РАДІОСИСТЕМИ
ТА ОБРОБКА СИГНАЛІВ

RADIO SYSTEMS
AND SIGNAL PROCESSING

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NOISE PROPERTY OF BREATHING AND HEARTBEAT INFORMATIVE SIGNALS

Subject and Purpose. *The subject of research is the flicker noise present in informative signals of search-and-rescue radars, specifically its properties and the effect it may have on algorithms for detecting and identifying manifestations of human breath and heartbeat processes during rescue operations. The work has been aimed at creating a suitable description of flicker noise for developing optimal algorithms of digital signal processing for quick detection and identification of informative signals during rescue missions.*

Methods and Methodology. *The low-frequency flicker noise has been modeled within the polynomial equations technique, proceeding from an analysis of real data on noise components in the output signals from a coherent search-and-rescue radar. A comparative analysis is done for a variety of approximating functions suggested for representing the low frequency portion of the spectrum observed.*

Results. *For the low-frequency range wherein spectral components of the informative signal owing to respiration and heartbeat of humans are concentrated, an adequate model of the fluctuating interference is the flicker noise model built on the basis of polynomial equations. The problem of optimized model representation of the noise in digital signal processing algorithms has been analyzed for the case of a coherent search-and-rescue radar. A model of the fluctuating process has been suggested, based on a polynomial approximation for the spectral function in the low-frequency range of the signals observed at the radar output.*

Conclusion. *Spectral characteristics of both interference and informative signals have been investigated. A structural diagram has been proposed for a high sensitivity, coherent search-and-rescue radar implementing a signal storage algorithm based on the polynomial model of the fluctuating process. The advantages and disadvantages of the radar are discussed, with examples given of real signal implementations and of noise spectrograms. Methods of effective estimation of Doppler signal phases are presented. The paper suggests an analysis of basic requirements as to parameters and performance characteristics of the rescue radar.*

Keywords: *polynomial model, flicker noise, algorithm, probe signals, low-frequency noise, Doppler-shifted signal, coherent search-and-rescue radar, opaque obstacles.*

Introduction

The rescue operations carried out during various kinds of natural or man-made disasters can be significantly fastened by using the portable Doppler-type radar systems [1, 2] for damaged people detection. Informative sign of damaged alive human being covered by optically opaque obstacle is a phase modulation of returned radar's signal which is caused by Doppler effect when parts of the human body or

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chest are moving. An optically opaque obstacles, like a fragment of a brick wall or a concrete slab acts to significantly (from 30 to 90 dB) attenuate the radar signal as that propagates to the target and back. Generally, the magnitude of the Doppler shift appears in the reflected signal due to chest movements of a breathing human is in the range of 0.1…0.25 Hz. The effect from heartbeat is observed in the range of 0.95…1.25 Hz, with nearly 40 dB lower amplitude than such from chest movements. As a result, the informative signals are under the jamming impact of noise. As is known, the spectral distribution of noise in the infra-low frequency range cannot be approximated to by a Gaussian type law. The spectral components of the flicker noise in this frequency range have a significant amplitude and, after being detected on a nonlinear element, generate a fluctuation process with new properties that are not taken into account in the synthesis of the decision rule. Stochastic methods for detecting and identifying targets require knowledge of the properties of noise and interference, otherwise the decision-making rules and algorithms would yield erroneous results. Therefore, in this article, the main attention is focused on refining the statistical and spectral characteristics of noise and interference in the frequency range of the information signal of human respiration and heartbeat. In general terms, the spectral density of such noises is described by relations of form $S(f)=S_0/f^{\alpha}$ [3, 4], where S_0 stands for the spectral density of noise at $f=0$ and α is some parameter the value of which determines properties of the noise at $f \to 0$. Studies of real spectra of the signals arriving to the processing unit from the radar output have shown the parameter α to depend on how close the frequency f to zero. In other words, the parameter α is not a constant, but a frequency-dependent function $\alpha(f)$. To find an appropriate model of this dependence one would need to compare calculations within some mathematical models with experimental data.

1. Analysis of the frequency-dependent noise parameter of the radar signal

Since the main sources of noise in radar are electronic devices and oscillators it will be useful to investigate their mathematical model to understand noise property. After neglecting spurious amplitude modulation, the sideband spectra of oscillator signals are generally by more than 20 dB lower compared with phase modulation sidebands. Therefore, it will be discussed simplified noise mathematical model like this

$$s(t)=S_0\cos(\omega_0 t+\varphi(t)),$$

where S_0 is amplitude; $\omega_0=2\pi f_0$; f_0 is the central frequency, and $\varphi(t)$ the spurious phase fluctuations which is random in nature.

The first statistical moment of the spurious phase derivative $\dfrac{d\varphi(t)}{dt}$ is:

$$E\left\{\frac{d\varphi(t)}{dt}\right\}=0,$$

where $E\{\cdot\}$ is the expectation operator.

It is important to note that $E\{\varphi(t)\}$ is not equal to zero. While the standard practice is to measure the frequency-domain spectral density $H(f)$ of power, time-domain weighted variances can be estimated as well,

$$z(t)=f_0^{-1}\frac{d\varphi(t)}{dt}.$$

The main measure of oscillator frequency stability is Allan's two sample variance [5] which is defined as one half of the time average of squared differences between two successive readings of the frequency deviation as sampled over same period,

$$\sigma_z^2(\tau)=\frac{1}{2}E\left\{\left(E\{z_{k+1}\}-E\{z_k\}\right)^2\right\}.$$

Here $E\{z_k\}$ is the mean fractional frequency taken over time τ, i.e.

$$E\{z_k\}=\frac{1}{\tau}\int\limits_{t_k}^{t_k+\tau} z(t)dt.$$

In practice the spectral density $H_f(f)$ of the signal $s(t)$ may, in some cases, be more important than the spectral density of the phase noise, $H_{\varphi}(f)$. We will evaluate their relationship later.

By analyzing the spectral densities of actual noise power for a variety of oscillations, one could find that in nearly all cases the following polynomial approximations is true

$$f_0^{-2}H_f(f)=(f^{-2}H_{-2}(f)+f^{-1}H_{-1}(f)+ +f^0H_0(f)+f^1H_1(f)). \quad (1)$$

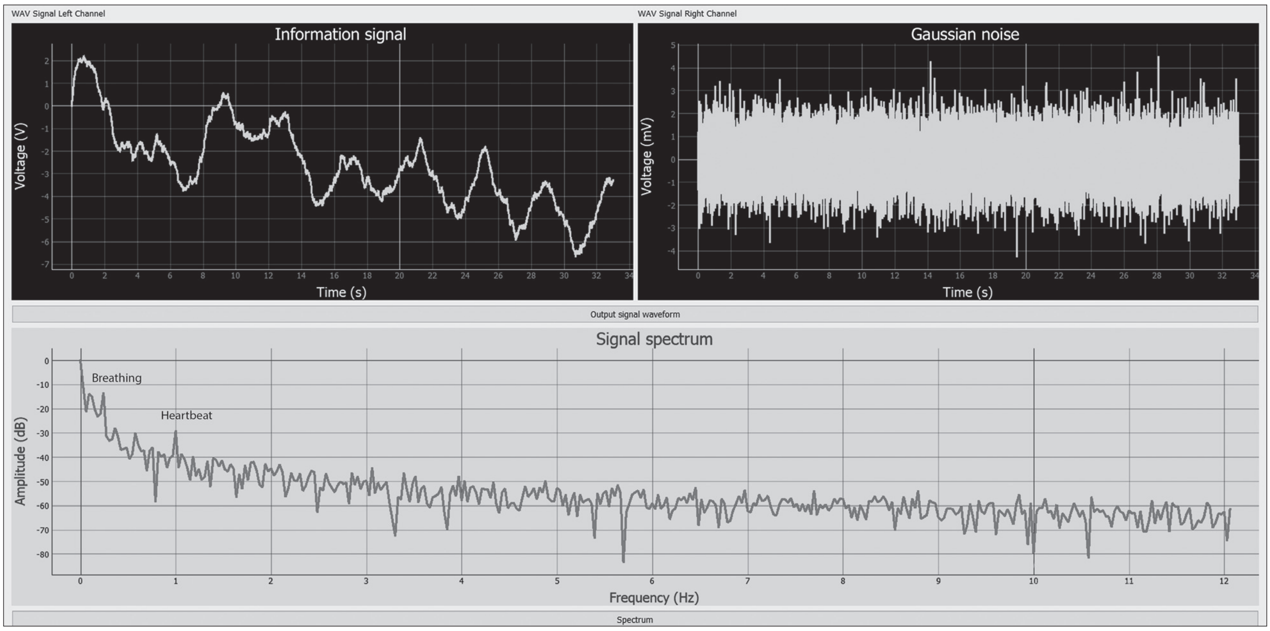

Fig. 1. The general view of rescuer radar interface windows in digital signal processing

Figure 1 shows the general view of rescuer radar interface windows in digital signal processing.

The upper left corner shows a fragment of the implementation of the information signal at the output of the analog part of the radar. The fluctuation component of the signal is shown in the upper right part of the screen, and the spectral density of the signal is displayed in the lower part of the screen, on which the signal responses due to human breathing and heartbeat are marked.

2. Structure of rescuer radar

A feature of the structure of a radar with pseudo-random periodic sequences (PRPS) signals [6—8] is the need to form coherent modulating functions which use both the receiving and transmitting blocks of the radar. Figure 2 shows a block diagram of a coherent radar with a quadrature receiver [9].

The basis of the circuit is a common highly stable master oscillator *1* with a relative frequency instability of signal $10^{-5}...10^{-6}$ at a carrier frequency of 2 GHz. The output signal of this generator is simultaneously fed to the amplitude modulator *2* and two frequency dividers *3* and *4* with division factors 20 and 10, respectively. The other input of the amplitude modulator *2* receives oscillations with a frequency of 100 MHz from the output of the divider *3*. Narrow-band filters *8* and *9*, connected to the output of the modulator *2*, separate the oscillations of the upper (filter *8*) and lower (filter *9*) side frequencies of the amplitude-modulated oscillation. The frequency spacing of coherent oscillations at the outputs of filters *8* and *9* is 200 MHz. The high side frequency signal from output of filter *8* is used in the transmitter, and the low side frequency signal from output filter *9* is used as the oscillation of the receiver local oscillator.

The probing signal is formed on the balance modulator *7*, amplified by the power amplifier *6* to a value of about minus 10 dB/W and is radiated by the transmitting antenna *5* into space. The other input of the balance modulator *7* receives the modulating function of the PRPS signal generated by the PRPS generator *10*. The clock frequency of the PRPS generator is formed from the frequency of the master oscillator *1* by dividing frequency in the divider *3*. In the PRPS generator *10*, a delayed PRPS is digitally formed — a modulating signal used to obtain a subcarrier oscillation with a frequency of about 1.3 kHz. In this case, the period of the subcarrier oscillation is exactly two periods of the PRPS signal. After multiplying them, the signal delayed on one elementary pulse duration is obtained to form the local oscillator signal. Circuit *11* controls the time delay of the local oscillator signal. The delay determines the distance to the target. The signal of the local oscillator of the receiver is formed at the output of the balance modulator *12*, to the inputs of which oscillations coherent with the signal of the transmitter are received from the filter *9* and delayed, modulated by the PRPS signal on the subcarrier from the output of the generator *10*. After amplification and filtering in amplifier *13*, the local oscillator signal is fed to the balance mixer *16* which is used as a correlator. The other input of the mixer *16* receives the oscillations from antenna *14*, reflected from the target and amplified by a low-noise amplifier *15* with a noise factor of up to 2 dB and a gain of no more than 10…15 dB. At the output of the mixer *16* there is a band-pass filter *17*, from which an information signal in an intermediate frequency 200 MHz is fed to two identical quadrature channels *18*, *19*. On the balance mixers *20* and *20′* of each channel, the information signal is transferred to the frequency of the subcarrier of 1.3 kHz with simultaneous suppression of the corresponding quadrature component of the signal due to the phase shift of the local oscillator signal by *9* in the phase rotator *27*. These signals are filtered using band-pass filters *21*, *21′*, amplified in narrow-band low-frequency amplifiers *22*, *22′*, and then squared in blocks *23*, *23′* and summed in adder *24*. The decision on the presence or absence of a target is made (after the information signal is extracted in the band-pass filter *25*) in the solver *26*.

This scheme showed satisfactory performance and a fairly high sensitivity to weak signals from a person behind an obstacle with a high suppression of interfering reflections from stationary local objects. However, with its relatively simple structural scheme, the technical implementation of individual blocks causes certain difficulties. Hardware requirements are becoming more stringent in the effort to obtain ideal signals during modulation, emission, propagation over a complex path, reflection, receiving and processing of signals. The main problem of the radar shown in Fig. 2 is the parasitic leakage of the transmitter signal to the input of the receiver. Since it is usually impossible to suppress the signal of the parasitic carrier in the spectrum of the PRPS signal at the output of the modulator by more than 40…50 dB, and the narrow-band rejection leads to the inevitable losses in the spectrum of the PRPS, it is necessary to apply various methods of suppression of signals and interference received on the carrier frequency. These methods, as a rule, are complex in realization and unstable in work. The problem of parasitic leakage of the transmitter signal to the input of the receiver can be solved by other radar's schemas.

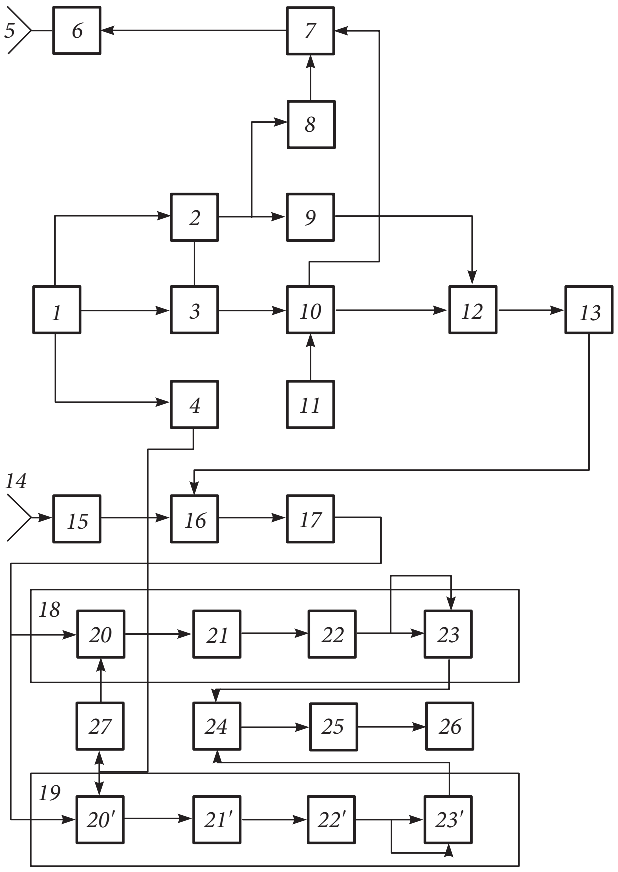

Fig. 2. A block diagram of a coherent radar with a quadrature receiver. Units on Fig. 2 are: *1* — master oscillator; *2* — amplitude modulator; *3* and *4* — dividers with division factors 20 and 10, respectively; *5* — transmitting antenna; *6* — power amplifier; *7*, *12* — balance modulator; *8* and *9* — narrow-band filters; *10* — PRPS generator; *11* — time delay control circuit; *13* — amplifier; *14* — receiving antenna; *15* — low-noise amplifier; *16* — balance mixer; *17* — band-pass filter; *18*, *19* — quadrature channels; *20*, *20′* — balance mixers; *21*, *21′*, *25* — band-pass filters; *22*, *22′* — narrow-band low-frequency amplifiers; *23* — square-law detector; *24* — adder; *26* — solver; *27* — phase rotator

Conclusion

Thus, when synthesizing signal processing algorithms in Doppler radars for detecting living people behind optically opaque obstacles, the fluctuation interference model that masks the spectral components of the information signal in the frequency range of 0.1…0.5 Hz can be implemented with the use of the polynomial approximation Eq. (1). The model is compact and easy to implement. The spectral density of the flicker noise has a character Eq. (1)

and practically does not differ from the observed process in a real device (Fig. 2). It is important to note that, in contrast to computationally cumbersome filter methods [10, 11] for generating implementations of the noise model, the model based on the polynomial Eq. (1) does not give surges to infinity at zero frequency. This is fully consistent with the situation in a real radar, since the constant component, the signal at zero frequency, is completely suppressed by the hardware.

And it is important for the rescuer radar (Fig. 2) which has a high sensitivity, selectivity in spatial coordinates, and the ability to detect targets by ultra-low values of the Doppler frequency shift.

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ВЛАСТИВОСТІ ШУМІВ У ІНФОРМАЦІЙНИХ СИГНАЛАХ ДИХАННЯ ТА СЕРЦЕБИТТЯ

Предмет і мета роботи. Предметом дослідження є флікер-шум у спостережуваних сигналах, їх властивості та вплив на алгоритми виявлення й ідентифікації процесів дихання і серцебиття при обробці сигналів радара для рятувальників. Метою роботи є створення адекватного опису флікер-шуму для побудови оптимальних алгоритмів цифрового оброблення сигналів і швидкого виявлення та ідентифікації ознак інформаційних процесів при використанні доплерівського радара у рятувальних роботах.

Методи та методологія. Для реалізації моделі низькочастотного флікер-шуму застосовано метод поліноміальних рівнянь. Методологія базується на аналізі експериментальних даних, що отримані з виходу когерентного радара для рятувальників, та порівнянні різних функцій для апроксимації спектрів низьких частот спостережуваного сигналу.

Результати. Показано, що в низькочастотній смузі, де зосереджені спектральні складові інформаційного сигналу, який генерується диханням і серцебиттям, адекватною моделлю флуктуаційної інтерференції є модель флікер-шуму, що побудована на основі поліноміальних рівнянь. Досліджено проблему оптимального опису моделі шуму в алгоритмах цифрового оброблення сигналів у когерентній РЛС рятувальника. Побудовано модель флуктуаційного процесу на основі поліноміальної апроксимації спектральної функції в низькочастотному діапазоні спектра спостережуваних реалізацій процесу на виході радіолокатора.

Висновок. Досліджено спектральні характеристики завад та інформаційного сигналу. Запропоновано структуру високочутливого когерентного радара для рятувальників, алгоритм накопичення сигналу якого використовує поліноміальну модель флуктуаційного процесу. Обговорюються переваги та недоліки радара, наводяться реальні реалізації сигналів та спектрограми шумів. Розроблено методику ефективної оцінки фази доплерівського сигналу. Проведено аналіз основних вимог до параметрів і характеристик РЛС для рятувальників.

Ключові слова: *поліноміальна модель шуму, флікер-шум, алгоритм, зондувальні сигнали, низькочастотний шум, доплерівський сигнал, когерентний радар для рятувальників, непрозорі перешкоди.*