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Influence of Noise on Process of Finding Extremum in Extreme Automatic Control Systems

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The article considers several issues related to the functioning of discrete extreme control systems. Namely, the influence of noise in the measuring path of the extreme control system on the process of finding the extremum of the characteristics of the control object. White noise with a centered Gaussian distribution is used as a noise model. To organize the process of finding the extremum in discrete extreme control systems, it is necessary to measure the extreme characteristic of the control object. After the measurements, the results are compared and a decision is made on the direction of finding the extremum. The presence of noise in the measuring path of the extreme control system distorts the measurement results. Depending on the characteristics of the noise and the extreme characteristic of the control object, the results of comparing the measured values in each specific case may be correct or incorrect. In the case of an incorrect result of comparing the measured values of the extreme characteristic of the control object, an incorrect decision is made about the direction of finding the extremum. This leads to an increase in the time of finding the extremum. The article determines the maximum possible probability of making an incorrect decision about the position of the extremum. Various cases of noise influence on the results of measuring the extreme characteristic of an object, which are the cause of erroneous determination of the position of the extremum, are considered. The dependences of error probability in determining the position of the extremum on the noise variance and the steepness of the extreme characteristic of the control object are obtained. Various options for organizing the search for the extremum are considered, which allow reducing the probability of error. An algorithm for searching for the extremum in extreme control systems is proposed, which minimizes the probability of error in the process of searching for the extremum.

Keywords: white noise; extreme regulation system; signal-to-noise ratio; finding the extremum; error probability

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Introduction

There is a certain class of control objects that have an extreme characteristic $F_{reg} = f(X)$ (ECCO). As an example, we can consider a photovoltaic battery, the dependence of the output power of which on the voltage (current) is extreme [1–3], an ultrasonic piezoelectric transducer, the mechanical power of which has an extreme dependence on the excitation frequency [4–6] and others [7]. The task of the extreme control system is to find the extremum on the ECCO and ensure the functioning of the object at the point of the extremum regardless of external disturbances. Extreme control systems are often used in radio electronics. For example, [8] describes a system for tuning the resonator into resonance according to the criterion of minimum reflected power. The article [9] describes the use of an extreme control system for the organization of a wireless power supply system for biomedical sensors. Methods for finding extremum can be divided into two types: analog (continuous) and discrete (digital) [10]. These methods and devices for their implementation are described in [11–15].

Discrete methods are based on measurements of the values of the ECCO $F_{reg}(i) = f(X(i))$ for different discrete values of the search action step size $X(i)$. Subsequently, the values of the ECCO $F_{reg}(X(i))$ and $F_{reg}(X(i+1))$ are compared. Based on the results of this comparison, a conclusion is made about the further direction of the search for the extremum. In real automatic control systems, noise is always present in the measurement path. The presence of noise causes errors in the measurements $F_{reg}(X(i))$ and $F_{reg}(X(i+1))$. If the measured value

$$F_{measure1} = F_{reg}(X(i)) + \varepsilon_1 \tag{1}$$

is greater than the measured value

$$F_{measure2} = F_{reg}(X(i+1)) + \varepsilon_2, \tag{2}$$

where ε_1 and ε_2 are random variables, the appear due to noise, and the true value $F_{reg}(X(i)) < F_{reg}(X(i+1))$, an incorrect conclusion will be made about the position of the extremum.

1 Determining the probability of an incorrect decision about the position of the extremum in the presence of noise

Let us assume that the measurement channel contains noise with a Gaussian distribution of absolute values of the noise signal ε, with zero mathematical expectation $\mu = 0$:

$$f_\varepsilon = \frac{1}{\sigma\sqrt{2\pi}} * exp\left(-\frac{\varepsilon^2}{2\sigma^2}\right), \tag{3}$$

σ^2 – variance.

Let us also assume that the noise signal is ergodic and its properties are close to those of white noise, i.e. the noise autocorrelation function R_τ approaches the delta function. Or, in the case of "colored" noise, the time interval of measurements exceeds the correlation interval. This means that the random variables $\varepsilon_1, \varepsilon_2$ have the same distribution of absolute values and are statistically independent. We will also assume that the time interval between measurements is greater than the transient time in the control system.

2 Determining the maximum possible probability of an incorrect decision about the position of the extremum

Figure 1 shows all possible variants of the results of the ECCO measurements, which make up a complete group of events. This means that the probability P of an event, which consists in the realization of one of the measurement variants shown in Fig. 1, $P = 1$.

If the measurement result corresponds to that shown in Fig. 1, b, that is, when $\varepsilon_1 > 0$, $\varepsilon_2 > 0$, it is possible to make both the correct and incorrect decision. The probability of this is equal to the product of the probability that the random variable $\varepsilon_1 > 0$ and the random variable $\varepsilon_2 > 0$. This probability: $P_{\text{b}} = 0,25$.

In the case of the variant Fig. 1, c, when $\varepsilon_1 < 0$, $\varepsilon_2 < 0$, it is also possible to make both the correct and incorrect decision, the probability of which is also equal to $P_{\text{c}} = 0,25$. The situation is similar to the variant Fig. 1, d, when $\varepsilon_1 < 0$, $\varepsilon_2 > 0$, $P_{\text{d}} = 0,25$. Instead, the measurements are presented in Fig. 1, a, when $\varepsilon_1 > 0$, $\varepsilon_2 < 0$, unlike the others, is only favorable for making the right decision. The probability of this is also equal to $P_{\text{a}} = 0,25$.

Therefore, we can conclude that the probability of making a wrong decision about the position of the extremum cannot be greater than:

$$P_{mistake(max)} \leq 0,75. \tag{4}$$

3 Calculating the probability of wrong decision about the position of the extremum

To determine the method for calculating the probability of an incorrect decision about the position of the extremum, let us consider one of the cases of measurements of the ECCO $F_{measure}(i)$, $F_{measure}(i+1)$, favorable for making both the correct and incorrect decisions, namely the case shown in Fig. 1, c.

The measurement result in Fig. 1, c, will be incorrect when:

$$\begin{gathered} |\varepsilon_1| > |\Delta F_{ref}| + |\varepsilon_2|, \\ \varepsilon_1, \varepsilon_2 < 0. \end{gathered} \tag{5}$$

The probabilistic characteristics of the random variables $\varepsilon_1, \varepsilon_2$ are completely described by the probability density function (1). Figure 3 shows the corresponding distribution functions taking into account their position relative to ECCO $F_{reg} = f(X)$. The probability that the random variable ε_2 appears in the interval $\Delta\varepsilon_2 = -\varepsilon_2(i) + \varepsilon_2(i+1)$ is approximately equal to $P(\varepsilon_2(i)) \approx f(\varepsilon_2(i))\Delta\varepsilon_2$, where $f(\varepsilon_2(i))$ is the value of the density function of the random variable ε_2 at any point in the interval $\Delta\varepsilon_2$. In order for a wrong decision about the position of the extremum, it is necessary that the random variable ε_1 be in the interval $\varepsilon_1 \in (-\infty;$ $-(\Delta F_{reg} + i\Delta\varepsilon_2)$ (Fig. 3). The probability of this is equal to:

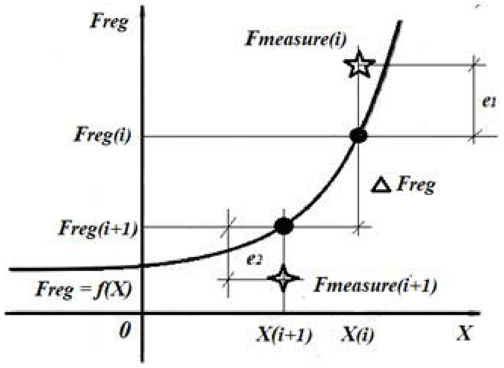
$$P(\varepsilon_1(i)) = \int_{\infty}^{-\Delta F_{reg}+i\cdot\varepsilon_2} f(\varepsilon_1)\, d\varepsilon_1, \tag{6}$$

where $f(\varepsilon_1)$ is the density distribution of the random variable ε_1.

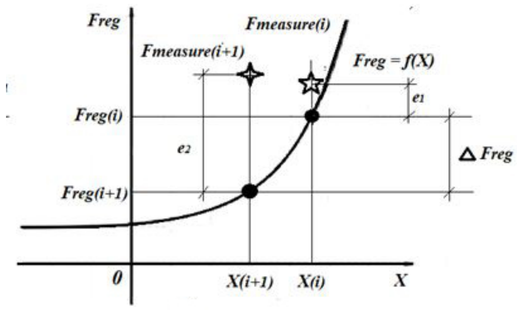
Since the random variables $\varepsilon_1, \varepsilon_2$ are statistically independent, the probability of an erroneous decision in this case is equal to the product of these probabilities:

$$P_{\sum}(i) = f(\varepsilon_2(i)) \cdot \varepsilon_2 \int_{\infty}^{-\Delta F_{reg}+i\cdot\varepsilon_2} f(\varepsilon_1)\, d\varepsilon_1, \tag{7}$$

$$\begin{aligned} P_{\sum 1} \approx f(\varepsilon_{21}(i)) \cdot \Delta\varepsilon_2 \int_{\infty}^{-P_{\sum 1}F_{reg}+\varepsilon_2} f(\varepsilon_1)\, d\varepsilon_1 + \\ + f(\varepsilon_{22}(i)) \cdot \Delta\varepsilon_2 \int_{\infty}^{-\Delta F_{reg}+2\cdot\varepsilon_2} f(\varepsilon_1)\, d\varepsilon_1 + \\ + f(\varepsilon_{2n}(i)) \cdot \Delta\varepsilon_2 \int_{\infty}^{-\Delta F_{reg}+n\cdot\varepsilon_2} f(\varepsilon_1)\, d\varepsilon_1, \end{aligned} \tag{8}$$



(a)



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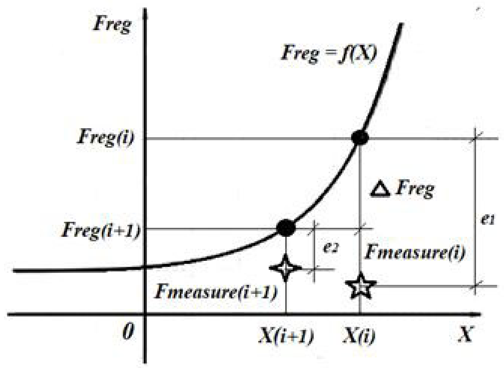

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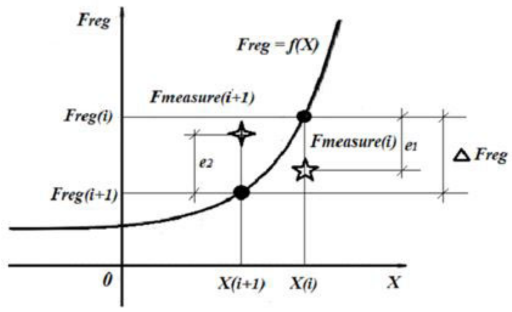
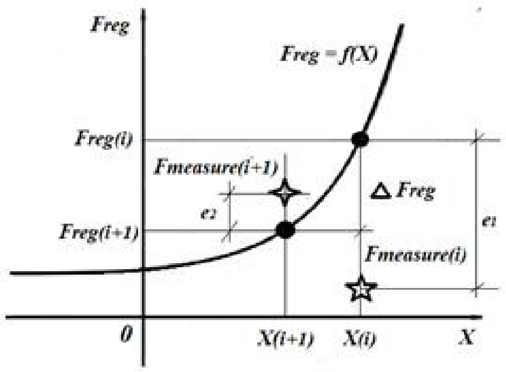


(d)

Fig. 1. Possible results of ECCO measurements



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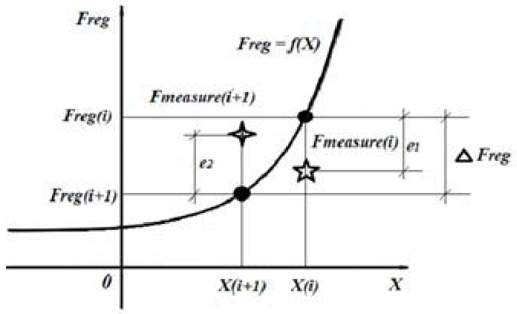

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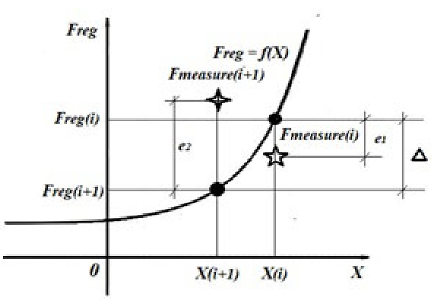
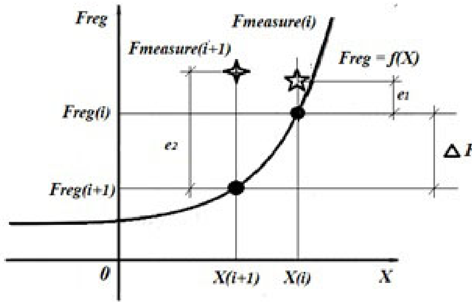


(c)



(d)

Fig. 2. Results of measurements of ECCO values, favorable for wrong decision about the position of the extremum

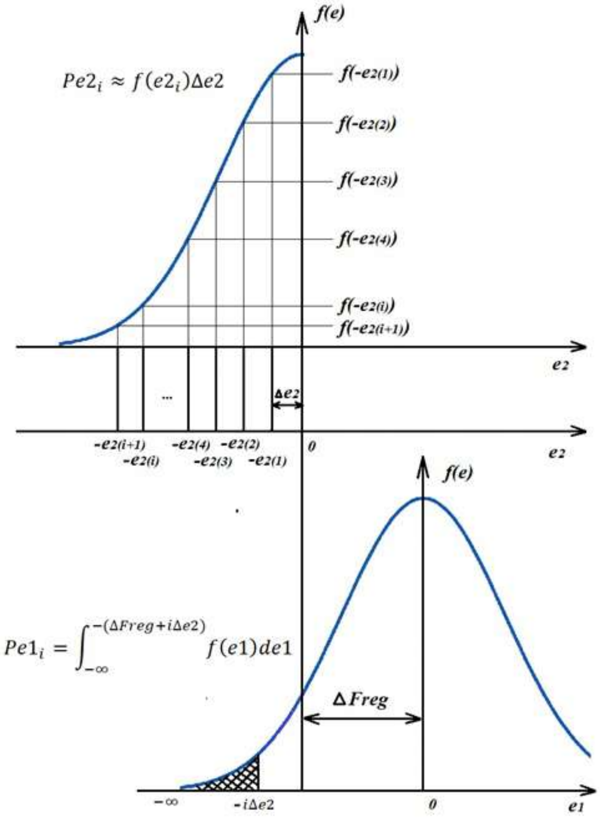


Fig. 3. Probability characteristics of the events shown in Fig. 1, c

$$P_{\sum 1,\Delta\varepsilon_2\to 0} = \lim_{i\to\infty}\sum_{i=1}^{\infty} f(\varepsilon_{2n})\cdot\Delta\varepsilon_2 \times \\ \times \int_{\infty}^{-\Delta F_{reg}+i\cdot\Delta\varepsilon_2} f(\varepsilon_1)\,d\varepsilon_1 = \\ = \int_{-\infty}^{0} f(\varepsilon_2)\int_{-\infty}^{-\Delta F_{reg}+\varepsilon_2} f(\varepsilon_1)\,d\varepsilon_1\,d\varepsilon_2. \quad (9)$$

Since $f(\varepsilon_1) = f(\varepsilon_2) = f(\varepsilon)$, relation (9) can be written as:

$$P_{\sum 1} = \int_{-\infty}^{0} f(\varepsilon)\int_{-\infty}^{-\Delta F_{reg}+\varepsilon} f(\varepsilon_1)\,d\varepsilon\,d\varepsilon. \quad (10)$$

To find the total probability of a wrong decision in the situation shown in Fig. 1, c, it is necessary to add up the probabilities (7) for all i and take the limit transition as $\Delta\varepsilon_2 \to 0$.

It is known that $\int f(\varepsilon)\,d\varepsilon$, where $f(\varepsilon) = \frac{1}{\sigma\sqrt{2\pi}}\exp\left(-\frac{\varepsilon^2}{2\sigma^2}\right)$ cannot be expressed in terms of elementary functions. Therefore, $P_{\sum}$ was calculated by a numerical approximation method. The result of calculating the probability of error for the variance $\sigma^2 = 1$, $\Delta F_{reg} = 1$ is shown in Fig. 4. From Fig. 4, it is seen that when $\varepsilon_2 \to \infty$, $P \to 0.11123$.

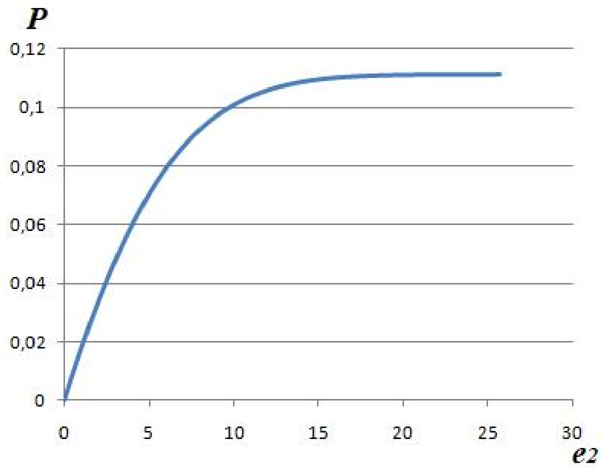


Fig. 4. Dependence of the probability of an incorrect decision about the position of the extremum on the absolute value of the random signal ε_2, for the situation in Fig. 1, c, at $\sigma^2 = 1$, $\Delta F_{reg} = 1$

For the convenience of numerically determining the probabilities of the remaining events favorable for wrong decision (i.e., the options in Fig. 1, b, d), we present them in the form shown in Fig. 2.

For the situation shown in Fig. 2, a, the probability of wrong decision is equal to:

$$P_{\sum 2} = \int_{0}^{\infty} f(\varepsilon_2)d\varepsilon_2\int_{-\infty}^{-\Delta F_{reg}} f(\varepsilon_1)\,d\varepsilon_1 = \\ = \frac{1}{2}\int_{-\infty}^{-\Delta F_{reg}} f(\varepsilon)\,d\varepsilon\,. \quad (11)$$

For Fig. 2, b:

$$P_{\sum 3} = \int_{0}^{\Delta F_{reg}} f(\varepsilon_2)\int_{-\Delta F_{reg}}^{-(\Delta F_{reg}-\varepsilon_2)} f(\varepsilon_1)\,d\varepsilon_1\,d\varepsilon_2 = \\ = \int_{0}^{\Delta F_{reg}} f(\varepsilon)\int_{-\Delta F_{reg}}^{-(\Delta F_{reg}-\varepsilon)} f(\varepsilon)\,d\varepsilon\,d\varepsilon. \quad (12)$$

For Fig. 2, c:

$$P_{\sum 4} = \int_{-\infty}^{0} f(\varepsilon_1)d\varepsilon_1\int_{\Delta F_{reg}}^{\infty} f(\varepsilon_2)\,d\varepsilon_2 = \\ = \frac{1}{2}\int_{\Delta F_{reg}}^{\infty} f(\varepsilon)\,d\varepsilon. \quad (13)$$

For Fig. 2, d:

$$P_{\sum 5} = \int_{0}^{\infty} f(\varepsilon_1)\int_{\Delta F_{reg}+\varepsilon_1}^{\infty} f(\varepsilon_2)\,d\varepsilon_2\,d\varepsilon_1 = \\ = \int_{0}^{\infty} f(\varepsilon)\int_{\Delta F_{reg}+\varepsilon}^{\infty} f(\varepsilon)\,d\varepsilon\,d\varepsilon. \quad (14)$$

Considering the parity of the function $f(\varepsilon)$, we can state that: $P_{\sum 1} = P_{\sum 5}$, $P_{\sum 2} = P_{\sum 4}$.

The total probability of wrong decision will be equal to the sum of all probabilities:

$$P_{\sum} = 2 \cdot \int_0^{\infty} f(\varepsilon) \int_{\Delta F_{reg}+\varepsilon}^{\infty} f(\varepsilon)\, d\varepsilon\, d\varepsilon + \\ + \int_{\Delta F_{reg}}^{\infty} f(\varepsilon) + \int_0^{\Delta F_{reg}} f(\varepsilon) \cdot \int_{-\Delta F_{reg}}^{-\Delta F_{reg}-\varepsilon} f(\varepsilon)\, d\varepsilon\, d\varepsilon. \tag{15}$$

Graphs of the dependence of the probability of an incorrect decision on the noise variance σ^2 for different values of the ECCO increment ΔF_{reg} are shown in Fig. 5. Graphs of the dependence of the probability of an incorrect decision on the value of the ECCO increment ΔF_{reg} for different values of the noise variance σ^2 are shown in Fig. 6.

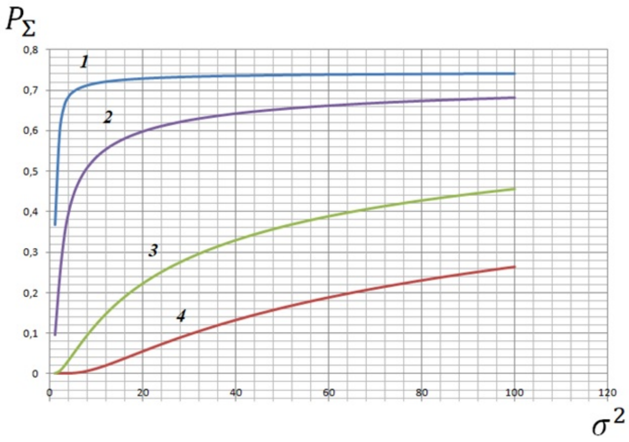


Fig. 5. Dependence of the incorrect decision about the position of the extremum on the noise variance σ^2 for the following values of the increment ECCO ΔF_{reg}: Curve 1 – $\Delta F_{reg} = 0.1$, Curve 2 – $\Delta F_{reg} = 1$, Curve 3 – $\Delta F_{reg} = 5$, Curve 4 – $\Delta F_{reg} = 10$

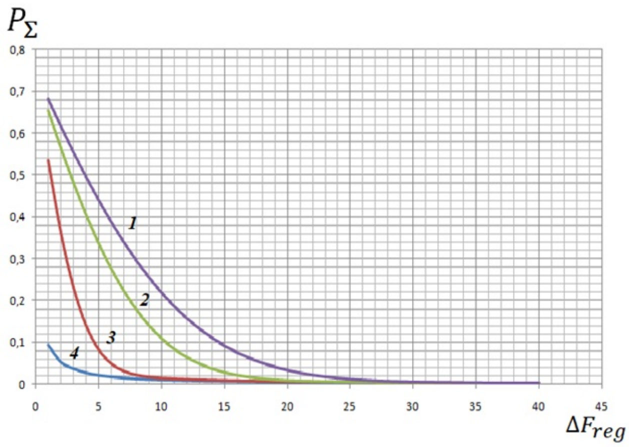


Fig. 6. Dependence of the incorrect decision about the position of the extremum on the value of the increment the ECCO ΔF_{reg} at the following values of the noise dispersion: Curve 1 – $\sigma^2 = 100$, Curve 2 – $\sigma^2 = 50$, Curve 3 – $\sigma^2 = 10$, Curve 4 – $\sigma^2 = 1$

4 Discussion of results

From Fig. 5 and 6 it can be seen that the probability of a wrong decision about the position of the extremum asymptotically approaches the value $P_{mistake\ max} \leq 0.75$, i. e. condition (1) is fulfilled. Also, it can be concluded that an increase in the noise variance σ^2 causes an increase in the probability of error when searching for the extremum, whereas an increase in the ECCO increment ΔF_{reg} reduces this probability.

The magnitude of the ECCO increment ΔF_{reg} depends on the magnitude of the step of searching for the extremum $\Delta X = X(i+1) - X(i)$ (Fig. 2, 3), as well as on the “steepness” of the ECCO, i.e., the derivative $\frac{dF_{reg}}{dX}$, namely:

$$\Delta F_{reg} \approx \frac{dF_{reg}}{dX} \Delta X.$$

When approaching the extremum $\frac{dF_{reg}}{dX} \to 0$, therefore, the probability of error is increasing. In addition, with a large step ΔX, the accuracy of finding the extremum is decreased, so the step ΔX cannot be made too large, at least in the vicinity of the extremum point.

To reduce the probability of error, it is advisable to reduce the noise variance, which is achieved by multiple measurements of the ECCO with subsequent averaging of the results. This decreases the variance of the noise signal by $\sqrt{n}$ times, where n is the number of measurements [16].

However, such a procedure may increase the time to reach the extremum: the measurement frequency depends on the statistical characteristics of the noise signal, namely on the form of its autocorrelation function R_τ. On the other hand, a significant probability of error in determining the position of the extremum also increases the time to reach the extremum, and with an error probability $P_{err} > 0.5$, movement in the direction of the extremum stops altogether.

The number of measurements n will be determined by how many times the variance needs to be reduced to achieve the desired level of error probability. To achieve the effect of variance reduction, the measurement time interval must be greater than the correlation interval.

For the practical implementation of an extreme control system that operates with a high level of noise in the measuring path, the following operating algorithm can be proposed:

1. Before starting the movement towards the extremum, the necessary measurements (system training) are performed: measurement of the noise variance σ^2 — that is, measurement of the autocorrelation function R_τ at zero delay τ. The correlation interval is determined, and the value ΔF_{reg} is estimated as the mathematical expectation:

$$\Delta F_{reg} \approx E(F_{measure2} - F_{measure1}).$$

2. Using relation (15), the probability of error in determining the direction of movement towards the extremum is calculated.
3. If this probability turns out to be greater than acceptable, two options are considered: averaging the measurement results or increasing the step of searching for the extremum.
4. If the value of the correlation interval turns out to be such that allows the required number of measurements to be made without a significant delay in moving to the extremum, a decision is made to reduce the variance by averaging. When approaching the extremum, the probability of error increases due to the decrease in ΔF_{reg}. An indicator of the increase probability of error can be the increasing frequency of change of sign of the measured value of the ECCO:
$$\Delta F_{reg\ measure} = F_{measure2} - F_{measure1}.$$
5. In this case, it is necessary made to increase the number of measurements for averaging. The decision to reach the extremum is made when, over a certain period of time, the number of measurements $\Delta F_{reg\ measure}$ with a $+$sign is approximately equal to the number of measurements $\Delta F_{reg\ measure}$ with a negative sign.
6. If the correlation interval turns out to be such that averaging will lead to an unacceptably long time to reach the extremum, a decision is made to increase the step of searching for the extremum. In this case, the probability of error also increases as the extremum is approached. To reduce the probability of error, the actions described in section 5 should be performed. Due to the fact that the averaging process in this case begins in the vicinity of the extremum point, the time to reach the extremum will not be too long.

5 Conclusions

To reduce the probability of error in an extreme automatic control system, it is necessary to provide for the possibility of measuring the characteristics of the noise and ECCO. Knowing the parameters of the noise signal and the ECCO, it is possible, using (15), to construct a control system in such a way as to minimize the probability of error in determining the direction of movement to the extremum.

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Вплив шуму на процес знаходження екстремуму в екстремальних системах автоматичного керування

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В статті розглядаються деякі питання функціонування дискретних екстремальних систем управління. А саме: вплив шумів у вимірювальному тракті екстремальної системи управління на процес пошуку екстремуму. Як модель шуму використовується білий шум із центрованим гаусовим розподілом. Для організації процесу пошуку екстремуму в дискретних екстремальних системах управління необхідно проводити вимірювання екстремальної характеристики об'єкта управління. Після проведення вимірювань результати вимірювань порівнюються і приймається рішення про напрямок пошуку екстремуму. Наявність шумів у вимірювальному тракті екстремальної системи управління спотворює результати вимірювань. В залежності від характеристик шуму і екстремальної характеристики об'єкта управління результати порівняння виміряних значень в кожному конкретному випадку можуть бути правильними, або неправильними. У випадку неправильного результату порівняння виміряних значень екстремальної характеристики об'єкта управління приймається невірне рішення про напрямок пошуку екстремуму. Це призводить до збільшення часу пошуку екстремуму. В статті визначена максимально можлива ймовірність прийняття неправильного рішення про положення екстремуму.

Розглянуто різні випадки впливу шуму на результати вимірювання екстремальної характеристики об'єкта, які є причиною помилкового визначення положення екстремуму. Отримано залежності ймовірності помилки у визначенні положення екстремуму від дисперсії шуму та крутизни екстремальної характеристики об'єкта керування. Розглянуті різні варіанти організації пошуку екстремуму, які дозволяють зменшити ймовірність помилки. Запропоновано алгоритм пошуку екстремуму в екстремальних системах управління, який мінімізує ймовірність помилки в процесі пошуку екстремуму.

Ключові слова: білий шум; система екстремального регулювання; відношення сигнал/шум; знаходження екстремуму; ймовірність помилки