The Acousto-Optical Means for Optimal Radio Receiving

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Abstract

The article substantiates the importance of radar and analyzes its main characteristic features. It is shown that one of its most essential problems is the selection of a weak signal comparable with noise from a signal-to-noise mixture. It is noted that the problem can be solved only with the use of special technical means. The possibility of using an optimal linear filter for solving the problem is discussed. It is proved that the optimal linear filter, the parameters of which are adapted to the parameters of the probing signal, can provide effective receiving of the signal reflected from the object. It is shown that the main component of such an optimal linear filter is a device that provides a time delay for the signal. Most of radar systems use delay lines that provide a fixed time offset, in which case only one known pulse can be received. The peculiarities of the photo-elastic effect are discussed in the context of the formation of the required time delay. It is shown that in this case it is possible to smoothly adjust the required time delay in a wide range. It has been proven that an optimal linear filter with wider functional potentialities can be synthesizes on the basis of an acousto-optical delay line.

Keywords: radar, noise, optimal linear filter, photoelastic effect, delay line, acousto-optics.

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Optimal radioqəbul üçün akustooptik vasitələr

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Xülasə

Məqalədə radiolokasiyanın önəmli əhəmiyyəti əsaslandırılmış və onun əsas xarakterik xüsusiyyətləri araşdırılmışdır. Göstərilmişdir ki, onun əsas problemlərindən biri küy ilə müqayisə oluna biləcək zəif siqnalın siqnal-maneə toplumundan ayrılmasıdır. Qeyd olunmuşdur ki, problem yalnız xüsusi texniki vasitələrin tətbiqi ilə həll oluna bilər. Məsələnin həlli üçün optimal xətti süzgəcin tətbiqinin mümkünlüyü araşdırılmışdır. Sübut olunmuşdur ki parametrləri, zondlayıcı siqnalın parametrlərinə uyğunlaşdırılmış optimal xətti süzgəc obyektdən əks olunan siqnalın effektiv qəbulunu təmin edə bilər. Göstərilmişdir ki, belə optimal xətti süzgəcin əsas tərkib hissəsi siqnalın zaman ləngiməsini təmin edən qurğudur. Məlum radiolokasiya sistemlərində fiksə olunmuş zaman sürüşməsi verən ləngitmə xətlərindən istifadə olunur və bu halda yalnız məlum parametrli bir impulsun qəbulu mümkün olur. Fotoelastik effektin xüsusiyyətləri tələb olunan zaman ləngiməsinin formalaşdırılması kontekstində araşdırılmışdır. Göstərilmişdir ki, bu halda tələb olunan zaman ləngiməsini geniş intervalda səlis tənzimləmək mümkün olur. Sübut olunmuşdur ki, daha geniş funksional imkanlara malik optimal xətti süzgəc akustooptik ləngitmə xətti əsasında reallaşdırıla bilər.

Açar sözlər: radiolokasiya, küy, optimal xətti süzgəc, fotoelastik effekt, ləngitmə xətti, akustooptika.

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Акустооптические средства для оптимального радиоприема

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Аннотация

В статье обоснована важность радиолокации и анализированы ее основные характерные особенности. Показано, что одной из ее важнейших проблем является выделение, сравнимого с шумами слабого сигнала из смеси сигнал-помеха. Отмечено, что проблему можно решить только с применением специальных технических средств. Обсуждена возможность применения оптимального линейного фильтра для решения задачи. Доказано, что оптимальный линейный фильтр, параметры которого адаптированы к параметрам зондирующего сигнала, может обеспечить эффективный прием отраженного от объекта сигнала. Показано, что основным компонентом такого оптимального линейного фильтра является устройство, обеспечивающее временную задержку сигнала. В известных радиолокационных системах используются линии задержки, которые обеспечивают фиксированный временной сдвиг, и в этом случае можно обеспечить прием только одного импульса с известными параметром. Особенности фотоупругого эффекта обсуждены в контексте формирования требуемой временной задержки. Показано, что в этом случае можно плавно регулировать требуемую задержку времени в широком интервале. Доказано, что оптимальный линейный фильтр с более широкими функциональными возможностями может быть реализован на основе акустооптической линии задержки.

Ключевые слова: радиолокация, шум, оптимальный линейный фильтр, фотоупругий эффект, линия задержки, акустооптика.

Introduction

One of the most important areas of modern radio electronics is radiolocation. Its wide use in the defense industry has intense the principality of this direction. One of the signals used here is an echo signal which it is formed backscattering wave from an object. The probing signal transmit by radar interacts with the object and scatter in different directions. A small part of the backscattering wave is propagation the direction of the radar and is received by the radar receiver [1]. The received signal $s_g(t)$ is time-shifted copy of probing signal $s_v(t)$

$$s_g(t) = A \cdot s_v(t - \tau), \qquad (1)$$

where A is attenuation factor and τ shifting time interval. Usually attenuation factor in (1) is $A << 1$. The amplitude of the received signal can be small enough to be compared with the root means square of noise volatage at the input of the receiver. This issue can be discussed example of STAR-2000 surveillance radar. In this case attenuation factor in (1) is defined as follows:

$$A = G \cdot \sigma_{eff} \cdot S_t/(4\pi R^2)^2, \qquad (2)$$

where G is the antenna gain, σ_{eff} is the effective scattering area of the radar object, S_t is the effective area of the antenna and R is the distance from the radar to the object.

The effective area of the antenna is defined as next formula

$$S_t = {G \cdot (c/f)^2}/{4\pi}, \qquad (3)$$

where $c = 3 \cdot 10^{8}$ m/s velocity of electro-magnit waves in vacuum, f is operating frequency.

The urgency of the problem

Let's assume that the observation object with an effective scattering area $\sigma_{eff} = 40\ m^2$ is located at a distance of $R = 100\ km$ from the radar. The necessary parameters [2] of STAR-2000 surveillance radar for calculation and some calculations results based on (2) and (3) are illustrated in Table. It is clear that if a complex of special measures is not implemented, it will not be possible to ensure receiving of the signal in the range of values of the attenuation factor depicted in Table. For the tackling of this problem research is being conducted different directions. The one of these directions is that the created and applying best detecting devices for the signal which distorted from the noise effect.

Table – The some parameters of STAR-2000 surveillance radar and calculation results

№	Parameter	Parameter Value	Note
1	Operating frequency	2,7 – 2, 9 GHz	The radar works on one of the frequencies in this range
2	Peak power	15 kWt	If the radar works with 15 modules
3	Pulsewidth of the probing signal, τ_i	1 μs and 75 μs	
4	Antenna gain, G	34,3 dB	
5	Effective area of the antenna, S_t	2,645 – 2,293 m^2	
6	Attenuation factor, A	$1{,}8 \cdot 10^{-17}$-$1{,}563 \cdot 10^{-17}$	

At the simple situation can be use from frequency filtering. In this case, the frequency transfer coefficient $K(j\omega)$ of the linear stationary filter is chosen so that amplitude-frequency response |K(jω)| values are large in the frequency range where the main part of the signal energy is concentrated and small in the frequency range where the spectral density of the noise power is large. When a sum of the signal and noise is given to the input of such a filter, it can be expected that the share of the signal at the output will increase significantly. A system with frequency selectivity that ensures the processing of the sum of the signal and noise in any good way is called an optimal linear filter [3].

It is not required to maintain the shape of the useful signal when the radar system is working. In addition, in the work process, it is desirable to transform the useful signal in such a way that at input of the filter a significant "increase" in the instantaneous values of the output signal at any moment. Usually, a signal consisting of Gaussian noise is less likely to have large increases. Therefore, the fact that the output signal is significantly higher than the effective noise voltage at certain moments of time, most likely confirms the fact that there is a useful signal at the input of the receiver.

Optimal linear filter for probing signals. If the input of the linear stationary filter with impulse response $h(t)$ is affected by the signal $s_{in}(t)$, the signal $s_{out}(t_0)$ with its maximum value at its output at the moment t_0 is found by means of the Duhamel integral as follows:

$$s_{out}(t_0) = \int_{-\infty}^{\infty} s_{in}(\tau) h(t_0 - \tau) d\tau. \quad (4)$$

According to the Cauchy-Bunyakovsky inequality (4) can be written follow as:

$$\left| \int_{-\infty}^{\infty} s_{in}(\tau)\, h(t_0 - \tau) d\tau \right| \leq$$

$$\left[\left| \int_{-\infty}^{\infty} s_{in}{}^2(\tau) d\tau \int_{-\infty}^{\infty} h^2(t_0 - \tau) d\tau \right| \right]^{1/2} \quad (5)$$

In this expression, the equal sign is possible only if the products of the integrand given in (4) are proportional to each other:

$$h_{opt}(t_0 - t) = k \cdot s_{in}(\tau), \quad (6)$$

where k characterizes an arbitrary coefficient.

By formally replacing the variable as $t = t_0 - \tau$, (6) can be written as follows:

$$h_{opt}(t) = k s_{in}(t_0 - t). \quad (7)$$

It is clear from the last mathematical expression that the impulse response $h_{opt}(t)$ of the optimal linear filter is a scaled copy of the input signal which located in a mirror order on the time axis (this is seen from the minus sign in (7)). In addition, the impulse response of the optimal linear filter is shifted by t_0 with respect to the $s_{in}(-t)$ signal [4].

Optimal linear filters are applied in pulse radar receivers. In this case, the these filters are placed in the intermediate or low-frequency tract for easier technical installation.

Since the impulse response of a linear stationary system and the frequency transfer coefficient are related to each other by Fourier transform, according to the (7) the following formula can be written as

$$K_{opt}(j\omega) = k \int_{-\infty}^{\infty} s_{in}(t_0 - t) e^{-j\omega t} dt. \quad (8)$$

Including the new integration variable $\xi = t_0 - t$ is getting next formula:

$$K_{opt}(j\omega) = k e^{-j\omega t_0} \int_{\infty}^{-\infty} s_{in}(\xi) e^{j\omega \xi} d\xi. \quad (9)$$

The spectral density of amplitude of input signal $s_{in}(t)$ is define with Fourier transform follow as:

$$S_{in}(j\omega) = \int_{-\infty}^{\infty} s_{in}(t)\, e^{-j\omega t} dt. \quad (10)$$

Accordingly, the (9) found for the frequency transfer coefficient of the optimal linear filter can be written as follows:

$$K_{opt}(j\omega) = kS_{in}^{*}(j\omega)e^{-j\omega t_0}, \quad (11)$$

where $S_{in}^{*}(j\omega)$ is complex conjugate function of $S_{in}(j\omega)$.

It can be seen from the last statement that the frequency transfer coefficient of the optimal linear filter is expressed by the spectral density of the received useful signal. The proportionality coefficient k in the (10) determines the level of amplification of the filter. The t_0 is included only in the expression of the phase characteristic of the filter. In this case, the $e^{-j\omega t_0}$ represents the shift of the output response on the time axis by t_0.

Optimal linear filter for radar with single probing pulse. For complete clarity of the matter, let us assume that the radio receiver is designed to receive a single radio pulse width τ_i and the optimal linear filter is placed in the low-frequency tract of the radar receiver. In this case, a rectangular video pulse $s_{in}(t)$ with width τ_i and amplitude U_0 is formed at the input of the optimal linear filter.

The spectrum of the pulse signal $s_{in}(t)$ is found based on the frequency transfer coefficient of the optimal linear filter according to the (11):

$$S_{in}(j\omega) = \frac{U_0}{j\omega}(1 - e^{-j\omega\tau_i}). \quad (12)$$

The frequency transfer coefficient of the optimal linear filter, which provide to detecting of the video signal with pulse width τ_i is founded follow as:

$$K_{opt}(j\omega) = k(\frac{1}{j\omega})(1 - e^{-j\omega\tau_i}). \quad (13)$$

The obtained result fully defines the structure of the optimal linear filter for a rectangular video pulse. According to the last equation the optimal linear filter, which provides the detection of a rectangular video pulse known width, consists of a stepwise combination of three linear loops. The first loop is amplifier (A), which its gain is k, the second loop is an ideal integrator (I) and the third loop is a device with frequency transfer coefficient $K(j\omega) = [1 - exp(-j\omega\tau_i)]$. The third loop also consists of delay lines (DL) that delays the signal by τ_i, an phase inverter (PI) that changes the phase of the signal and an summer (S). The structural scheme of the optimal linear filter for a single rectangular video pulse which synthesized according to the given explanation is described in Figure 1.

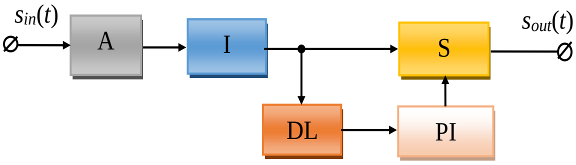

Figure 1 – The structural scheme of the optimal linear filter for a single rectangular video pulse

Solution. From the common analysis of the analytical description given above and the structural scheme shown in Figure 1, it is clear that one of the main components of the optimal linear filter is the device that ensures the delay of the video pulse by τ_i.

It is depicted in given table that the STAR-2000 surveillance radar uses two probing signals which the pulsewidth of them is 1 μs and 75 μs. In this case, the synthesis of the optimal linear filter require the two delay lines providing a fixed time delay.

Obviously, in this situation, the optimal linear filter cannot be tuned to receive two signals which have different pulsewidth. This requires the application of a tunable delay time device. It is possible to solve the problem by using the properties of the photoelastic effect [5].

The photoelastic effect is realized in the acousto-optic modulator (AOM) (Figure 2). The AOM consists of a photoelastic medium (PEM) attached to an electroacoustic converter (EAC) [6]. In the AOM can be used glass and crystalline PEM. The EAC converts the electrical signal $s_{in}(t)$ to an acoustic wave. This acoustic wave interacts with the optical wave in the PEM. As a result, part of the light beam is diffracted.

The light beam in the diffraction pattern falls on the photosensitive surface of the photoreceiver device (PD) through the diaphragm.

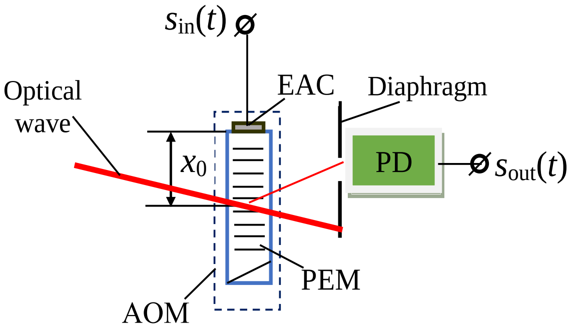

Figure 2 – The structure of the acousto-optical delay line

The signal $s_{out}(t)$ formed at the output of the PD is a copy of the voltage at the input $s_{in}(t)$ delayed by $\tau = x_0/v$, where v is the propagation velocity of the acoustic wave in the PEM. The propagation velocity of the acoustic wave v is approximately 10^5 times smaller than the propagation velocity of the optical wave. Therefore, it is not difficult to ensure that the output voltage is delayed by several 10 μs compared to the input [7, 8].The operation of the acousto-optical delay line illustrates in Figure 3. The oscillogram in Figure 3 it was obtained with relevant laboratory model as Figure 2. Here, the pulse formed at the output (Figure 3, *2*) is delayed by 4 μs compared to the pulse at the input (Figure 3, *1*). The pulsewidth of both signals (it is set at the level of 0.5 of the maximum value) is 1 μs.

It is clear that by changing the distance x_0 from the EAC to the photoelastic interaction area (for example, by electromechanical means), it is possible to adjust the delay time τ over a wide range. Therefore, an optimal linear filter realized on the basis of an acousto-optical delay line can be easily tuned to receive pulses with different width, that is, such a filter has wider functional potentiality.

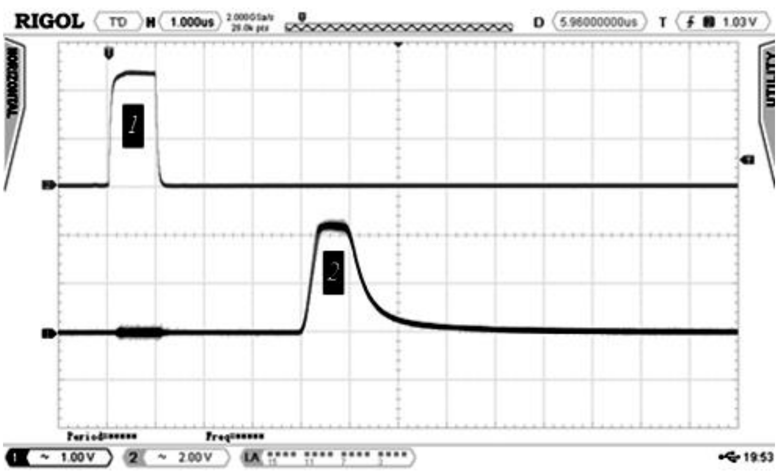

Figure 3 – The output and input oscillogram of the acousto-optical delay line

Conclusion

One of the effective means of detecting weak signals from the noise background is the optimal linear filter. The main components of this device is the delay line. In known filters, delay lines providing a fixed time shift are used for this purpose. As a result, it is possible to match the optimal linear filter with only one probing pulse. The application of an acousto-optic delay line, which provides a smoothly adjustable time shift in a large interval, allows to realize an optimal linear filter with wide functional possibilities. In this case, by smoothly changing the time shift (for example, by mechanical displacement of the photoelastic medium), tuning of the optimal linear filter for receiving an pulse with different parameters is easily ensured.

Conflict of Interests

The author declares there is no conflict of interests related to the publication of this article.

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