Model-free PID Controller Autotuning Algorithm Based on Frequency Response Analysis

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ABSTRACT

PID controllers are the most popular group of controllers in practical applications. Many theoretical techniques and procedures have been developed for PID controllers with the aim to optimize the function of the control circuits. However, these techniques are seldom applied, except in cases where there are some extreme requirements for the safety and the operational quality of the control loops. Even autotuning of controllers, which some producers have been offering for a quite long time, is not exploited as it might be. There are several reasons for this unsatisfactory state of affairs, one of which is the necessity to master a difficult theoretical background, often requiring perfect models of the dynamics of the controlled process. In this paper, using a laboratory set-up in model representation and also in physical representation, we will discuss some of these reasons in a confrontation with the new idea of performing controller autotuning without knowledge of the controlled plant model.

Keywords: PID controller, oscillation, control quality indicator, harmonic oscillation, model-free

1. INTRODUCTION

Generally, control algorithms are characterized by various levels of complexity. The algorithms that they use can be divided into two groups: algorithms that contain built-in autotuning features, and the algorithms without autotuning features. The most-used controllers usually use algorithms without autotuning features. The simplest controllers are two- or three-state controllers, usually implemented as a two- or three-state relay. PID-type controllers are more advanced than two- and three-state controllers. In addition to standard PID controllers, some alternatives of this algorithm are offered e.g. PID controllers with two degrees of freedom, fuzzy PID controllers, and fractional PID controllers.

PID-type controllers are the most used in almost all industrial branches [2]. It is easy to explain why they are favoured so much, even when there are many better algorithms in existence, and a new or improved algorithm emerges almost every month (recent improvements include control error reference course control [15] and the matrix PID controller [10]). The reason is that the PID controller is easy to implement. No deep mathematical theory is necessary to understand how the PID controller works, so everybody is able to imagine what is happening inside the controller during the control process [16].

In situations when there are high demands on control process quality, especially in cases when the complex dynamics of the controlled processes is extremely difficult to master, model-free PID controllers are usually not sufficiently powerful control tools. Then, it is necessary to implement control algorithms designed on the basis of a more detailed knowledge of the controlled plant dynamics. Control with a state variable feedback is an example of such advanced algorithms. The results of controllers based on the use of state variables are usually much better than the results with other types of controllers; this is because state controllers work as controllers in multiple feedback loops. Many other advanced control algorithms are designated for controlling processes with a time delay [23]. A special group of controllers are those based on neural networks, genetic algorithms and other artificial intelligence tools and combinations of tools [4].

The weakness of standard PID-type controllers in comparison with model-based control algorithms, i.e. the absence of autotuning features inside the control algorithm, can be removed by adding an external tuning algorithm. Many tuning algorithms have been presented [3], [5], [9], [12], but they are mostly based on a model of the controlled process/device. This is an unsatisfactory situation, because industrial practice prefers control algorithms and tuning methods that do not need any model of the controlled process or device. As a result, the more than 50-year-old Ziegler-Nichols me-
method [22] and its derivates, such as the Chien-Hrones-Reswick method and the Cohen-Coon method, are still in use. Nowadays, the relay method [1], [8] is becoming popular. Many modifications have been made to the relay method to improve some of its properties, usually by adding a second relay [6], [11] or by adding an integrator [17] into the loop, but the basic variant is the most widely used [21]. Industrial controllers are usually equipped with this method as a pre-tuning tool, because the method needs the control process to be stopped temporarily. Special cases of controllers equipped with autotuning features are those produced by Honeywell, equipped with the Honeywell Loopcote Algorithm, and those produced by Foxboro, equipped with the Foxboro Exact Algorithm. However, exact details about how they work are not published - some knowledge has, however, been obtained by reverse engineering.

The reasons mentioned above have motivated us to develop a new autotuning algorithm for PID-type controllers that does not use a model of the controlled plant and that does not need to break the control function when the controller parameters need to be changed. These positive properties are balanced by the fact that the algorithm is not suitable for rapid controller adaptation, because time is taken to achieve an optimal setting when tuning it. This not a very disturbing consideration if the controller needs to be retuned after a certain operational time when the control process is not necessary to be stopped.

2. PRINCIPLES OF THE PROPOSED AUTOTUNING

For any autotuning method, it is important to describe somehow the changes in the control loop behaviour which are to be compensated by correcting the controller setting. Among all experimental ways to identify the current dynamic properties of the controlled plant, preference is mostly given to the following two, both of which evaluate the time responses to a defined input excitation. The first way assumes the use of step responses, while the second evaluates the responses to a harmonic signal, which are processed in dynamic characteristics known as frequency responses. The use of step responses usually focuses on obtaining the step response of a controlled plant alone, and therefore the control function of the control circuit must interrupted by disconnecting the controller. During the experiment all inputs, except the input which has changed stepwise, must be kept at constant steady values. These conditions are difficult to ensure, and for this reason an evaluation of frequency responses is preferred in autotuning procedures. There is no problem in obtaining the frequency response of the controlled process just from measurements performed in the closed control loop. Autotuning, which is able to set the optimal parameters of the controller without breaking the control process, is of course preferred [14].

The principle of the autotuning method presented here is based on tools provided by linear theory [7], especially on one of the tools - control quality indicators. In linear theory, the control quality indicators are connected with the Nyquist plot [18]. The two most-known control quality indicators are the Phase Margin and the Magnitude Margin. In the proposed tuner, the control quality indicators are evaluated from the frequency responses obtained by experiments in real closed control circuits. If the control circuit is excited by a harmonic excitation signal added to the control error, it is possible to evaluate from the response to this excitation in the closed control loop the magnitude and phase shift of the oscillation, as if it was obtained in the open loop. Changing the frequency of the excitation and setting the controller allows us to achieve the recommended optimal values of the open-loop control quality indicators [19]. The measure in which the controlled process is disturbed can be influenced by setting the size of the amplitude of the added harmonic signal. The only condition is that the response to the added harmonic signal must remain measurable.

More details about model-free frequency-based autotuning based on control quality indicators evaluated from frequency response analysis are published in [20].

3. TESTING DEVICE

Figure 1 - Scheme of a Three-Tank Cascade

A laboratory model of a Three-Tank Cascade was used for testing the algorithm. The scheme of the cascade is shown in Figure 1. Water is supplied into tank one and tank three. Each tank is equipped with a pressure sensor that is used for measuring the water level. In addition to
the mutual interconnection, each of the tanks in the cascade has its own outlet valve, enabling various operation modes with different dynamics to be simulated. All valves in the laboratory model are adjustable only manually.

The laboratory model is controlled by a WinPAC programmable automation controller equipped with Rex control software. This software also offers RexLib library, containing all function blocks of Rex control software for the Simulink toolbox of the Matlab program. This allows us to separate the tuning algorithm from our own control algorithm which, together with a harmonic signal generator, is executed in WinPAC. The tuning algorithm can then be executed directly in Simulink, where both new values of the controller parameters and requests for changes of the harmonic excitation signal frequency are computed.

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**Figure 2** - Block scheme of algorithm splitting

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The Ziegler-Nichols method of critical oscillation

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The relay method

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Figure 3 - Ziegler-Nichols method of critical oscillation autotuning experiment (manipulated variable $q_1$ depicted after dividing the values by 10)

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Figure 4 - The relay autotuning experiment (manipulated variable $q_1$ depicted after dividing the values by 10)
4. RESULTS OF EXPERIMENTS

The features of several methods were tested and compared by means of the Three-Tank Cascade laboratory setup in the configuration depicted in Figure 1. The autotuning features are simulated in the following sequence: first, using changes in the controller setpoint, the water level in Tank 2 is increased by \( \Delta h_2 = 0.1 \text{ dm} \), and then it is decreased back to the initial height. During the second phase, the controller is tuned, and, finally, the same experiment as in step one is repeated, but with a new controller setting after autotuning.

Five methods were tested: the new model-free frequency-based autotuning, the critical setting according to the Ziegler-Nichols method, the Ziegler-Nichols step response method, the relay method, and the momentum method [13].

The methods were tested from the following viewpoints:
- first, what are the differences in the achieved “optimal” controller parameter values, and what are their impacts on the control responses, and
- second, what will happen if a disturbance occurs, or how is the control function restricted during the period of controller tuning.

Figures 3 to 7 show the results of this test. There are clear differences in the achieved controller parameter values according to the tuning method, and their impact on control quality is evident. Only the settings obtained by the Ziegler-Nichols method of critical oscillations and by the relay method are similar to each other. This was to be expected, because the relay method is just another way to
invoke critical oscillation, and then the setting follows the Ziegler-Nichols rules. All methods differ in the time needed for controller tuning. The time needed for tuning is a characteristic sign of the quality of a tuning method. Even tuning methods providing a good controller setting can be considered worse than methods that provide less good results (still better than without any tuning), but that achieve them in a short time. Another important attribute is the possibility to make an automatic evaluation of the response. It is easier and less memory-consuming to detect peaks in the response to a harmonic signal than to find an inflection point in a step response and to compute the parameters of the tangent at this inflection point, especially in cases when the type of step response changes with the change in operating point. Finally, it is easier to evaluate the integral of the pulse response than to evaluate a frequency response.

Use of the Ziegler-Nichols method of critical oscillation and the relay method lead to oscillating responses, while use of the Ziegler-Nichols method, the momentum method, and the model-free frequency-based method lead to non-oscillating responses. Generally, oscillating responses are not totally excluded, but in this case, such a result leads to excessive wear of the actuating device. The main disadvantage of the new model-free frequency-based autotuning presented here, in comparison to the other methods, is that the new algorithm takes much more time to obtain the optimal controller setting.

There is one important consideration that the figures do not show sufficiently clearly: new model-free frequency-based autotuning is the only tuning method among those tested here that does not require disconnection of the controller or any degradation of the control function during tuning. This means that the tuning process is safer, and can be applied in real conditions. The momentum method, the Ziegler-Nichols step response method and the relay method perform experiments only with the controller disconnected from the controlled plant, i.e. the controlled plant is totally uncontrolled during tuning. In the Ziegler-Nichols method of critical oscillations, the controlled plant is brought into oscillations with an unpredictable amplitude size. As a result, these methods should be used preferably in tuning which is under manual control of the operator. A further limiting factor that has not been mentioned is the restriction of the Ziegler-Nichols step response method and the momentum method to plants with non-oscillating step responses.

5. CONCLUSIONS

The new model-free frequency-based PID controller tuning method that uses control quality indicators has been presented not only in terms of its operating principles, but mainly in terms of the experience obtained during its implementation and testing. From this testing, in which the controlled plant was represented by various kinds of models (linear, nonlinear, physical), we chose testing based on the simulation model of a real physical laboratory model, reflecting all essential nonlinearities and data of the laboratory model, with emphasis on modeling all the details corresponding to the real application. This consideration is very important, because only if we reflect all real conditions under which autotuning starts and runs is it possible to make a serious and useful comparison of various approaches and of autotuning efficiency. This is what is often missing in the literature.

Figure 7 - Frequency-based autotuning experiment (manipulated variable $q_1$ depicted after dividing the values by 10)
A significant advantage of a controller equipped with the proposed model-free frequency-based autotuning method is that the controller is fully serviceable during tuning. In contrast to the other tuning methods, where the operator cannot influence the controller setting obtained by these methods, the model-free frequency-based method also allows the operator to change the criteria and their optimal values at any time, if the response does not satisfy the expected course.

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6. REFERENCES