# The Two Methods of Reverse Overshoot Suppression in Automation Systems

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***Abstract*—The task of controlling oscillatory objects is extremely difficult. In the case of a complex object, analytical methods are weaker than the methods based on numerical optimization of the regulators (controllers). The tools incorporated in this method are the set of structures of regulators, the set of target functions and the software for modeling and optimization. Our research has been devoted to studying the methods of constructing the cost (objective, target) functions, their advantages and disadvantages, as well as the reasons for opting VisSim program for simulation and optimization. The most often used control structure is a serial PID-regulator (controller, PID) that contains the proportional, integrating and differentiating paths. Although the special measures for choosing a cost functions allows for suppressing the oscillations in the system, in some cases, these measures are not effective. This paper discusses that the structural methods of suppressing the oscillations in the systems to control the objects are prone to oscillatory instability. These measures include the use of more complex structures rather than the traditional PID. The proposed methods tested on mathematical modeling using simulations to calculate the transient processes confirmed the effectiveness of these methods.**

***Index Terms*—Regulator; Controller; Automation; Feedback Control; Speed; Accuracy of Control; Transient Processes; Numerical Optimization; Simulation.**

## I. INTRODUCTION

Precise control of technological objects is important in all branches of industry, engineering, technology and science. This problem is always resolved with feedback systems. In such systems, changes in input control signals feeding the object achieve the required value of the object output with high static and dynamic accuracy because the deviation from the setting (control error) is continuously measured and is used to control exposure. The success of this task requires the correct structure of the system and the correct calculation of the regulator. All the complexity usually consists of finding the regulator model, since the structure of the system is usually typical as shown at Figure 1. The output signal of object is subtracted from the prescribed value (setting), and the obtained difference (error) is fed through a regulator to the input of the object.

Calculation of the regulator in such a structure is based on the knowledge of the mathematical model of the object, that is its transfer function, which describes the conversion of the input signal to an output value. There are objects that are prone to oscillations of the output value. Even their response to the step impact has the form of oscillations, often with increasing amplitude. In some cases, such oscillations can be easily suppressed by the action of feedback. There are also cases where such oscillations are too extremely inherent to the object, resulting in the difficulty to calculate or tune the configuration of the regulator which would suppress these oscillations in the system. The tendency to suppress the oscillations in the resulting system is composed of one or more of the three following undesirable properties:

1. A large number of oscillations before the output value becomes established in a desired equilibrium state.
2. A large overshoot i.e. exceeding by the output value of the required value (setting) for a significant amount (in percent).
3. A reverse overshoot i.e. change of the output value in a direction opposite to the desired setting, which is spaced farther from the prescribed setting than the starting value.

To solve the control problem of such objects, as well as to control any other objects regulators c proportional, integrating and differentiating paths ("PID-regulator" or simply "PID") can be applied. The coefficients of these paths are calculated by different methods, for example by numerical optimization. The generalized structure of the traditional system is shown in Figure 1.

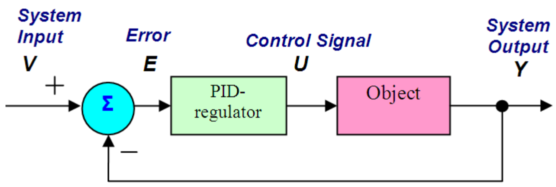


Figure 1: The structure of traditional system.

The general view of the output of the PID is given by the following equation:

$$U(t) = K_P E(t) + K_D \frac{dE(t)}{dt} + K_I \int_{t_0}^{t} E(t)dt \quad (1)$$

The KP, KI, KD are proportional, differentiating and integrating coefficients (gain) of the regulator paths. The design of the regulator in this case consists of calculating the values of these coefficients to provide the required speed, accuracy and stability of the system [1–3].

This paper resolves the task of finding the methods to improve the quality of the transient process in the control system with objects prone to oscillations, which would allow excluding a large number of oscillations, a large overshoot (more than 5 %) and reversing overshoot.

## II. The Proposed Method for Solving Problems

### *A. Switching of the coefficients as a function of the derivative of the error module*

This method is based on the growth of a proposed error growth detector or improper movements' detector [1]. This detector detects a situation where the control error increases in magnitude. This can be done by analyzing the sign of the derivative of the modulus of the error or the sign of the product of errors to its derivative.

To determine these parts of transient process, an appropriate detector is necessary. It is connected to the output of the subtracting element that calculates the error of control. A variant of such detector is shown in Figure 2. The detector consists of a series-connected rectifier that calculates the module of error, the derivative link calculates the derivative of this value, and a nonlinear link that converts the analog signal to a logic one to control the switches of the commutator.

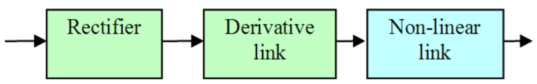


Figure 2: Detector according the first variant

Figure 3 shows another variant of such detector. It contains a derivative link that calculates the derivative of error signal, a multiplier that multiplies this derivative to the error, and a non-linear element for logic signal forming. The proposed solution to this problem is based on the analysis of transient process that splits it into two types of fragments, namely: a) at parts where the error is constant or decreases; b) at parts where the magnitude of the error increases. Each of the shown detectors can be used to identify such areas and generate a logic signal, for example, it can be a logical unit. With such detector, we proposed a system as shown in Figure 4.

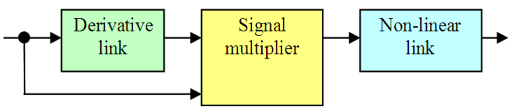


Figure 3: Detector according to the second variant

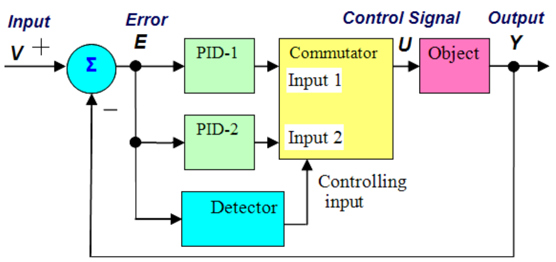


Figure 4: The proposed system structure

The proposed system works as follows. In the initial state, the switch connects to its output, hence the object input signals from one of its inputs, i.e. the output of one of the regulators, the first or the second. Thus, when the control system loop is closed by using one of the two regulators. This loop works in any system with feedback, namely the output signal of the object is subtracted from the input signal of the system, the error signal E(t) is obtained at the output of the subtractor. This error signal is converted by one of the regulators into the control signal, which is supplied through the switch to the input of the object and acts upon it so as to change its output signal in the desired direction. Due to the action of the feedback, output of the object becomes equal to the specified value (setting), which is applied to the input of the system. The detector analyzes this error signal from the output of the subtractor, and on the basis thereof generates a logic signal which controls the operation of the switching device (commutator). Depending on this signal, the signal from the commutator of the first or second input is switched to its output. The detector, depending on whether the error module is reduced or increased in size connects to the first or the second regulator. Both of the regulators are reconfigured by the methods of numerical optimization according to a software, such as VisSim.

The theoretical justification for this method can be given based on the following considerations. We call parts of the process, when the error is reduced in size, "right movements", and when the error increases, respectively, "wrong movements". Since there is a change between the "right" and "wrong", the output signal of the object in the system can be sequenced. It can be interpreted as an alternation of success and failure of the regulator. Therefore, it may be a question of correcting an unsuccessful operation of the regulator by changing its coefficients. To test the efficiency of this idea, it is sufficient to simulate such a system. In this case, both regulators can have the same mathematical models. However, they have different coefficients (gains) for each path, which are determined by the numerical optimization. If this method is not effective, then the numerical optimization procedure should give the same coefficients for both regulators because the switching of the regulators does not reduce the value of the cost function. On the other hand, if the simulation shows that the procedure produces different coefficients for the two regulators, it can be considered as a proof of the effectiveness of the method to the problem under investigation. This system can be further improved, as shown in Figure 5. The positive effect of this improvement is that it is unnecessary to switch the integrative path of the regulator. Therefore, we proposed to include this integrative path passing the commutator, directly to the input of the object, but the adder is necessary for these purposes.

The proposed system is shown in Figure 5. Taking into account the internal structure, this system is simpler than the system shown in Figure 4. In fact, as shown in Figure 5, each regulator of the system has three paths, and one adder with three inputs. Each of these regulators has only two paths and one adder having two inputs. However, the system showed in Figure 4 has six adjustable coefficients, while the system in Figure 5 has only five adjustable coefficients, as only the integrative path has constant coefficient, but not the two switching gains. Note that simplification is not a goal as itself: The traditional PID is even easier, but in the structure showed in Figure 5, a positive effect can still be achieved, which justifies this complication.

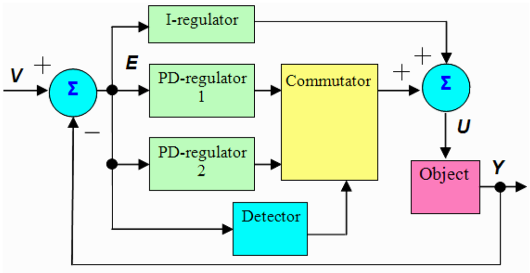


Figure 5: An improved version of the proposed system

### B. *Application of additional external loop*

This method is based on the use of the obtained output signal in the first step system, which is considered as a new complex object. The application for the object derived from the new external control system comprising an additional regulator. The structure of such a system is shown in Figure 6. The object with PID in the inner loop forms a system in which the transient process is unsatisfactory. This system is treated as a new object, and the external PI-regulator with its loop controls this complex object so that the quality of the transient process would be in line with the requirements for it.

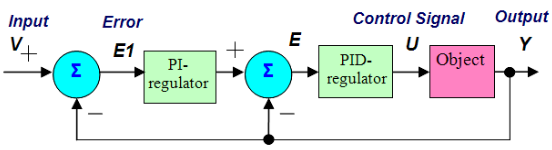


Figure 6: The structure of the system according the method of the additional external loop

## III. THE INVESTIGATION OF THE PROPOSED METHODS WITH NUMERICAL SIMULATION

### A. *Example 1*

Let us consider a linear object, which mathematical model is given in the form of the following transfer function:

$$W_O(s) = \frac{1}{s^3 + s^2 + s + 1} \tag{2}$$

Here, s is the argument of the Laplace transform, similar to the operator of derivation in the description of the object in the form of differential equations. Figure 7 shows a project for the system simulation in VisSim program, according structure showed in Figure 1. The result drawn from the system transient process in the initial stage showed a wrong direction, which is not up but down. This means that there is an inverse overshoot. Then, it goes in the right direction, but after reaching the prescribed value process, it has a small overshoot, and then again has a large value of overshooting, which is about 15%. There are oscillations with at least four distinct maximums.

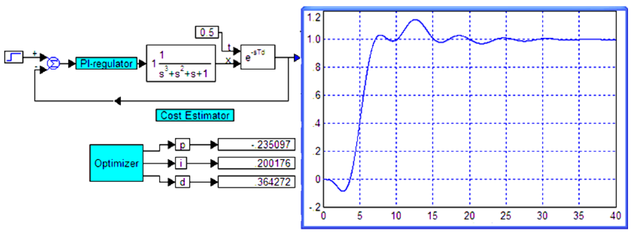


Figure 7: Structure with simple PID-regulator and transient processes in it

Figure 8 shows a project of the simulation system according the structure showed in Figure 4, which is run in VisSim program, where we used the method of switching coefficients. In this structure, there are three composite blocks: the regulator (PI-regulator), the optimizer (Optimizer) and a block for estimating a cost function (Cost Estimator). In the simulation, we used different types of regulators, not only PI-regulator, but PID also. The block name was preserved not to recast the entire project, but to make changes only by modifying the structure of the block. Figure 9 shows the internal structure of the regulator, while Figure 10 presents the internal structure of the Cost estimator, and Figure 11 shows the structure of the Optimizer. Cost estimator block has the calculator of the integral of the computer error module multiplied by the time. Further, the output of the detector's incorrect movements with the gain equals to ten is introduced under the integral. This signal is indicated by a variable "dnd". As seen in Figure 9, in the detector, the control error, indicated by the variable "e", is multiplied to its derivative by the multiplier, indicated by the symbol "starlet". The derivative is computed by the block "derivative". Product of error to its derivative from the output of multiplication block is supplied to two series-connected nonlinear elements, which are limiter and relays. Together they form the desired non-linear element, as shown in Figure 3. If the error increases in magnitude, the said product is positive. However, if it decreases in size, the product is negative. Nonlinear element converts the signal to digital signal with two possible output levels. This signal is input to the block "merge", which connects one of its analog inputs to its output, that is, it realizes the function of the commutator. The coefficients calculation is made in the optimization mode provided in the program VisSim [3].

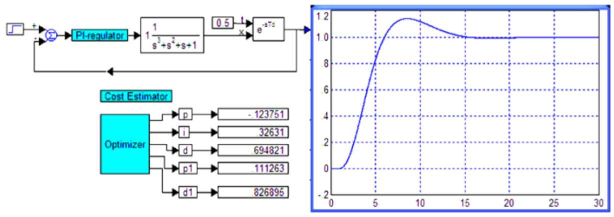


Figure 8: Structure with switching PID-regulator and transient processes in it

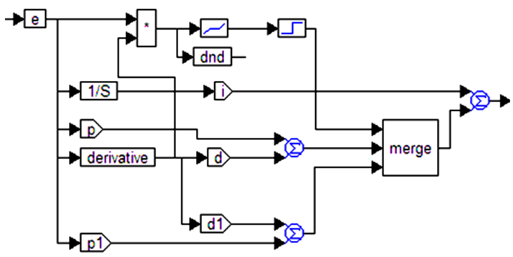


Figure 9: Structure of the block named "PI-regulator" where PID is realized

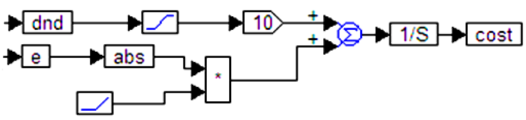


Figure 10: Structure of the block named Cost Estimator

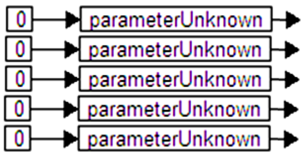


Figure 11: Structure of the block named Optimizer

The graph obtained by the system is shown in Figure 8 to the right. It can be seen that the quality of control in Figure 8 is better than the quality of control in Figure 7. Indeed, in the second case, the process is initially monotonous, until the level crosses the prescribed value. Further, there is an overshoot of about 15%, after which the process continuously (asymptotically) rushes to the prescribed value with virtually no additional oscillations.

It is also an indirect sign of the effectiveness of the proposed method since the optimization procedure gave significantly different values for the coefficients of PI-regulator: They even have different signs. These values are shown in the displays of the produced output variables. For example, a simple PID calculation gave the following coefficients of the regulator: coefficients of proportional, integrating and derivative paths are respectively $K_P = -0.235$; $K_I = 0.200$; $K_D = 0.3644$.

In the case of the system showed in Figure 8, the obtained coefficients for the first regulator are the following: $K_P = -0.123$; $K_D = 0.695$; coefficients for the second controller: $K_P = 0.111$; $K_D = 0.286$; coefficients for a third regulator is $K_I = 0.326$.

Therefore, for the above example, the method of switching coefficients that depend on the derivative module error has a positive effect.

### B. *Example 2*

Consider the object of [4]. In this paper, the linear object has a mathematical model given in the form of the following transfer function:

$$W_O(s) = \frac{s^3 + 4s^2 - s + 1}{s^5 + 2s^4 + 32s^3 + 14s^2 - 4s + 50} \tag{3}$$

Figure 12 shows the result of the system optimization s with the object according to equation (3) as well as the results of optimization of coefficients and the graphs of transients.

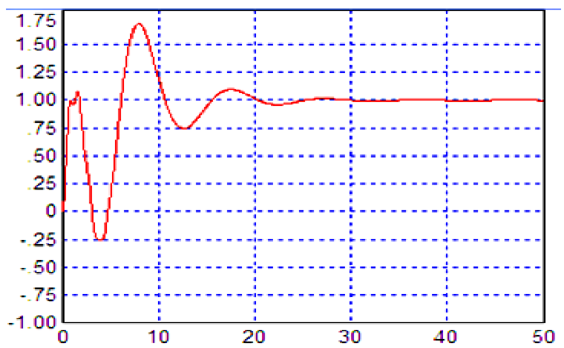


Figure 12: The result of optimization of system according Example 2

It can be seen that the transient is much worse than in Example 1. In fact, there is an inverse overshoot at 25 % of the prescribed jump, and it occurs after the output value has already reached a prescribed value of the object. If this value remains in the area of a prescribed value, the transient process would be ideal. However, the process is far from ideal since it goes in the opposite direction, and even goes to an additional 25 % further from the prescribed value than it was at the beginning of the process,.

Furthermore, 70% of overshoot took place. In general, the process has three distinct oscillations. To overcome these shortcomings, we used the method of switching coefficients, but it did not give positive results. In addition, more complex regulator was tested which contains not only a proportional, integrating and derivative paths but also the path of double derivative. Thus, PIDD-regulator was realized, or as it is called, PID$^2$-regulator. The second derivation yielded insignificant improvement. Attempting to enter third-order derivation into the regulator, as well as band-limited differentiation, not only it did not give a positive effect, but it also led to a breach of the stability of the system. Each time after the change in the structure of the regulator, optimization procedure was used, so it can be argued that these structures do not provide a noticeable improvement in the quality of the system under any values of the coefficients of the regulator.

Therefore, the second method has been applied, i.e. method using an additional external loop. Here, the internal regulator coefficients resulting from optimization have been fixed. External regulator was given as PI. The structure for modeling and optimization of this method is shown in Figure 13. It also obtained the coefficients of external regulator as well as the internal coefficients of the PID$^2$-regulator.

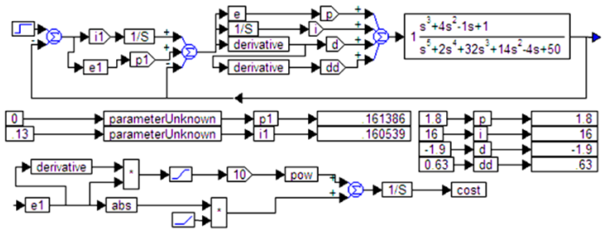


Figure 13: Structure for optimization of system according Example 2 with the use of the method of additional external loop

Figure 14 shows the resulting transients. The most rapid process with small fluctuations (blue line) is the result of the optimization of the external PI-regulator. For comparison, the figure also shows the graphs using integral regulator with the gain coefficients, respectively, 0.1 and 0.05. In all these cases, there was no inverse overshoot. In the last two cases, there was the usual overshoot too.

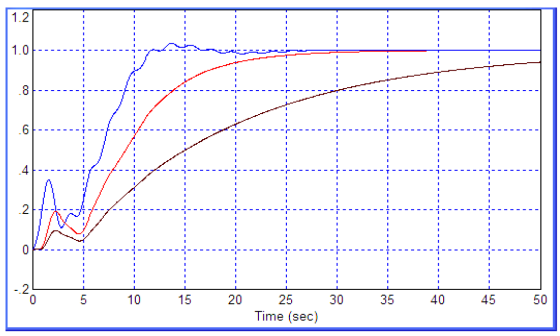


Figure 14: Transients in the system of Figure 13: blue line is process with the calculated PI-regulator, red line is this with integral control by a coefficient 0.1 and black line is this with integral controller with a coefficient 0.05

## IV. Conclusions

Reverse overshooting is a very objectionable feature of feedback control system. It means that the control loop acts in the incorrect direction at the first part of the process. For example, in the temperature stabilization system, it produces heating when the object must be cooled, and cooling when it must be heated. This means over-expenditure of energy for the control, and it can be dangerous for the safety of the object in come cases. Therefore, the removal of the reverse overshooting is the most important. The two methods has been proposed and studied to provide an effective tool to overcome the reverse overshoot. With the object of Example 2, the first considered methods did not lead to the desired result, but the second method allowed for a completely elimination of both types of overshoot and elimination of the fluctuations in the transient process. In both cases, the duration of the transient process has not been deteriorated, thus the improvement of its quality is achieved only at the cost of the complexity of the regulator, but not at the cost of the system speed. The increasing complexity of the regulator in the state of art is not important because most regulators are carried out on the basis of digital techniques, and a small change in the equations for calculating the control signals also does not complicate the system as a whole.

## Acknowledgment

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## References

[1] Zhmud V.A. 2012. Simulation Study And Optimization Of Closed Systems Of Automatic Control. Novosibirsk, Publishing House of the NSTU, 335

[2] Zhmud V.A., Frantsuzova G.A., Vostrikov A.S. 2014. Dynamics of Mechatronic Systems: Proc. Manual. Novosibirsk: Publishing House of the NSTU, 176

[3] Zhmud V.A., Zavorin A.N. 2014. Method of Designing Energy-Efficient Controllers for Complex Objects With Partially Unknown Model. Proc.: The Control And Modeling In Complex Systems. Proceedings of the XVI Int. Conference 557-567.

[4] Tan N., Derek P. Atherton. 2006. Design of PI and PID controllers. International Journal of Systems Science. 37(8):543–554.

[5] Russian Foundation for Basic Research, URL; http://www.rfbr.ru/rffi/eng.