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SONAR SIGNAL WAVEFORM IMPACT ON INTERFERENCE RESISTANCE

Victor Pjachev, Valeriy Valeyev

Ural State Technical University
32, Mira St, Yekaterinburg, 620002, Russian Federation.
Phone: +7 (912) 6211177, E-mail: pjachev.victor@gmail.com
www.ustu.ru

ABSTRACT

The given work investigates the influence of sonar signal waveform type on the performance of slow-moving targets detection in the presence of ambient noise, interfering reflections, mutual interference of several sonar systems operating in the same water area.

The continuous wave (CW) and frequency modulated (FM) waveforms are considered along with more complex waveforms with periodic frequency modulation. The investigation of active sonar pulse types is based on the analysis of the signal properties associated with corresponding ambiguity function.

For sounding signals with periodic frequency modulation the proposed processing algorithm utilizes known moving target detection methods.

As a preliminary evaluation, the Matlab model is developed to demonstrate the efficiency of the processing technique.

Simulation results demonstrate improvement of the detection based on the processing of signals with periodic frequency modulation.

1. STATEMENT OF THE PROBLEM

The specific task of active sonar systems is protection of important water approaches from incursion of divers. The difficulty of diver detection is aggravated by the low velocities, presence of reverberation-noise, interfering reflections with a structure of a sounding signal (structural interference) and the mutual interference from a neighboring sonar in case of multipoint system for underwater observation.

Hence, the common distinctive feature of the outlined types of interference is the distribution of a possible time-frequency shifts in interfering signals. This distribution is evaluated as a narrow stripe area (as it is shown in Figure 1) along the time axis. Figure 1 displays the possible arbitrary time-shifts and comparatively low Doppler shifts of receiving interference due to sonar platform mobility and peculiar properties of reverberation.

In comparison with expected Doppler shifts of target echo, the interference has a narrow bandwidth but nevertheless the influence can not be ignored.

The theoretical optimal signal-to-noise ratio, and thus theoretical detection probabilities in a noise-limited situation, depends only on the noise power density and the total energy of the signal [1,2], and therefore its duration and power efficiency. In order to improve detection performance while maintaining range resolution, it is therefore desirable to increase the bandwidth of the signal without a corresponding decrease in the duration of the signal. This implies that the time-bandwidth product of the transmitted signal must be made larger than unity. Modulating the frequency or the amplitude of the transmitted waveform will result in an increased time-bandwidth product. Amplitude modulation, however, results in a decrease of power efficiency, so it is more common to use frequency modulated signals.

In practice active sonar performance depends on reverberation rejection, and thus on pulse design. Moreover, since the reverberation is strongly correlated with the signal, classical detection methods like matched filtering (MF) are inefficient [3].

With respect to the described conditions the choice of sonar waveform providing the best performance can be difficult. This work has a goal to reveal the influence of a sounding signal waveform on interference resistance in detection of slow-moving targets.

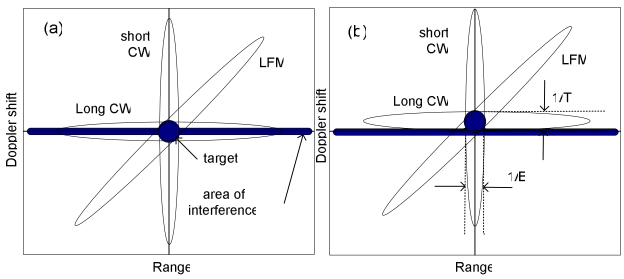

Figure 1- Ambiguity function profiles for long CW, short CW and Linear FM pulse designs. (a)-Stationary target, (b)-Moving target.

2. TYPICAL SOUNDING SIGNALS

Nowadays most of the sonar systems use two types of transmitted waveform. These are the Continious Wave (CW) and the linear FM (LFM) or chirp transmission. The choice of the waveform determines the ability of the system to resolve targets in distance and velocity (Doppler) range, and also impacts on the detection capabilities of the system.

Convenient tool for sonar signal analysis is ambiguity function, which is expressed according to:

$$\chi(\tau, f) = \int_{-\infty}^{\infty} s(t)s^*(t+\tau)e^{j2\pi ft}dt \qquad (1)$$

Where *s(t)* – complex envelope of the sounding signal [4]. This function represents the envelope of the matched filter response to a target in both range and Doppler. The ability of a signal to resolve a target can be estimated based on the width of the main lobe of the ambiguity function. The sidelobes of this function will also help to determine how well a signal can resolve multiple targets, or a target within a reverberant environment.

To determine the interference level after matched filtering, the range-Doppler distribution of the scatterers must be known. Approximate interference levels were derived in terms of the pulse parameters and the range Doppler extent of the scatterers [5]. The case of our interest is when the reflecting scatterers are uniformly distributed over a long range, but confined to a narrow band of Doppler shifts assumed to be less than T^{-1} (T –period of sounding). The relative interference power levels for the different pulse designs can be approximated from the proportion of the interference distribution which is enclosed by the ambiguity function of the target echo.

When using long CW pulses echo signal waveform, moving target is so much the less overlapped with area of interference the longer time duration and the higher velocity of the target. Thus, the influence of interference is decreasing along with the increasing of signal duration and target velocity (Figure 1).

Figure 1 also demonstrates that the proportion of the interference level enclosed by both the short CW and the LFM ambiguity functions is smaller than that enclosed by the ambiguity function of the long CW pulse by a factor proportional to time-bandwidth product. As a consequence, the interference level observed using a short CW or LFM pulse will be around $10\log_{10}BT$ decibels smaller than with the long CW pulse although the magnitudes of the point target responses will all be equal. Furthermore, in Figure 1(b) the proportion of the interference distribution enclosed by the short CW and LFM pulses remains virtually unchanged, whereas the ambiguity function of the long CW pulse is now separated from the reverberation due to the relative motion of the target. This implies that the interference level observed using the long CW pulse should now be negligible, although it remains constant for the Doppler-tolerant short CW and chirp pulses.

3. PERIODIC FREQUENCY MODULATION WAVEFORMS

To improve detection capability in the presence of interference the periodic frequency modulated signals can be considered as providing superior performance.

Thus, if the frequency-modulation function of a waveform is periodic, the spectrum of the waveform will consist of many individual spectral lobes spaced at multiples of the repetition frequency of the FM function. The energy of the pulse will therefore be spread over frequency, as with a linear FM pulse, although the narrow spectral lobes will cause it to be as sensitive to the Doppler effect, as an equivalent length CW pulse.

With respect to such type of signals the sinusoidal frequency modulated (SFM) and periodic linear frequency modulated signals (PLFM) can be considered.

The following equation describes SFM signal:

$$S_{SFM}(t) = A_{SFM}(t)\exp(j2\pi f_0 t + j\beta\sin(2\pi f_m t)) \qquad (2)$$

where $A_{SFM}(t)$ is the amplitude window of the pulse, f_0 is the centre frequency, f_m is the modulating frequency and β is the modulation index which defines the bandwidth of the pulse

The power spectrum of a sinusoidal frequency modulated pulse will be a symmetrical comb, centered around f0 and with a frequency spacing of fm. Albeit the magnitudes of the peaks will not be uniform but can be calculated using Bessel functions. Moreover, in comparison with a LFM/CW pulse the energy in the pulse is now distributed between several peaks instead of all being concentrated in a single main lobe (Figure 2).

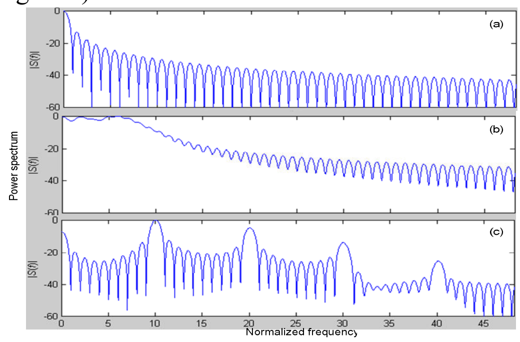

Figure 2 - Power spectrums: (a) - CW signal, (b) - LFM signal, (c)-SFM signal.

The PLFM signal can be considered as a package of N identical LFM pulses following one by another without pauses. The duration of partial pulse is T_e.

$$T_e = T_s/N$$

The analytic expressions are describing PLFM signal:

$$S_{PLFM}(t) = A_{PLFM}(t)\sum_{k=1}^{N} U_e[t-(k-1)T_e] \qquad (3)$$

where $0< t <T_s$ and $A_{PLFM}(t)$ is the amplitude of the signal.

$$U_e(t) = \cos\left[(\omega_0 - \Delta\omega/2)t + \frac{\Delta\omega}{2T_e}t^2\right] \qquad (4)$$

where $0< t <T_e$, $\Delta\omega$ (rad/s) – LFM pulse deviation,
ω_0 (rad/s) – center frequency of LFM spectrum.

To attain a better efficiency for signal processing the duration of sounding Ts pulse should be selected according to the following condition:

$$T_s \geq 1 / F_{min}$$

where F_{min} (Hz) is a minimal Doppler frequency for expected echo-signals (signals from target).

Furthermore, the energetic potential and resolution capability for sounding signal governed by expression (3) will be equivalent to one LFM-pulse T_s seconds long. The following conditions should be satisfied:

$$T_s = 1 / F_{min} \text{ and } N >> 1$$

Under these conditions phase variation of the reflected signal occurring due to the Doppler frequency inside one period of LFM can be neglected. In addition, relative phase variation of different partial pulses can be utilized for Doppler detection of moving targets.

The ambiguity functions of LFM, PLFM, CW and SFM signals are shown in Figure 3.

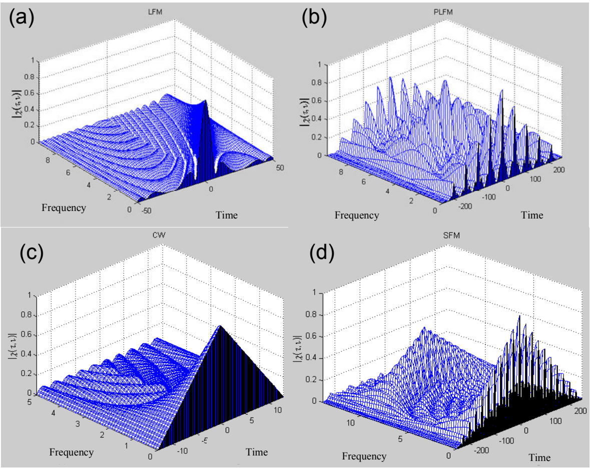

Figure 3 - Ambiguity functions: (a)-LFM, (b)-PLFM, (c)-CW, (d)-SFM.

The periodic large range sidelobes will enclose a smaller proportion of the interference distribution than a CW pulse would lead to a corresponding decrease in the interference level. However the drawback of the comb-like spectrum is the appearance of large sidelobes at Doppler scalings where adjacent spectral lobes overlap one another. This is an inevitable consequence of the volume invariance property of the ambiguity function [4].

Theoretically the large range ambiguities mean that comb-spectrum pulse designs cannot be used to accurately detect in a wide Doppler range. Although, energy spectrum redistribution can lead to significant improvement of the low-moving target detection.

4. Q-FUNCTION ANALYSIS AND EVALUATION

Under the assumption that the interference field is caused by a time-invariant scattering surface composed of uniformly distributed uncorrelated scatterers, the estimated interference level can be evaluated as a Q-function of target range and Doppler .

$$Q(\eta) = \int_{-\infty}^{\infty} |\chi(\tau,\eta)|^2 d\tau \qquad (5)$$

The Q-function can be used to compare the reverberation processing capabilities of different pulse types [5].

The given work considers Matlab models of several sonar waveforms with corresponding ambiguity and Q-functions. Figure 4 shows the normalized Q-functions for four types of waveforms – CW, LFM, SFM, and PLFM. Figure 4 demonstrates that LFM chirp provides the best reverberation suppression (i.e. the lowest Q-function) for extremely low-Doppler targets. Besides, LFM is ahead of CW for speeds in the range of $\pm f_m/6f_0$. The SFM exhibits several peaks: adjustment of the modulating frequency can move these peaks out to larger Doppler positions, at the expense of slightly reduced reverberation suppression.

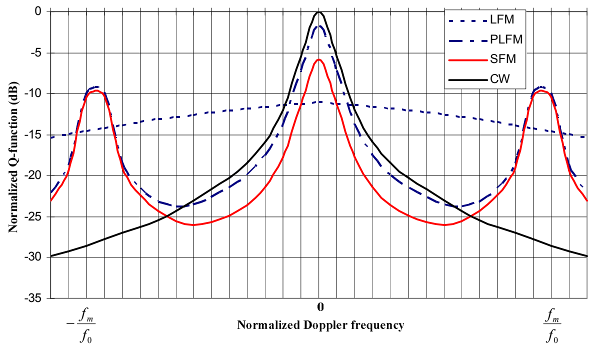

Figure 4- Normalized Q-functions for LFM, PLFM, SFM and CW signals.

If the desired range is located between the peaks, an extra 12 dB can be attained for SFM and up to 10 dB for PLFM with the same number of modulation periods. Hence, both PLFM and SFM can provide significant interference suppression if the area of low Q-function will be defined according to the target range of velocities.

To confirm the latter conclusion the following part of the paper considers the method of sonar signal processing aiming to achieve outlined periodic FM features and investigates the properties and advantages of the simulated sonar system.

5. PROPOSED PROCESSING ALGORITHM

In most active sonar receivers conventional matched filtering (MF) is utilized to process echo-signals. Assuming additive white Gaussian noise, the signal to noise ratio (SNR) at the output of matched filter is easily calculated [6]. Performance bounds for SNR enhancement were previously considered for narrowband signals in [7]. However the MF performance is still sub-optimum when there noise is strongly correlated with the FM signal. Thus, classical matched filtering is inefficient concerning to mutual interference of several sonar systems operating in the same water area.

The proposed algorithm for improved detection is inner-period signal processing within formed angle channel of sonar [8]. Hence, processing is optimised for SFM and PLFM signals described above. The processing is considered according to the Figure 5.

In the first step signal $U_{in}(t)$ is processed in a matched filter (MF).The period of matching is chosen in a way to compress each period of periodic FM during T_s sounding time. Further, the initially compressed signal $U_c(t)$ is processed in two quadrature branches A and B. In both branches corresponding quadrature signals $U_1(t)$ and $U_2(t)$ after the phase detectors (PD) can be obtained from expressions (6) and (7):

$$U_1(t) = U_c(t)\cdot\cos(\omega_0 t) \qquad (6)$$

$$U_2(t) = U_c(t)\cdot\sin(\omega_0 t) \qquad (7)$$

Then every quadrature component is delayed for the time equal to one period of FM T_e and subtracted from non-delayed copy of itself (8, 9). The purpose of this procedure is to suppress interfering reflections.

$$U^I_1(t)= U_1(t) - U_1(t - T_e) \qquad (8)$$

$$U^I_2(t)= U_2(t) – U_2(t - T_e) \qquad (9)$$

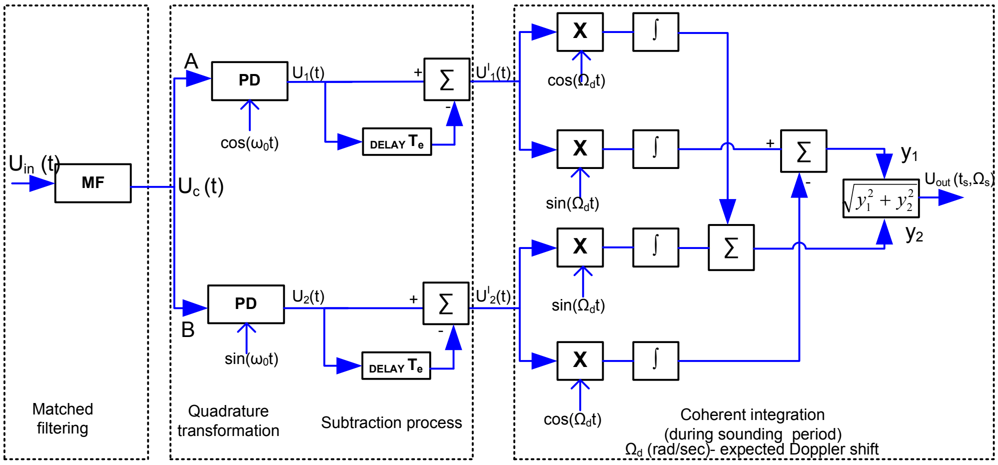

Figure 5 – The algorithm for echo-signal processing.

Subtraction in expressions (8) and (9) produces compensation of received signals which do not change their amplitude and phase from one period of FM T_e to another within sounding pulse. Hence, compensation occurs when echo-signal from sea bottom is received or any signal which does not affect phases within sounding pulse is received from stationary matter. In addition, if a signal from a moving target is received, a result of subtraction can be calculated which in turn will be proportional to the phase incursion $\Delta\varphi$ according to expression (10).

$$\Delta\varphi = \Omega_d \cdot T_e \qquad (10)$$

where Ω_d (rad/s) is a cyclic Doppler frequency of the echo-signal. Further, signals are sent through the coherent integration procedure [1]. Coherent integration is realized taking into account the expected Doppler shift Ω_d and the time of receiving echo "ts" from the target (11, 12, 13). Coherent integration is provided as shown in Figure 5.

$$U_{OUT}(t_s, \Omega_d) = \sqrt{y_1^2 + y_2^2} \qquad (11)$$

where

$$y_2 = \left(\int_{t_s}^{t_s+Ts} U'_1(t) \cos \Omega_d t dt \right) + \left(\int_{t_s}^{t_s+Ts} U'_2(t) \sin \Omega_d t dt \right) \qquad (12)$$

$$y_1 = \left(\int_{t_s}^{t_s+Ts} U'_1(t) \sin \Omega_d t dt \right) - \left(\int_{t_s}^{t_s+Ts} U'_2(t) \cos \Omega_d t dt \right) \qquad (13)$$

6. ANALYSIS OF DETECTION IMPROVEMENT IN THE PRESENSE OF INTERFERING REFLECTIONS

Efficiency of Doppler detection was investigated with Matlab 7.0 model which provides generating signals (2), (3), matched filtering, quadrature processing (6), (7) subtraction (8) and (9) and coherent integration during the sounding pulse. Signals were formed as a matrix of samples during observation time which was equal to the duration of several sounding pulses. The PLFM echo-signal from moving targets was simulated according to the analytic expression (2) where $U_e(t, k)$ is governed by the following evaluation (14):

$$U_e(t,k) = \cos\left[(\omega_0 - \Delta\omega/2)t + \frac{\Delta\omega}{2T_e} t^2 + 2\pi f_d (k-1) T_e \right] \qquad (14)$$

The value $2\pi f_d (k-1) T_e$ under cosine function simulates Doppler shift. The echo-signal from static objects or from neighboring sonar is modeled with the same equations as (2) and (14) but with significantly decreased or null Doppler shift. The SFM echoes were simulated using the same approach.

For simulation the following parameters were used:

T_s = 20 ms	– time of sounding pulse,
T_e = 2 ms	– period of LFM/SFM,
f_0 = 75 000 Hz	– center frequency (LFM/SFM),
Δf=30 000 Hz	– deviation (LFM/SFM),
F_d=50÷450 Hz	– Doppler range (targets),
F_r=0÷20 Hz,	–Doppler range (interference),
Q_{in}=10^{-3}	– inner value of "Signal to Interference Ratio" (SIR).

As criteria for efficiency of the proposed detection technique the coefficient of improvement K is evaluated from expression (15):

$$K = Q_{out} / Q_{in} \qquad (15)$$

The value of output of SIR -Q_{out} is obtained as a relation of the maximums of function (11) according to expression (16). These maximums are considered as a result of the processing of the echo-signal from the moving target or for interfering reflection respectively (16). In a common case all signals can be received from different distances as it shown in Figure 6 where the values of function $U_{out}(t_s, \Omega_d)$ is represented in a range of expected delays for echo-signal with Doppler shift Ω_d=2π*250 (rad/s) and for interfering signals with Ω_r=0.

$$Q_{out} = U^2_{OUT}(t_s, \Omega_d) / U^2_{OUT}(t_r, \Omega_r) \qquad (16)$$

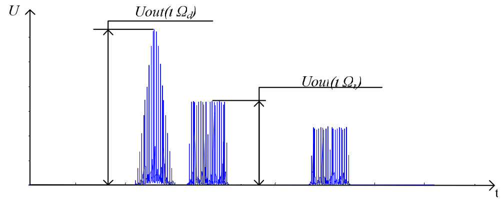

Figure 6 - Determination of values $U_{OUT}(t_s,\Omega_d), U_{OUT}(t_r,\Omega_r)$

In Figure 7(a,b) the coefficients of improvement as a function of expected Doppler shift are represented for SFM and PLFM signals. These characteristics were derived in the way of full-matched filtering and coherent integration in every point of range $F_d=(50\div450)$ *Hz* and can be considered as practical boundaries of improvements for proposed method.

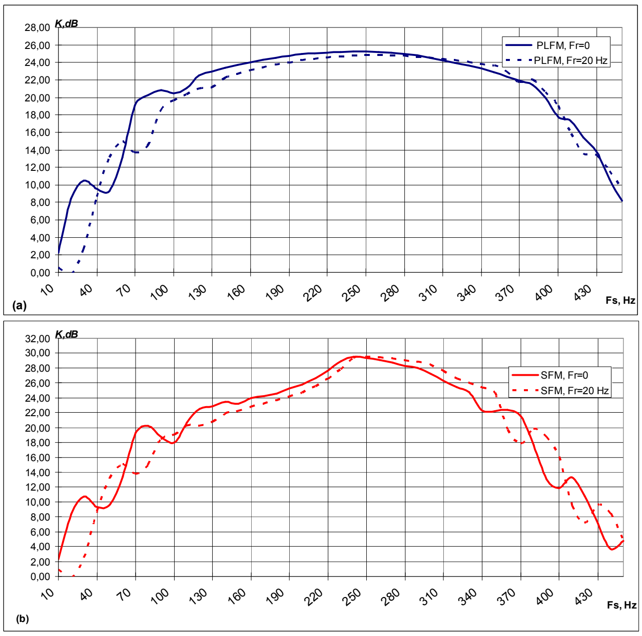

Figure 7- Coefficient of improvement K, dB as function of Doppler frequency *(a) PLFM* $(F_r = 0, F_r = 20$ *Hz).*
(b) SFM $(F_r = 0, F_r = 20$ *Hz).*

Performance capabilities for conventional matched filtering of LFM echo-signals are shown below for the equivalent parameters and $Ts = 20$ *ms* (Figure 8);

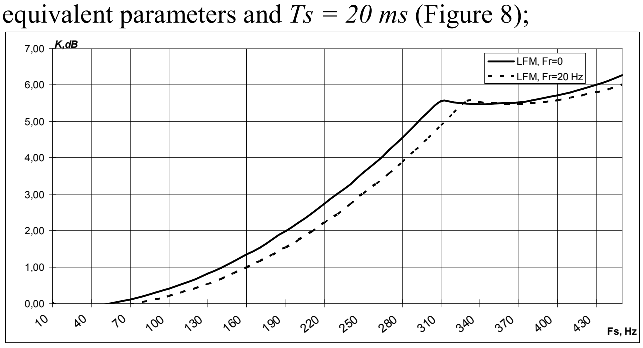

Figure 8- Coefficient of improvement K, dB as function of Doppler frequency (conventional MF of single LFM).

The shown characteristics demonstrate the significant advantage of using periodically modulated signals for low-moving target detection in the presence of specified interference. This benefit allows achieving up to 20 dB superior SIR ratio depending on target velocity. To realize maximum processing gain the primary signal processing should be performed in several Doppler channels.

7. CONCLUSION

The given work conducted a comparative analysis of interference resistance of the sonars, which use several types of sounding signals for slow-moving target detection. Reverberation noise, interfering reflections and mutual noise of several, single-type sonar systems operating in the same water area were considered. In addition, typical signals were compared – tone bursts and LFM pulses, as well as signals, which are not widely used so far – with periodic frequency modulation. The benefits of using the latter signals were demonstrated – namely possibility to increase signal-noise ratio at the input of a decision-making device for up to 10-20 dB, depending on the target velocity whereas conventional processing using one LFM pulse of the same length allows achieving only 5.5 dB .

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