Zpětnovazební rychlostní regulace pneumatického vřetena (Pneumatic Spindle Feedback Speed Control)

Ing. Petr Konečný

Vedoucí práce: Doc. Ing. Jaroslav Rybín, CSc.

Abstrakt
Práce se zabývá problematikou rychlostní regulace pneumatického vřetena. Zejména se věnuje aplikaci různých typů PID regulátorů ve zpětnovazební regulaci rychlosti. Podrobně jsou popsány jednotlivé vlastnosti různých algoritmů PID regulátoru a jejich vliv na regulovanou soustavu. Prvním krokem je matematická simulace jednoduchého PID regulátoru a následně je provedena implementace několika typů PID regulátorů do PLC, které zajišťuje úlohu řízení rychlosti vřetena a sledování jejich chování při simulaci regulovaného děje.

Klíčová slova
rychlostní regulace, zpětná vazba, PID regulátor, pneumatické vřeteno

1. Introduction

Proportional-Integral-Derivative (PID) controllers have already been used in industrial applications for decades. The reason for this fact arises from simplicity of PID controller, simplicity by means of both theoretical design and practical application. What also adds to preferring PID controllers before others is their good performance even in complicated non-linear processes. All these reasons lead to a decision of using the PID controller for the task of governing desired speed of pneumatic spindle and keeping the speed constant in various conditions exploiting a feedback loop. The pneumatic spindle itself (see Fig. 1) is a product of research and engineering work of specialists in Research Center of Manufacturing Technology (RCMT) at Czech Technical University (CTU) in Prague (see [1], [2] and [3]).
This paper deals with a problem of choosing an adequate PID controller that will be used to control the speed of the spindle. Using modern technology we have number of options of how the actual PID controller will look like. In this case the controller algorithm will be implemented in a Programmable Logic Controller (PLC), therefore the form of PID controller is going to be digital, which means the optimal PID controller algorithm is being sought after. Advantages of different forms of PID controllers are going to be discussed and reasoned for use in pneumatic spindle speed control.
As mentioned above the pneumatic spindle resulted from work in RCMT. For further investigation into spindle's properties a testing platform has been constructed (see Fig. 2).

2. Pneumatic Spindle Speed Control

When designing spindle speed control (see [4]) there are two main ways to be taken into consideration. These are direct control (open-loop) and feedback control (closed-loop).
Whereas the first option offers a very simple solution of design as well as of practical solution it doesn't provide very satisfying results. The direct control has no ability to influence the behavior of controlled process in any way. Under load the spindle's RPM (revolutions per minute) decrease rapidly which is undesirable due to technological requirements. This type of control is therefore not suitable for governing spindle speed.

Fig. 1. *Pneumatic spindle V1*

The other kind of control, the feedback control, offers much better results when constant speed under load is required. Closed-loop control design however needs more sophisticated approach than direct control. Even practical solution takes more resources than open-loop. Despite its complexity feedback control has been chosen to regulate spindle speed for technological requirements to be met.

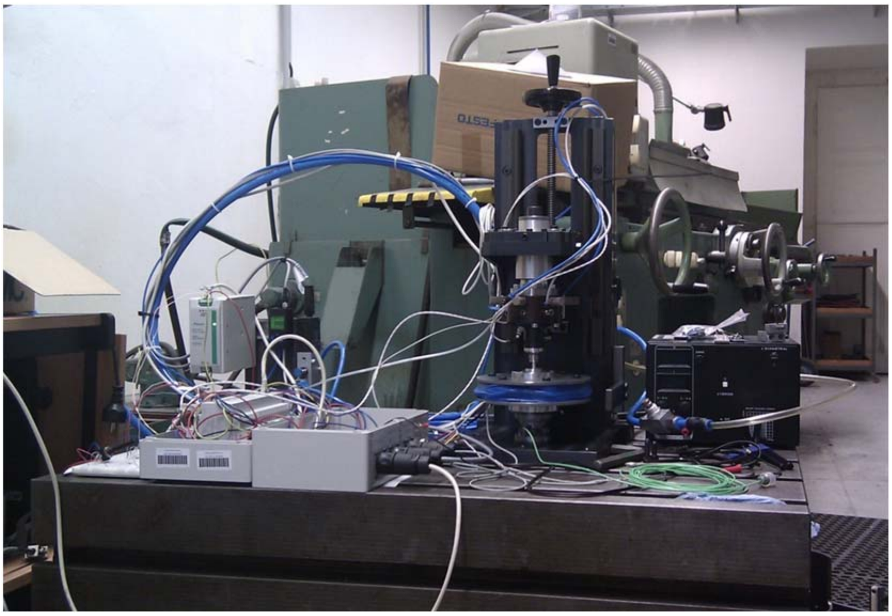

Fig. 2. *Testing platform*

To design a feedback control we need to carry out a mathematical analysis and assess a model to describe our system's behavior. We can see a simplified model in Fig. 3

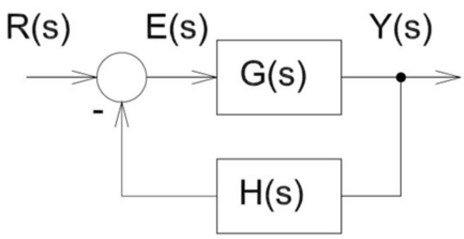

Fig. 3. *Feedback control scheme*

Conducting mathematical analysis of feedback control has been described in [5]. Most importantly we have to calculate the output of the closed-loop system

$$Y(s) = \frac{G(s)}{1 + G(s)H(s)} R(s) \tag{1}$$

where

Y (s) Output variable in Laplace domain
G (s) Process variable in Laplace domain
H (s) Feedback variable in Laplace domain
R (s) Input variable in Laplace domain

Determining the mathematical model of the whole system is necessary to estimate parameters that will affect behavior of the feedback speed control. Our system can be represented by a model in Fig. 4.
By observing results of a solution provided by the mathematical model for different parameters we are able to estimate the correct value of the parameters. The conditions under which the system should operate are described in [6].

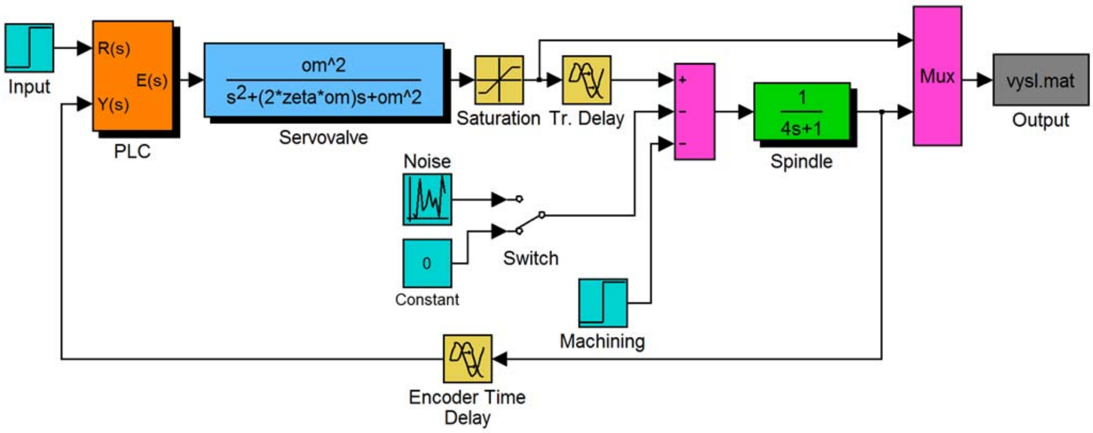

Fig. 4. *Mathematical model of the whole system*

Behavior of the system depends mostly on correct setting of PID controller parameters. After some manual tuning we have found out that the best step response of the system is obtained with the following parameters:

Table 1. *PID controller parameters after manual tuning in Simulink*

Proportional gain $\mathbf{K_P}$	Integral time constant $\boldsymbol{\tau_i}$	Derivative time constant $\boldsymbol{\tau_d}$
5.0	0.5 s	0.2 s

The response of the model to a step input when applying the determined parameters can be seen in Fig. 5.
In practice the feedback needs a measurement of the spindle's output. This is done using an inductive encoder attached inside the spindle's body. The "brain" of the whole system is a programmable logic computer (PLC) that acts as a PID controller and also processes the encoder output and compares it to the desired spindle speed thus creating a feedback loop.
As it was mentioned above the parameters of PID controller affect the behavior of the system it is also very important what type of PID is chosen for the task. Particularly this issue is the main aim of this work.

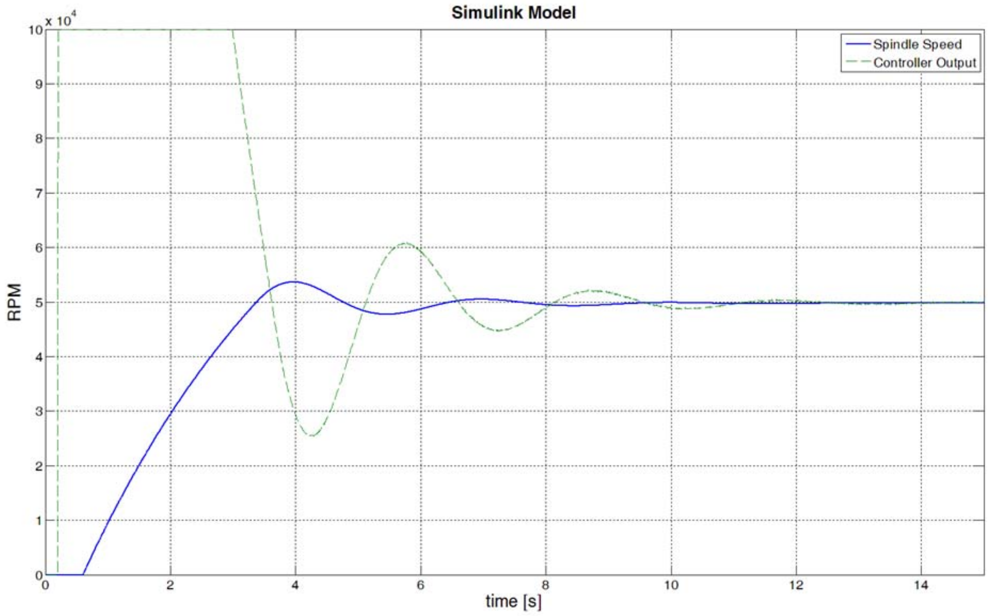

Fig. 5. Mathematical model step response

3. Simple PID Controller

The type of PID controller that has been formerly used in the PLC program is a simple (one degree of freedom (1DOF)) PID controller. Its mathematics and use are well described in [7] and the function can be understood from Fig. 6.

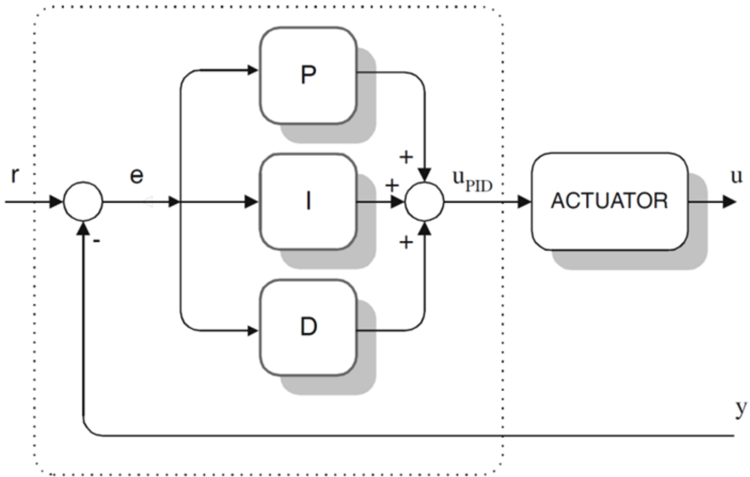

Fig. 6. Simple PID controller scheme

Mathematically the behavior of such a controller can be described as:

$$u(t) = K\left[e(t) + \frac{1}{\tau_i}\int_0^t e(t)d\tau + \tau_d \frac{de(t)}{dt}\right] \tag{2}$$

It can be seen that all P, I and D channels react on the error signal. It is however much more convenient to possess means of routing the error signal particularly for each component of PID controller. We will see further that this can be achieved when using a two input (two degree of freedom (2DOF)) one output PID controller.

For simulation purposes we can obtain a mathematical model in Simulink (see Fig. 7). Note the filter attached after derivative component. The derivative component of PID controller can add noise to output and it is therefore vital to filter it out using in this case the first order filter.

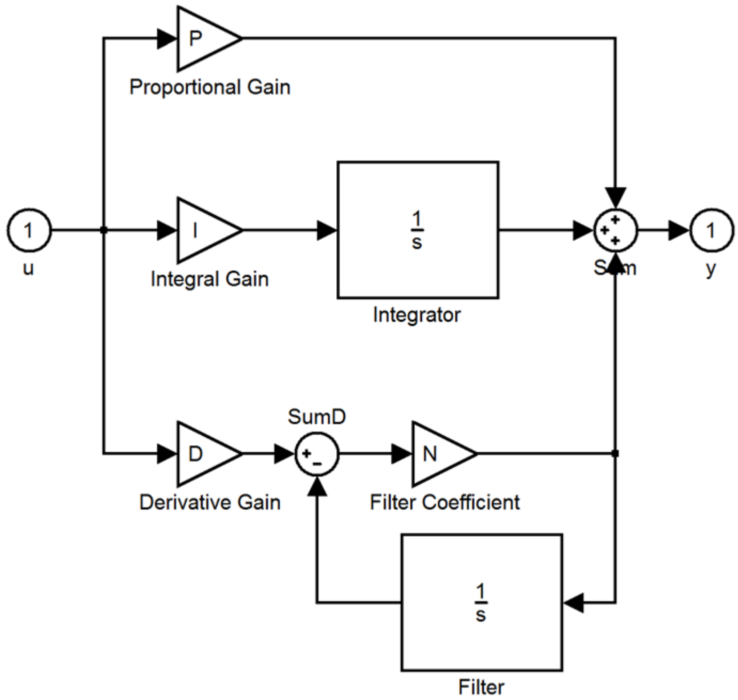

Fig. 7. *Simple PID controller in Simulink*

After assembling and seeing how the mathematical model works we have to implement a controller's algorithm in a PLC main program. PLC that is used for purposes of governing our pneumatic spindle speed is by TECO a.s. company. Their PLCs are being programmed in a software environment called Mosaic. We can use Mosaic's built-in control libraries and apply programming method of function block diagrams (FBD). In Fig. 8 we can see the whole feedback speed control expressed in form of FBD.

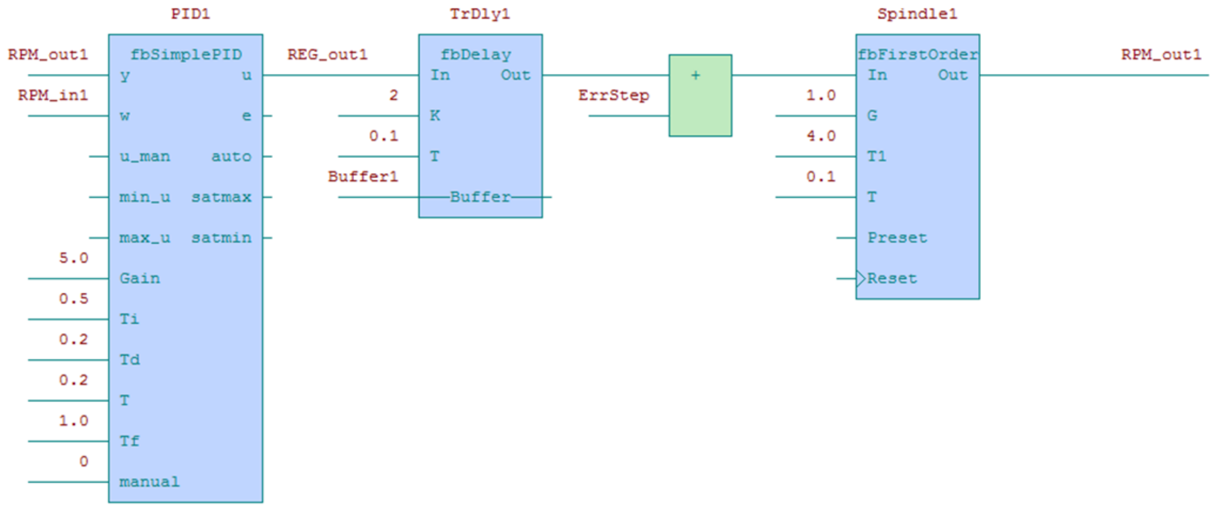

Fig. 8. *Feedback speed control with simple PID in Mosaic*

The system has been simulated using parameters from Table 1. Step response is shown in Fig. 9.As for now we can conclude that it matches simulated mathematical model from Fig. 5.

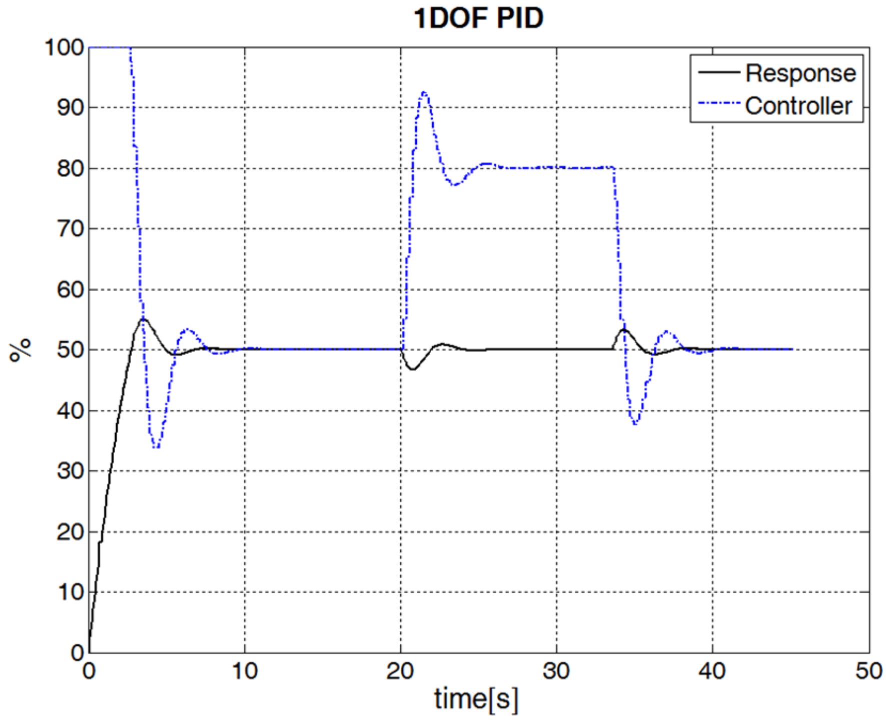

Fig. 9. *Simple PID simulated control loop with step response in Mosaic*

We will see later that we can improve the response just by using a different type of PID controller set to the same parameters. In addition we can see a unit disturbance response in Fig. 9. This can also be improved by another controller type application.

4. 2DOF PID Controller

Another more advanced type of PID controller is represented by a 2DOF PID controller. Its advantages and use description can be found in [8]. In the simplest way we can think about a 2DOF PID controller as of a 1DOF controller with an additional feedforward compensator (see Fig. 10). This feedforward loop brings another input into the system, hence we have two inputs and that's why this type of controller is called a two input or two degree of freedom PID controller.

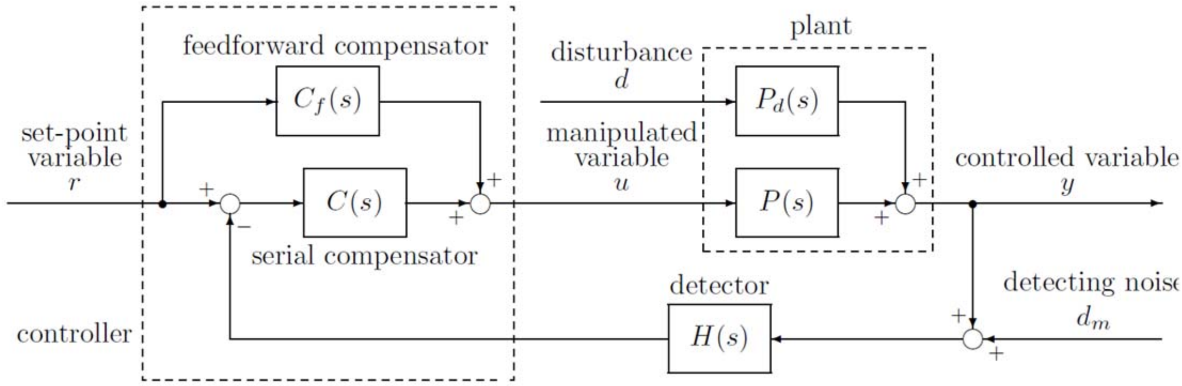

Fig. 10. *Basic scheme of 2DOF PID controller*

From (8) we can learn that the controller consists of two compensators $C(s)$ and $C_f(s)$, and the transfer function $P_d(s)$ from the disturbance d to the controlled variable y is assumed to be different from the transfer function $P(s)$ from the manipulated variable u to y. $C(s)$ is called the serial (or main) compensator and *Cf (s)* the feedforward compensator. The closed-loop transfer functions from *r* to *y* and *d* to *y* are, respectively, given by

$$G_{yr2}(s) = \frac{P(s)\{C(s) + C_f(s)\}}{1 + P(s)C(s)H(s)} \tag{3}$$

$$G_{yd2}(s) = \frac{P_d(s)}{1 + P(s)C(s)H(s)} \tag{4}$$

It can be shown that the steady-state error to the unit step change of the set-point variable, *ε r*, step, and the steady-state error to the unit step disturbance, *ε d*, step , become zero robustly if equation (5) imposes conditions on the controller.

$$\lim_{s\to 0} C(s) = \infty, \lim_{s\to 0} \frac{C_f(s)}{C(s)} = 0 \tag{5}$$

$$\lim_{s\to 0} H(s) = 1 \tag{6}$$

$$\lim_{s\to 0} P(s) \neq 0, \lim_{s\to 0} \left|\frac{P_d(s)}{P(s)}\right| < \infty \tag{7}$$

The simplest case that satisfies these conditions is the one that *C(s)* includes an integrator and $C_f(s)$ does not. (6) requires that the detector is accurate in the steady state.

Considering that the major advantage of the PID controller lies in its simplicity, it was proposed to include only the proportional and/or the derivative components in $C_f(s)$. In this case, *C(s)* and $C_f(s)$ are given by

$$C(s) = K_P\left\{1 + \frac{1}{\tau_i s} + \tau_d s\right\} \tag{8}$$

which is only Laplace transform of (2) and

$$C_f(s) = -K_P\{\alpha + \beta\tau_d s\} \tag{9}$$

In [7] we can find a form of 2DOF PID Controller that is commonly used in industrial applications (see Fig. 11).

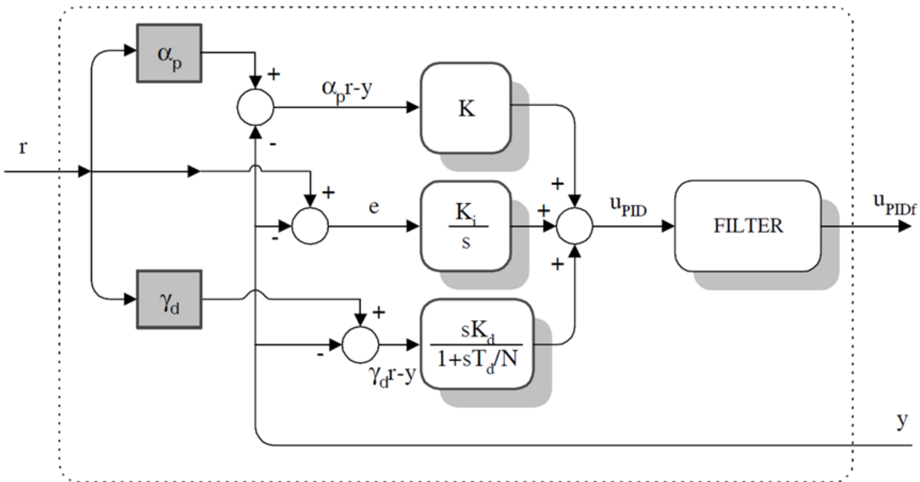

Fig. 11. *Commonly Used 2DOF PID Controller Configuration*

The equation that describes function of such a controller configuration as a whole is following:

$$U_{PID}(s) = K\left\{[\propto_P R(s) - Y(s)] + \frac{1}{s\tau_i}E(s) + \frac{s\tau_d}{1 + s\frac{\tau_d}{N}}[y_d R(s) - Y(s)]\right\} \qquad (10)$$

By changing α and β or α_p and γ_d which are called setpoints we can decide what components of the PID controller will dominate and therefore decidedly affect controller's output.
If we are to model 2DOF PID controller in Simulink we will find this interpretation among the common blocks:

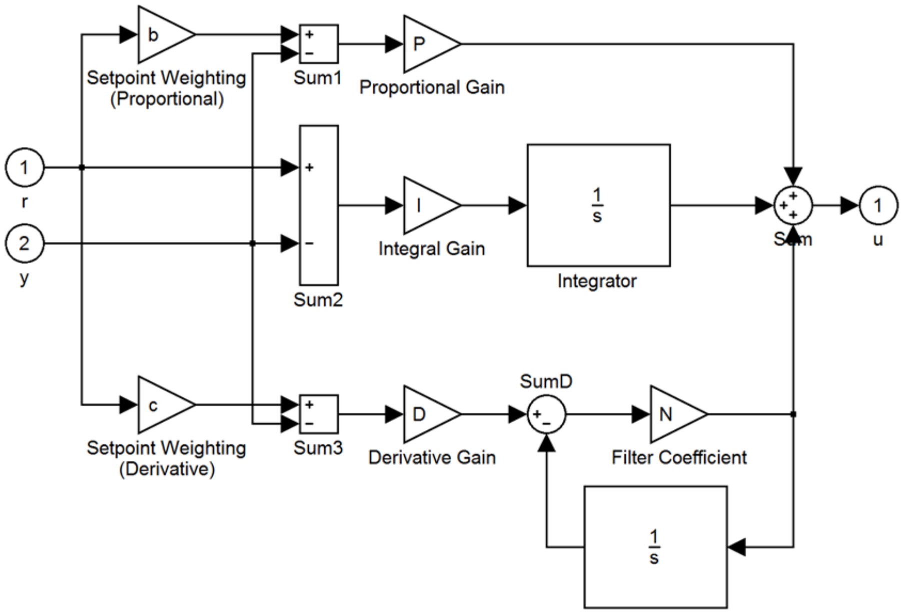

Fig. 12. 2DOF PID Controller in Simulink

Implementing 2DOF PID controller in Mosaic is achieved again using its built-in libraries blocks. The overview of the whole system simulation loop is given in Fig. 13.

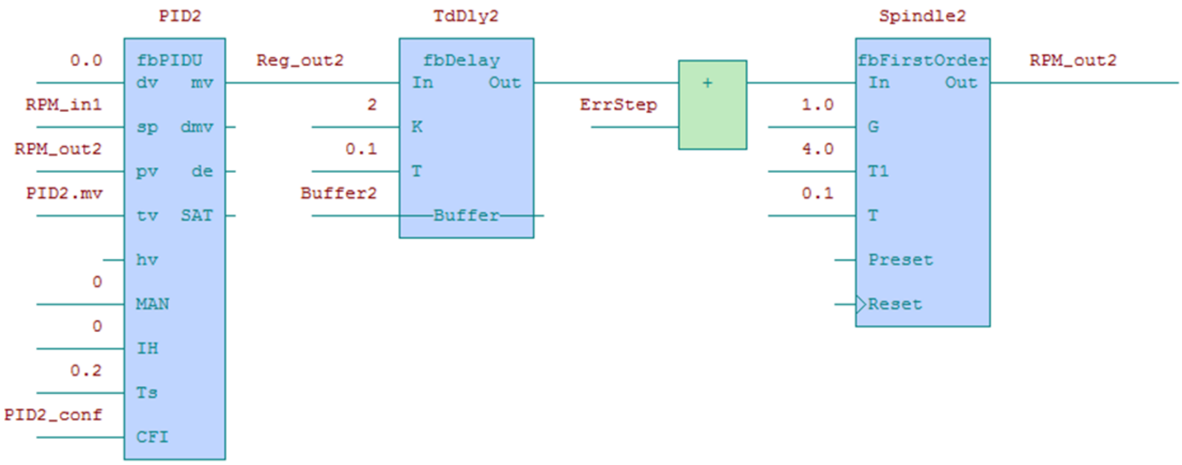

Fig. 13. *Feedback speed control with 2DOF PID in Mosaic*

The system has been simulated using the same parameters that have been previously used for 1DOF PID controller (see Table 1). Step response is show in Fig. 14. When comparing to system behavior with 1DOF controller the system with 2DOF PID has a larger overshoot but better unit disturbance response. We will compare these properties more closely later.

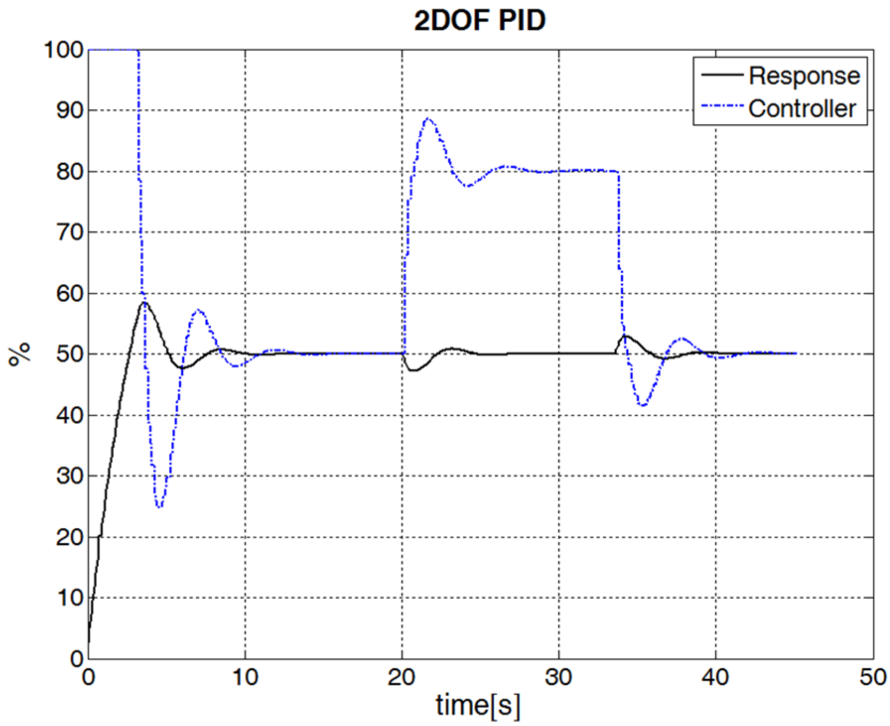

Fig. 14. Simulated control loop with 2DOF PID step response in Mosaic

Even further improvement can be made to the system by introducing an auto-tuning algorithm that is able to estimate parameters of PID controller from the whole system's behavior.

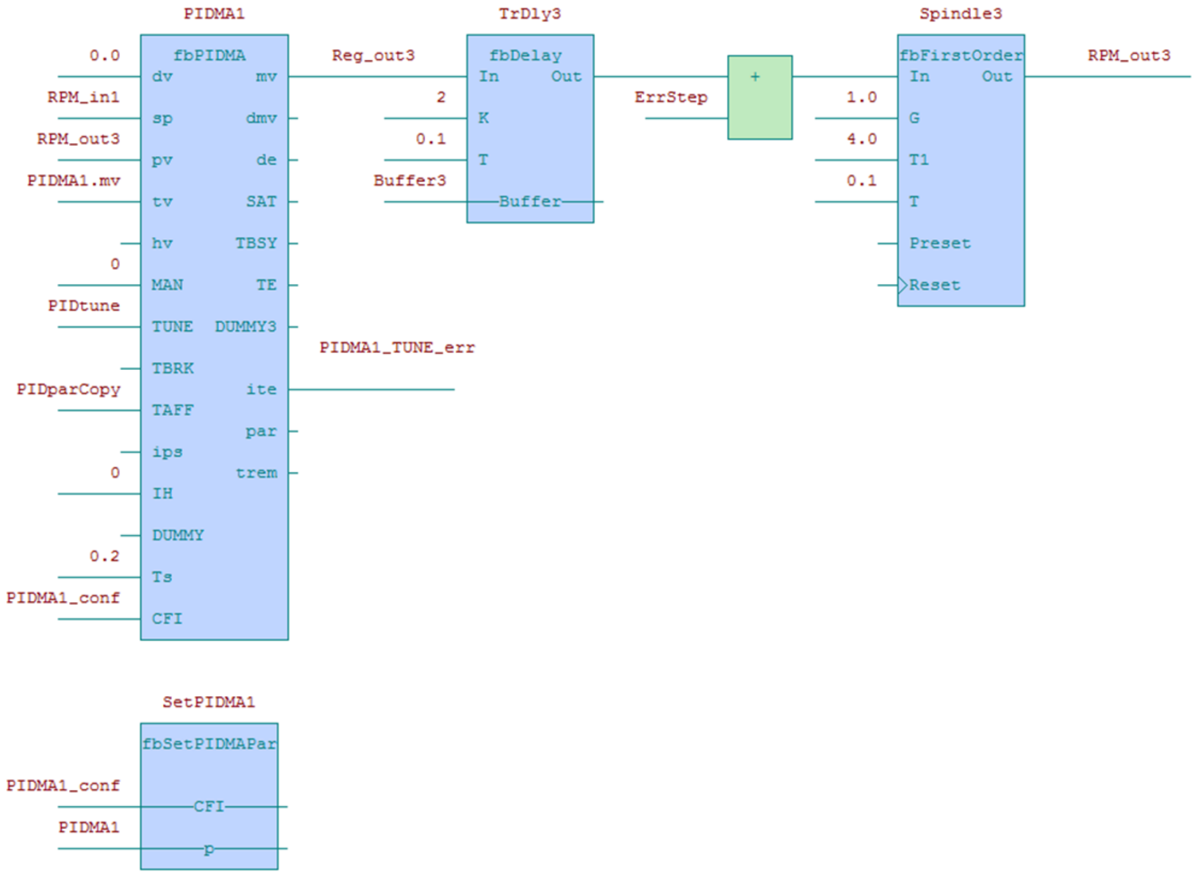

Fig. 15. Feedback speed control with 2DOF PID with auto-tuning in Mosaic

A block can be found in Mosaic that acts as a 2DOF PID controller but is supplemented with an auto-tuning option (see Fig. 15). Auto-tuning has to be properly set so that the parameters are estimated properly.

Table 2. *2DOF PID controller parameters after auto-tuning*

Proportional gain KP	Integral time constant τi	Derivative time constant τd
5.3	0.34 s	0.32 s

Values of controller parameters that have been estimated by an auto-tuning algorithm can be found in Table 2.

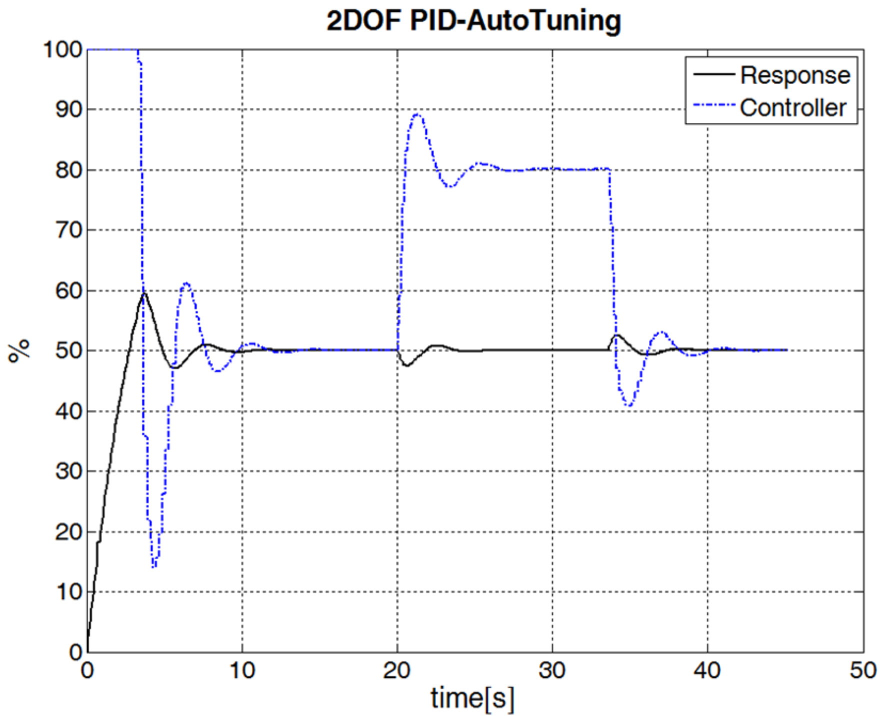

Fig. 16. *Simulated control loop with 2DOF PID with auto-tuning step response in Mosaic*

Simulated system's unit step response can be seen in Fig. 16. The overshoot of the system is now even higher than in the previous case but a step disturbance response is better.

5. Comparison

Let us now compare (response wise) different types of PID controllers when used in governing the pneumatic spindle speed.

Using MATLAB software all three PID controller types responses to unit step have been put into a single chart (see Fig. 17) and can now be easily compared. The overall comparison can be found in Fig. 17. A step of 50% of the overall speed magnitude has been introduced to the input of the system and a system response was being observed. After settling the output on the input value a disturbance has been introduced to the system. Observing step input response and disturbance response are the two main characteristics that determine the quality of controller.

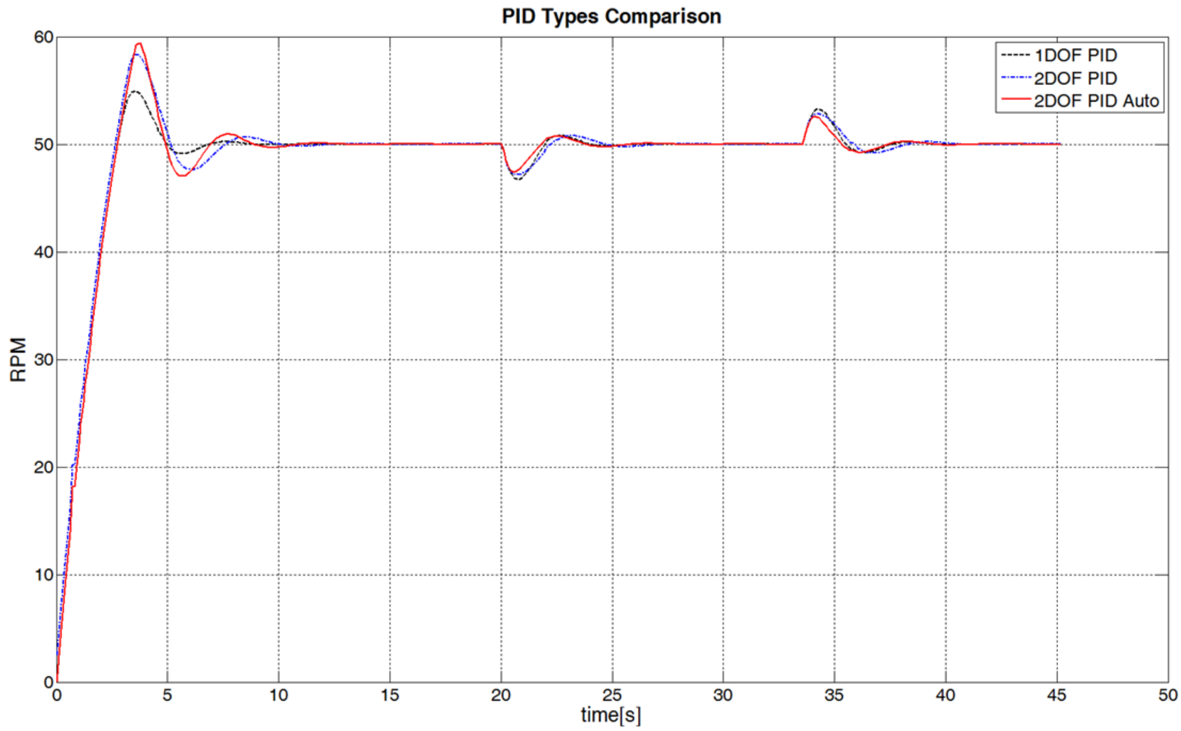

Fig. 17. Simulated step response comparison of different PID controllers

For better observing the system response details of transient part and disturbance response can be seen in Fig. 18 and in Fig. 19 respectively.

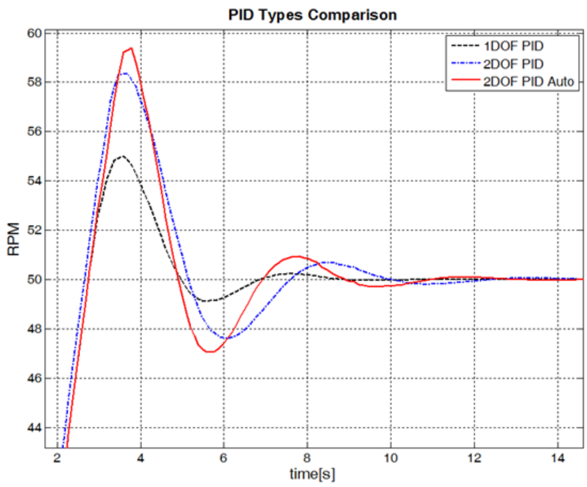

Fig. 18. Detail of step response transient part

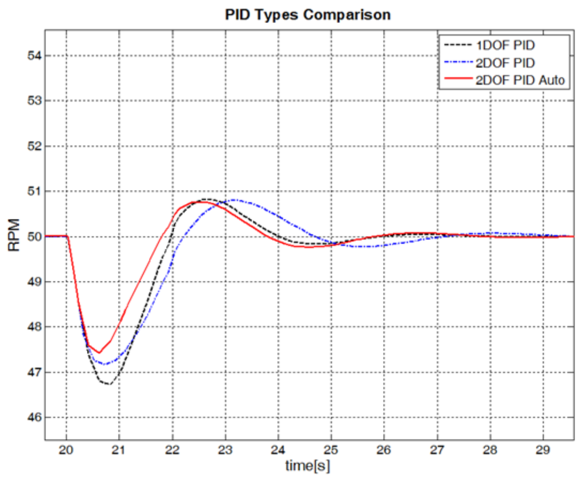

Fig. 19. Detail of step disturbance response

As for the transient part of step input response we can conclude that the 1DOF PID controller shows the lowest overshoot and shortest settling time. 2DOF PID controller is more sensitive therefore it shows greater overshoot and longer settling time. Auto-tuning allowed for shortening of the settling time while keeping the overshoot about the same level.

When we concentrate on a disturbance response we see that the best result can be observed for the case when a 2DOF PID controller with auto-tuning has been used. The drop of the controlled variable is the lowest in this case and settling time is the shortest one. In case of controlling pneumatic spindle speed disturbance response is much more important than input step response as the input will not vary during the spindle's operation very much. The best type of controller for maintaining pneumatic spindle speed is therefore a 2DOF PID controller with auto-tuning option.

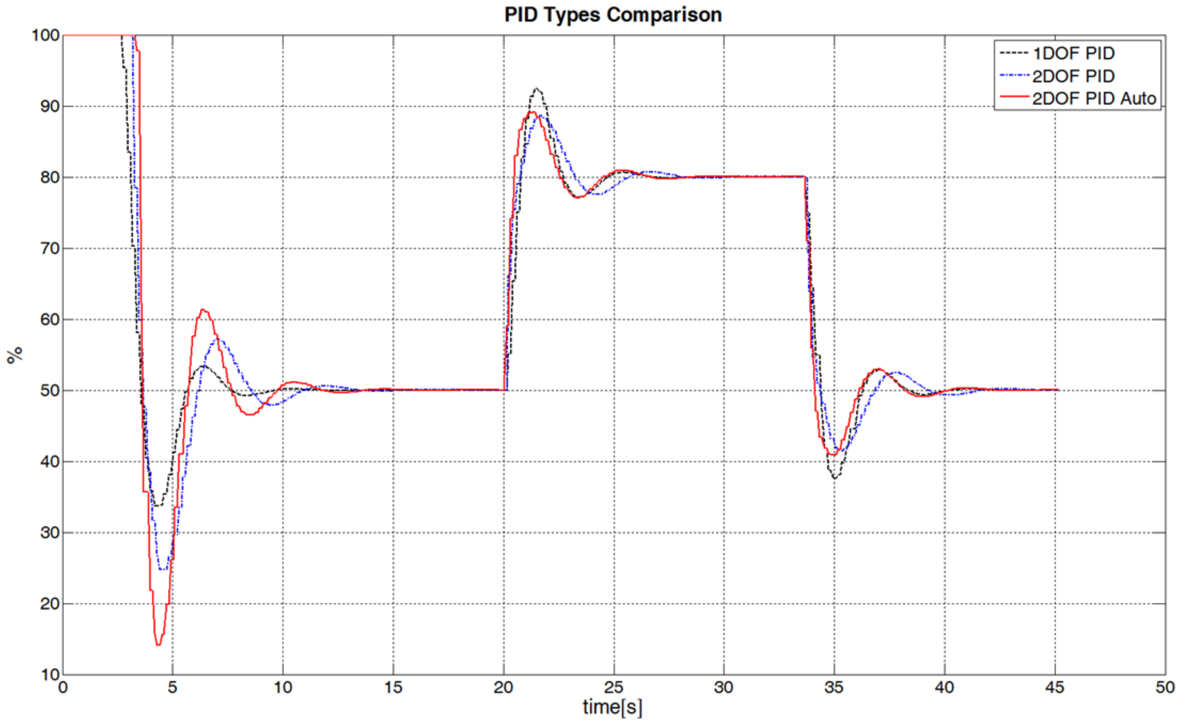

Fig. 20. PID controller output comparison to step input

We can also compare controller output when the system is responding to a unit step and then to a disturbance (see Fig. 20). Again details from the overall plot can be seen in Fig. 21 and Fig. 22.

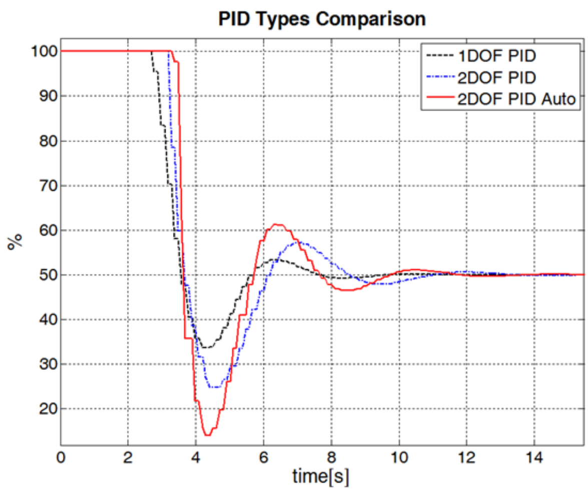

Fig. 21. *Transient part of controller output*

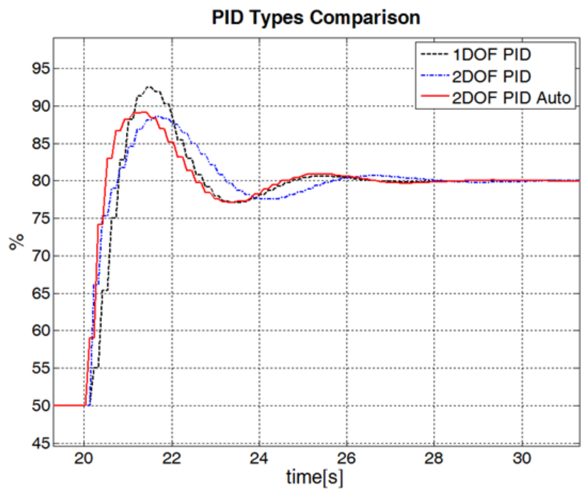

Fig. 22. *Controller output to a step disturbance*

When looking at the transient part of step response controller output we can see that the action of 1DOF PID controller is the longest of all but it is the least vigorous. On the other hand 2DOF PID controller with auto-tuning showed the fastest action which was also the strongest. As for the disturbance response the best results are given by a 2DOF PID with auto-tuning for it reacts very fast with a relatively light action when compared to 1DOF PID. This fact is again a reason for opting for a 2DOF PID controller with auto-tuning as a controller for maintaining pneumatic spindle speed.

6. Conclusion

Three different types of proportional, integral, derivative (PID) controllers have been used for a particular task of governing a pneumatic spindle speed. The main purpose of this work was to find the most suitable one apt for this case. At first a mathematical analysis has been conducted to prove the properties of particular controllers' types. This indicated that a 2 degree of freedom (2DOF) PID controller has the highest potential in handling the speed control task.

The next step was implementing PID algorithm in an actual controller which in this case was a programmable logic controller (PLC). Algorithms of all types of controllers have been implemented into the PLC and their behavior was compared on a speed control process simulation where the actual spindle has been substituted by the first order system. Comparison showed that indeed a 2DOF PID controller generated the best results. Hence the conclusion of this work can summarized in successful choosing the best type of PID controller for maintain pneumatic spindle speed. Further work will be dedicated for observing a behavior of the real system.

7. Bibliography

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