Identification and Control of Object with Time-Delay Link

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***Abstract*—The importance of control for objects with time-delay links is very high; the rising number of control theory publications proves this case. However, the theoretical results are often very far from practical results. We can assume that the most common reason for this is fundamental simplification of the model in the system identification process. This paper presents the example of a plant from [1] to test the model's validity and its feasibility in the case of the control design with negative feedback loop. The paper resolves the stated problem by means of mathematical modeling (simulation) in program package VisSim.**

***Index Terms*—Control; Time-Delay; System Identification; Configuration of Control; Modeling; Simulation; Simulation Correctness; Model's Validity.**

I. Introduction

The importance of the tasks to control objects with delay link by means of its mathematical model is well known. For example, paper [1] has revealed the importance of above said in its introduction. The delay greatly limits the possibilities to ensure high speed operation of the control loop. Therefore, researchers have traditionally assumed that the proper calculation of the delay time and the gain values for a particular plant or object largely depends on the mathematical model accuracy. In addition to the delay, minimal-phase model of the object must describe the additional features. This part is free of delay and contains only filter in the transfer function form as the relation of the two polynomials. The simplest example of the model is a first order filter. Some authors mistakenly restrict the model with only first-order filter for the simplicity, but really, its order can be higher. Therefore, the object's simplified model can be described by means of the transfer function in the following form [1]:

$$W(s) = \frac{k}{Ts+1} \cdot e^{-\tau s} \quad (1)$$

where k is coefficient of transmission; τ is a delay time; T is the time constant. In common form, it is better to use the following transfer function description:

$$W(s) = \frac{k(b_m s^m + ... + b_1 s + 1)}{a_n s^n + ... a_2 s^2 + a_1 s + 1} \cdot e^{-\tau s} \quad (2)$$

where a_i and b_j are coefficients.

This paper describes how such a restriction, i.e. the use of Equation (1) instead of (2), is correct. The relevance of the work is due to the fact that generalization of (1) underlies in many controller tuning methods, which are still used quite often, despite their low fitness.

Small fitness of the previously mentioned methods we can see, for example, in a proposed controller design algorithm: "Controller loop setting consists of three important stages:

1. Identification of the object's model;
2. Calculation of the regulator (controller) parameters;
3. Adjustment of the regulator (controller).

The third stage is usually associated with manual adjustment of the regulator parameters, which is necessary to improve the control quality" [1]. The authors of [1] used manual adjustment after the theoretical calculation of the parameters. It is incorrect way because if there is a manual tuning then the calculation is not effective, and vice versa: if the calculation is effective, it does not require manual tuning.

We propose to use one of the following controller design methods:

1. Analytical approach
   a. Identification of the object;
   b. Calculation of the regulator (controller) parameters;
   c. Implementation of control (without adjustment).
2. Empirical method
   a. Implementation of the regulator (controller);
   b. Tuning of the control setting empirically.
3. Complex method
   a. Identification of the object;
   b. Calculation of the regulator (controller) parameters;
   c. Implementation of control (no adjustment);
   d. Identification of refined object;
   e. Clarification of the calculation of the regulator;
   f. Implementation of the adjusted regulator.

The proposed method in [1], in our opinion, is not correct not because it does not fit to any of the above proposed schemes, but by the fact that the parameters calculation shall not make any difference and, therefore, the identification does not matter, so essentially it is an empirical method. Our study focuses on the analysis of the impact of unrecorded features of a real object, not included in the model (1).

II. Analysis of The Object's Properties

The paper [1] proposed the method to determine the transfer functions of the objects, based on the ramp, its form for the selected object is shown in Figure 1. In this case, it is a priori assumed that the object model is sequential connection of an aperiodic and delay links.

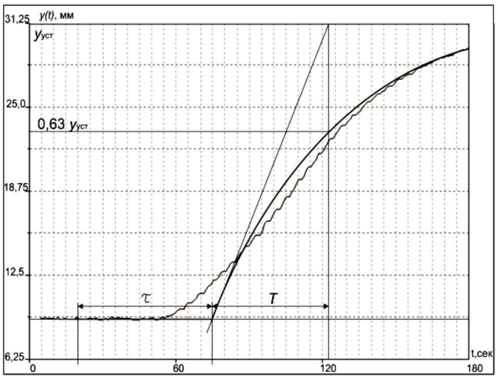

Figure 1: Acceleration curve as a reaction to the stepwise input action delayed on 40 c [1]

Acceleration curve is a response to the single input step at the object. The minimum-phase component of the model provides the transient process in the form of an exponential function. Asymptote's value of this function as asymptote's value of acceleration curve tends to the gain's value of the object. On Figure 1, asymptote apparently tends to the value in the maximum value of the scale, which is approximately 31 units. From this, it follows that the input signal was not equal to one and authors have forgotten to consider object's gain. Because later in this paper the gain of object is everywhere unity, it is advisable to take the first version, assuming the coefficient referred to the magnitude of the input step jump.

The authors of the paper [1] have determined the following transfer function from the graph in Figure 1:

$$W(s) = \frac{1}{47s+1} \cdot e^{-55s} \tag{3}$$

They also mentioned that from the relation τ / T < 1 we must assume some difficulties in the regulator tuning by the traditional methods.

The results of using the calculated regulator by the model (2) in [1] differ from the results of simulation, predicted those.

Let us try to understand the reasons for this discrepancy. We pay attention to the difference between the two graphs – theoretical and experimental ones in Figure 1. These differences are:

1. Experimental process begins smoothly, without sharp break of the line, but the theoretical process begins abruptly with a characteristic line break.
2. Experimental process begins at t = 55 s, and theoretical process begins at t = 75 s.
3. The point of the first matching of experimental and theoretical processes is about t = 85 s.
4. Further, the magnitude of the experimental process is less than this of the theoretical one, the maximum deviation is about half the division (the whole process tends asymptotically to the value relevant to seven divisions), the maximum deviation corresponds to the time t = 100 s.
5. In the experimental process, there are high frequency small oscillations, which do not take into account in the theoretical calculation.
6. The amplitude of the aforesaid oscillations are generated by the insufficient stability merge, increases with the growth of the output signal derivative; at a low rate of change of the output signal these oscillations decreases their value.
7. Upon reaching the time t = 180 s, the both processes become almost equal to each other, however, this does not mean that they continue to match further, although this is not excluded. The further process does not exist.

The reason for the overall progress of discrepancy obviously lies in high-order model's insufficiency.

Firstly, we try to use the second order model, for example, in the form of the following two sequentially connected filters of the first order. At the same time, by reducing of the pure delay and by choosing of new values of the time constants we can achieve the desired progress in control. Figure 2 shows a structure for the simulation of this process and the process itself obtained as compared to the output process, using model from the Equation (2). In addition, circuit with feedback on the stability bound state is introduced into models to provide a simulation of small oscillations, which can be seen in Figure 1.

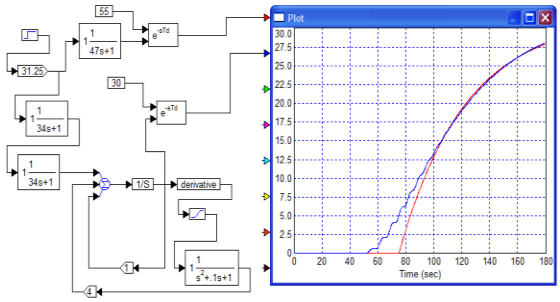

Figure 2: The structure for simulation of the object and the results compared with the model by the relation (2): a process model (2) - the red line, the process in model in the first iteration - blue line

An analysis of the graph in Figure 2 shows that it is more similar to the experimental process shown in Figure 1 but it is still not enough corresponds to it. Namely, conditions 3, 4 and 6 are not performed.

To ensure the conditions 6, we made fluctuations dependent not on the magnitude of the signal but on its derivative. For this purpose, we use the filter, estimating a derivative, and supply at its output the "dead zone" element with the bandwidth equal to one. With all this, we introduce the oscillation signals to the main path. The weighting factor is equal to five, KW = 5, has been matched experimentally with some margin, in accordance with the development of the ideas formulated in [3], according to which it is better to use the worse object model when calculating the regulator, than improved one. Therefore, in case of doubt, we choose the worst-case scenario, actually it would be sufficient to use a coefficient equal to two, KW = 2. In order to ensure conditions 3 and 4, we use the model in the form of three first order filters, i.e. increase the order of the object from the second to the third.

Figure 3 shows the corresponding object model with all the changes. The new value of the time constant and the new delay were chosen experimentally for a better match of the curve with the experimental process.

Figure 4 shows the resulting transient process in the new model (blue line) in comparison with the process to the model (3) (red line).

It is evident that now match the two graphs shown in Figure 4 with the two graphs shown in Figure 1, is quite correct. The red graph in Figure 4 coincides with the corresponding graph in Figure 1 due to the identity of their models and inputs, so you can use this curve as a reference for the analysis of the second curve, which is blue.

Differences between blue graph (Figure 4) and the red graph in the same figure close enough to the difference between the experimental curve shown in Figure 1 from the theoretical curve in the same figure. Therefore, we can conclude that the model shown in Figure 3 and its transient process (blue graph in Figure 4), is much more consistent with the experimental behavior than the model from the Equation (3).

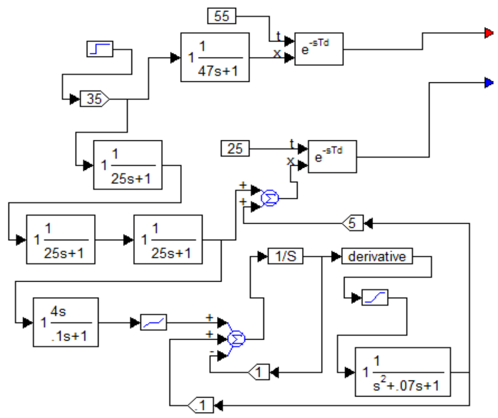

Figure 3: Structure of the second iteration of the simulation model (blue output), as well as reference model (3) (red output)

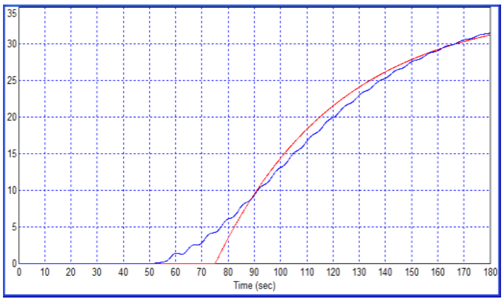

Figure 4: Transient processes obtained at the second iteration of the simulation model (blue output), as well as output of the reference model (3) (red output)

III. CALCULATION OF PID-REGULATOR FOR THE OBTAINED OBJECT'S MODEL

The paper [1] shows the experimental transient processes, however, there is not scale on the time axis of these processes, so the use of these processes to compere the practical results with the theoretical ones is not feasible.

For the calculation of robust regulator, we used the technique proposed and developed in [2], based on the numerical optimization. For this purpose, we use the structure shown in Figure 5.

Figure 6, 7 and 8 show the structures of the blocks Regulator, Optimizer and Cost Estimator (note that the structure of block Regulator corresponds to the PID-regulator).

The transient process in the system is shown in Figure 9. Appointment of standard blocks parameterUnknown is clear from any textbook on VisSim, for example [1]. These blocks carry out the search optimal output values that gives minimal resulting value of the cost function, which is calculated in the block Cost. These blocks work together in the optimization mode, and the number of parameterUnknown blocks can be several, but block Cost must be the only one. Block derivative in the structure in Figure 6, calculates the time derivative of the input signal.

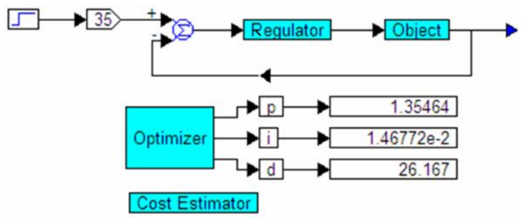

Figure 5: Structure of the system for the optimization of regulator

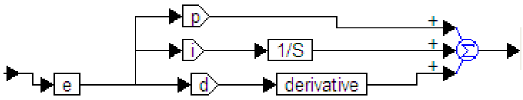

Figure 6: Structure of block *Regulator* in the system according to Figure. 5

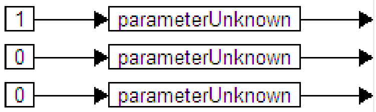

Figure 7: Structure of block *Optimizer* in the system according to Figure 5

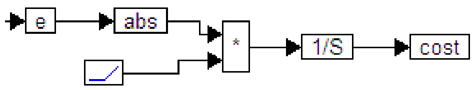

Figure 8: Structure of block *Cost Estimator* in the system according to Figure 5

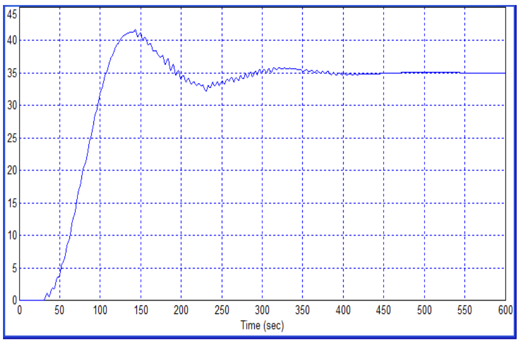

Figure 9: The transient process in the system of Figure 5

IV. ROBUST PID-REGULATOR CALCULATION

Patent [3] gives recommendations for the robust controller calculation. The essence of it is to ensure that it is necessary to increase the intentional delay in the model used to calculate the regulator. Then the real object will be steady with regulator obtained for such model. The authors of the paper [1] have defined delay equal to 55 s, we take this value with the reserve, namely: use of 60 s.

We get the following setting in the result of optimization procedure: KP = 0.85; KI = 0.009; KD = 37.6. Figure 10 shows transient process with said deteriorated object model.

In it the contribution coefficient is KW = 5 and the delay is taken τ = 60 s.

It is evident that the transient process on the whole is stable, steady-state error is zero on average due to the action of the integrating circuit, but there are flashes of high frequencies in the process because of stay at the border of sustainability. Figure. 11 shows the same process in the case where the contribution rate KW = 2. Flash of the generation decreased to a negligible value. It is significant that in the paper [1] the tendency of the object to the oscillatory excitation was not discussed and is not considered in the model.

Figure 12 shows the same process in the case where the contribution rate KW = 5 and τ = 25 s. System is also stable, oscillations fade with the time.

Figure 13 shows the same process in the case where the contribution rate KW = 2 and τ = 25 s. System is also stable with the good reserve of stability, oscillations are absent. This process describes the real system because real results of the object identification on the base of the acceleration curve according Figure 1 were used for its calculation.

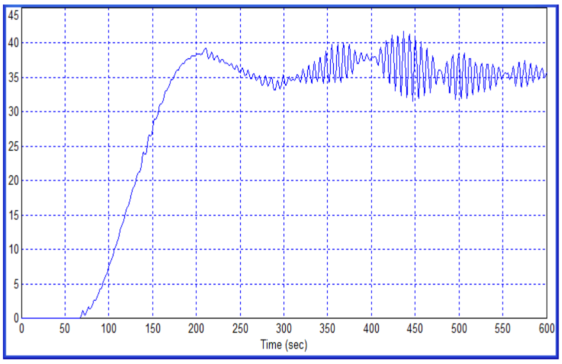

Figure 10: Transient process in the system with the calculated PID-regulator when $K_W = 5$, $\tau = 60$ s

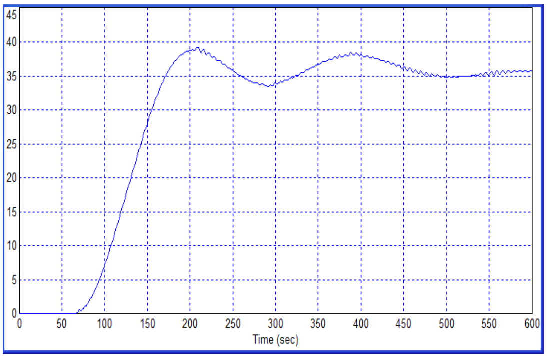

Figure 11: Transient process in the system with the calculated PID-regulator when $K_W = 2$, $\tau = 60$ s

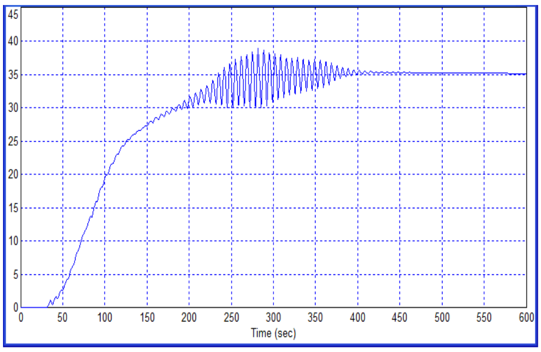

Figure 12: Transient process in the system with the calculated PID-regulator when $K_W = 5$, $\tau = 25$ s

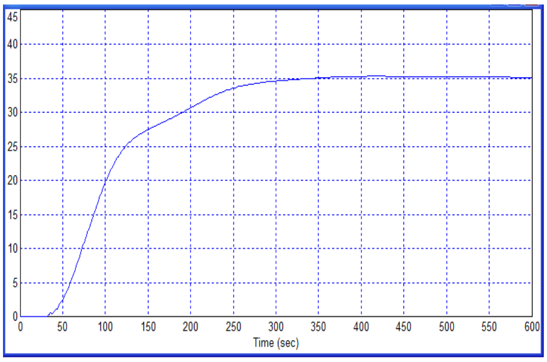

Figure 13: Transient process in the system with the calculated PID-regulator when $K_W = 2$, $\tau = 25$ s

Figure 14 shows transient process in the system with the calculated PID-regulator where KW = 2, and delay changes from τ = 25 s to τ = 65 s. In all cases, it is stable, so the calculated regulator is robust.

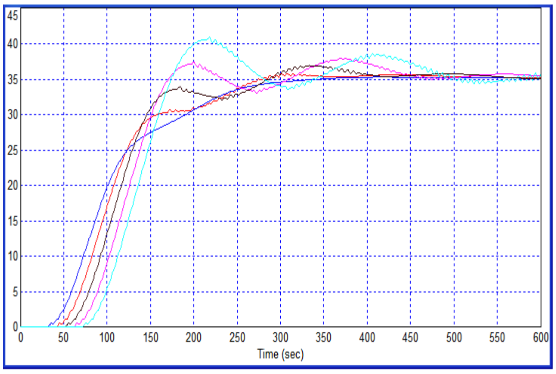

Figure 14: Transient process in the system with the calculated PID-regulator when $K_W = 2$, and delay changes from $\tau = 25$ s to $\tau = 65$ s

Finally, we apply the resulting object model to control object with the model according to the equation (3), which is proposed in [1]. The result of such way is shown in Figure 15.

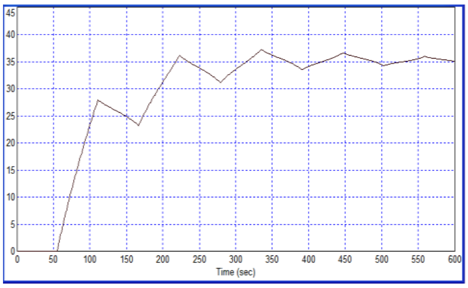

Figure 15: Transient process with the control object according the model in by the Equation (3)

It is evident that in this case, the system remains stable, although the transient process is characterized by sharp jumps of the derivative. This feature is derived from the object model (3), which can be seen in the graph of Figure 1, since this feature is not present in the real object. So it is reasonable to propose that system with the real object will not have such feature.

Thus, it can be assumed that the object specified by the acceleration curve according to Figure 1, successfully identified, and designed on the basis of this identification regulator fits to the control task most adequately. It is expected that the regulator does not require additional tuning after its implementation.

V. Conclusions

Based on these investigations, the following conclusions can be made:

1. Identification of the object on the base of the accelerating curve shown in Fig. 1 can be made more accurately than proposed in [1] model (3). The most accurate model is given by:

$$W(s) = \frac{1}{(25s+1)^3} \cdot e^{-25s} \quad (4)$$

2. We can recommend the use of the following model for the optimization procedure:

$$W(s) = \frac{1}{(25s+1)^3} \cdot e^{-60s} \quad (5)$$

It allows you to calculate the regulator providing a stable transient process with a sufficient phase margin of stability, which allows it to define the system and the regulator as robust ones.

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