Correlation model of enrichment process creation

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Abstract
The possibility of a linear approximation creation for iron ore enrichment model based on correlation analysis without interfering in the process and further refine of the process model to account its nonlinearity is considered.
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Iron ore enrichment processes are multistage. However, the common factor is the presence of randomness properties of raw material, nonlinearity nature of the process, the effect of uncontrolled internal disturbances (deterioration of liner) and others.

To create the control systems of any object we need to make its adequate mathematical model. Traditionally, models have the form of differential or difference equations, transfer functions. We should choose the order of equations and their parameters. For simple objects it is possible to use the laws of physics and create analytical model. But the model parameters cannot always be calculated theoretically. Some parameters of this complex objects can be determined experimentally. To make this we should stop the production process, give to the inputs the appropriate testing actions and fix the output reaction. After this using calculation we can determine the object model parameters. But this traditional way has the following disadvantages:

– stopping of the production process;
– adequacy of the calculating data only for experimental conditions;
– not taking into account the nonlinearity of the process;
– fast "obsolescence" of nonlinear characteristics.

The first regulators were created under the assumption that the object parameters cannot be changed or can be changed slightly during operation. In case of this the synthesis process of regulator was simplified. But it was necessary to proper the settings of regulator. This approach was due to the fact that it is quite difficult to consider the object control parameters changing, the nonlinearity of its characteristics, randomness of the surrounding conditions changes. Regulators based on the ideas of parametric adaptation could change their settings according to changes in the object parameters. Regulator structure generally does not change but configuration algorithms are quite difficult. Regulators of this type are not adapted to the changes in the structure of control object. Regulators which are built on the principle of minimizing of the sensitivity function with unchangeable structure could be effective only when object parameters are changing in the narrow range.

For more accurate consideration of object parameters have been proposed methodologies based on the determination of the frequency object characteristics by means of experiments. These experiments were made by the giving of harmonic signals with different frequencies on the object input, construction of frequency characteristics and calculation of transfer functions parameters and synthesis of regulator structure and parameters. There were created the methodic and the relevant hardware. This way is only right that the frequency characteristics can actually contain detailed information about the object. But in practice to implement this way in most cases is impossible for the following reasons:

- it takes time to take characteristics, to process them, during which the parameters of the object can be changed so that the performed work will be unnecessary;
- when we give harmonic signals on the object input, it could appear the resonance, which can lead to unintended consequences; (if at the resonant frequencies frequency response must rise, then we can’t eliminate these frequencies without significant loss of information about the object);
- to remove these characteristics during normal operation is practically impossible, since it violates the manufacturing process.

The idea to change structure during a given trajectory tracking of control system moving is seemed very perspective. Results for insensitivity of such systems to change object parameters were impressive. But for each form of trajectory we should take into account the conditions of existence of the sliding mode.

Systems that are able during the object work to automatically adjust their settings using control methods to minimize errors such as gradient, Gauss-Seidel, can work reliably if the control object structure is sustainable, and we have automatically pick relevant parameters of the regulator.

The creation of control system as known consists of identifying the structure and object parameters of the facility and subsequent synthesis of controller. Correction of regulator structure and parameters is possible only if we have adequate identification of object control. Since this is a main issue when creating control systems, let consider it in more detail. Typically, after creation of control object model equation all further researches that include checking the stability, controllability, sensitivity, obtaining of frequency characteristics etc. are made from the resulting model, but not the object itself. Objects settings which are considered are changing almost constantly.

To take into account the identified issues there are different possible approaches. In this work we offer an approach based on the following provisions:

- first is to obtain of approximate correlation discrete model of the object using of Wiener-Hopf equation, which allows to filter the interference portion, to get an accurate linear approximation to the object model;

- the second, after obtaining approximate model it assumes the rectification at every control interval as values of discrete interval and number of correlation functions intervals that are used to produce models which is equivalent to variation of model order.

This approach is similar to the idea of dual control, first formulated by Feldbaum A.A. [1]. Without this, in terms of the authors, in cases of such complex processes as minerals enrichment, to be limited to purely analytical methods may not be effective enough or incorrect.

If to represent the correlation functions in a discrete form, then obtaining of correlation model of control object is greatly simplified. However, in this case we have a question of estimation of interval number of correlation functions which could be used to obtain a first approximation of the model.

So it is proposed a simpler approach to creating of control systems of enrichment technology complex processes. It is showed that to get the model of first approaching object it is sufficiently to confine the calculation of correlation functions, their further Z-transformation and obtaining of difference equations of linear approximation process models. Numerical test of this approach showed that in the first approximation it is sufficient to use only a few first values of correlation functions.

It is important to note that such systems must not interfere in the production process to identify the parameters of the controlled process or installation. Launched earlier idea of dual control [1] is to join the process of identification and control. Moreover, on the basis of the object state and the value of the control action identification is made, and on the basis of identification – the determination of the control action. Thus, identification and control are treated as a single inseparable process, as it should be. The idea of dual control allows the input signal of arbitrary shape, including occasional.

This approach has a number of fundamental advantages:

– does not require submission of test signals to the input object, accordingly, does not affect the normal course of the producing process;
– can be used continuously;
– in the linear approximation can be applied in the identification of each control interval to objects with stationary and non-stationary influences;
– in future to correct the linear model according to their data as current-process operation.

It may be noted in [2], [3] with the successful use of the method. However, despite the obvious advantages, it has not get so far widespread in developing of enrichment process control systems. In addition, well-known cases of the Wiener-Hopf equation are not brought to obtain the difference equation of control object. This form of control object model is the most suitable to use digital synthesis controller.

Wiener-Hopf equation can be applied in the case of stationary processes. This requires previous preparing data. This is the preparing in clustering of technological processes parameter values so that to calculate it needs to select parts of data on the past development of technological process, which correspond to the current situation (the center of the cluster). That is, they have approximately the same statistical characteristics. Thus, the data location that corresponds to the flow of processes over time is stored. It, in fact, allows to obtain correlation functions in stationary intervals. Let explain this more detail. Each value of the process is a vector, which is characterized by its technological parameters such as: the content grades of ore which is entering the processing, moisture content, costs of ore, water, iron content and total magnetic content and other process parameters that define the processing of ore. This vector can be called the state production process vector.

In the database, these vectors are located in the temporal order. Each of the state vector corresponds the set of technological parameters such as for complex iron-ore deposit of Ingulets Iron Ore Enrichment Works:

$\boldsymbol{x_i} = \{C_1, C_2, \ldots, C_8, F_{м1}, F_{м2}, \ldots, F_{м8}, Q_{11}, C_{(+20)}, П, E_{11}, \varphi_{11}\}$.

where $C_1, C_2, \ldots C_8$ - the content of the 1, 2, ..., 8 grade of iron ore in cargo flow, which goes to processing, relative units; Q_{11} – section performance, t/h; $C_{(+20)}$ - class +20 mm content in the cargo flow, %; E_{11}, φ_{11} - specific electricity consumption and therefore water on enrichment, hrn.; $П_{11}$ - grinding (content of class - 44 microns in concentrate), %;

This state vector with a smaller number actually precedes the state vector with a large number. At the present time the production process is characterized by some current state vector $\boldsymbol{x_n}$

$\boldsymbol{x_n} = \{C_{1\,n}, C_{2\,n}, \ldots, C_{8\,n}, F_{м1\,n}, F_{м2\,n}, \ldots, F_{м8\,n}, Q_{11\,n}, C_{(+20)\,n}, П_n, E_{11\,n}, \varphi_{11\,n}\}$.

This vector is compared coordinate-wise with each of the state vectors $\boldsymbol{x_i}$ from the database according to the criterion of proximity

$$\rho_i = \sum_{j=1}^{j=n} \left| x_{ij} - x_{пот\,ij} \right| \xrightarrow{i} \min,$$

where i – is the number of the record in the database of the production process; j – is the number of process parameters; $x_{пот\,ij}$ - is the component of given vector of current situation; n – is the number of records which are processed in the database.

In the last expression distance is formed as the sum of the absolute values of differences between the current value and the value of the same parameter from the database. Each line of database sometimes is characterized by time of its receipt (as tour or hour) and a set of values of all process parameters, which were measured at this time.

For example, the distance between the current vector and the vector of situations from the database for two options can be written as follows:

$\rho_i = |(C_1)_i - C_{2\,n}| + |(F_{м1})_i - F_{м1\,n}|$,

where

i – is the number of situations vector in database.

Each time a comparison is made with the same

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vector of the current situation. Thus, an array of distances of vectors from the database from the current situation vector is formed.

Let sort these distances in order of increasing distance. Then in the top lines would be vectors from the database which by the chosen criteria are next to the current situation vector. That is in the top lines will be selected the past situations that best fit the current. This means that the model of the technological process in such situations is closest to the current one. The selected data can be used to obtain a mathematical model.

But this approach can be improved, if to use the weight coefficients of impact of each input variables. As these factors can be used cross-correlation coefficients k_{ij} between input and output variables.

In this case, the formula for the distance can be represented as:

$$\rho_{ij} = \sum_{j=1}^{j=n} \left| \frac{x_{ij} - x_{пог\,ij}}{k_{ij}} \right| \xrightarrow{i} \min$$

where k_{ij} - is the correlation coefficient between the i input value and value of the j process parameter. The last expression shows that the greater cross-correlation coefficient between input and output variables makes the less distance towards the appropriate coordinates. Therefore, on the basis of minimum distance there will be selected precisely those vectors (data from base), which are characterized by the smallest distance that takes into account the greatest impact of input (values of technological parameters) variables to the output data (for example, the quality of the finished product).

Correlation functions which are obtained from such database, will reflect the most accurately reflect the relationship between the values of parameters of producing processes on the first interval of their arguments. Wiener-Hopf correlation model can be build on this base.

In the present work we state the task of developing a methodology that allows to obtain control object model in the form of discrete transfer function and difference equations without interference in its work. The initial data are input autocorrelation functions of input actions and mutually correlation function between input and output operations.

Often in solving of the such problems correlation functions are transforming in the form of approximation by analytic functions in selected class. Typically, these are exponential and harmonic functions and their linear and nonlinear combinations. In these cases, you can get satisfactory results in the case of sufficiently accurate matching of these substitutions of correlation functions.

One of the traditional ways of obtaining control object model using correlation functions lies in determination of the impulse transfer function $w(t)$ from the integrated form of Wiener-Hopf equation.

$$R_{uy}(\tau) = \int_0^\infty R_{uu}(\tau - t) w(t) dt,$$

where $y(t)$, $x(t)$ - are the output and input actions respectively; $R_{uy}(\tau)$, $R_{uu}(\tau - t)$ - are the autocorrelation and mutually correlation functions respectively; $w(t)$ - is impulse transfer or weight function.

As it is known [5], the precise definition of correlation functions does not guarantee unambiguous interpretation of above equation solving relative to $w(t)$. Incidentally, it is typical for all integral equations.

Therefore, to obtain the difference model of control object the value of correlation functions is used without their transformations (approximation) and without solution of the Wiener-Hopf integral equation.

Based on the fact that the correlation function R (τ) characterizes the degree of linear relation between the values of the random function, that distant between each other by time τ. In the most cases of the production processes corelational functions are damped. It means that the impact of technological parameters values separated by τ decreases. This allows us to use just by consideration of the relatively small number of values of technological processes.

Let consider the principle of correlation models obtaining using the example of scalar input and scalar output. For example the input action can be ore flow and the output is concentrate amount. This approach can be extended to models with multiple inputs and outputs. By analogy with [3] transfer function for discrete objects can be seen in the form

$$W(z) = \frac{R_{uy}(z)}{R_{uu}(z)} = \frac{y(z)}{u(z)}, \quad (1)$$

where z - is variable discrete z – is transformation; $y(z)$- z - is image of output action; $u(z)$- z - is image of input action.

To have the possibility of physical realization of the transfer function denominator degree should be not less than the degree of the numerator.

The numerator and denominator of the transfer function (1) is practice to present in the form of power series, to use the internal discrete transform property, which is the record type of

$$R_{uy}(z)= z^{0} R_{uy}(0)+ z^{-1} R_{uy}(1)+ z^{-2} R_{uy}(2)+,\ldots+ z^{-j} R_{uy}(j),\ldots z^{-N_{uy}} R_{uy}(N_{uy}), \qquad (2)$$

or in general

$$R_{uy}(z)=\sum_{j=0}^{N_{uy}} z^{-j} R_{uy}(j)$$

means a sequence of impulse signals shifted in time for the number of intervals equal to the degree of parameter *z* of discrete transformation,

where $R_{uy}(z)$ - is z-image of mutually correlation function of input u (t) and output y (t) action; $R_{uy}(j)$ - arethe calculated values of mutually correlation function of input u (t) and output y (t) action on j interval; $j = 0 \ldots N_{uy}$ – is the number of discrete values of the correlation function; N_{uy} –is the number of the last value of the correlation function $R_{uy}(\tau)$ taken into account. Similarly, we can obtain images of autocorrelation function of the input u (t) action

$$R_{uu}(z)= z^{0} R_{uu}(0)+ z^{-1} R_{uu}(1)+ z^{-2} R_{uu}(2) +,\ldots+ z^{-j} R_{uu}(j),\ldots z^{-N_{uu}} R_{uu}(N_{uu}), \qquad (3)$$

or in general

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where $R_{uu}(z)$ -is z-image of autocorrelation function of input u (t) action; $R_{uu}(j)$ - are the calculated values of autocorrelation function of input u (t) action on j interval; $j = 0 \ldots N_{uu}$ – is the number of discrete values of the autocorrelation function; N_{uu} –is the number of the last value of the correlation function $R_{uy}(\tau)$ taken into account.

Similarly, we can obtain images of *u (z)* and *y (z)*. Image of transfer function (1) can be written as

$$W(z)=\frac{R_{uy}(z)}{R_{uu}(z)}=\frac{\sum_{j=0}^{N_{uy}} z^{-j} R_{uy}(j)}{\sum_{j=0}^{N_{uu}} z^{-j} R_{uu}(j)}=\frac{y(z)}{u(z)}. \qquad (4)$$

To get the image of transfer function in the discrete region we must find a classic case according to analytical expression of the series sum of type (2), (3), but endless, which also must converge [5]. If you can find such sums, the task of obtaining the transfer function can in principle be solved. However, for even given recurrent relations it is not always possible. When we talk about production processes, the possibilities of an analytical approach to obtain analytical expression of the sum of power series, whose values of members are exposed to complex laws of raw materials processing and not to artificially chosen mathematical functions or recurrent relations are almost absent.

Let consider a specific example. From (4), (2), (3) we obtain

$$y[i+2]=\frac{1}{R_{uu}(2)}(R_{uy}(0)u[i]+R_{uy}(1)u[i-1]+R_{uy}(2)u[i-2]-$$
$$-R_{uu}(0)y[i]-R_{uu}(1)y[i+1]).$$

Shifting process in one interval so that the next process value was labeled as $y[i+1]$, we'll have

$$y[i+1]=\frac{1}{R_{uu}(2)}(R_{uy}(0)u[i-1]+R_{uy}(1)u[i-2]+R_{uy}(2)u[i-3]- \qquad (5)$$
$$-R_{uu}(0)y[i-1]-R_{uu}(1)y[i]).$$

The values of the correlation functions have the role of difference equations coefficients. Therefore, the shift applies only to control and output actions. This shift as known corresponds to multiplication of numerator and denominator of the corresponding transfer function to one and the same Z^{+1}.

In general

$$y[i+1]=\frac{1}{R_{uu}(N_{uu})}(\sum_{k=0}^{N_{uy}}R_{uy}(k)u[i+k-1]-\sum_{j=0}^{N_{uu}-1}R_{uu}(j)y[i+j-1]) \qquad (6)$$

where N_{uu} and N_{uy} – are the numbers of recent numbers of recorded intervals of correlation functions.

Let's notice that the number of intervals N_{uu} and N_{uy}, discounted to obtain the transfer function, may be different for $R_{uy}(\tau)$ and $R_{uu}(\tau)$, and they define the structure (including the order) of control object model. By changing these settings, you can optimize the structure of model for obtaining the minimum error between the values of production process and its model.

Correlation function $R_{uy}(\tau)$ is a measure of the connection density of function values that separated each other on the time interval τ. The value of the correlation functions on the first interval is usually dominated by the values of these functions at these intervals because the connection between the values of technological parameters of the production process is reduced over time. The accuracy of calculation of correlation functions values decreases with increasing of interval number. Therefore, the operation of determining of infinite series sum analytical expression, as it usually happens in purely theoretical studies, is simply incorrect, and therefore unacceptable. It is well known for researchers who perform practical calculations of characteristics of random processes. This is another argument in favor of using only the first few intervals of correlation functions.

But in this research formulation the question arises: if analytical methods based on estimation of the infinite series sums, which consist of correlation functions values, got by measuring in technological processes, are unsuitable, then which number of intervals is enough for obtaining a given or minimum model error of production process.

From the perspective of the authors, one of the most reliable approaches that meets the production conditions can be presented in the following action sequence:

Calculation of correlation functions. The value of correlation functions, as seen from (5) and (6) play a role of coefficients of difference equation model. These values, as shown by numerical experiments, can be close to optimal.

Original version of the difference equation model with the form of (5) or (6) is forming.

The adequacy of the obtained model on the basis of data on past exploitation downtime is checking by simple substitution in difference equation of the process data models . If the model error is unacceptable, the model is refined in recent operating data object.

Let's note that the idea of coefficients optimizing of the control object model or the regulator is not new. In the present work it is different by the wide use of the correlation discrete form and the possibility of optimization not only through coefficients but also structure by changing the number of terms in the difference model of (5), (6).

In [6], [7] methods of obtaining of disintegration process model for solids are presented. Dot matrix device, which is rather logically justified is used. However, to take into account of the constant changes of material properties it is necessary to make laboratory measurement of relevant parameters and conversion models. Using this technique the changes of process parameters are reduced in value correlation functions and are not need in regular requiring laboratory analysis.

Conclusions

Possibility of producing of simple model without interference in the course of the production process is shown.

The accuracy of the model can be improved by clustering of data production process during its operation.

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