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Vessel detection using extremely low frequency magnetic anomaly detection signal

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Vessel detection using extremely low frequency magnetic anomaly detection signal

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Abstract: Extremely low frequency (ELF) electromagnetic fields generated from a vessel are often measured with bottom-mounted systems. Research at DRDC has shown that these ELF magnetic fields can be detected with the magnetic anomaly detection (MAD) system suspended from a helicopter (towed body). However, to detect a vessel at a tactically useful range with the ELF signal only, the signal to noise ratio (SNR) has to be substantially improved.

This paper addresses the problem of ELF signal enhancement in noisy environments when only the noisy (after the normal aircraft compensation) MAD signal from a scalar magnetometer is available. A variety of ELF noise sources were examined in conjunction with the noise floor required in order to make detection at a given range. The signal processing algorithms to detect ELF signatures already exist for acoustic detection and can be adapted easily. The noise reduction technique is expressed as a short-time spectral gain depending on the a priori SNR. It is shown that, when applied to real data, the enhanced ELF signal offers improved target detection and can provide information about the target heading.

1. Introduction

Corrosion damage is a major factor in ship maintenance and availability, so that measures are taken to reduce it. An associated problem to the corrosion damage and implicitly to the cathodic protection is the presence of the corrosion currents and the currents generated by the impressed current cathodic protection (ICCP) system in the sea water. The corrosion currents travel from the hull through the seawater to the propeller(s), then up the shaft through the bearings back to the hull to complete the electric circuit.

The electromagnetic emission from the vessel in the typical ELF band is due to the modulation of corrosion currents caused by the variation of the shaft-hull resistivity as the shaft rotates. The signal occurs at the shaft rate and its harmonics. This signature is usually eliminated by (passive or active) shaft grounding [1].

Extremely low frequency (ELF) electromagnetic fields generated by vessels are routinely measured with bottom mounted systems and are thought to be used by modern mines as a trigger signal. Research at DRDC has shown that these ELF magnetic fields can be detected with the magnetic anomaly detection (MAD) system. Usually the MAD system is placed on board or towed by an airplane or helicopter.

When present, the magnetic field produced by the time varying electric sources decreases with the second power of distance offering the possibility of relatively long detection ranges. However, the detection range is limited by the noise due to the external sources and to the measurement system. In principle, the noise and the ELF signal from a ship are not correlated and thus the noise could be removed by using a reference signal located away from the aircraft.

Unfortunately, the use of a reference sensor is not a practical solution in the MAD technique and thus only the noisy signal is available. This paper addresses the problem of noise reduction in a single channel when the signal was degraded by uncorrelated additive noise. Single channel noise reduction is useful in many applications such as voice communication and speech recognition, so that the technique is extensively used in acoustic applications. Here, the method of single channel frequency domain noise reduction is adapted to enhance the ELF signal present in noisy environments and thus to increase the detection capability of the MAD system.

2. The noisy ELF signal from a ship

A set of measurements were taken with the MAD equipment suspended from a helicopter (towed body). The equipment consists of a scalar and a tri-axial magnetometer, a GPS antenna, and a tri-axial accelerometer. The magnetic field present in the proximity of the MAD equipment makes an impact on the magnetic detection because the target's signal will be covered by the local field. The towed body may contain ferromagnetic and electrical conductive materials, and other electrical devices that generate a magnetic field. Neglecting the unknown noise for the moment, the output of the magnetometers without any target present is given by the local geomagnetic, and permanent, induced, and eddy current magnetic vectors. A magnetic field model proposed in [2] attempts to represent these effects as a function of the attitude of an aircraft (the towed body in this case), and thus part of the local magnetic field can be estimated and separated from measurements.

The total intensity of the interference magnetic field was estimated using the following 18 term model:

$$
\begin{aligned}
&H = c_1 \cos X + c_2 \cos Y + c_3 \cos Z + \\
&+ H_e \{ c_4 \cos^2 X + c_5 \cos X \cos Y + c_6 \cos X \cos Z + c_7 \cos^2 Y + c_8 \cos Y \cos Z + c_9 \cos^2 Z + \\
&+ c_{10} \cos X (\cos X)' + c_{11} \cos X (\cos Y)' + c_{12} \cos X (\cos Z)' + c_{13} \cos Y (\cos X)' + \\
&+ c_{14} \cos Y (\cos Y)' + c_{15} \cos Y (\cos Z)' + c_{16} \cos Z (\cos X)' + c_{17} \cos Z (\cos Y)' + c_{18} \cos Z (\cos Z)' \}
\end{aligned}
$$

where H_e is the Earth's magnetic field, (cosX, cosY, cosZ) are the directional cosines of the Earth's field vector with the longitudinal, transverse, and vertical axes of the aircraft, and ( )' represents differentiation with respect to time. The directional cosines are provided by the tri-axial magnetometer.

In the above equation, the first 3 terms represent the permanent source interference field, followed by 6 terms standing for the induced source interference field, and the last 9 terms express the eddy current interference. Once the 18 coefficients are obtained (e.g. by ridge regression), we have an explicit model for predicting the aircraft interference that can be subtracted from the magnetometer signal. Thus, part of the environmental noise is cancelled and the detection of a magnetic target is enhanced.

This procedure was applied on a signal collected during a trial from where a segment was selected as an example to be presented in this paper. The sampling rate of the data collection was 10Hz. As part of the process of determining the compensation coefficients, it is generally considered necessary to high pass the data. Fig. 1 presents the signal recorded from -25 to +25 seconds before and after the closest point of approach (CPA) when the towed body was flying at about 100m altitude and with a horizontal offset from a surface vessel. A matching algorithm based on Anderson functions yields an offset of 55 m, but there is no independent tracking data for comparison. The signal was filtered with a 1Hz high-pass filter, and the noise has been reduced with the 18 term model. From the power spectral density (PSD) of the signal shown in Fig.2, one notes peaks at 2.25Hz, 3.8Hz, and the second harmonic of the 2.25Hz peak at 4.5Hz. The peak at 3.8Hz appears after 10 seconds from the CPA and may not be related to the ship, but the peaks at 2.25 and 4.5Hz are an indication of the presence of the ELF signal from the ship.

Obviously the processed ELF signal contains additional noise from other sources than the ones given by the 18 terms of the model. Such sources of noise that may be of concern in the ELF frequency band include:

a. spectral leakage from very large total field anomalies
b. temporal changes in the Earth’s magnetic field
c. vibration of the towed body.

The noise produced by these and other unidentified sources amounts to about 1.0 pT/√Hz in the signal already compensated with the 18 term model.

3. Influence of noise on the detection range

One can investigate the influence of noise on the detection range by simulations. The target is assumed to be known and, by using an appropriate model, the detection range can be estimated for a specific noise level. Algorithms to detect periodic signals in the presence of random noise are well developed, but here we will assume for simplicity that the detection occurs when the signal from the target is above the noise level.

The source that produces the ELF signal is adequately represented by a series of electric dipoles. The magnetic field components at the point (x, y, z) above water from an electric dipole aligned with the x-axis submerged in a conductive half-space can be approximated in the quasi-static limit by the equations [3]:

$$
\begin{aligned}
B_X &= -100\ p\ e^{j\omega t}\ xy[2(z-h-r)/r\rho^4 + (z-h)/r^3\rho^2] \\
B_Y &= \ \ 100\ p\ e^{j\omega t}\ [(x^2-y^2)(z-h-r)/r\rho^4 - y^2(z-h)/r^3\rho^2] \\
B_Z &= \ \ 100\ p\ e^{j\omega t}\ y/r^3 \\
r^2 &= x^2+y^2+(z-h)^2 \\
\rho^2 &= x^2+y^2
\end{aligned}
\tag{2}
$$

where p is the amplitude of the electric dipole moment in A-m, ω is the radial frequency, and t is time in seconds. The dipole position is given by the coordinates (0, 0, -h).

The ELF signature was simulated for the helicopter flying along a straight path with the towed body at the altitude of 100m. The target is represented by an electric dipole with the intensity of 10A-m and frequency of 1Hz. The dipole is pointing North and is placed at (0, 0,-20) meters, a position that is not directly under the sensor path, as shown in Fig. 3. The inclination and declination angles at the site are 70° and 0°, respectively. For this specific scenario, the calculated ELF magnetic total field signal is plotted in Fig. 4.

The procedure can be repeated for increasing altitudes of the towed body until the ELF signal reaches the noise level of the signal without any target present. The above measured noise value of 1.0 pT is reached at an altitude of 400m, which represents the detection range in this case. From this point of view, a detection range of 1200m may be achieved for a magnetometer having white noise floor of 0.1 pT/√Hz.

4. Improved ELF signal estimation

The enhancement of the signal-to-noise (SNR) ratio when only the noisy data is available has been extensively applied in voice communication and speech recognition. The noise reduction is performed in the frequency domain based on the assumption that the spectral components are statistically independent. Since these methods are well documented [4 – 8], only a short description will be presented here. Consider a noisy signal that includes the signal, s(t), and the additive noise, n(t):

$$v(t) = s(t) + n(t) \tag{3}$$

This signal will be analyzed frame by frame assuming that its behavior is quasi-stationary over the duration of the analysis frame. For each short-time frame, m, designate the ω_k spectral component of the noisy signal as $V(m,\omega_k)$, of the signal as $S(m,\omega_k)$, and of the noise as $N(m,\omega_k)$. The noise reduction process consists in the application to each short-time frequency spectrum, $V(m,\omega_k)$, of a spectral gain, $G(m,\omega_k)$, which is a function of two parameters: the *a priori*, $SNR_{prio}(m,\omega_k)$, and *a posteriori*, $SNR_{post}(m,\omega_k)$, signal-to-noise ratios:

$$\begin{aligned} G(m,\omega_k) &= f\,[SNR_{prio}(m,\omega_k),\, SNR_{post}(m,\omega_k)] \\ SNR_{post}(m,\omega_k) &= \frac{|V(m,\omega_k)|^2}{E\{|N(m,\omega_k)|^2\}} \\ SNR_{prio}(m,\omega_k) &= \frac{E\{|S(m,\omega_k)|^2\}}{E\{|N(m,\omega_k)|^2\}} \end{aligned} \tag{4}$$

where E is the expectation operator. The function f can be chosen from a variety of methods proposed in the literature including the power estimate [6], Wiener estimate [5], or minimum mean square error [4].

The calculation of the amplitudes (4) requires unknown information because, in practical implementations, the power spectral densities of the signal, $|S(m,\omega_k)|^2$, and of the noise, $|N(m,\omega_k)|^2$, are not available. The noise power spectral density can be estimated during the periods when the signal from the target is not present using the recursive relation [4]:

$$\hat{\gamma}_n(m,\omega_k) = \lambda\,\hat{\gamma}_n(m-1,\omega_k) + (1-\lambda)|V(m,\omega_k)|^2 \tag{5}$$

where $0 < \lambda < 1$ is the smoothing factor. Then the *a priori*, and *a posteriori* SNRs are estimated:

$$\begin{aligned} S\hat{N}R_{post}(m,\omega_k) &= \frac{|V(m,\omega_k)|^2}{\gamma_n(m,\omega_k)} \\ S\hat{N}R_{prio}(m,\omega_k) &= 0.98\frac{|\hat{S}(m-1,\omega_k)|^2}{\gamma_n(m,\omega_k)} + 0.02\,P\left[S\hat{N}R_{post}(m,\omega_k) - 1\right] \end{aligned} \tag{6}$$

Here P denotes half-wave rectification and $S(m-1,\omega_k)$ is the estimated signal spectrum at the previous frame obtained as follows:

$$\hat{S}(m-1,\omega_k) = G(m-1,\omega_k)\,V(m-1,\omega_k) \quad (7)$$

This noise reduction technique was applied on the ELF signal compensated with the 18 term model. The pure noise spectrum (5) was calculated during a period when the helicopter was flying a pattern off to the side of the ship for instrumental calibration. Then, the noisy signal was divided in frames of 30 seconds each with 50% overlap, and the ELF signal was estimated using equations (6) and (7). The time domain result for the same portion of the signal used as an example before is presented in Fig. 5, and its power spectrum in Fig. 6. The background noise was reduced to 3 fT/√Hz making the ELF signal clearly visible, a fact confirmed in Fig. 6 where only two peaks, the 2.25Hz and its second harmonic, are present in the power spectrum. This information, the presence of a fundamental and its second harmonic alone in a portion of the signal when activity is recorded, can be used as a target detection method.

By reducing the noise level, the detection range can be considerably increased and so making the measurement of the ELF signal a reliable means of target detection. The applied spectral gain suppresses all the amplitudes in a given frequency band when the ELF signal is not present, including the magnetometer white noise. However, the detection range is still limited by the level of noise in the magnetometer because, once the signal is buried in noise, it cannot be separated. Finally, as shown in Fig. 5, it is possible now to find the best fit of the measured data with the calculated values from a horizontal electric dipole from where one can obtain information about the target heading, which is -18° in this case in the GPS coordinate system.

5. Conclusions

We used a noisy signal obtained from the MAD system to detect a ship from its ELF radiation alone. To enhance the ELF signal, we applied a noise reduction technique adapted from acoustics in addition to the classical 18 term model method. The reduction of the background noise was so substantial, such that the ELF radiation offers a clear means of detection.

References

[1] Holmes J. John, Reduction of a Ship's Magnetic Field Signature *Synthesis Lecturers in Computational Electromagnetics vol. 23*, Editor C. A. Balanis, Morgan and Claypool Publishers, 2008, Denver, CO.

[2] Leliak P., Identification and evaluation of magnetic field sources of magnetic airborne detector equipped aircraft, IRE Trans. on Aerospace and Navigational electronics, 1961, pp. 95-105.

[3] Wilson H.S., Notes of the calculation of the field of a horizontal electric dipole, DRDC Atlantic Technical Memorandum (DREA TM 1996/208).

[4] Ephraim Y. and Malah D., Speech enhancement using a minimum mean square error short-time spectral amplitude estimator, IEEE Trans. Acoust., Speech, Signal Process., ASSP-32 (6), pp. 1109-1121, 1984.

[5] Lim J.S. and Oppenheim A.V., Enhancement and bandwidth compression of noisy speech, Proc. IEEE, vol. 67 (12), pp. 1586-1604, 1979.

[6] Boll S.F., Suppression of acoustic noise in speech using spectral subtraction, IEEE Trans. Acoust., Speech, Signal Process., ASSP-27 (2), pp. 113-120, 1979.

[7] Cohen I., Optimal speech enhancement under signal presence uncertainty using log-spectral amplitude estimator, IEEE Signal Process. Lett., vol. 9 (4), pp. 113-116, 2002.

[8] Plapous C., Marro C. and Scalart P., Improved signal-to-noise ratio estimation for speech enhancement, IEEE Trans. Audio, Speech, and Language Process., vol. 14 (6), pp. 2098-2108, 2006.

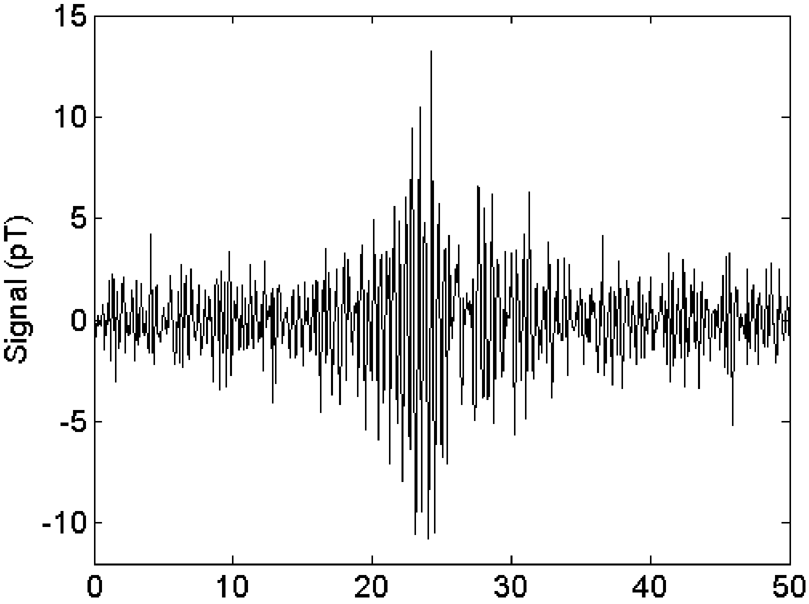

Fig.1. Measured ELF signal compensated with the 18 term model.

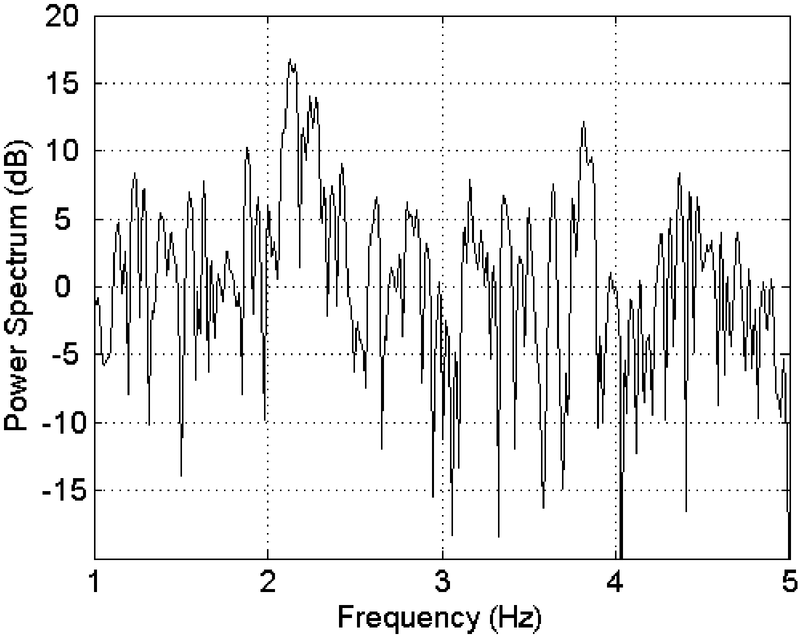

Fig.2. Power spectrum density of the signal in Fig.1.

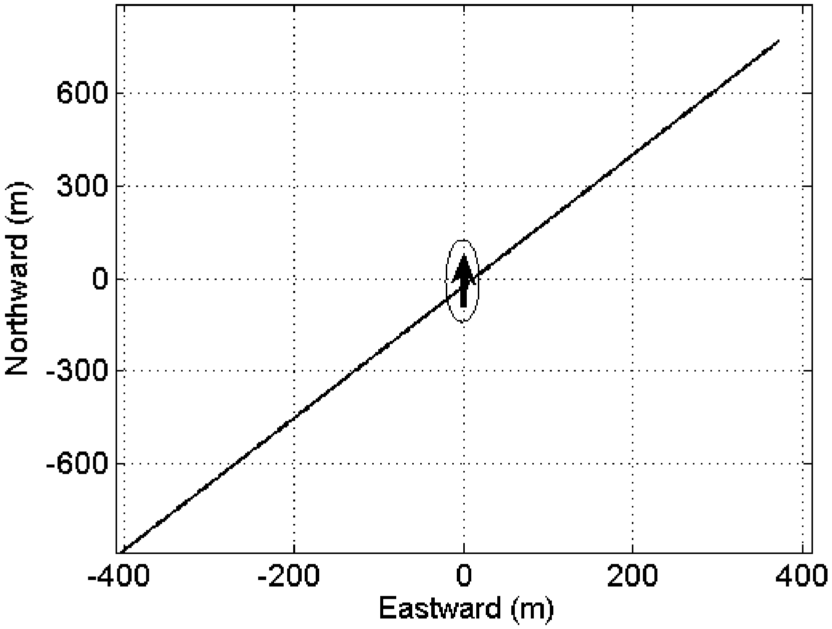

Fig.3. Simulated trajectory used as example.

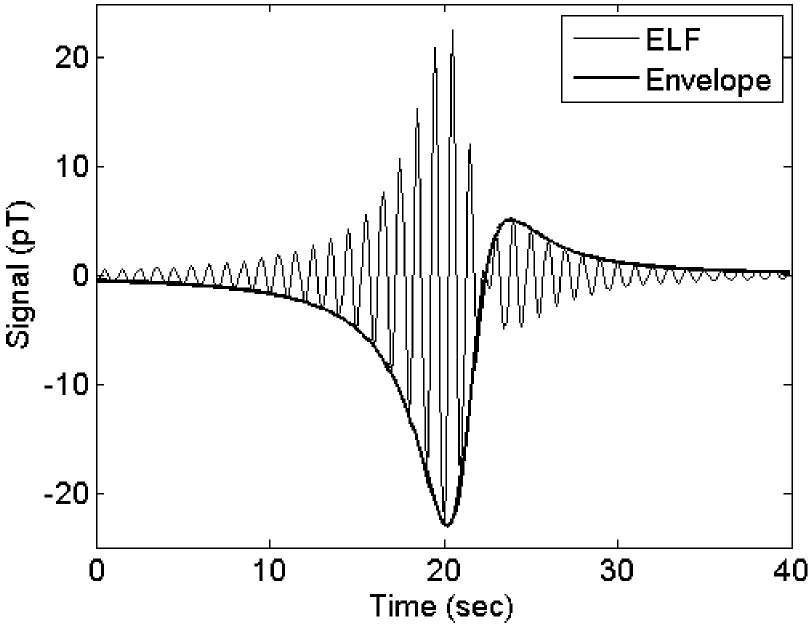

Fig.4. Simulated ELF signal generated by a horizontal electric dipole.

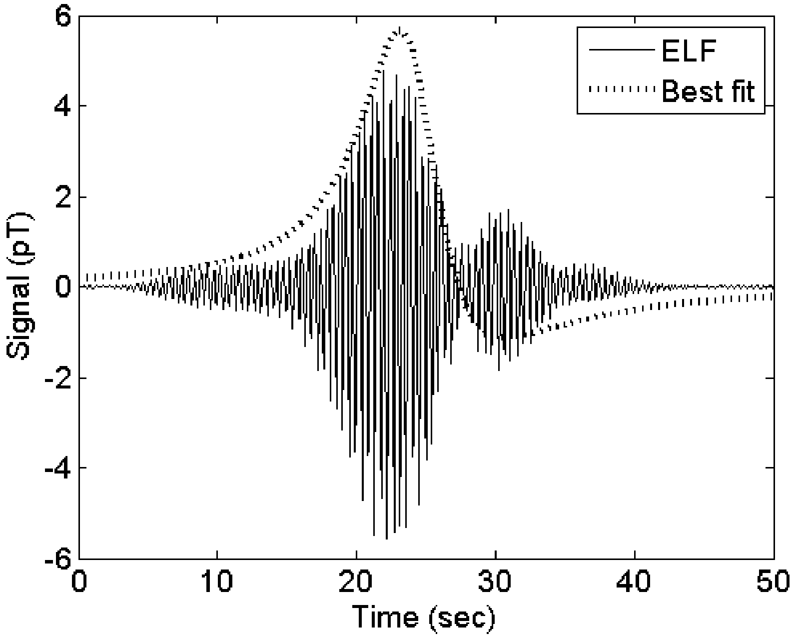

Fig.5. Measured ELF signal after additional noise reduction.

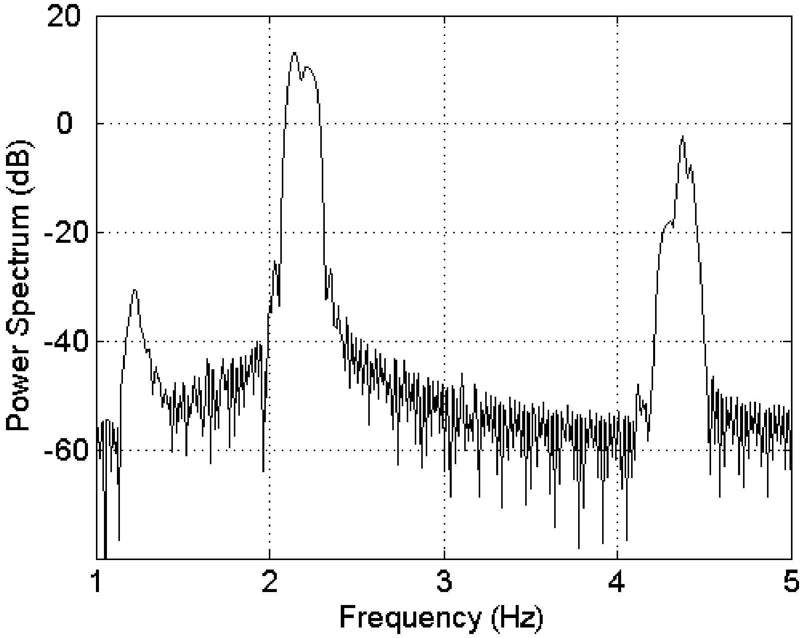

Fig.6. Power spectrum density of the signal in Fig.5.

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