American Scientific Research Journal for Engineering, Technology, and Sciences (ASRJETS)

ISSN (Print) 2313-4410, ISSN (Online) 2313-4402

http://asrjetsjournal.org/

A Fast PID Tuning Algorithm for Feed Drive Servo Loop

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Abstract

The behavior of the dynamic systems is directly related to the mechanical structure. The CNC vertical milling machine has a control structure where an algorithm for trajectory generation is implemented in order to achieve the final objective such as high productivity and high surface quality. Tool positioning accuracy determines the machining surface quality level which is provided by feed drive system for each axes and is directly related with efficiency of a power electromechanical system, and the structural characteristics, like guides stiffness, damping values. The Feed drive control of milling process has some general control requirements based on specific process requirements for the optimum control dynamics with fast response, higher stability and no oscillations. The PID control strategy is based on a control algorithm that involves three separate parameters P, I and D, and on calculation of control action as a sum of these tree factors. It is very important to find reasonable gains based on how much control effort it's available and how much error it is expecting to have and fast method for tuning the PID. In order to observe the basic impacts, of the proportional, integrative and derivative gain to the system response and the suitable tuning method for this we propose a fast tuning algorithm based on empirical method. Usually, all manual tuning techniques, after proportional parameter tuning starts with the integral ones. According to the analysis related to the feed drive control and its specifications of control, we propose a simple and fast way by giving more damping effect during feedback control loop execution. In this paper we have presented a flow chart for fast adjustment of the PID parameters closed loop only for DC proper for the feed drive system, without including the impact of nonlinearities.

Keywords: Fast tuning; PID; CNC; Feed drive; servo control.

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1. Introduction

Relative movement between work piece and cutting tool is important for position accuracy of CNC. The feed drive mechanisms of a three-axis vertical milling machine consist of a DC servomotor which is directly connected to lead-screw shaft drives the table and work piece [1]. Relative structural deformations between work piece and cutting tool are important for position accuracy of CNC. The machine tool vibrations during machining can cause errors, damages and poor surface quality. The frequency of vibrations is influenced mostly by the stiffness, the mass and the damping. To accelerate the lead-screw assembly and the table with work-piece, the motor, has to generate a high torque for a short period of time, and sufficient to overcame the friction in the slide ways, bearings and cutting force. This torque produced by the motor is important for acceleration of inertia reflected in the motor shaft. But, when a high speed command is given, that causes problems with controlling the relative movement between work piece and the tool because of vibration and inertia in the mechanical system.

To overcome all these nonlinearities and difficulties during the system control, over the years have been used various PID based controllers, in order to improve the dynamic characteristic of the feed drive control loop [2, 3]. Ziegler-Nichols is one of the most widely used PID tuning methods in the literature [4, 5, 6, 8]. There are more advanced and intelligent PID tuning methods and algorithms, such as Genetic Algorithm (GA), Particle Swarm Optimization or Fuzzy Logic [8], but all these techniques require deep analysis.

The control performance may be effective or not depending of the frequency of the set point changes. The implementation of design constrains during the controller design is a very important and it is the main factor which determines very critical the overall quality of product, cost. That's mean that properly designed controller will be able to achieve the desired level of performance to overcome the stability and robustness problems.

The motivation of this study comes by the idea of finding simplest methods and techniques for algorithm implementation and includes the controller design according to system requirements. The idea includes also the tendency of keeping the "simplicity" for the mathematical model and the efforts searching for simplest techniques for parameter optimization.

2. Feed Drive and PID

On the CNC feed drive system of the vertical milling machine, the statics loads that have to be highlights as important is the friction in the sideways and in the feed drive bearings. Another source of static loads is cutting forces, which usually have opposite direction of the moment of the feed drive. So, the first challenge for high precision and high-speed machining motion control is the presence of friction as a nonlinear phenomenon that exists in every mechanical system. The total feed force acting on the drive consists of cutting and friction loads:

$$Ffeed=Fcut+Ffriction \qquad (1)$$

The design of feed motors and the mechanical components is initially carried out by considering only the rigid body dynamics and static stiffness of the system. From the application requirements, a suitable combination of the design parameters of ball screw, nut, bearings, motor torque, nominal motor speed, spindle pitch and transmission ratio are determined.

The control loop design depends mostly on the mechanical configuration of the system, which in most cases has found the solution to the DC motors, whose circular motion is converted to the linear through the nut-bolls crew pair. In our case, but, most of the other cases, the connection between the servomotor and the bolls screw is direct, for the fact that the only executable element in this system that provides controlled force for the axial movement of the table. For the control of nonlinearities, decisive will be the fast response of the system which is achieved by a successful combination of the elements of the feedback control loop.

The feed drive system functions by a combination of a speed control loop by a tachometer and a encoder for position feedback control loop. It control of the vertical movement of milling mechanism is carried out through the loop of the speed control and loop of the position. The position control with the closed loop through the rotary encoder located on the motor shaft and the circulated ball screw via the servomotor and so we cannot access the real position of the work table.

For simulations purposes, the dynamic characteristics of the mechanical components of feed drive are calculated based on mechanical principles, taking only the impact by the friction on the slides and the stiffness of the screw and guides, thus approximating the friction of the balls and the screw. The mathematical model it is simplified as a two mass (work piece and table) with friction on the slide and stiffness of the ball screw. The electrical part, it is presented by a transfer function according to [3] and gives a actuator force to the second part which is the model of mechanical system and which is simplified to a two-mass system with a spring and a damper element . For simulations purposes, the dynamic characteristics of the mechanical components of feed drive are calculated and are implemented on MatLab by a S-function program, even if, in this paper is shown only the model of DC

In order to model the feed drive for control purposes, we have simplified the system in a two degree of freedom structure. For this servomechanism, the transfer functions of the individual system components are usually known or have to be calculated. The electrical part, is presented by a DC transfer function according to [1] and, which gives a actuator force to the second part which is the model of mechanical system simplified to a two-mass system with a spring and a damper element [3].

$$G(s) = 2/(s^2 + 12s + 24) \qquad (2)$$

The servo control system uses amplifies to achieve the peak current and its time duration. The direct current motors or brushless DC are most common types that’s allows that range of large torque required by feed drive system. Motor torque is proportional to motor current and as the consequence the motor torque feedback signal can't be derived without be amplified output current level. The comparison of this voltage value from command torque as a referent torque the comparator produce the error which is sent to the amplifier.

So, we need a amplifier to present the proportional part of the controller, by which should be amplified the signal that represent the error voltage as a difference between reference value of voltage for a given command (desired) and the actual value of the shaft speed:

$$e = \omega_d - \omega_a \qquad (3)$$

This configuration it is known as torque amplifier or current amplifier and the value of multiplication we call the gain. By increasing the voltage level, increases the feedback and the torque in output, even if the error increases too. The amplification increases the output until the feedback it's large enough to drive the error to zero, and to stabilize the output level with the input ones.

3. PID Algorithm

The mathematical expression of PID control strategy is based on a control algorithm that involves three separate parameters P, I and D, and on calculation of control action as a sum of these tree factors. In the practical view we should have a mathematical mechanism to make fast corrections, to take care of the error actual value, to consider the error accumulation effect and to predict possible error changes.

$$\mathrm{u(t)} = \mathrm{K_p} e(t)dt + K_i \int_o^t e(t)dt + K_d \frac{de(t)}{dt} \qquad (4)$$

The three controls relate to the time-dependent error signal Proportional is dependent upon the present error, Integral is dependent upon the accumulation of past error, and Derivative is the prediction of future error. Adjusting the coefficients should mean achieving the control objectives that is to increase system performance by amplifying the power and decreasing rise time, settling time, overshot and the steady state error. The role of PID in any servo loop is to hold the system at a predetermined value for long periods of time, as to hold it at the set point by generating an error signal (figure1).

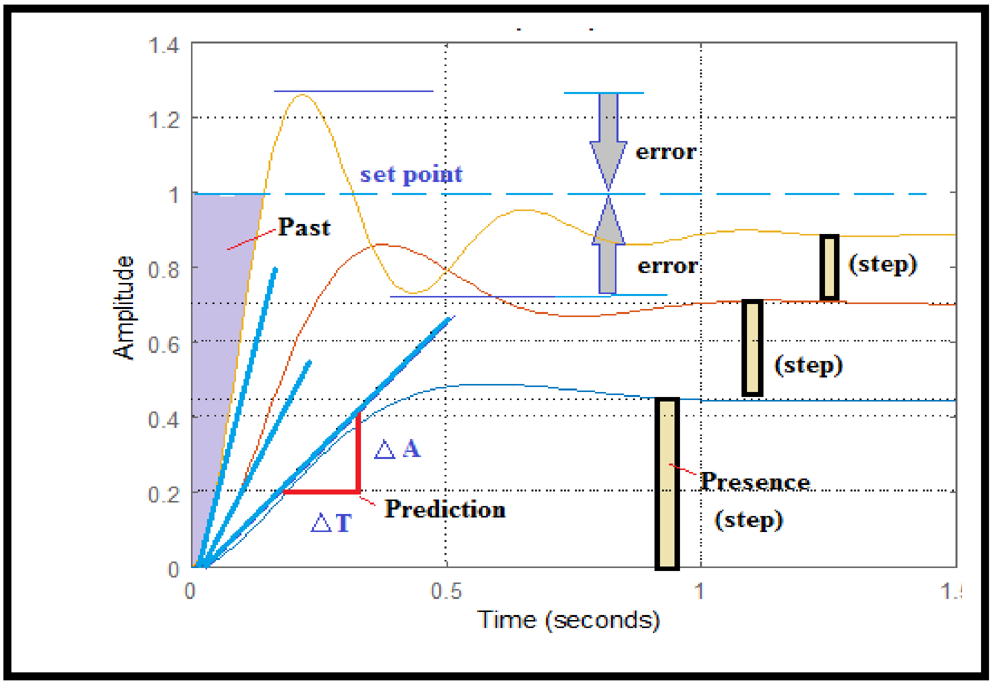


Figure 1: PID strategy

3.1. Cause-effect relations

The proportional control it is a direct response to the error signal generated by the circuit. If the gain is too low then the loop cannot respond to changes of the system properly. By increasing the gain we can cause fast response to the circuit but too high values can cause oscillation of the value.

Integral control it is a sums of error which was not corrected in previous action. It goes a step further than proportional gain, it just the magnitude of the error and also the duration of the error. High gain values can cause significant overshoot and instability with oscillations. Too low and the circuit will be significantly slower in responding to changes in the system.

Derivative control presents the damping action and attempts to reduce the overshoot and ringing potential from proportional and integral control. As a compensator it can reduce the overshoot and oscillations caused by integral and proportional control. To high values of derivative control parameter will slow the response of the loop. The main idea is based on the empirical method and the interest to reach quickly the approximate values of PID parameters.

Manual tuning of the gain settings is the simplest method but it does require some amount of experience and understanding. There is not a static set of rules for what the values should be for any specific system, following the general procedures should help in tuning a circuit to match one's system and environment. Based on the table below there are some rules for driving us to the best solution appropriate for the system (table 1).

Table 1: Performance relations with parameter increase

Parameter increase	Rise Time	Overshot	Settling time	SSE
Kp	decrease	increase	small change	decrease
Ki	decrease	increase	increase	eliminates
Kd	small change	decrease	decrease	small change

3.2. Down -Up algorithm

Basic definitions used in this algorithm are Big steps for parameter increase and small steps for decrease:

BIG STEPS means increasing the parameter by geometric step of form: $\mathbf{10^i}, were\ i = 1, 2, 3, then\ \Delta K = 10, 100, 1000$

SMALL STEPS means decrease with delta of lowered level of increasing:

$$10^{\mathrm{i}-1},\ \text{were i} = 1, 2, 3 \quad \text{(one level lower)}$$

$$\text{Ex: if i=3 then } K = 10^{i} = 100, \text{then } \Delta k = 10^{i-1} = 10$$

START 1: Let's starts with torque amplification of Kp=1, Kd=0, Ki=0

Down-UP start with: Kp= 1, 10. 100, 1000, looking for the first overshot (figure 3a). That's the response with Kp=100. To verifier the result we increase again the value of Kp and we get the response with a high oscillation. As we know from control theory the proportional gain increase only the gain and doesn't change the shape of the signal.

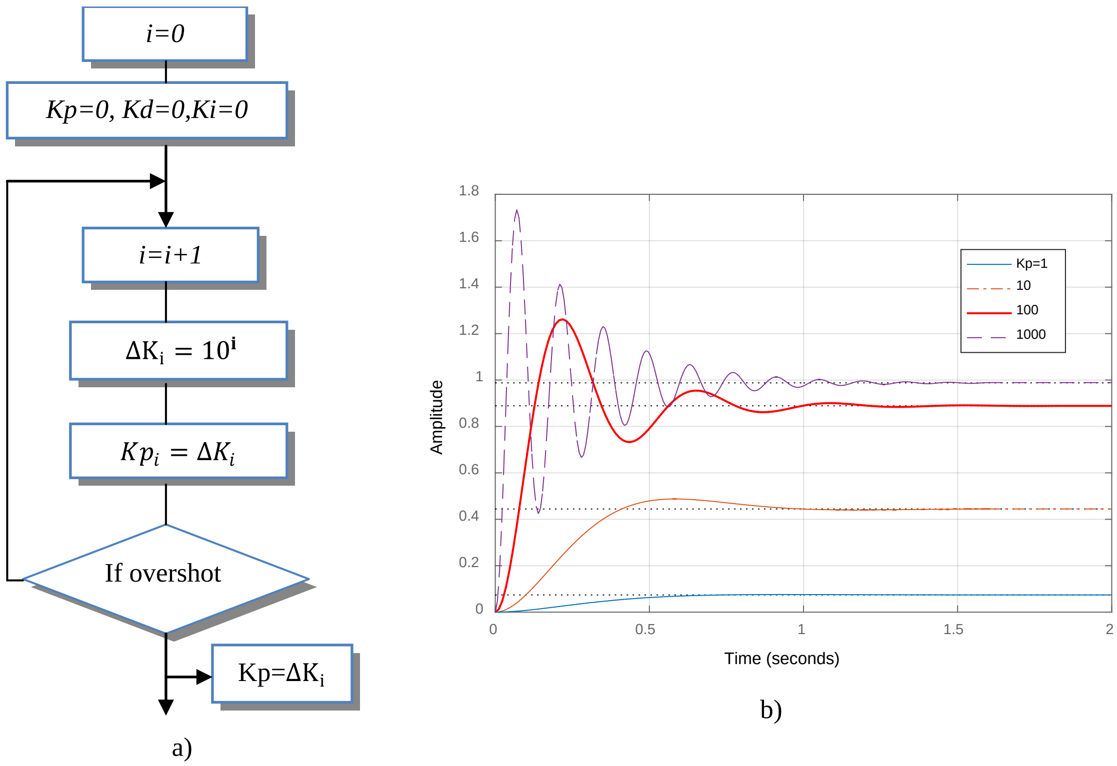


Figure 2: Big Step algorithm (a) and Kp values (b)

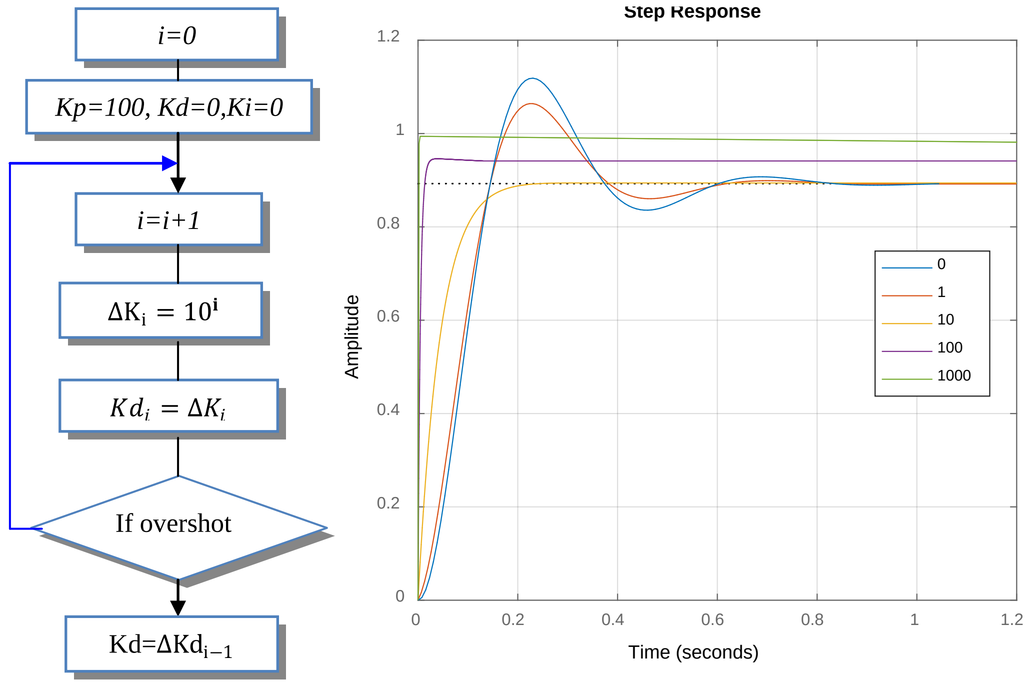
Rule 1: It is clear that the large proportional gain typically results in faster response of a system and decreases the rise time and goes faster to the reference point. According to this, we can choose the parameter value that one's which gives the best rise time and smallest steady stead error, but the large proportional gain makes it impossible to regulate accurately the system error, there is continuous vibration and abnormal noise. Therefore, the amount of the proportional gain is restricted due to this reason [6].

Now have to come back to the value of 100 and starts with tendency to raise the damping effect (figure 3a)

START 2:

As the second, we choose to tune the derivative parameter Kd, called the derivative gain of the derivative control, aiming to manage the slope of the error. This is the derivative gain, which has to be calculated, for damping the system and removing the vibration of the system during a steady state. Continuous with big steps down-up from Kd=1, 10, 100, 1000, we decrease the overshoot (figure 3a).

BIG STEP UP for Kd:



a) b)

Figure 3: Big step for Kp (a) and Kd (b)

Rule 2: Larger derivative gain results in a faster response. However, large derivative gain causes vibration of a system. Therefore, the amount of the derivative gain should be restricted because the first derivative of position over time is sensitive to noise.

Returning to the Kd=100 which is the first response with overshoots and we consider that as final, we noticed that there is a local overshot (figure 4).

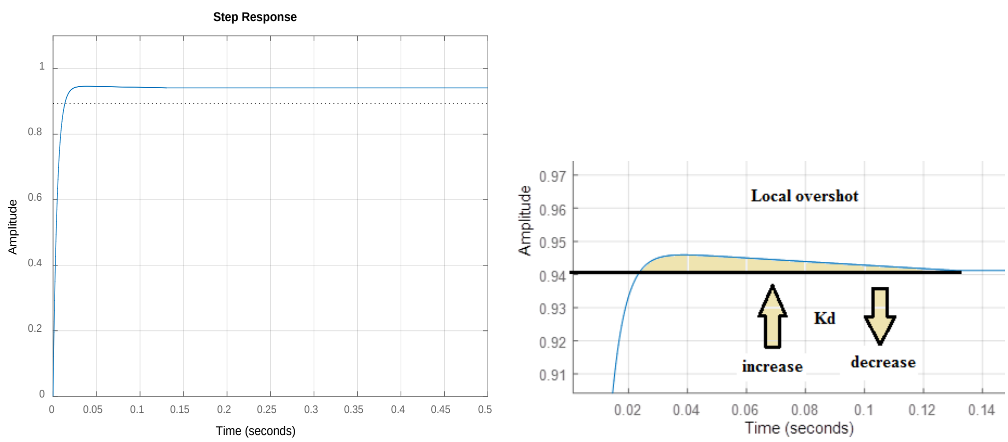
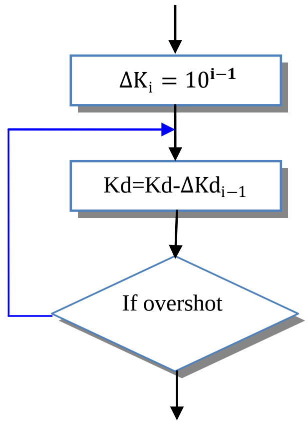


Figure 4: Big steps Kd and overshoot

3.3. Small Steps



SMALL STEPS DOWN:

So the values are Kp=Kd=100

Now we have an overshot that has to be eliminated going up-down direction with a negative small step of level $\mathbf{10^{i-1}}$.

Figure 5: Small steps algorithm

After implementation of these steps we stop at Kd=40 (figure 6).

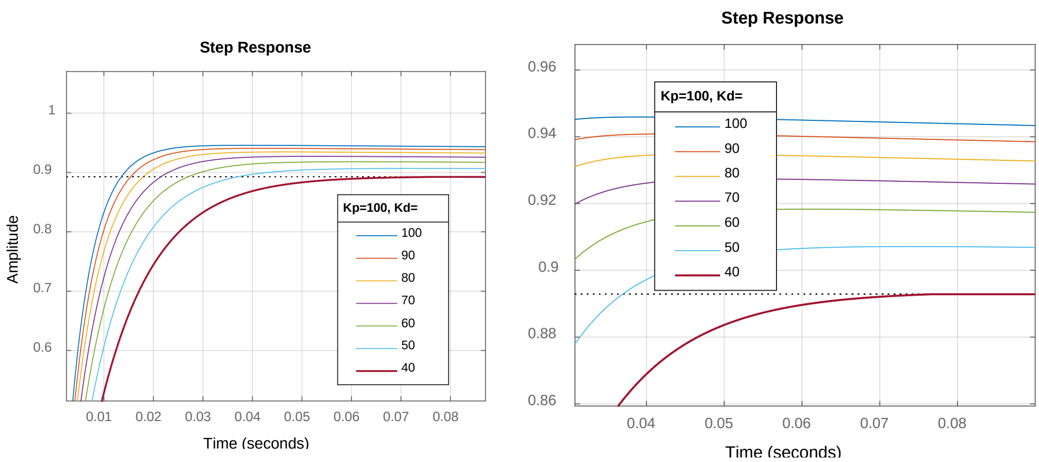


Figure 6: Small steps down and Kd

START 3: Integral control is used in the case of not going to the reference point after transition to the steady state. In I control, the error is integrated over a period of time, multiplied by a constant Ki, called the integral gain, to reduce the integrated errors from the past. Larger integral gain results in faster response during transition states and reduces the SSE: Kp=100, Kd=40, Ki=1, 10, 100, 1000 .

The flow chart is the same as shown for Kp above

Rule 3: Integral control has to be used because fact that gives output even when the error is zero. Accordingly, it is necessary to use an integral gain within an adequate range because large integral gain results in excessive overshoot or undershoot.

The flow chart is the same as shown for Kp above. The results shows that the performances do not change.

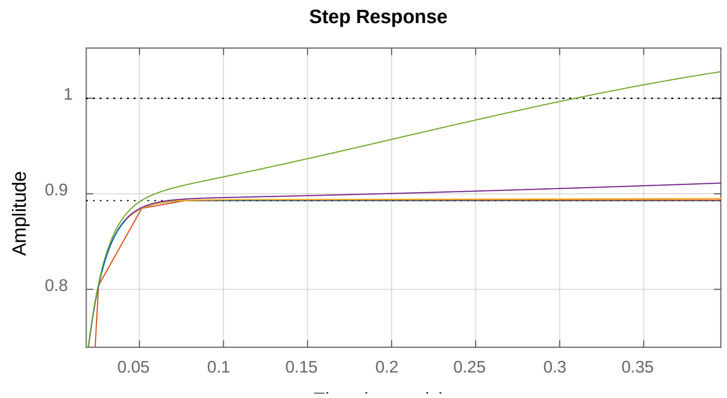


Figure 6: Big steps for Ki

If the Ki big steps doesn't influence the improvement, we double the parameter values Kp=200, Kd=80 than we continue with Ki increase.

START 4: Multiplication constant of integral part rises with $2^i, i = 1, 2, 3$, ex: (2, 4, 8)*Kp.

Let's try combination Kp=200, Kd=80 Ki=1, 10, then start decreasing with small steps Up-down.

For Ki=again small steps down: 10-1 until and stops at Ki=7 with feedback transfer function:

M(s) =160 s^2 + 400 s + 14/ s^3 + 172 s^2 + 424 s + 14 (5)

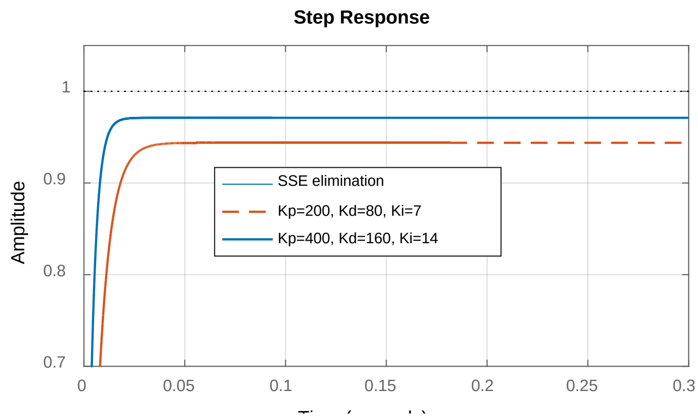


Figure 7: Final values parameters

4. Conclusions

The last curve shows that a good performance can be achieved by using the PD controller, which can be considered as the desired controller with very fast and simple procedures.

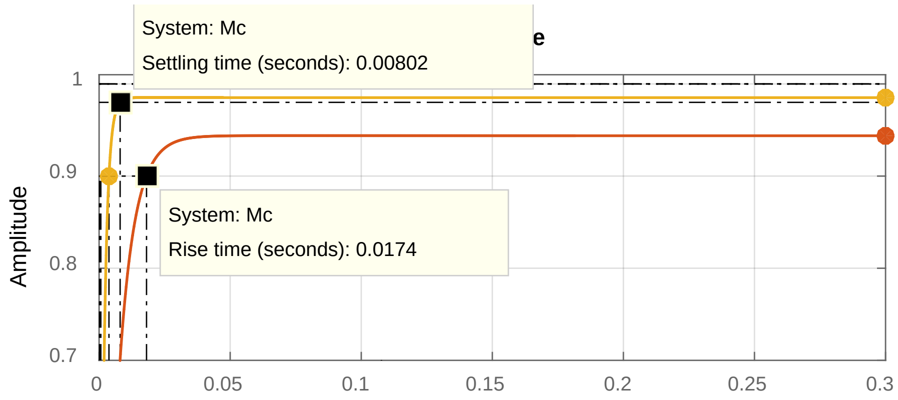


Figure 8: Rise time

On the table below is described all steps of flow chart for fast tuning method and other supplier elements for status action for each steps. Obviously the method is suitable for systems with fast response needed (figure 7).

Table 2: Flow chart and performances

	Kp	Kd	Ki	Result	Status-action	Value
Start with Kp	**1**	**0**	**0**	**Amax-0.08**	+	
	10			0.45	+	
	100			0.9	+(overshot 1.16)	
	1000			1	(oscillations)back	**Kp=100**
Add damping (Kd)	**100**	**1**	**0**		+(overshot 1.16)	
		10	0	SSE=1.1	+	
		100	0	SSE=0.172	+	**Kd=100**
		1000	0		+(overshot)-back	
Small steps down		**100,90...40**			**ok**	
Start with Ki	**100**	**40**	**1**		**no change**	**Kp=100, Kd=40**
			10		-(overshoot) back	
Doubling	**200**	**80**	0	Ts=0.037	+very good fig 6.	**Kp=200, Kd=80**
Small steps down			10,9...7		ok	**Ki=7**
Final values	**200**	**80**	**7**	**Tr=0.017**		**ok**
Doubling	800	320	28	Tr=0.008		

Comparing this method with other methods such as genetic algorithm shows very good results, but with the advantage that it is very simple to learn and implement (figure 8).

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