Development of an Algorithm for Control Metallurgical Processes of Fluidized Roasting Using an Adaptive Controller

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Abstract. In this article, we consider the solution of adaptive control problems by developing a unified algorithm for regulator tuning. The task of adaptive control of dynamic processes in real time, today plays a key role in the development of modern control systems. Existing adaptive management development assumes, as a rule, an unchanged structure of the technological process, where only the parameters of the process under investigation are subject to change. To create such systems, detailed modeling of the technological process is necessary, while the typical management model after identification becomes unique for a particular enterprise due to the parameters found. This system is designed for operating objects that allows you to take into account the dynamic change of parameters in the process of object identification while the stage of mathematical modeling is replaced by a standard approximating model.

Introduction

In ECS problems, just like in stabilization problems, we have a model of the object and a control quality criterion. The models in the two aforesaid systems are principally different: for stabilization the model tends to be linear; while for extremal control, the dependence of input of the object on output cannot be approximated by a linear model, since the output of the object has an inertial and extremal nature. The latter properties characterize the object with an extreme dependence, and, therefore, they must be taken into account in mathematical formulation of the problem. This is the key feature of control in such systems. A.A. Feldbaum called this the dual control [1]. The term implies the duality of goals of controlling actions: it is, on the one hand, a search for the extremum of the quality criterion by special search steps affecting the object; and on the other hand, operational steps in order to approach the extremum [2]. It bears noting that the term “linear” refers to the approximating model, rather than to the object, since the object itself has a direct dependence of output on input. Also, it is worth adding that the object with a direct dependence of output on input can be controlled by a feedback method; however, such control becomes impossible if the object has an extreme dependence of output on input. The only way to control such objects is to search for an extremum by the “trial and error” method [3, 4].

Historically, the extremal control theory considered the objects as combinations of linear multidimensional dynamic links and static quadratic links [5-7]. Thus, the properties of the object were divided into inertial and nonlinear, though the object, of course, manifests these properties in combination. It should be pointed out that these properties must be modeled only at the extreme point of the output criterion.

Description of the ECS algorithm

Let us take the input of the dynamic link as the m-dimensional control vector U and the r-dimensional measured disturbances vector V. The output of the Static Link (SL) is a scalar criterion of
the control quality $Y$. The output of the Dynamic Link (DL) is the $n$-dimensional coordinate vector of the state $X$. Both the control vector $U$ and the measured disturbance vector $V$ can be easily combined into a generalized $n$-dimensional input vector $Z$. The structural diagram of this approximating model is shown in Fig. 1.

![Fig. 1. The scheme of the approximating model](image)

Parameters $U$, $V$ and the output criterion $Y$ reflect real parameters of the technological object. They are measurable parameters, however, the value of $Y$ does not have to be measured; it can be calculated through other measurable parameters of the object. The state vector $X$, on the contrary, has no physical interpretation; it is fictitious and, therefore, not measurable. This is how the lack of current information about the state of the extreme object is modeled. It should be noted that in mathematical formulation of the problem of extreme criterion control the dependence of $Y$ on $X$ is not known \[17\]. However, the optimal control system should not go far from the extremum of $Y$, therefore the dependence of $Y$ on $X$ can be quite accurately modeled around the extremum point. The multidimensional parabola $Y = Y_0 + X^T \cdot X$ is a suitable universal approximation of such extremal dependence. For this parabola the steepness coefficient and coordinates of the extremum point are unknown, but since the vector $X$ is fictitious, its vector basis can be chosen arbitrarily, so that $X$ can be a deviation from the extremum, while the quadric form matrix (the steepness coefficient of the parabola) can be considered as a unit matrix $a$ ("+" for a minimum criterion or "-" for a maximum). The dimension of the vector $X$ must not be less than the number of controls, that is, $n \geq m$. In view of the foregoing, let us put down the formula of the approximating model, where $X$ is a scalar.

The mathematical tools of control theory do not permit to synthesize a control algorithm for nonlinear objects with insufficient current information. That is why, so far it has been impossible to obtain general and universal results, unlike solution results of the stabilization problem in the linear control theory. However, this paper reduces the initial problem of extremal control to a problem that formally coincides with the stabilization problem. Thanks to this, it became possible to divide the stabilization problem into two: estimating the state of the object and stabilizing the estimates.

Interpretating the result, we can conclude that transformation of the approximating model converts the quadric static link into the linear State Measurer (SM) of a dynamic link, and the object model is reduced to this dynamic link. The scheme of this transformed approximating model is shown in Fig. 2.

![Fig. 2. Structural diagram of the transformed approximating model](image)

The position of the criterion extremum is known a priori - it is point $X=0$, therefore, the extremal problem of minimization (maximization) of the criterion $Y$ can be reformulated into the stabilization problem of the linear object state near zero. Since the solution of such problems is well known, we can immediately put down the optimal control algorithm. However, there is one peculiar feature: in the absence of search steps, the measurer loses its informative value, due to the fact that $Z(t) = 0$ and the value of $X(t)$ cannot be determined by the equation (2). This manifests the dual nature of control and
the lack of current information about the state of the object. Because of this feature, the problem of determining the minimum of the control criterion can only be divided partially: the problem of the optimal estimation of the state of the object is solved independently of the control law, while the problem of control law optimizing by the estimate depends on the solution of the estimation problem.

The feedback loop for such ECS problem consists of two blocks, connected in parallel: the estimation filter block (EF) and the “regulator block”. The first block outputs the estimation of the state of the object, and the second computes the controlling action. Let us introduce the symbol $X''$ for the estimate of the vector $X$ made by measurements of $dY$ at the criterion measurement block (CM). The enlarged structural diagram of this ECS is shown in Figure 3.

![Fig. 3. The enlarged structural scheme ECS](image.png)

The solution of the first problem - the algorithm of the object state estimation filter - turns out to be standard; this algorithm consists of two steps. First, a one-step prediction of the $X'$ state is computed using the previous state estimate $X''_{i-1}$ and the $U_{i-1}$ control [8,9]. In the second step of the algorithm, the results of $Y_i$ measurements are used to compute the residual error $e_i$, and the prediction is adjusted by this error. As a result we get a current estimate $X''_i$. The estimation filter algorithm has a variable filter-transfer coefficient $G_i$ and the variance of the estimation error $D$ (the adjustable parameter of the estimation filter).

**Modeling**

When developing ECS, the task was to identify the control object and adjust the regulator. As an example, let us consider how the extremal control algorithm applies for the fluidized bed furnace. The main stages of the system design were as follows:

1. Determine the technological parameters that affect the selected criterion.
2. Select the model of the technological object and determine the data pool in real time.
3. Identify the constants in the model of the object and the measurer.
4. Clarify the constants of the estimation filter and the regulator in the course of system setting.

We identified the basic control channels in terms of controlled and uncontrolled fluctuations [10,11]. Pursuant thereto, the bed temperature is the basic process parameter that makes a decisive impact on almost all other parameters. Increase in the temperature can result in partial material melting and sintering into large pieces, which disrupts the fluidized bed. Decrease in the temperature results in incomplete sulfides oxidation, i.e. in a decreasing efficiency of the furnace. Since the fuel for the furnace is a concentrate, the bed temperature depends mainly on the supply of the concentrate to the furnace and on its quality. The process is sensitive to changes in concentrate consumption in terms of output parameters such as amount of sulfur dioxide and dust in gases. For instance, the content of sulfurous anhydride in gases varies in frequency and amplitude just like the concentrate consumption, i.e. without inertia.

However, the system of automatic bed temperature control by controlling the concentrate supply has fundamental drawbacks. The controlled object - furnace - has a large time constant in this control channel, which leads to a considerable inertia of the control system. Apart from that, technological tests
show that in the absence of serious disturbances in the control system, the bed temperature maintained within ±10°C results in material consumption fluctuations of ±30%. Such an irregular furnace operation, i.e. irregular efficiency and concentration of sulfur dioxide behind the furnace will adversely affect subsequent processes. Therefore, in order to reduce fluctuations in the furnace efficiency, caused by work of the bed temperature control system, it makes sense to use a scheme for stabilizing the concentrate supply adjusted by the bed temperature.

As a result, we developed a program and logic diagram in the MATLAB software package. Our deliverable combines both previously developed model of metallurgical concentrates roasting in a fluidized bed furnace [12] and the ECS proposed herein [13].

According to the above-described ECS algorithm, the logic diagram is as shown in Fig. 4. The controlling action goes to the input of the object. The output of the adder calculates the residual error of the object's output against the task. The identifier receives a residual error and computes $\Delta A$. The digrator receives $\Delta A$ and recursively calculates the constants for the regulator $K_{opt}$. The regulator receives a residual error and the optimum values of the regulator coefficients; $K_{opt}$ arrives at the delay unit.

**Fig. 4. Structural diagram ECS with adaptive tuning of the regulator**

**Result and discussion**

Before beginning of modeling, we supposed that the fluidized bed furnace was in a "cold" state. According to the modeling conditions, the bed was heated up to temperatures allowing the supply of copper concentrate, i.e. ~650°C. Alongside with that we modeled a standard automatic control system with the optimum PID controller coefficients, see Figure 5.
Fig. 5. Graphs of temperature variations of the furnace working zone for various automatic control systems

The authors made numerous experiments by mathematical modeling methods, which show that the above-described solution can identify the controlled object and calculate the regulator settings without special effects that divert the output of the object from the nominal value [14].

All the above-said drives to the following conclusion: the information necessary for the system design is received directly from identification of the object, and is specified in the course of the system operation. This fundamentally differs from the existing methods of creating control systems for technological facilities by applying technical and economic criteria [15, 16]. In order to create conventional systems we need a detailed modeling of the technological facility, so such control systems can only be made by specialists. However, in our case, the stage of mathematical modeling is replaced by a standard model with subsequent identification of its parameters. After identification the standard model becomes a unique one for a certain facility due to the identified constants. The object-identifying procedure is related to collection of actual information about the facility in operation; that is why it is applicable for operating facilities rather than for the facilities (technologies) yet to be designed, as the latter have no actual values of the parameter. In this case we can only calculate the technological production process, without accounting for any possible "bottlenecks" in the technological process, and design the stabilization systems for this process. Therefore, designing and creating a system of operational technology optimization by the proposed method is feasible after the technological process has been successfully introduced and mastered in the industry, so usually it is applied this way.

**Conclusions**

1. The approximating model is non-linear, therefore it is impossible to control by the feedback principle. Another problem is lack of current information about the state of the object.
2. The model in question (presented herein) can be properly transformed into a linear model with an object state measurer; consequently, it is possible to synthesize the ECS by the feedback principle with the optimal regulator and the object's estimation filter.
3. Control of economic or technical-economic indicators at large technological facilities can be made through the current values of the measured parameters. The optimal control is identified by a searching method. We found an alternative method for building the ECS by the feedback principle, just like in case of stabilization systems. Creation of the proposed systems does not require a detailed study of the technological facility, while the approximating model has a standard form and becomes unique only when it is identified by actual data.
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