Model for Assessing the Immunity of Channels Using Frequency Manipulation Signals

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Abstract. The issues of noise immunity of control channels of robotic systems using signals with frequency shift keying are considered. The article presents the results of estimating the probability of a bit error depending on the duration of the intervals at which the time coincidence of the structural interference with the signal occurs. Proposals are formulated for the practical use of the results obtained.

1. Introduction

The widespread use of robotic systems is one of the priority directions in the development of modern radio engineering [1–4]. First of all, this is due to the possibility of their use in technogenic and life-threatening situations: on fires, in areas of chemical and radiation contamination of the area, etc. [5–7].

However, since robotic systems are controlled by a radio channel, they become vulnerable to interference, especially to interference with a time-frequency structure close to control signals [8–10]. We will define such signals as structural interference. The limited frequency range used to control robotic systems leads to the fact that with the simultaneous use of several robotic systems in a limited space, there is a possibility of time-frequency coincidence of their control signals. Thus, a situation arises of unintentional impact of structural interference on the control channels.

Consequently, the issues of ensuring the safety of radio control channels and their resistance to unintentional structural interference should be given primary attention both in the design and operation of robotic systems.

The analysis of approaches to organizing the functioning of robotic systems showed that a rather limited set of commands is used to control them [11, 12]. Moreover, signal structures based on frequency shift keying are historically used as a modulation format [13–14]. In the future, it is possible to switch to broadband signals, which are currently used to control lightweight unmanned aerial vehicles [1, 6, 15, 16].
Thus, it is the presence of a radio channel that makes robotic systems vulnerable to external influences, which can be unintended structural interference.

With regard to this article, the process of influencing control channels will be considered only from the side of unintended structural interference.

2. Conditions and nature of the impact of structural interference on control channels using frequency-shift keying signals

In the context of this article, only the process of influence of structural interference in the form of frequency-shift key signals with a time-frequency structure close to the control command signals will be considered. This kind of destructive effect is reduced to replacing the useful signal with interference in the receiving path of the control channel [17, 18]. As a result, conditions are created under which the value of the received signal symbol will be determined by the noise structure symbol (Fig. 1).

![Figure 1](image1.png)

**Figure 1.** Time structure of the useful signal \( s(t) \), structural interference \( u(t) \) and the resulting mixture of signal + interference \( z(t) \).

So in fig. 1 shows three clock intervals \( \tau_1, \tau_2, \tau_3 \) of a two-position frequency-shift keyed control signal \( s(t) \), corresponding to the information symbols “1” and “0”. It also shows the structural noise \( u(t) \) corresponding to the information symbol "0", transmitted within the clock interval \( \tau_2 \), within which the information symbol "1" is transmitted via the control channel.

As a result, for control channels using FM-2 signals, structural interference of a destructive nature will create a situation at the input of the demodulators in which the decision on the received signal symbol is carried out randomly.

Indeed, the resulting mixture \( z(t) \) contains information about both the useful signal corresponding to the information symbol "1" and the interference corresponding to the information symbol "0".

This situation is more clearly reflected by the time-frequency representation \( z(t) \) on the duration of the clock interval \( \tau_2 \), shown in Fig. 2.

![Figure 2](image2.png)

**Figure 2.** Time-frequency representation of the process of influence of structural interference.

In fig. 2a shows the time-frequency representation of the control signal \( s(t) \), with the selected fragment \( \tau_2 \) corresponding to the information symbol "1". In fig. 2b – representation of the signal \( z(t) \).
It is obvious that for the duration $\tau_2$ shown in Fig. 2b, it is difficult to make an unambiguously correct decision about the true value of the transmitted symbol based on the energy criterion alone.

Note that the situation under consideration is possible only if the structure of the interference at each time instant corresponds to the opposite symbol transmitted over the FM-2 signal control channel.

From the standpoint of suppressing the system, the considered situation of such a complete clock coincidence of the structural noise and the information signal is ideal.

Note that in view of the rather high dynamics of movement of robotic systems, for control channels with FM-2 signals it is possible to use only the method of incoherent detection, which ensures the probability of a bit error equal to

$$P_B = \frac{1}{2} \exp \left( -\frac{E_B}{2N_0} \right) = \frac{1}{2} \exp \left( -\frac{1}{2} h_0^2 \right).$$

(1)

where $E_B$ is the energy per bit (for binary transfers - per $E_C$ symbol); $N_0$ is the noise power spectral density; $h_0^2 = \frac{E_B}{N_0} = \frac{E_C}{N_0}$ – the ratio of the signal energy to the noise power spectral density (SNR) (in the considered situation, the power spectral density of the structural noise).

In fig. 3 shows the dependence of the bit error on SNR in dB.

**Figure 3.** Dependence of the bit error probability for incoherent reception of FM-2 signals on SNR.

In conditions of structural interference, the $P_B$ value can be converted to the following form:

$$P_B = \frac{1}{2} \exp \left( -\frac{E_B}{2N_0} \right) = \frac{1}{2} \exp \left( -\frac{1}{2} h_0^2 \right).$$
where $E_I$ is the energy of the simulated noise over the duration of the symbol.

In fig. 4 shows the dependence of $P_b$ on SNR in conditions of structural interference with power $E_I = E_C / 2$ and $E_I = E_C / 4$ in conditions of clock coincidence of interference and signals.

3. Probabilistic assessment model

It should be noted, despite the determinism of the command structure, the high dynamics of movement of robotic systems leads to the fact that in real conditions the clock interval of the structural noise and signal will be a random value. Therefore, to assess the degree of destructive damage caused by the structural interference, it is proposed to introduce the concept of the coefficient of destructive damage caused by the structural interference $\rho$, which will characterize the temporary discrepancy between the structural interference and the useful signal at the demodulator input.

In fig. 5 shows diagrams explaining the physical essence of the coefficient $\rho$

![Diagram](image.png)

**Figure 5.** Time structure of the useful signal $s(t)$, structural interference $u(t)$ and the resulting mixture at the input of the demodulator $z(t)$ with clock mismatch between the interference and the signal.

In accordance with logical reasoning, the proposed coefficient $\rho$ lies within the limits $\rho \in [0; 1]$, i.e. the value $\rho = 1$ corresponds to the conditions of complete suppression, in which a logical symbol completely opposite to the symbol transmitted by the control signal is formed by the interference during the clock interval. And when $\rho = 0$, a condition arises under which the symbol transmitted by the interference completely coincides with the symbol transmitted by the useful signal, i.e. will contribute to its reliable reception. In other words, the higher the $\rho$ value, the higher the destructive damage done.

With reference to Fig. 5 on the clock interval $\tau_2$, the value of the coefficient $\rho$ will be determined as

$$\rho = \frac{\tau_2 - \Delta \tau_2}{\tau_2}$$

Note that for the clock interval $\tau_3$, on the contrary, for the duration of the interval $\Delta \tau_2$, the structural noise coincides in its structure with the useful signal. Such conditions lead to an increase in the reliability of the correct reception.

From an energy standpoint, the worst situation for a robotic system occurs when the energy of the structural interference $E_I$ and the energy of the useful signal $E_C$ on the solver are equal. Such a situation can arise under the condition.

$$E_I = E_C / \rho,$$

(3)

Note that condition (3) should occur at the input of the receiving path of the robotic system. In this case, a destructive effect is achieved even with a value of $\rho < 1$.

But in this case, the use of threshold limiters at the input of FM-2 signal demodulators does not allow achieving equality (3), which contributes to an increase in the noise immunity of the channel.
Taking into account these remarks, expression (1) can be represented as follows:

\[ P_a = \frac{1}{2} \exp\left( -\frac{E_c + (1 - 2\rho)E_r}{2N_0} \right), \]

Next, we transform expression (4) to the following form:

\[ P_a = \frac{1}{2} \exp\left( -\frac{E_c}{2N_0} + \frac{(2\rho - 1)E_r}{2N_0} \right) = \frac{1}{2} \exp\left( -0.5h^2_0 + (\rho - 0.5)h^2_0 \right), \]

where \( h^2_0 = \frac{E_c}{N_0} \) is the ratio of the interference energy to the noise power spectral density.

If we assume that the equality of values \( h^2_0 = h^2_0 \), for example, provided by the limiter at the input, then formula (5) can be represented as

\[ P_a = \frac{1}{2} \exp\left( -h^2_0 + \rho h^2_0 \right) = \frac{1}{2} \exp\left( h^2_0 (\rho - 1) \right), \]

Expression (6) clearly allows you to evaluate the effect of clock coincidence of the structural noise and the useful signal, which is graphically shown in Fig. 6.

The analysis of the obtained results indicates the high sensitivity of the reception channel to the value of the time interval of coincidence of the structural interference and the signal. So at SNR of 10 dB, a 10% increase in the overlap interval between the structural interference and the signal lead to a more than 15 increase in the bit error probability.

![Figure 6](image_url)

**Figure 6.** Dependence of the probability of a bit error in the case of incoherent reception of FM-2 signals on the coefficient of destructive damage at a given value of SNR.

Note that the results shown in Fig. 6, characterize only a particular case \( (h^2_0 = h^2_0) \) described by formula (6). For the general case, it is advisable to consider expression (4) as a model for assessing the error probability in a frequency modulation channel under conditions of unintended structural interference.

This expression can be considered as a model for assessing the destructive damage caused as a result of the impact of structural interference on the control channels of robotic systems using frequency shift keying signals.

Model (4) characterizes the dependence of the bit error probability on the clock coincidence of the interference and the useful signal (coincidence in time), which is taken into account in expression (4) by means of the parameter \( \rho \).
So, for \( \rho = 1 \), i.e. at \( P_B = 0.5 \), we have a complete uncertainty on the deciding device of the demodulator, and at \( \rho = 0 \), as a result of the summation of the signal energy and interference, the reliability of making a correct decision increases.

It should be noted that the analysis of the results presented in Fig. 6, unambiguously indicates that the inflicted information damage is determined not only by the value of \( \rho \), but also by the current values of the signal-to-noise ratio and the interference-to-noise ratio. The lower the initial SNR value, the higher the effectiveness of the destructive effect, since a lower value of the interference energy must be applied at the same time synchronization with the signal to provide the desired value \( P_B \).

4. Conclusion

Studies have shown that structural interference, even of an unintentional nature, is a real threat to control channels. This is due to the fact that the detection of structural interferences, which have a time-frequency structure close to control signals, is associated with certain difficulties.

The destructive damage caused by structural interference depends significantly on the time coincidence of the clock intervals of the interference emission and signals at the demodulator input. Therefore, it is advisable to use instructions with different clock intervals of signal repetition (use pseudo-random mode) [16], which will significantly increase the probability of clock mismatch between the interference and the signal.

Another constructive measure to minimize the damage done is to install an indicator of the received signal level at the input of the demodulator. Obviously, in the presence of structural interference, both the energy of the total signal at the input of the demodulator and the value of its dispersion will increase. These features can act as signs of a destructive effect even at the stage of signal detection.

Further research is seen in the development of methods for reducing destructive damage based on correcting errors caused by structural interference.

5. References

[1] Tariq M, Trivailo P M, Simic M 2018 EEG-based BCI control schemes for lower-limb assistive-robots Frontiers in Human Neuroscience T 12 С 312
[2] Tatievskyi D 2018 Synthesis of the laws governing the non-holonomic model of a two-link road train with reverse motion (off-axle hitching model) (Eureka: Physics and Engineering) 2 pp 40-51
[3] Kryachko A F, Dvornikov S V, Pshenichnikov A V 2019 The radiotechnical systems simulation in conflict situations of a cognitive nature 2019 Wave Electronics and its Application in Information and Telecommunication Systems (WECONF 2019) С 8840137
[4] Bradley J M, Atkins E M 2015 Optimization and control of cyber-physical vehicle systems Sensors T 15 9 С 23020-23049
[5] Pyatibratov G, Danshina A, Altunyan L 2019 Optimal force compensating control of robotic lifting mechanisms Proceedings - 2019 International Russian Automation Conference RusAutoCon 2019 С 8867811
[6] Dvornikov S V, Dvornikov S S, Erokhin S D, Balenko E G 2019 OFDM system with various channel modulation schemes 2019 Wave Electron-ics and its Application in Information and Telecommunication Systems (WECONF 2019) С 8840613
[7] Ajayi M O, Djouani K, Hamam Y 2020 Interaction control for human-exoskeletons Journal of Control Science and Engineering C 8472510
[8] Kryachko A F, Dvornikov S V, Pshenichnikov A V 2019 Theoretical aspects to signal quadrature constellation diagrams transformation 2019 Systems of Signal Synchronization, Generating and Processing in Telecommunications SYNCHROINFO С 8814154
[9] Anaya F, Thangavel P, Yu H 2018 Hybrid FES–robotic gait rehabilitation technologies: a review on mechanical design, actuation, and control strategies International journal of intelligent robotics and applications T 2 1
[10] Yakushenko S A, Dvornikov S V 2019 Model of access to the resources of the satellite radio navigation system in the conditions of destructive radio-electronic exposure 2019 Wave Electronics and its Application in Information and Telecommunication Systems (WECONF 2019) C 8840652

[11] Godzhaev Z, Lobachevsky Y P, Alekseev I, Prilukov A, Godzhaev T Z 2020 Control systems for unmanned combine harvester E3S Web of Conferences Key Trends in Transportation Innovation KTTI 2019 C 01018

[12] Lobotskiy Y G, Khmara V V, Kabyshev A M, Dedegkaev A G 2015 The principle of the complex systems of container pneumatic transport using multi-purpose switch throwers Modern Applied Science Т 9 5 pp 228-245

[13] Xu W, Verl A W, Ohishi K 2017 Motion control for novel emerging robotic devices and systems IEEE Transactions on Industrial Electronics T 64 2 pp 1623-1625

[14] Garcia C A, Lanas D, Alvarez E M, Altamirano S, Garcia M V 2019 An ap-proach of cyber-physical production systems architecture for robot control Proceedings: IECON 2018 - 44th Annual Conference of the IEEE Industrial Electronics Society 44 pp 2847-2852

[15] Simonov A, Fokin G, Sevidov V, Sivers M, Dvornikov S 2019 Polarization direction finding method of interfering radio emission sources Internet of Things, Smart Spaces, and Next Generation Networks and System pp 208-219

[16] Dvornikov S V, Dvornikov S S, Erokhin S D 2019 Frequency selection for FHSS mode 2019 Systems of Signal Synchronization, Generating and Processing in Telecommunications SYNCHROINFO 2019 C 8814233

[17] Malygin I V, Luchinin A S, Surgutskaya V A, Kozlov Y V 2020 One of the ways to protect a spread spectrum communication system from such structural in-terference 2020 Systems of Signal Synchronization Generating and Processing in Telecommunications SYNCHROINFO 2020 C 9166090

[18] Dvornikov S V, Dvornikov S S, Balenko E G 2020 Proposals for compensation structural interference in radio channels 2020 International Multi-Conference on Industrial Engineering and Modern Technologies FarEastCon 2020 C 9271416