Bispectral Analysis of Underwater EM Pulses

L. Persson[*], D.E. Asraf[†], P. Sigray[‡] and P. Krylstedt[§]
Defense Research Establishment FOA, S-172 90 Stockholm, Sweden

M.J. Hinich[¶]
Applied Research Laboratories, University of Texas at Austin, P.O 8029, Austin, TX, 78713-8029

Abstract

In this paper we investigate higher-order spectral properties of an electromagnetic (EM) transmission channel. We compare conventional ensemble averaging to higher-order signal reconstruction for signal to noise enhancement of received real underwater EM pulses. The reconstructed signal is estimated from the bicepstrum and are shown to outperform conventional stacking techniques. Appropriate features based on higher-order moments, bicoherence and cross-bispectrum for object classification are discussed. We use bicoherence for estimation of nonlinear properties in the received pulses. There are no significant quadratic nonlinear contributions in the signal. The nonlinearities are essentially around the power supply frequency and at a region above 17 kHz. The transmission channel transfer function is investigated based on the cross-bispectrum. It is found that several frequencies in the signal bandwidth contain a significant part with a nonlinear gain.

1. Introduction

During the last few years there has been an increased interest of active underwater electromagnetic (EM) systems, operating at the extreme low frequency (ELF) band, for communication, mine detection and object classification. These active EM systems often use pulse-echo reflection techniques to make fast detection and classification. The attenuation and the propagation velocity of EM pulses in sea water are highly frequency dependent. The signal distortion due to the wave propagation media is high, even at moderate distances. Thus, the shape of the transmitted EM-pulse needs to be optimized with respect to the amplitude for both the transmission channel and the objects to be detected and classified. The electromagnetic signals used in this paper are generated by a submerged hertzian horizontal electrical dipole (HED) in the Baltic Sea and received by an antenna at some distance from the transmitter, see section 4. The transmitter-receiver system is shown in Fig. 1.

In order to achieve reliable classification it is essential to reduce the ambient noise (i.e. signal enhancement and reconstruction) and to deconvolve the distortion effects due to the transmission channel from the received signal. In the signal processing literature, several methods for signal detection and reconstruction based on higher-order statistics have been published, e.g. Hinich [3], Bartlett et. al. [1], Matsuoka and Ulrych [6], Giannakis [2] and Papadopoulos and Nikias [7]. In our application, the pulses contains a high proportion of third-order statistical information (skewness). Classification techniques based on higher order statistics has been used by several, e.g. Hinich et. al. [4] and Persson and Toral [9]. The outline of the paper is as follows. Formulas used for the analysis are presented in Section 2. Properties of the EM transmission channel are treated in Section 3. The experimental setup and the generation of the underwater EM signals are explained in Section 4. Sections 5 and 6 covers the data analysis and presents the results, respectively. Concluding remarks are drawn in Section 7.

2. Preliminaries

The transmission of EM pulses in sea water can be considered as a linear process for moderate pulse energies. Therefore, we can describe the received signal as $\tilde{y}(n) = y(n) + w(n)$, where $w(n)$ is additive i.i.d. noise and $y(n)$ is the convolution of the transmission channel $g(n)$ and the emitted input signal $x(n)$

$$y(n) = g(n) * x(n), \;\; n = 0, 1, \ldots, N-1, \qquad (1)$$

where N is the length of the time series. If the channel, $g(n)$, is nonminimum phase (NMP) then the techniques used for signal estimation of $y(n)$ and system identification of $g(n)$ need to utilize higher order methods to preserve the NMP structure of the signal and system. The conventional

[*]E-mail: leifp@sto.foa.se [†]E-mail: daniela@sto.foa.se
[‡]E-mail: peters@sto.foa.se [§]E-mail: peterk@sto.foa.se
[¶]E-mail: hinich@mail.la.utexas.edu

bispectrum $B_y(\omega_1,\omega_2)$ for the signal $y(n)$ is defined as

$$B_y(\omega_1,\omega_2)=\sum_{k_1=1}^{N}\sum_{k_2=1}^{N}C_3(k_1,k_2)e^{-j(\omega_1 k_1+\omega_2 k_2)}, \quad (2)$$

where $C_3(k_1,k_2)$ is the third-order correlation. The l:th order correlation is defined as

$$C_l(k_1,\ldots,k_{l-1})=\mathcal{E}[y(n)y(n+k_1)\cdots y(n+k_{l-1})]. \quad (3)$$

We use the FFT based bicepstrum method proposed by Pan and Nikias [8] for the signal reconstruction problem due to the long support of the cepstrum. The bicepstrum is achieved by

$$b_y(m_1,m_2)=\mathcal{F}_2^{-1}\frac{\mathcal{F}_2(k_1C_3(k_1,k_2))}{\mathcal{F}_2(C_3(k_1,k_2))} \quad (4)$$

where $\mathcal{F}_2\{\cdot\}$ denotes the 2-D Fourier transform and $\mathcal{F}_2^{-1}\{\cdot\}$ the inverse. The cepstral parameters are then retrieved along the diagonal in the bicepstrum domain.

In order to perform effective classification of objects it is essential to use several significant features. Since, objects with conducting properties that differ from the environment, could have a more or less pronounced nonlinear response with regard to the exiting EM field there is motivation to use higher-order based techniques. Bicoherence $B_y^c(\omega_1,\omega_2)$ is an appropriate feature defined by

$$B_y^c(\omega_1,\omega_2)=\frac{|B_y(\omega_1,\omega_2)|^2}{P_y(\omega_1)P_y(\omega_2)P_y(\omega_1+\omega_2)} \quad (5)$$

where $B_y(\omega_1,\omega_2)$ is the bispectrum and $P_y(\omega)$ is the power spectrum of $y(n)$. We use the bicoherence to estimate nonlinearities in the received signal prior target classification in order to avoid miss-classification. Other features more easily interpreted for classification are higher-order correlations. We study how the transmission channel affects the convergence of the 2:nd and 3:rd moment at zero lag, of the received signal $\tilde{y}(n)$, i.e. $C_2(0)$ and $C_3(0,0)$ given in eq.(3).

The transmission channel transfer function is investigated using the nonlinear cross-bispectrum based gain G_y by Hinich and Wilson [4]. The nonlinear gain is defined by

$$G_y(\omega_1,\omega_2)=\frac{B_{xxy}(\omega_1,\omega_2)\sqrt{P_x(\omega_1+\omega_2)}}{B_{xxx}(\omega_1,\omega_2)\sqrt{P_y(\omega_1+\omega_2)}} \quad (6)$$

where $B_{xxy}(\omega_1,\omega_2)$ is the cross-bispectrum between the transmitted signal $x(n)$ and the received signal $y(n)$, $B_{xxx}(\omega_1,\omega_2)$ is the bispectrum of $x(n)$ and $P_y(\omega)$ and $P_x(\omega)$ are the corresponding power spectra. If the gain is larger then 1 we have a nonlinear component in the transfer function.

3. EM Transmission Channel

The transmitted pulse $x(t)$ can be optimized for both the dispersive effects of the channel and the target to achieve optimal features for detection and classification. The EM channel is represented by the propagation from the transmitter to the receiver. Song and Chen [10] found a time domain solution for the optimum antenna current in order to achieve a maximum EM pulse intensity at a particular distance. Their work was restricted to a homogeneous medium of infinite extent. In a shallow water environment it is necessary to take into account the EM effects caused by the interfaces to the water surface and bedrock. The geometrical configuration of our problem can be seen in Fig. 1. The electrical field (expressed in cylindrical coordinates), $E_p=(E_\rho,E_\varphi,E_z)$, at a point of observation (PO), $p=(\rho,\varphi,z)$, from a HED antenna submerged in a three layer environment and located at the origin of the coordinate system, can be formulated using the method of image sources [5]. In order to obtain a crude insight to the analytical properties of the EM channel transfer function, the contributions from the interfaces are omitted and the PO is chosen to $\varphi=\pi/4$ and $z=0$, this gives $E_\rho=0$ and $E_z=0$. The electrical field is then expressed in the Laplace domain as

$$E_\varphi(s)=\frac{Idl}{4\pi\epsilon\rho^3}\frac{1+\gamma(s)\rho+\gamma^2(s)\rho^2}{s+\frac{\sigma}{\epsilon}}e^{-\gamma(s)\rho}sin(\varphi)X(s) \quad (7)$$

where $\gamma(s)=\sqrt{s^2\mu\epsilon+s\mu\sigma}$, $X(s)$ is the Laplace transform of the transmitted current ($x(t)=\delta(t)$, then $X(s)=1$) and σ, ϵ, μ are the conductivity, permittivity and permeability respectively. By finding the roots to $1+\gamma(s)\rho+\gamma^2(s)\rho^2$ eq.(7) can be expressed as the product of a rational function and $e^{-\gamma(s)\rho}$

$$G(s,\rho)=\frac{(s-z_1)(s-z_2)(s-z_3)(s-z_4)}{s-p_1}e^{-\gamma(s)\rho} \quad (8)$$

where $z_{1,2,3,4}$ and p_1 are the zeros and pole for the rational function, respectively. The zeros are $z_{1,2}=\frac{-a\pm\sqrt{a^2-2b(1-i\sqrt{3})}}{b\rho}$ and $z_{3,4}=\frac{-a\pm\sqrt{a^2-2b(1+i\sqrt{3})}}{b\rho}$ where $a=\mu\sigma\rho$ and $b=\mu\epsilon$, the pole is $p_1=-\frac{\sigma}{\epsilon}$. Hence, the transfer function for the EM channel consists of both zeros and a pole, with values dependent on both the environment (μ,σ,ϵ) and the PO (p), and is therefor not restricted to a minimum-phase system.

4. Experimental Arrangements

We performed the field trials in an ice-covered bay of the Baltic sea in the Stockholm archipelago. The size of the bay is about 200 m times 500 m. The conductivity in the water was measured to 5.66 S/m with a temperature of 2 C. No vertical variation of the water were found during the trials. The transmitter is a 6 m long rod attached with two 1 m long Titanium cylinders, the latter constituting the transmitter electrodes. The output power from the amplifier is limited to 50 A. The pulse shapes are optimized with respect to the amplitude at different distances. The receiver system is based on Ag/AgCl electrodes with a distance of 1 m. The source-receiver distance was 115 m at a water depth of 6 m and 10 m. The received pulses could either be averaged (conventional stacking) or appended in a file. A low-pass anti-aliasing filter was used below the Nyqvist frequency of 25 kHz.

5. Data Analysis

The ambient noise during the experiment resulting in a low and difficult SNR scenario makes it important to succeed with the signal enhancement and reconstruction. In Fig. 2 time series of the ambient noise, single pulse, transmitted pulse and conventional stacking of 100 pulses together with the power spectra are displayed. Conventional enhancement of the SNR is based on the assumption that a set of similar pulses, $x(n)$, are transmitted and synchronized in time. The time domain average is then calculated as $\hat{y}(n) = \sum_{k=1}^{K} \tilde{y}_k(n)$, where $\tilde{y}_k$ is the k:th received pulse and $\hat{y}(n)$ is an estimate of $y(n)$ in eq.(1). The obvious problem with this procedure is the time alignment of the received signals. This problem is circumvented by performing the averaging in the bispectrum domain:

$$\hat{B}_y(\omega_1, \omega_2) = \sum_{k=1}^{K} B_{\tilde{y}_k}(\omega_1, \omega_2) \qquad (9)$$

where $\hat{B}_y(\omega_1, \omega_2)$ is the estimate of $B_y(\omega_1, \omega_2)$, which is used for bicoherence, bicepstrum and nonlinear gain estimation.

6. Results

In Fig. 3 the second- and third-order moments at zero lag are displayed as a function of ensambles for averaging. The stability of the third-order estimate are reached before 100 ensambles for both ambient noise and signal plus noise. Examples of bicoherence are shown in Fig. 4 for signal plus noise and in Fig. 5 for the ambient noise. The larger values above 0.5 are related to the power supply frequency of 50 Hz and the higher frequencies related to a VLF Omega[1]system. The bicepstrum for the signal in Fig. 2 is displayed in Fig. 6. The diagonal is used for the reconstruction of the signal. In Fig. 7 the transmitted signals optimized for the distances 70, 115 and 140 m are displayed together with corresponding received stacked signals and reconstructed signals, using 100 ensambles. The noise suppression is larger for the reconstructed signals compared with the stacked. The nonlinear gain in Fig. 8 show some frequency combinations with nonlinear gains, i.e. $G_y > 1$.

[1] Omega is the name of a navigation system.

7. Discussions and Conclusions

The analysis of the transmission channel is important prior classification of received echoes from objects. If the channel properties is known a priori there is a possibility to perform deconvolution of the effects from the wave propagation medium. Here, we discuss different bispectral based methods for estimation of the properties. We use bicoherence for QPC identification and found only significant nonlinear effects at higher frequencies and at the power supply frequency at 50 Hz. We also use bicepstrum for signal-to-noise enhancement. The noise level is successfully suppressed if the number of realizations is large enough. The last part of the analysis consists of estimating the nonlinear gain show some frequencies with second-order nonlinearities. The higher-order properties of the channel we estimate will be considered at a range of distances and used prior the classification procedure.

References

[1] H. O. Bartlett, A. Lohmann, and B. Wirnitzer. Phase and amplitude recovery from bispectrum. *App. opt.*, 23:3124–3129, 1984.

[2] G. B. Giannakis. Signal reconstruction from multiple correlations: Frequency- and time-domain approaches. *J. Opt. Soc. Am. A*, 6:682–697, 1989.

[3] M. J. Hinich. Detecting a transient signal by bispectral analysis. *IEEE Trans. ASSP*, 38:1277–1283, 1990.

[4] M. J. Hinich and G. R. Wilson. Time delay estimation using the cross bispectrum. *IEEE Trans. SP*, 40:106–113, 1992.

[5] P. Krylstedt. Static electromagnetic fields in layered media studied by an asymptotic image theory. *Proc. Hydroakustik*, FOA-R–95-00173-2.2-SE, 1995.

[6] T. Matsuoka and T. Ulrych. Phase estimation using the bispectrum. *Proc. IEEE*, 72:1403–1411, 1984.

[7] C. Padadopoulos and C. Nikias. Parameter estimation of exponentially damped sinusiods using higher order statistics. *IEEE Trans. ASSP*, 38(8):1424–1436, 1990.

[8] R. Pan and C. L. Nikias. The complex cepstrum of higher order cumulants and nonminimum phase system identification. *IEEE Trans. ASSP*, 36(2):186–205, 1988.

[9] L. Persson and J. Toral. Discrimination of local seismic events in panama by means of higher-order statistics. *Proc. of SPWHOS97, Banff Canada*, 23:14–20, 1997.

[10] J. Song and K. Cheng. Propagation of em pulses excited by an electric dipole in a conducting medium. *IEEE Trans. on Antennas Propagat.*, 41(10):1414–1421, 1993.

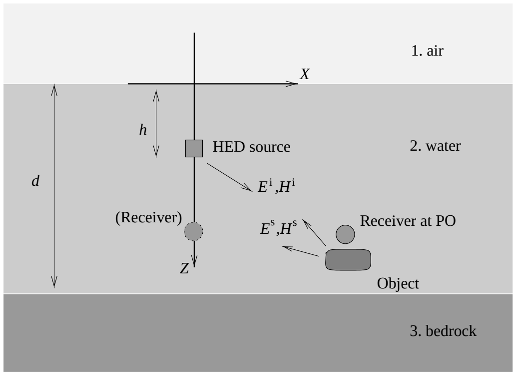

Figure 1. The experimental transmitter-receiver system.

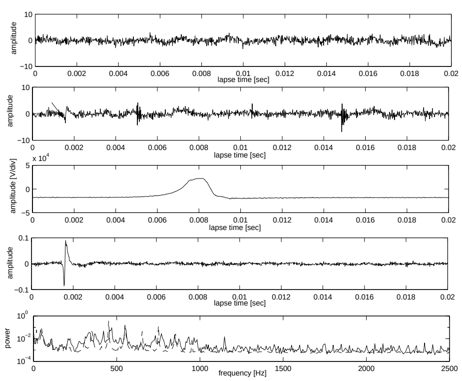

Figure 2. Time series of ambient noise (top), one received pulse at lapse time 0.002 (second), the pulse at the transmitter (third), conventional stacked pulse based on 100 averaged pulses (fourth) and power spectrum for the noise (dashed) and the pulse (solid line) (bottom).

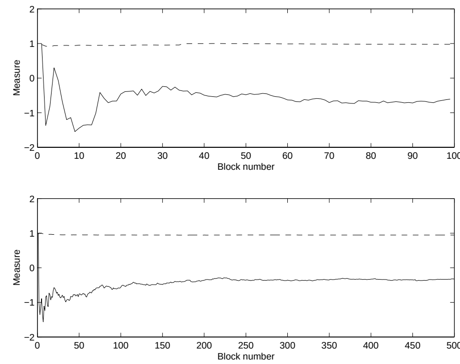

Figure 3. Properties of second and third order moments at zero lag vs. number of blocks used for averaging. Solid line third-order moment and dashed line second-order moment. Estimates with one transient in each block (top). Estimates from ambient noise (bottom).

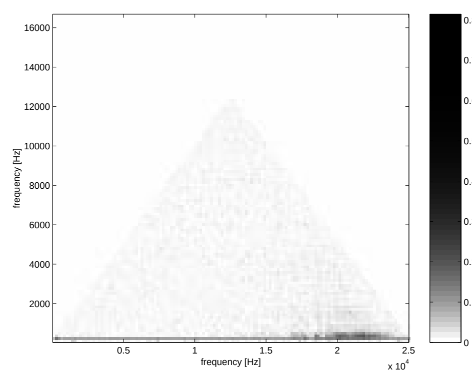

Figure 4. Bicoherence of received transients. Estimated from 100 blocks, each with 1000 samples.

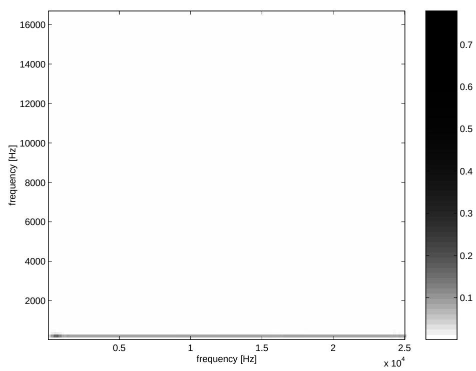

Figure 5. Bicoherence of the ambient noise. Estimated from 100 blocks, each with 1000 samples.

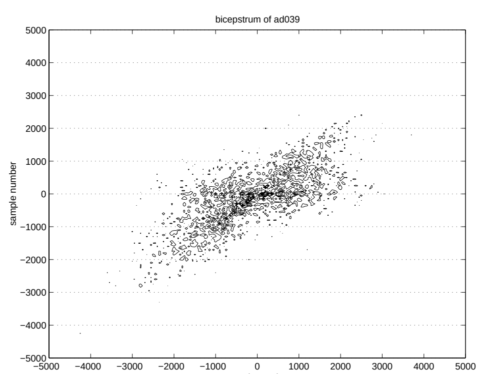

Figure 6. Bicepstrum of received transients. Estimated from 100 blocks, each with 1000 samples.

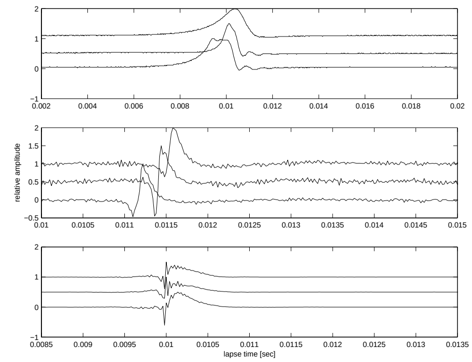

Figure 7. Time series of transmitted pulses optimized for distances 70, 115 and 140 m (top), corresponding time series of stacked received pulses (middle) and reconstructed pulses (bottom).

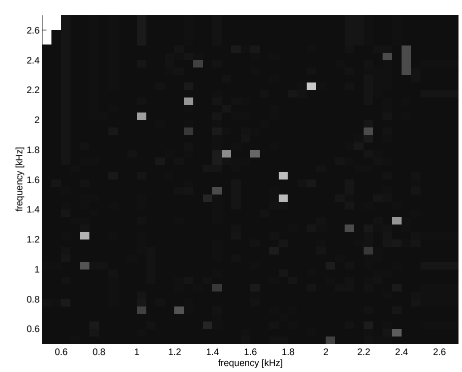

Figure 8. Nonlinear gain estimated with the cross-bispectrum from 100 blocks, each with 1000 samples.