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SYNTHESIS OF AN AUTOMATIC CONTROL METHOD FOR MAJOR OIL PIPELINES BASED ON INVERSE DYNAMICS PROBLEM CONCEPT

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Abstract

A new approach to synthesis of automatic control of objects is proposed, based on application of the inverse dynamics concept. A nature of PID control of objects is studied as well as causes that stipulate search for automatic control methods alternative to PID control; the above-mentioned approach to synthesis of automatic control methods is developed. A new generation PID controller is synthesized, featuring higher control quality, simplicity of adjustment and high accuracy. Such results were obtained thanks to application of a new method of digital differentiation of signals. Currently Russian oil pipelines use controllers from the different manufacturers, international, such as ABB, Foxboro, Honeywell, Yokogawa, Toshiba, Siemens, Omron, and Russian, such as Kontravt, Oven, Tekon, NIL AP; they all have a common disadvantage that they use a finite difference algorithm for differentiation, thus leading to lower quality of control and increased complexity of adjustments.

Keywords: *automatic controller; PID control; inverse dynamics; derivative*.

1. Introduction

The purpose of this paper is to lay out a new approach to synthesis of automatic control, based on application of the inverse dynamics concept. In this concept, just like in reality, any changes in behavior of the controlled object are considered consequence of some change in control action, which is formed by the automatic controller and delivered to the controlled object. At that, the task to form the control action u_t in any moment of time t (at the t th cycle of object control) is formulated as an inverse problem, that is, as a problem to find an unknown value (in this case a value of u_t), whose inputs are predefined (desirable) value of $y_{t+1,z}$ of the control variable Y of the controlled object in the following moment of time $t+1$ and a difference equation linking its values y_{t+1}, y_t, y_{t-1}..., to values u_t, u_{t-1}, u_{t-2},....

A nature of PID control of objects is studied as well as causes that stipulate search for automatic control methods alternative to PID control; the above-mentioned approach to synthesis of automatic control methods for objects is developed below.

2. The essence of PID control

As it is known from multiple sources [1-3], one of the types of automatic controllers finding the widest range of application in automatic and automated control systems for different process parameters (APCSs), are so-called PID controllers. The main idea, determining the name and essence of this type of controllers is that the value u_t of the control action U exerted onto the process variable Y of the controlled process (CP) in any given moment of time t is formed in accordance with the following equation (law of control):

$$u_t = c_1 \Delta y_t + c_2 \int_{t_0}^{t} \Delta y_\tau d\tau + c_3 d\left(\Delta y_t\right) dt. \tag{1}$$

Here Δy_t is a deviation (error value) of an actual value y_t of the process variable Y in the moment t from a predefined value y_{zt} of the variable (setpoint of the controller), which is calculated with the equation in the form of

$$\Delta y_t = y_t - y_{zt} \tag{2}$$

where: c_1, c_2 and c_3 are adjusted parameters (coefficients) of the PID controller; t_0 is the initial moment of CP control; τ is the integration variable all the values of which satisfy the condition $\tau \in I_t$, where I_t is the time interval, described by the equation

$$I_t = [t_0, t]. \tag{3}$$

The most important advantage of PID controllers, which has determined and is still determining their popularity and wide application in automation of diverse processes, is that the law of control (1) has tuning parameters c_1, c_2 and c_3. Having such parameters in (1) allows selecting their numeric values in each concrete case (adjusting the PID controller) in such a way that the values of u_t, t=1, 2, 3,..., calculated from the equation (1), provide satisfaction of a sequence of equations in the form of

$$y_t = y_{zt}, t = 1,2,3,.... \tag{4}$$

Here, just like in equation (2), y_{zt} is a predefined (desirable) value of Y in moment t. Taken together the equations (1) and (4), evidently, mean, that the control actions u_t exerted onto the process variable Y shall provide change of its values in time and in accordance with a preset (desirable) law of change.

3. Two problems arising from practical application of PID controllers

The vast number of theoretical and experimental studies of PID controllers [1-3], as well as over a hundred years of practical application in automation of diverse processes [1-4] revealed two topical issues, which significantly complicate and limit practical use of such controllers. The first one is the PID controller tuning problem, which comes down to determination and setting of numeric values of parameters c_1, c_2 and c_3 in the law of control (1) such, that their implementation allows for calculation of controlling actions u_t, providing satisfaction to the equation (4). Finding such parameters is a non-trivial task and its solution is available only to high quality specialists with expertise not in process automation, in specific domain knowledge of the controlled process itself.

The second problem that limits practical application of PID controllers is due to the fact that the law of control (1) includes the derivative $d(\Delta y_t)/dt$ of Δy_t deviation. As it is known [5-6], calculation of a derivative of any signal (signal differentiation) is one of a classical examples of ill-posed problems. The characteristic feature of such problems is that their solutions are extremely sensitive to even the slightest changes in input data. As for the error value Δy_t differentiation problem, whose solution and inputs are, respectively, a derivative $d(\Delta y_t)/dt$ and a error value Δy_t, the above noted feature of ill-posed problems means, that in case where the values y_t, t=1,2,3,... are not exact, the value of the derivative that is calculated and then applied in (1), may be indefinitely different from its actual value. As evident from (1), in any such cases, the value of u_t will be indefinitely far from its actual value as well. Taking this into account, as well as the fact that in real life the values of y_t are the results of measurement of the process variable Y with some kind of a transmitter or other measurement instrument, thus introducing the measurement errors, it is evident, that, first, the process of adjustment of the variable Y with the help of the PID controller is unstable as a whole. Second, the cause of this instability is the fact that PID controllers use a derivative of error value Δy_t with respect to the deviation time.

4. Two possible solutions for the problem of practical implementation of PID controllers

If we set our goal as to remove PID controller instability thus extending their practical applicability, and consider the facts set out before, it is evident, that to achieve this goal we may either regularize the differentiation of the error value Δy_t, using some regularization method applied to ill-posed problems [6-7], or withdraw from application of PID controllers and replace them with an analogue which does no use the derivative of the process variable. The first way was implemented by the authors in [8]. At that, regularization of differentiation of the process variable is provided by the use of moving quadratic approximation of change in the variable and analytical differentiation of algebraic second order polynomials. The results of the work show that the PID controller proposed there has a higher interference immunity and provides a higher control accuracy.

The second possibility to improve the automatic control methods and their efficiency is shown in this paper. From the above-mentioned concept of inverse dynamics problems we propose a method of process automatic control, alternative to the PID control and other automatic control methods based on process variable differentiation. At that, second order difference equations are used as a mathematical model to describe the connection between the values y_t, t=1,2,3... of the process variable Y and the values u_t of the controlling action U. For this case a numerical algorithm is synthesized for calculation of controlling actions u_t, t = 1,2,3....

5. Synthesis of an automatic control method based on difference equations and inverse problem concept

Taking into account the features of the inverse dynamics problems noted above, we synthesis the automatic control method. To simplify the following, we will hold that:

1. Values $\boldsymbol{y_{t+1}, y_t, y_{t-1}, y_{t-2}}$ of the process variable $\boldsymbol{Y}$ of the controlled object (CO) in moments of time $\boldsymbol{t+1, t, t-1, t-2}$ are linked among themselves and with the values $\boldsymbol{u_t, u_{t-1}}$ of its input $\boldsymbol{U}$ (control actions) by a difference equation in the form of

$$y_{t+1} = \alpha_1 y_t + \alpha_2 y_{t-1} + \alpha_3 y_{t-2} + \alpha_4 u_t + \alpha_5 u_{t-1} \tag{5}$$

coefficients $\alpha_1 - \alpha_5$, are some constants independent of values u_t, u_{t-1} of the input $\boldsymbol{U}$ of the CO and of the values $\boldsymbol{y_t}$, $\boldsymbol{y_{t-1}}$ and y_{t-2} of its input $\boldsymbol{Y}$.

2. A desired (necessary) law of changes in values y_{zt} of the process variable Y through time is determined by the equations

$$y_{zt} = \varphi(t), t = 1,2,3..., \tag{6}$$

where $\varphi(t)$ is a certain function of time $\boldsymbol{t}$.

3. Values $\boldsymbol{u_t}$ of the control actions shall be selected in such a way that values $\boldsymbol{y_t}$ of the controlled object output $\boldsymbol{Y}$ in any moment t satisfy the equations

$$y_t = y_{zt}, t=1,2,3..., \tag{7}$$

and the equation (**5**) holds true.

The initial data, represented by the equations (5) – (7), are necessary and sufficient conditions for synthesis of an automatic control method, which is of our interest. Indeed, the equation (5) links values $\boldsymbol{y_{t+1}, y_t, y_{t-1}}$ of the process variable $\boldsymbol{Y}$ in each moment t to the values **$\boldsymbol{u_t}$ and $\boldsymbol{u_{t-1}}$ of the control action $\boldsymbol{U}$ and thus, using this equation and equation (5),** to calculate the desirable values u_{zt}, t = 1,2,3..., we may compose an equation in unknown value u_t

$$\alpha_1 y_t + \alpha_2 y_{t-1} + \alpha_3 y_{t-2} + \alpha_4 u_t + \alpha_5 u_{t-1} = y_{zt} \quad (8)$$

Values y_t, y_{t-1}, y_{t-2} and y_{zt}, in this equation are known, as well as those of u_{t-1} , and as evident form (8), only the value u_t. , which is of interest to us, is unknown. Having moved the known summands $\alpha_1 y_t, \alpha_2 y_{t-1}, \alpha_3 y_{t-2}$ and $\alpha_5 u_{t-1}$ to the right part of the equation, let us represent it in a form, which is more compact and traditional in linear algebra:

$$\alpha_4 u_t = \Delta z_t, \quad t = 1,2,3,.... \quad (9)$$

here $\Delta z_t = y_{zt+1} - \alpha_1 y_t - \alpha_2 y_{t-1} - \alpha_3 y_{t-2} - \alpha_5 u_{t-1}$. The resulting equation is the simplest linear algebraic equation in u_t. Its solution is determined by the following evident equation:

$$u_t = \Delta z_t / \alpha_4, \quad t = 1,2,3,.... \quad (10)$$

4. Let us check the correspondence of the calculated value u_t to the conditions of its physical realizability which appear as a formula

$$u_t \in I_t \equiv \left[u_t^{min}, u_t^{max}\right] \quad (11)$$

where u_t^{min} and u_t^{max} are some given numbers, selected with respect for physical limitations applicable in a moment of time t to the values of the control action u_t.

If the calculated value u_t satisfies this formula, we suppose that it is the desirable control action u_{zt}, and, correspondingly assume

$$u_{zt} = u_t \quad (12)$$

Otherwise, that is, if the calculated value u_t does not satisfy the given formulas, we use it to calculate the desirable value u_{zt}, which is obtained from the equation

$$u_{zt} = \begin{cases} u_t^{min}, & \text{если } u_t \le u_t^{min}; \\ u_t^{max}, & \text{если } u_t \ge u_t^{max}. \end{cases} \quad (13)$$

Here u_t^{min} and u_t^{max} are some given functions of time t, such, that $u_t^{min} < u_t^{max}$. In the simplest case these functions are defined by the equations $u_t^{min} = u^{min}$ and $u_t^{max} = u^{max}$, where u^{min} and u^{max} are some given constants, satisfying the inequality $u^{min} < u^{max}$.

To finalize the synthesis of the proposed automatic control method let us produce the following comments that provide more insight into its nature, features and possibility of practical implementation.

1. As directly seen from equations (5)–(10), none of them includes derivative $d(\Delta y_t)/dt$ of the error value Δy_t, defined by the equation (2), and thus, the method lacks the main cause determining instability of PID controller and other control types that employ such derivative.
2. The synthesis of a proposed automatic control method given above is performed for a particular case of a controlled object, where the link between the process variable values and those of the control action are described by a difference equation (5). However, it is evident, that similar reasoning and actions may lead to synthesis of such method for other, both simpler and more complex controlled objects where the link between the process variables and control actions is described by a difference equation [9-10]. Such methods will differ from the controller synthesis given above only in their respective difference equations used, primarily by the number of summands with the value of process variable and control actions in the difference equation. General scheme of calculations that implement the control method being synthesized stays the same in all cases.

3. Currently, a number of methods is known for transformation of the ordinary differential equations commonly used in theory and practice of automatic control into difference equations.

Thus, as it was undertaken above, when synthesizing a certain automatic control method it is always possible to hold that the link between a process variable and control actions is described by a difference equation of some sort.

6. Conclusion

Summarizing the above, let us note the following main results.

1. The nature of inverse dynamics problems is explained as applied to the automatic control tasks.
2. PID control, being one of the most popular methods of control, is discussed and problems in its practical application are noted; those problems are new to instability of calculated control actions when there are measurement errors prominent in the process variable of the controlled object.
3. An automatic control method was synthesized on the basis of inverse dynamics problem and difference equations linking process variable values to the controller's control actions.
4. It is shown, that the proposed method of automatic controller synthesis is quite universal and allows synthesizing regulators for any controlled objects whose functioning may be described with either ordinary differential equations or difference equations of any order.

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References

[1] Yurevich EI. Automatic Control Theory. 4th Ed., revised and enlarged – Saint Petersburg: BHV-Peterburg, 2016; 560 p.

[2] Rotach VYa. Calculation of adjustments for actual PID controllers. Teploenergetika, 1993; 10: 31-35.

[3] Maystrenko AV, Svetlakov AA, Starovoytov NV. Digital Signal Differentiation in Automatic Process Control Systems with Multi-Point Methods. Doklady TUSURa, 2009; 2(20): 86-89.

[4] Maystrenko AV, Svetlakov AA. Indirect Pumped Liquid Flow Measurement in Pump Units. Doklady TUSURa, 2014; 4 (34): 215-220.

[5] Tikhonov AN, Arsenin VYa. Solution Methods for Ill-Posed Problems. 2nd ed. Moscow: Nauka Publishing, 1979; 286 p.

[6] Vasin VV. On Stable Calculation of Derivative. Computational Mathematics and Mathematical Physics, 1973; 13(6): 1383 -1389.

[7] Tikhonov AN. On Ill-Posed Problems of Linear Algebra and Their Stable Solution Methods. Proceedings of the USSR Academy of Sciences, 1965; 163(3): 591-594.

[8] Maystrenko AV, Svetlakov AA, Starovoytov NV. Real-Time Diginal Signal Differentiation with Moving Quadratic Approximation. Omsk Scientific Bulletin. Series: Instruments, Machines and Technologies. 2006; 7(43): 106-108.

[9] Maystrenko AV, Svetlakov AA, Gandzha TV, Dmitriev VM, Aksenova NV. Application of numeric signal differentiation methods to determine stationarity of a process. Pet Coal, 2017; 59(3): 311-318.

[10] Maystrenko AV, Svetlakov AA, Gandzha TV, Aksenova NV. Indirect measurement of flow of liquid pumped with pump packages. Pet Coal, 2017; 59(2): 244 - 249.

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