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THEORETICAL ANALYSIS OF THE ADAPTIVE SYSTEM FOR SUPPRESSION OF THE INTERFERENCE CONCENTRATED ON A SPECTRUM

Об'єктом дослідження є процес зменшення перешкоди в пасивному радіометричному приймачі, зосередженої по спектру перешкоди, з випадковою або змінною частотою. Перешкодостійкість можна підвищувати за допомогою спеціальних схем, що запобігають перевантаженню приймача і використовують відмінності в характеристиках корисних сигналів і перешкод для зменшення останніх. Як правило, ніколи точно невідома частота коливань перешкоди і, крім того, реальна перешкода ніколи не буває чисто гармонійною. Тому виникла необхідність теоретичного розгляду ступеня зменшення перешкоди вхідним ланцюгом радіометра при невідомому значенні частоти перешкоди і кінцевій ширині спектра, а також теоретично обгрунтувати можливі способи побудови адаптивних пристроїв зменшення реальної вузькосмугової перешкоди.

Отримано вираз для коефіцієнта зменшення зосередженої по спектру перешкоди, який показує, що перешкода буде зменшуватися автоматично при оптимальному виборі параметрів ky, τ, T системи, що стежить.

У роботі приведена функціональна схема радіометричного приймача, яка використовує адаптивну систему для зменшення зосередженої по спектру перешкоди. Адаптивна система була заснована на включенні в схему радіометричного приймача додаткового компенсуючого перешкоди ланцюга. Компенсуючий перешкоду ланцюг дозволяє підвищити чутливість приймача до 10–20 Вт з точністю до 0,1 °C і швидкодією 2...4 с. Крім зменшення перешкоди компенсуючою ланкою, що стоїть після підсилювача проміжної частоти, забезпечується зменшення перешкоди і вхідним ланцюгом. При цьому загальний виграш в завадостійкості досліджуваного радіометричного приймача в порівнянні з компенсаційним, як показують розрахунки для типових характеристик, буде не гірше, ніж в 30 дБ.

Ключові слова: *радіометричний приймач, зменшення зосередженої по спектру перешкоди, компенсуючі перешкоду кола.*

1. Introduction

Systematic control over the health of farm animals becomes a necessary condition for the functioning of livestock complexes, and its improvement is one of the most important tasks of veterinary science and best practice [1]. At present, the main indicator of the state of animals is temperature. In veterinary practice contact (thermometers) and non-contact (thermal imagers) methods of temperature measurement are used. The use of thermometers leads to injuries or rupture of the rectum. The use of thermal imagers requires the fixation of animals and special preparation of the skin surface [2]. Therefore, preference should be given to a remote method based on the reception of the thermal radiation of the animal organs. The power of thermal electromagnetic radiation of tissues and organs of animals is 10^{-15}–10^{-20} W. Veterinary diagnostic system of radiothermal mapping is intended for diagnosing circulatory disorders, tumors, inflammatory processes of internal organs of animals. The analysis of existing radiometric receivers shows that their parameters do not meet the requirements for accuracy, sensitivity and noise immunity. The sensitivity of existing radiometric receivers in the millimeter range does not exceed 10^{-10} W. A millimeter-wave radiometric system for measuring the animals' own electromagnetic radiation, having a relatively wide reception band, can be exposed to a combination of interference [3]. The main sources of interference for the radiometric system, in the zone of measurement with animals, are industrial disturbances [4]. A practical analysis shows that one of the dangerous is a spectrum-focused interference with a random or varying frequency, which can be suppressed by means of special circuits using differences in the characteristics of useful signals and interference [5]. Therefore, suppression of a noise-centered noise, with a random or varying frequency, is an actual problem.

2. The object of research and its technological audit

The object of research is the process of interference suppression in a passive radiometric receiver, concentrated along the spectrum of the interference, with a random or varying frequency. From the analysis of passive radiometric receivers of superheterodyne, modulation and additive-noise types, it follows that their measurement sensitivity depends on the action of a spectrum-centered noise with a variable frequency [3]. Considering the high probability of interference effects on the system in the area of measurements, both active and passive, it is necessary to provide for an increase in its noise immunity in the event of exposure to possible types of interference during the construction of the system. The following measures should be used as the basis for suppressing interference concentrated on the spectrum [5]:

– development of new schemes;

– improvement of known schemes (broadband bandwidth expansion, increase in integration time, increase in amplification, application of a delay line in the input circuit).

Thus, it can be concluded that in the construction of radiometric systems in the millimeter range, the following determining shortcomings should be considered:

– because of the randomness of the interference frequency, and also in the presence of a tunable interference, the degree of its suppression is unpredictable;
– for the purposes of passive radiometric reception, there are no ways to combat this kind of interference [5, 6];
– the impossibility of quickly (electronically) to adjust the delay time in the input signal circuit when operating in the millimeter wave band [1, 4].

In this regard, a method based on incorporating an interference compensating circuit is more preferable. The interference compensating circuit is installed in the intermediate frequency amplifier path after the frequency conversion. For the substantiation of this method it is necessary to carry out theoretical studies.

3. The aim and objectives of research

The aim of research is a theoretical analysis of the circuits in the structure of a radiometric receiver for suppressing a noise concentrated on the spectrum, with a random or varying frequency.

To achieve this aim, it is necessary to perform the following tasks:

1. To substantiate the interference compensating circuit in the intermediate frequency path of the passive radiometric receiver.
2. To determine the suppression coefficient of harmonic interference in power by the tracking system of the radiometric receiver.

4. Research of existing solutions of the problem

A millimeter-wave radiometric system for measuring the animals' own electromagnetic radiation, which has a relatively wide reception band, can be subjected to a combination of interference [6]. The main sources of interference for the radiometric system, in the zone of measurement with animals, are industrial disturbances [7, 8].

Literary analysis shows that one of the most dangerous is interference concentrated along the spectrum, with a random or changing frequency, which can be suppressed by means of special circuits using differences in the characteristics of useful signals and interference [9].

It is considered in [10] that the noise-centered interference will be suppressed by the input circuit with different degrees, depending on the amount of detuning of the carrier frequency of the interference from the central frequency of the input circuit. Due to the randomness of the interference frequency, and also in the presence of a tunable interference, the degree of its suppression is unpredictable [11, 12]. The analysis of works devoted to the passive radiometric reception of electromagnetic radiation of biological objects [13, 14] shows that there are no methods of combating this class of interference. In [15], a method for suppressing a narrow-band, spectrum-centered noise with a random or varying frequency is developed using an adaptive system. The principle of interference cancellation is based on the tuning of the delay time in the input circuit, until the interference frequencies and the center frequency of the input circuit coincide. However, this method has a number of disadvantages, the main one of which is the impossibility of quickly (electronically) realizing the delay time in the input circuit when operating in the millimeter wave band. In this regard, the method of suppressing interference concentrated on a spectrum with a random or varying frequency using special schemes using differences in the characteristics of useful signals and interference is more preferable.

5. Methods of research

The functional diagram of the radiometric receiver, which uses an adaptive system for suppressing the spectrum-centered interference, is shown in Fig. 1.

The circuit of the radiometric receiver (Fig. 1) additionally includes an interference compensating circuit, which is installed in the intermediate frequency amplifier (IFA) channel after the frequency conversion, as well as a scheme for automatically tuning the local oscillator frequency with respect to the frequency of the interference.

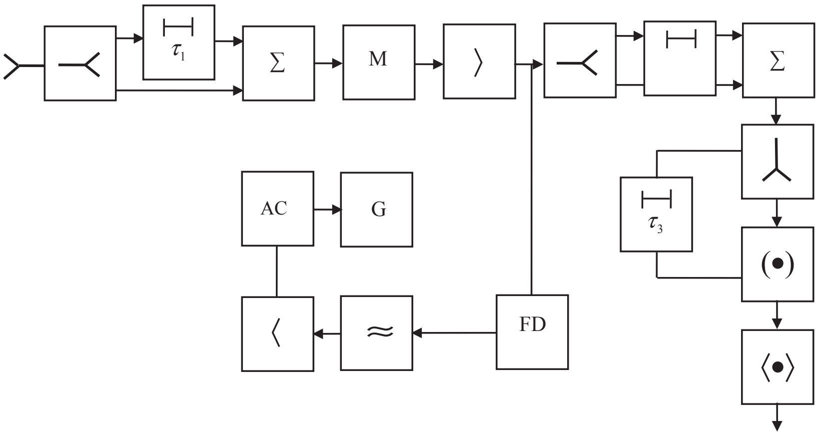

Fig. 1. Functional scheme of a radiometric receiver with an adaptive system for suppressing a spectrum-centered interference: τ_1, τ_2, τ_3 – delay time; Σ – signal summator; M – mixer; > – amplifier; ( ) – operation of generalized quadratic detection; < > – averaging operation; FD – frequency discriminator; G – generator; AC – amplifier of direct current and control device; ≈ – low-pass filter

To clarify the capabilities of the developed device, let's estimate the suppression degree of the narrow-band noise that appeared in the middle quarters of the IFA band.

Let's begin from the following basic assumptions:

1. The control element and the discriminator are inertia-free devices that use only linear sections of their static characteristics, and are characterized by the steepness of the S_C and S_D transformations, respectively.
2. The value of the amplification factor of the IF amplifier (intermediate frequency amplifier) and the DCA (DC amplifier) is taken into account in the steepness values S_D and S_C, respectively. Therefore, let's set the amplification factors of the $K_{IFA}=K_{DCA}=1$.

3. The filter is a linear element consisting of an RC chain, and its transfer function is defined by the expression:

$$K_F(P)=\frac{1}{T_F+1}, \tag{1}$$

where T_F – the time constant of the filter.

4. The interference is harmonic and acts at a constant frequency $f_I=\text{const}$ with constant amplitude of the A_C, and the tuning frequency of the discriminator exactly coincides with the center frequency of the compensating circuit $f_D=f_{0IF}$, which also remain unchanged in time.

Then, taking into account the foregoing, the frequency of interference in the IFA path will be determined from the expression:

$$f_{IIF}(t)=f_I(t)-f_O(t), \tag{2}$$

where $f_O(t)$ – the local oscillator frequency, and in the steady state, the accuracy of coincidence of the interference frequency at the intermediate frequency (IF) with the center frequency of the compensating circuit can be expressed in increments:

$$f_{IIF}(t)=-\Delta f_O(t), \tag{3}$$

that is, it is determined by the error of controlling the local oscillator frequency.

The error of the servo system is the difference between its actual output signal $f_O(t)$ and the required output signal $f_{O_0}(t)$, which consists of the error in working out the required amount of tuning of the local oscillator $\Delta f_{OT}(t)$ and the error resulting from the action of the system noise $\Delta f_{ON}(t)$, i. e.:

$$f_O(t)-f_{O_0}(t)=\Delta f_O(t)=\Delta f_{OT}(t)+\Delta f_{ON}(t). \tag{4}$$

Let's determine the error in working out the required adjustment value. Taking into account that the frequency of the interference is constant, on the basis of the theory of automatic control, the error in the determination is determined by the expression:

$$\Delta f_{OT}(t)=C_0\left|f_{0IF}-f_{IIF}\right|, \tag{5}$$

where C_0 – the error of position, which is determined by the value of the transfer function of the system $W(p)$ at the origin:

$$C_0=1-W(p).$$

For a circuit of automatic control of the local oscillator frequency, the transfer function of the system will look like:

$$W(p)=\frac{k_a}{T_p+k_a+1}, \tag{6}$$

where $k_a=S_D\cdot S_a$ – the total amplification coefficient of the open system.

Then the error rate C_0 will be written in the following form:

$$C_0=1-\frac{k_a}{k_a+1}=\frac{1}{k_a+1},$$

but the completion error:

$$\Delta f_{OT}=\frac{\left|f_{0IF}-f_{IIF}\right|}{k_a+1}. \tag{7}$$

From expression (7) it is easy to see that the error of working off depends on the absolute value of the required adjustment value. With a sufficiently large amplification of the open system $k_a\gg 1$, the error can be achieved by a predetermined degree of smallness.

Let's define the error of the system, which is the result of the action of noise. The main source of noise acting at the input of the frequency discriminator will be the internal noise of the radiometric receiver. It is known that the dispersion of the signal at the output of the system is determined by the expression [5]:

$$\sigma_\omega^2=\frac{1}{2\pi}\int_0^\infty S_X(\omega)A^2(\omega)\mathrm{d}\omega, \tag{8}$$

where $S_x(\omega)$ – the spectral density of the signal acting at the input of the system; $A(\omega)=\left|W(j\omega)\right|$ – module of the complex frequency response of the system.

Taking into account that the internal noises of the radiometric receiver arriving at the input of the discriminator are an ergodic normal random process of the type of quasi-white noise, with the spectral density S_0 acting in the IF band, and the modulus of the frequency response is given by:

$$A(\omega)=\frac{k_a}{\left|T_{j\omega}+k_a+1\right|},$$

then expression (8) for the control circuit of the local oscillator frequency can be rewritten in the following form:

$$\sigma_\omega^2=\frac{1}{2\pi}\int_0^\infty S_0\frac{k_a^2\cdot\alpha_{TN}}{\left|T_{j\omega}+k_a+1\right|^2}\mathrm{d}\omega=$$

$$=\frac{S_0\cdot k_a^2\cdot\alpha_{TN}}{2\pi}\int_0^\infty\frac{\mathrm{d}\omega}{\left|T_{j\omega}+k_a+1\right|^2}, \tag{9}$$

where $\alpha_{TN}=1\left[\mathrm{rad}^2/\mathrm{W}\right]$ – the unit coefficient, which takes into account the transformation of the amplitude noise into a frequency fluctuation.

After integration, let's finally obtain:

$$\sigma_\omega^2=\frac{S_0k_a^2\alpha_{TN}}{2T(k_a+1)}. \tag{10}$$

Thus, taking into account expression (3), the obtained value σ_ω^2 will be the variance of the frequency fluctuation of the interference at the input of the compensating circuit.

Let's find the expression for the dispersion of the interference amplitude at the output of the decompressing circuit.

In the general case, the interference signal is represented as:

$$U_I(t)=A_I\cos\left[\omega_{0IF}t+\int_t\Delta\omega(t)\mathrm{d}t\right], \tag{11}$$

where A_I – the amplitude of the interference; $\Delta\omega(t)$ – the fluctuations of the interference frequency.

In the case under consideration, the frequency fluctuations $\Delta\omega(t)$ will be slow, in comparison with $\cos\omega_{0IF}\cdot t$, by a stationary random process with the dispersion determined by the expression (10).

The dispersion of the interference amplitude at the output of the compensating circuit is determined in accordance with (8):

$$D_I = \frac{1}{2\pi}\int_0^\infty S_I(\omega)K^2(\omega)\mathrm{d}\omega, \tag{12}$$

where $S_I(\omega)$ – the spectral density of the interference at the input of the compensator; $K(\omega)$ – the transmission coefficient of the compensating circuit.

6. Research results

For the investigated case, under the normal distribution law of frequency fluctuations, the shifted interference spectrum at the input of the compensator has the form [6]:

$$\tilde{S}_I(\omega) = \frac{A_I^2}{2}\cdot\frac{1}{\sqrt{2\pi\sigma_\omega^2}}e^{-\frac{\omega^2}{2\sigma_\omega^2}}. \tag{13}$$

Thus, substituting expression (13) in (12) and taking into account the fact that $S_I(\omega)=2\pi\tilde{S}_I(\omega)$, let's obtain the dispersion of the interference amplitude at the output of the system:

$$D_I = \int_0^\infty \tilde{S}_I(\omega)\tilde{K}^2(\omega)\mathrm{d}\omega = \int_0^\infty \frac{A_I^2}{2}\frac{1}{\sqrt{2\pi\sigma_\omega^2}}\cdot e^{-\frac{\omega^2}{2\sigma_\omega^2}}\times$$
$$\times\sin^2\left(\frac{\omega\tau}{2}\right)\mathrm{d}\omega = \frac{A_I^2}{4}\left(1-e^{-\frac{\sigma_\omega^2\tau^2}{2}}\right), \tag{14}$$

where $\tilde{K}^2(\omega)=\sin^2\left(\frac{\omega\tau}{2}\right)$.

Finally, taking into account (10), let's write:

$$D_I = \frac{A_I^2}{4}\left[1-e^{-\frac{S_0 k_a^2\tau^2\alpha_{T\,N}}{4T(k_a+1)}}\right]. \tag{15}$$

From the expression (11) let's define the interference power at the input of the compensating circuit:

$$P_{I\,IN} = \frac{A_I^2}{2}. \tag{16}$$

Then the suppression coefficient of harmonic interference by the power of the servo system will be written as:

$$K_I = \frac{D_I}{P_{I\,IN}} = \frac{1}{2}\left[1-\exp\left(-\frac{S_0 k_a^2\tau^2\alpha_{T\,N}}{4T(k_a+1)}\right)\right]. \tag{17}$$

It is seen from (17) that in the absence of internal noises, the case $S_0=0$, the coefficient $K_I=0$ that is, the harmonic interference will be suppressed completely. Thus, with the optimal choice of the parameters k_a, τ, T of the tracking system for suppressing narrow-band noise, it will be automatically performed when the interference frequency is combined with the center frequency of the compensating link. It should be noted that in addition to interference suppression, the compensating link after the intermediate frequency (IF) amplifier will be provided with interference suppression and an input circuit. In this case, the overall amplification in the noise immunity of the radiometric receiver (Fig. 1) compared with the compensatory receiver, as calculations for typical characteristics show, will not be worse than 30 dB.

7. SWOT analysis of research results

Strengths. For the remote determination of the condition of animals, a passive radiometric receiver of the modulation type should be used. The radiometric receiver is designed for measuring the thermal electromagnetic radiation of tissues and organs of animals in the range of 30–40 GHz. The suppression of a focused noise, with a random or varying frequency, up to 30 dB allows:

- increase the sensitivity to 10^{-19} W, instead of 10^{-17} W;
- increase the detection of temperature fields to 10 cm, instead of 5 cm;
- increase speed up to 1 second, instead of 2…4 seconds;
- increase the reliability of diagnoses by an order of magnitude when analyzing the picture of the animal's thermal field.

Weaknesses. The weakness of the receiver is that it requires further development to protect against industrial and broadband interference.

Opportunities. The use of a radiometric receiver for the diagnosis of the condition of animals has allowed in their treatment:

- reduce the consumption of medicines by 15…20 %;
- to develop a feeding ration and conditions for their maintenance and, as a result, increase productivity by 20…25 %;
- save the economy (1000 head of cows) 5000…6000 USD.

The cost of completion will not exceed 10 % of the cost of the radiometric receiver.

Threats. The cost of modifying the receiver to protect against industrial and broadband interference will be approximately 10 % of the cost of the radiometric receiver.

8. Conclusions

1. The compensating circuit in the intermediate frequency channel of the radiometric receiver is justified. The peculiarity of this circuit is that it suppresses, at 30 dB, the interference concentrated on the spectrum, with a random or variable frequency.

2. An expression is obtained for the suppression coefficient of the interference concentrated on a spectrum, which shows that the interference will be suppressed automatically for the optimal choice of the parameters k_a, τ, T of the servo system.

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