustic communications providing a correlation amplitude value near to one due to the wide frequency bandwidth used. In this case, having used sweep-type signals for modulation permits its demodulation using the correlation analysis (see Fig. 6), which has a low computational cost (compared with other analyses in frequency) and is less affected by to background noise.

On the other hand, the parametric effect allows not only directive communications, but also to diminish for the most part the multiple reflection that could worsen the quality of the communication.

5. CONCLUSION

In this work, we have presented a novel digital modulation technique using nonlinear acoustic signals (parametric effect) focused on the transmission of information in the field of underwater acoustic communications. It has presented a modulation scheme using sine-sweep signals. In addition, the experiment carried out confirms the parametric generation and demodulation of these signals.

Received message decoding through the cross-correlation method is achieved, obtaining narrow and well-defined peaks in the expected time. Moreover, this type of modulation provides a signal decoding performance since received signals are highly directive, despite their use of low frequencies (ranging from 4 to 40 kHz).

6. ACKNOWLEDGMENTS

This work was supported by the grants PID2019-103982RB-C42, and TED2021-129336B-I00 funded by MCIN/AEI/10.13039/501100011033 and is a result of an internship funded by the Autonomous Community of the Region of Murcia through the Fundación Séneca - Agencia de Ciencia y Tecnología de la Región de Murcia (Seneca Foundation - Agency for Science and Technology in the Region of Murcia) and European Union NextGenerationEU programme.

María Campo-Valera is grateful for the postdoctoral program Margarita Salas—Spanish Ministry of Universities (financed by European Union - NextGenerationEU).

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