Signal properties correlation studying discrete control systems

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Abstract. In recent years, due to the intensive development of computer technologies in industrial automation, discrete control systems have been increasingly used. To determine the stability of the system, calculations of the correlation functions of signals of various types can be used. In practice, signals with different types of modulation are used: amplitude, phase and frequency, as well as their various combinations.

1. Introduction
In recent years, due to the intensive development of computer technology in industrial automation, discrete control systems have become increasingly used. The main element of a discrete system is a control computer (CC), which can be used either in the supervisory mode or in the direct digital control mode. In the supervisory mode, CC generates tasks for local control loops implemented with the help of traditional automation equipment. When direct digital control mode control loops formed control computer itself.

Systems with CC have significant advantages compared with the same continuous systems because it allows reconfiguration and reconfiguration of automatic control systems (ACS) without changes in hardware, only by reprogramming of CC, multichannel management, and provides easily accessible information flows that allow addition to the direct management to exercise the functions: control, optimization, coordination and organization of all processes in the framework of modern process control systems (PCS).

And quite a large number of signals are known, with good correlation properties. The defining property of such signals is that their autocorrelation function (ACF) has one main peak and several small lateral peaks\textsuperscript{1-2}. The autocorrelating process is a classical mathematical method widely used in engineering and applied sciences\textsuperscript{3}.

The works describe the properties of the autocorrelation and cross-correlation functions of signals\textsuperscript{4-5}.

Minimization of side peaks of ACF is carried out for the best allocation from noise of signals at the exit of matched filters. Various types of signals in which the side peaks of the multiplicative autocorrelation function are quite small are well known.

From the analogue in the video frequency range, they can physically be realized using potential coding, both binary and multi-valued, or using a modulated carrier frequency. Signals with various types
of modulation are actually used: amplitude, phase and frequency, as well as their various combinations. In some cases, when the interference spectrum is concentrated to the bottom it is advisable to use signal generation methods based on the generation of a carrier frequency in the frequency domain.

In addition, one of the main requirements to any effective control system is the stability to interference, system modeling errors, or parameter changes [6]. Interference or errors are often unavoidable in many control systems. Their presence can reduce the performance of control systems or even lead to instability of system if they are not considered. Several effective methods are designed for reliable management of control systems exposed by interference or errors including H-filtering approach [7-10].

2. The principle of the discrete control system

2.1. Estimations of correlation functions

The principle of operation of the discrete control system [11-12] is that the change of the controlled variable with the required accuracy occurs in accordance with a previously unknown function of time. Thus, the tracking system, like the software system, reproduces the driving force. However, this effect in the tracking system does not change according to a given program, but arbitrarily. Description unknown function and time using a random variable is formed by dialing a series of random numbers. The series must contain at least 120 numbers and represent it can be found both in tabular and in the form of a curve of a random function. Each number must be numbered from 1 to 100.

**Table 1.** The implementation of the signal at the input and output of the object of study.

| t  | x(t) | y(t) | t  | x(t) | y(t) | t  | x(t) | y(t) |
|----|------|------|----|------|------|----|------|------|
| 1  | 57   | 98   | 17 | 33   | 51   | 18 | 39   | 76   | 45   | 63   |
| 2  | 56   | 85   | 27 | 28   | 52   | 16 | 30   | 77   | 73   | 61   |
| 3  | 79   | 78   | 28 | 12   | 32   | 53 | 47   | 25   | 78   | 86   | 80   |
| 4  | 61   | 92   | 29 | 47   | 23   | 54 | 51   | 45   | 79   | 76   | 98   |
| 5  | 68   | 85   | 66 | 45   | 55   | 53 | 57   | 53   | 80   | 53   | 99   |
| 6  | 84   | 87   | 65 | 68   | 56   | 49 | 64   | 81   | 50   | 82   |
| 7  | 40   | 99   | 32 | 45   | 77   | 57 | 32   | 64   | 82   | 34   | 72   |
| 8  | 61   | 72   | 33 | 67   | 58   | 49 | 51   | 83   | 60   | 57   |
| 9  | 45   | 76   | 34 | 63   | 53   | 59 | 21   | 58   | 84   | 45   | 69   |
| 10 | 36   | 66   | 35 | 50   | 69   | 60 | 19   | 41   | 85   | 60   | 63   |
| 11 | 59   | 55   | 36 | 33   | 67   | 61 | 9    | 31   | 86   | 72   | 72   |
| 12 | 61   | 67   | 37 | 44   | 53   | 62 | 40   | 20   | 87   | 53   | 84   |
| 13 | 41   | 74   | 38 | 67   | 55   | 63 | 26   | 38   | 88   | 37   | 75   |
| 14 | 42   | 63   | 39 | 85   | 73   | 64 | 62   | 36   | 89   | 56   | 60   |
| 15 | 28   | 58   | 40 | 75   | 94   | 65 | 79   | 61   | 90   | 64   | 67   |
| 16 | 45   | 46   | 41 | 49   | 96   | 66 | 43   | 85   | 91   | 33   | 76   |
| 17 | 71   | 68   | 42 | 72   | 78   | 67 | 23   | 69   | 92   | 72   | 57   |
| 18 | 42   | 81   | 43 | 40   | 87   | 68 | 31   | 47   | 93   | 57   | 78   |
| 19 | 66   | 44   | 61 | 67   | 69   | 51 | 43   | 94   | 62   | 76   |
| 20 | 44   | 51   | 45 | 59   | 74   | 70 | 21   | 56   | 95   | 71   | 78   |
| 21 | 68   | 54   | 46 | 30   | 76   | 71 | 22   | 40   | 96   | 76   | 86   |
| 22 | 57   | 73   | 47 | 28   | 55   | 72 | 51   | 33   | 97   | 53   | 94   |
| 23 | 27   | 74   | 48 | 31   | 44   | 73 | 71   | 52   | 98   | 62   | 80   |
| 24 | 12   | 52   | 49 | 24   | 42   | 74 | 73   | 75   | 99   | 33   | 80   |
| 25 | 26   | 32   | 50 | 32   | 36   | 75 | 34   | 86   | 100  | 67   | 59   |

The data from table 1 is used to calculate the autocorrelation and cross-correlation function.
The calculation of correlation function estimates is made according to the formulas:

\[ R_{xx}(m) = \frac{1}{n-m+1} \sum_{k=1}^{n-m} (x_k - \bar{x})(x_{k+m} - \bar{x}), \]

\[ R_{xy}(m) = \frac{1}{n-m+1} \sum_{k=1}^{n-m} x_k - \bar{x})y_{k+m} - \bar{y}), \]

where \( n \) is the number of discrete values of random functions; \( m \) is a discrete argument of the correlation function; \( \bar{x}, \bar{y} \) - math scores waiting for signals at the input and output of the object.

Calculations are carried out up to the value \( m = (0.05 \ldots 0.1)n \). Calculation of the cross-correlation function \([13],[14]\) of \( R_{xy} \) made as for positive (the right branch is \( R_{xyR} \)), and for negative (left branch - \( R_{xyL} \)) values of \( m \), the calculation data are given in table 2, in graphical form presented in figure 1.

**Table 2. Autocorrelation and mutual correlation functions.**

| \( m \) | \( R_{xx} \) | \( R_{xyL} \) | \( R_{xyR} \) |
|--------|--------------|--------------|--------------|
| 0      | 352.02       | 147.3        | 147.3        |
| 1      | 57.36        | 74.84        | 121.36       |
| 2      | 61           | 61.88        | 260.52       |
| 3      | 36.86        | 61.67        | 159.83       |
| 4      | 52.4         | 40.63        | 98.41        |
| 5      | 47.57        | 0.97         | 76.99        |
| 6      | -11.32       | -3.11        | 64.32        |
| 7      | -36.16       | 56.91        | 20.51        |
| 8      | 35.35        | 56.58        | -18.69       |
| 9      | 65.72        | 22.32        | 13.26        |
| 10     | 30.81        | 2.54         | 54.72        |
| 11     | 4.03         | -12.63       | 47.54        |
| 12     | -25.12       | -4.16        | 28.02        |
| 13     | 2.62         | -18.75       | -4.29        |
| 14     | 1.94         | -43.85       | 2.02         |
| 15     | -22.46       | -46.34       | -0.19        |

**Figure 1.** Autocorrelation \( R_{xx}(m) \) and mutual correlation \( R_{xy}(m) \) functions.
Thus, the maximum value of the b of the ACF leaf lobe is determined for m=9, and the SRS is determined for m =10.

Determination of the parameters of the transfer function of the object under investigation using parametric identification methods with a custom model

The identification signal used in modelling an object to search for the parameters of the object under study is formed based on the autocorrelation function that we performed earlier.

On the curve of the autocorrelation function, the section with the smallest oscillations $R_{xx}(\tau)$ is selected. The initial value of this section we take as the initial value of the test signal $x_i$. As can be seen from Figure 2, this section begins at $x_i$=-3

The value of the priority coefficient is chosen in the range from 0 to 1, depending on the degree of confidence in the various intervals of the correlation function. The priority coefficients in the interval where the inter-correlation function has stably positive values are chosen equal to one or close to one. Outside the specified interval, the priority coefficients are set to zero or close to zero.

![Figure 2. Auto and cross-correlation functions of the object.](image)

Putting the priority coefficients calculate the values. Having determined the transfer coefficients of the identification object, we calculate the value of the objective identification function.

**Table 3.** Results of the signal identification experiment.

| Serial number | Priority factor | Test signal | Experimental Mutual Correlation Function |
|---------------|----------------|-------------|----------------------------------------|
| 1             | 0.5            | 36.86       | 61.67                                  |
| 2             | 0.6            | 61          | 61.88                                  |
| 3             | 0.7            | 157.36      | 74.84                                  |
| 4             | 1              | 352.02      | 147.3                                  |
| 5             | 0.7            | 157.36      | 321.36                                 |
| 6             | 0.6            | 61          | 260.52                                 |
| 7             | 0.5            | 36.86       | 159.83                                 |
| 8             | 0.4            | 52.4        | 98.41                                  |
| 9             | 0.2            | 47.57       | 76.99                                  |
| 10            | 0              | -11.32      | 64.32                                  |
| 11            | 0              | -36.16      | 20.51                                  |
| 12            | 0              | 35.35       | -18.69                                 |
| 13            | 0.1            | 65.75       | 13.26                                  |
| 14            | 0.1            | 30.81       | 54.72                                  |
| 15            | 0.1            | 4.03        | 47.54                                  |
| 16            | 0              | -25.12      | 28.02                                  |
| 17            | 0.1            | 2.62        | -4.29                                  |
| 18            | 0.1            | 1.94        | 2.02                                   |
| 19            | 0              | -22.46      | -0.19                                  |
| 20            | 0              | -49.13      | -16.41                                 |
Table 4. The ordinate curve of the output signal from the object model when exposed to the test signal.

| n   | R_{xy} | n   | R_{xy} | n   | R_{xy} | n   | R_{xy} |
|-----|--------|-----|--------|-----|--------|-----|--------|
| 1   | 0      | 6   | 255,92 | 11  | 18,53  | 16  | 22,3   |
| 2   | 28,61  | 7   | 150,46 | 12  | -20,6  | 17  | -10,51 |
| 3   | 58,88  | 8   | 89,23  | 13  | 19,14  | 18  | -2,2   |
| 4   | 145,87 | 9   | 76,63  | 14  | 58,75  | 19  | 0,62   |
| 5   | 332,02 | 10  | 67,8   | 15  | 47,59  | 20  | -17,19 |

Table 5. Spectral density of the disturbance signal.

| ω   | S_ω  | ω   | S_ω  | ω   | S_ω  |
|-----|------|-----|------|-----|------|
| 0   | 85,24| 0,75| 320,99| 1,5 | 98,58|
| 0,05| 88,7 | 0,8 | 309,11| 1,55| 97,41|
| 0,10| 98,86| 0,85| 292,73| 1,6 | 96,58|
| 0,15| 115,15| 0,9 | 272,9 | 1,65| 95,54|

Figure 3. Correlation functions.

The value of the objective function is 2304.25 with the values of the object transfer coefficient Kp = 1.3 and the time constant Tp = 1.1.

2.2. Determination of the spectral density of the disturbance signal

The task of choosing a discrete control system in the framework of this article is considered as the task of determining the optimal parameters of the regulating device of a given structure. The structure of the isodromic controller is given by the transfer function:

\[ w_p(p) = k_p + \frac{1}{T_i p} \]

where \( W_p(p) \) is the transfer function of the regulator; \( k_p \) - regulator transfer coefficient; \( T_i \) time isodrome regulator.

The control object is a specified part of the system and is determined by the transfer function:

\[ W_o(p) = \frac{k_o}{T_1 T_2 p^2 + (T_1 + T_2)p + 1} \]
0.2  136.58  0.95  250.76  1.7  93.92
0.25  161.93  1  227.53  1.75  91.47
0.3  189.73  1.05  204.36  1.8  88.16
0.35  218.38  1.1  182.29  1.85  84.12
0.4  246.28  1.15  162.18  1.9  79.68
0.45  271.89  1.2  144.66  1.95  75.27
0.5  293.85  1.25  130.1  2  71.43
0.55  311.03  1.3  118.65  2.05  68.74
0.6  322.62  1.35  110.17  2.1  67.76
0.65  328.15  1.4  104.34  2.15  68.95
0.7  327.53  1.45  100.68  2.2  72.67

The results of the calculation are shown in table 3, graphically presented in figure 4.

2.3. Search for optimal regulator parameters

The search for optimal control parameters $k_p$ and $T_i$ is performed purposefully changing controller parameters and by minimizing the objective function values. Each combination of $k_p$ and $T_i$ specified in the search correspond to certain properties of the regulating device and the autoregulatory system as a whole. These properties, in particular, the ability of the ACS to suppress disturbances acting on an object, are quantified by the value of the mean square regulation error.

When calculating the objective function, the amplitude-frequency characteristic is used. Search for optimal parameters $k_p$ and $T_i$ in this article it is most convenient to perform the Gauss – Seidel method [15]. The optimization procedure continues until the condition is met:

$$J = \Delta y^{-2} = \min$$

Influence of controller parameters on the properties of the CAP can be traced, or by type of transfer function:

$$w_{CAP}(P) = \frac{K_0 T_i P}{T_1 T_2 T_i P^3 + (T_1 + T_2) T_i P^2 + T_i (1 + k_0 k_p) P + k_0}$$

or on the amplitude-frequency characteristic of the system:

$$W(j\omega) = P(\omega) + j Q(\omega) = A(\omega) e^{j\phi(\omega)}$$

where $P(\omega)$ is the real frequency response:
\[ P(\omega) = \frac{\omega k_0 T_i [\omega T_i (1 + k_0 k_p) - \omega^3 T_1 T_2 T_i]}{[k_0 - \omega^2 (T_1 + T_2) T_i]^2 + [\omega T_i (1 + k_0 k_p) - \omega^3 T_1 T_2 T_i]^2} \]

Q(\omega) - imaginary frequency response:

\[ Q(\omega) = \frac{\omega k_0 T_i [k_0 - \omega^2 (T_1 + T_2) T_i]}{[k_0 - \omega^2 (T_1 + T_2) T_i]^2 + [\omega T_i (1 + k_0 k_p) - \omega^3 T_1 T_2 T_i]^2} \]

A(\omega) - amplitude-frequency characteristic:

\[ A(\omega) = \frac{\omega k_0 T_i}{\sqrt{[k_0 - \omega^2 (T_1 T_2 T_i)]^2 + [\omega T_i (1 + k_0 + k_p) - \omega^3 T_1 T_2 T_i]^2}} \]

When calculating the objective function, the amplitude-frequency characteristic is used. This characteristic, uniquely identifying all the dynamic properties of the ACS, has a simpler computational algorithm.

The results of the calculation are presented in tables 6-10 and are graphically presented in figures 5, 6 and 7.

Calculation of the transient characteristics of the ACS.

The calculation of the transient response of the automatic control system is carried out with a single step signal.

The transient response of the optimus system is determined by the expression:

\[ h(t) = 2 \int_0^{\omega_b} P(\omega) \frac{\sin(\omega t)}{\omega} d\omega \]

Where h(t) is the transient response; P(\omega) is the real frequency response of the system.

**Table 6.** Spectral density of the system at the input of the object.

| n  | Sₙ | n  | Sₙ | n  | Sₙ |
|----|----|----|----|----|----|
| 1  | 91,72 | 15 | 231,55 | 29 | 51,53 |
| 2  | 94,07 | 16 | 221,29 | 30 | 60,00 |
| 3  | 100,95 | 17 | 206,95 | 31 | 71,59 |
| 4  | 111,93 | 18 | 189,27 | 32 | 85,53 |
| 5  | 126,31 | 19 | 169,19 | 33 | 100,94 |
| 6  | 143,18 | 20 | 147,77 | 34 | 116,93 |
| 7  | 161,45 | 21 | 126,14 | 35 | 132,59 |
| 8  | 179,98 | 22 | 105,40 | 36 | 147,10 |
| 9  | 197,56 | 23 | 86,61 | 37 | 159,72 |
| 10 | 213,06 | 24 | 70,68 | 38 | 169,87 |
| 11 | 225,48 | 25 | 58,34 | 39 | 177,12 |
| 12 | 233,99 | 26 | 50,11 | 40 | 181,21 |
| 13 | 238,01 | 27 | 46,25 | - | - |
| 14 | 237,21 | 28 | 46,80 | - | - |

**Table 7.** Amplitude-frequency characteristic of the system with a regulator.

| ω  | A  | ω  | A  | ω  | A  | ω  | A  |
|----|----|----|----|----|----|----|----|
| 0  | 0  | 0.5 | 0.268 | 1  | 0.380 | 1.5 | 0.325 |
| 0.05 | 0.044 | 0.55 | 0.280 | 1.05 | 0.387 | 1.55 | 0.308 |
| 0.1  | 0.086 | 0.6 | 0.292 | 1.1 | 0.392 | 1.6 | 0.290 |
| 0.15 | 0.123 | 0.65 | 0.304 | 1.15 | 0.395 | 1.65 | 0.273 |
Table 8. Amplitude-frequency characteristic of the system without a regulator.

| ω   | A    | ω   | A    | ω   | A    | ω   | A    |
|-----|------|-----|------|-----|------|-----|------|
| 0   | 1,3  | 0.5 | 0.766| 1   | 0.361| 1.5 | 0.195|
| 0.05| 1.290| 0.55| 0.708| 1.05| 0.338| 1.55| 0.185|
| 0.1 | 1.262| 0.6 | 0.655| 1.1 | 0.316| 1.6 | 0.175|
| 0.15| 1.218| 0.65| 0.606| 1.15| 0.296| 1.65| 0.166|
| 0.2 | 1.162| 0.7 | 0.560| 1.2 | 0.278| 1.7 | 0.158|
| 0.25| 1.098| 0.75| 0.519| 1.25| 0.261| 1.75| 0.150|
| 0.3 | 1.030| 0.8 | 0.482| 1.3 | 0.245| 1.8 | 0.143|
| 0.35| 0.961| 0.85| 0.447| 1.35| 0.231| 1.85| 0.136|
| 0.4 | 0.893| 0.9 | 0.416| 1.4 | 0.218| 1.9 | 0.130|
| 0.45| 0.827| 0.95| 0.387| 1.45| 0.206| 1.95| 0.124|

Table 9. Spectral density of the system at the output of the object with the regulator.

| ω   | S_y  | ω   | S_y  | ω   | S_y  | ω   | S_y  |
|-----|------|-----|------|-----|------|-----|------|
| 0   | 0    | 0.5 | 21,14| 1   | 32,92| 1.5 | 10,46|
| 0.05| 0.175| 0.55| 24.52| 1.05| 30,72| 1.55| 9,262|
| 0.1 | 0.736| 0.6 | 27,66| 1.1 | 28,14| 1.6 | 8,169|
| 0.15| 1.755| 0.65| 30,44| 1.15| 25,34| 1.65| 7,154|
| 0.2 | 3.295| 0.7 | 32,74| 1.2 | 22,52| 1.7 | 6,209|
| 0.25| 5.372| 0.75| 34,47| 1.25| 19,81| 1.75| 5,330|
| 0.3 | 7.945| 0.8 | 35,55| 1.3 | 17,36| 1.8 | 4,528|
| 0.35| 10.92| 0.85| 35,93| 1.35| 15,22| 1.85| 3,811|
| 0.4 | 14.21| 0.9 | 35,61| 1.4 | 13,38| 1.9 | 3,188|
| 0.45| 17.66| 0.95| 34,58| 1.45| 11,81| 1.95| 2,665|

Table 10. Spectral density of the system at the output of the object without a regulator.

| ω   | S_y  | ω   | S_y  | ω   | S_y  | ω   | S_y  |
|-----|------|-----|------|-----|------|-----|------|
| 0   | 144.0| 0.5 | 172.5| 1    | 29.79| 1.5 | 3,764|
| 0.05| 147.6| 0.55| 156.1| 1.05| 23.35| 1.55| 3,336|
| 0.1 | 157.4| 0.6 | 138.4| 1.1 | 18.23| 1.6 | 2,974|
| 0.15| 170.8| 0.65| 120.5| 1.15| 14.24| 1.65| 2,652|
| 0.2 | 184.4| 0.7 | 103.0| 1.2 | 11.18| 1.7 | 2,355|
| 0.25| 195.3| 0.75| 86.71| 1.25| 8.883| 1.75| 2,076|
| 0.3 | 201.4| 0.8 | 71.84| 1.3 | 7.173| 1.8 | 1,815|
| 0.35| 201.7| 0.85| 58.69| 1.35| 5.914| 1.85| 1,574|
| 0.4 | 196.5| 0.9 | 47.33| 1.4 | 4.987| 1.9 | 1,357|
| 0.45| 186.3| 0.95| 37.73| 1.45| 4.295| 1.95| 1,170|
Figure 5. Amplitude-frequency characteristic of the optimal ACS.

Figure 6. Spectral density of the signal at the ACS output.

Figure 7. The spectral density of the disturbance signal.
According to the results obtained, it can be said that it is possible to use the obtained automatic control system in real conditions of industrial production.

3. Conclusion

The advantages of discrete control systems in comparison with analog ones are:

- Using one system, you can manage processes in several managed objects;
- Discrete elements provide higher accuracy of conversion and transmission of information. In digital systems it is possible to implement complex control algorithms. Because of this, the accuracy of discrete systems can be higher than the accuracy of continuous systems;
- Discrete systems in many cases are simpler in a constructive sense of similar continuous systems.

Much attention to the theory and practice of discrete control systems is explained by the increasing use of control computers in a closed control loop. This provides the system with significantly greater computational capabilities, high stability, and ease of restructuring its structure and parameters.

In this paper, we calculated some auto- and inter-correlation functions in discrete control systems. Summarizing the results of the above studies, it can be argued that the system under study is stable.

Comparison of the stability of continuous systems and discrete control systems allows us to conclude that they have some features associated with the form of the processed signal.

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