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A Searching Analyses for Best PID Tuning Method for CNC Servo Drive

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Abstract- The main problem of handling CNC machines the recent years has been the control of high-speed movements and accelerations on the conditions of high-speed machining. High-speed machining is known to reduce machining time and improve surface quality, but, inflicted by the inertia of the masses of the components of this system, vibrations appears in the acceleration phase. Especially the feed drive mechanism is the mechanism that has the main role in the execution of high-speed machining, so it is the one that makes the balance between the needs of quick and accurate machining and control requirements to achieve this.

The basic control requirement for Feed drive is the optimum control dynamics with fast response, higher stability and without oscillations. Controller design is a very important and it is which determines very critically the performance of the control loop which affect the overall quality of product, cost. So, 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. That's mean that properly designed controller will be able to achieve the desired level of performance to overcome the stability and robustness problems.

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 purpose, we have some different tuning methods by simulations made on MATLAB in continuous time with a transfer function for DC motor used on Feed Drive system

Keywords- *PID Tuning, Feed Drive, CNC*

I. INTRODUCTION

Mechanical machining of parts can be done in various machining centers and with different methods and operations, but, its common interest is to achieve accuracy that means maintaining the tolerances of the dimensions of the work piece and the quality of the machined surfaces. Of course, to get the specified tolerances, the machines should have a much higher precision than the tolerances of the work-piece. Among the main conditions guaranteeing the precision of the work is the increased rigidity of the machine tool structures, which leads to the reduction of the vibrations and elastic deformations of the system. Mechanical nodes are required to have: bearings with minimum backslash, low inertia, no vibration, less friction coefficient, etc [1].

The accuracy of the machine depends heavily on the static and dynamic deformities of the kinematic chain sections of the mechanism that transmit power and torque. These deformations also cause structural deformations between the work piece and machine tool. The source of relative deformations between the work-piece and the cutting tool at the contact point is derived from various thermal loads, part loads and workloads resulting from cutting resistances.

All rotating or moving elements of the CNC machine have a certain contact surface with the axles or with another element, which means the permanent presence of friction, the energy of which is converted into heat. Increasing the temperature is never uniform when passing through the car parts by changing their thermal coefficient and changing the heat source location. On the other hand, movement loads and weights alter the hardness of the parts and the relative displacements at the point of cutting between the instrument and the part of the work.

II. THE FEED DRIVE

High-speed CNC machining systems have computer control structure were an algorithm for trajectory generation it is implemented in order to achieve the final objective which is high productivity and high surface quality. The tool positioning accuracy determines the quality level and it is provided by feed drive system and directly related with efficiency of power electromechanical system, and the structural characteristics, like guides stiffness, damping values.

Contouring accuracy of a CNC it is related with position accuracy of separate feed of each axes mechanism and its control loop performance. Feed drives are powered by linear motors directly, or by DC or AC rotary motors via ball screw and nut assembly to move the table. So, these work conditions, for control system means: high start torque characteristic, high response performance, easier to be linear control [2]. The modeling process for feed drive has the priority on the most of authors [3] and the impact of work conditions [4].

Different types of controller have been using in DC motors such as PI and PID controllers. Some authors invest on the methodic of study to simplicity, explain and implement them [5].

Federate speed and feed drive position accuracy are directly dependent on the amount of torque and torque delivered by the servomotor and by the feed drive control algorithm executed by the Computer Numerical Control Unit. That's why the DC servomotor which is directly connected to lead-screw shaft drives the table and work piece and has to overcome both the static and dynamic loads. For the CNC milling machine the each ax has separate servo control system for positioning purposes.

The main problem of these types of feed drive systems is vibration, which requires the use of linear ruler or ball bearings instead of traditional slip guides, thus reducing the damping ability by decreasing viscose friction coefficient.

Given the working conditions of the feed system we are studying, as engineers we have two possibilities:

- To eliminate the cause, source of the problem, or,
- To improve the correction model.

DC uses a powerful magnetic rotor that connects to a sensor-encoding sensor that continuously sends the signal to the controller (thousands of times per second) and shows the position. The controller calculates the required power required to hold the engine within the motion control.

Correction of position error with PID controller is done by combination of proportional, derivative and integrative actions. Integrating action eliminates the error, especially when system excitations are of the ramp shape. With the derivative action is regulated the form of dynamic response of the system, but, both require proportional action that makes direct amplification of the error signal.

Firstly, we have to determine whether we are using a P controller, PI or PID controller. The control performance may be effective or not depending of the frequency of the set point changes. If the interval of oscillations-settling time is smaller than the frequency of set point changes, especially if we have integral criteria when the positive area cancels the negative ones, than, the control performance may be effective. In the other hand, if error falls down reasonably fast and stays so for long time we can tolerate it.

III. THE DC AND FEED DRIVE

In order to achieve control of the accuracy of the instrument position, modeling and analysis of the relative movement between the tool and the work-piece, as well as all the static and dynamic deformations that cause the respective errors. Mathematical models of mechanical subsystems are generally constructed by developing equations of motion between a motor and other mechanical components of a servomechanism.

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. 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.

The reflected torque can be estimated as the sum of friction on the guide-ways, the torque lost in the bearings and that reflected to the lead-screw:

$$T_{gf} = \frac{h_p}{2\pi}\left[\mu_{gf}(m_t + m_w)g + \mu_{gf}F_z\right] + \mu_b\frac{d_b}{2}\left[F_f + F_{pr}\right] + \frac{h_p}{2\pi}F_f$$

h_p-pitch of feed screw

μ_{gf}, μ_b-friction coefficient on the guide-ways and bearings

m_t-mass of table

m_w-mass of work-piece

F_f, F_{pr}-feed and preload force

F_z-normal cutting force

d_b-mean bearing diameter

The movement of the table with the work-piece and the lead screw actuator generates a momentum of inertia reflected on the motor's shaft. So the motor has to have enough power capacity to deliver adequate moment to accelerate the table and to fulfill the time aspects meets the control requirements.

The moment of the motor it is proportionally related to the armature current and the peak current have to be given for the short period of the time of two or three seconds.

T(t)=K_(τ) i(t)

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.

During the speed changes which are inevitable and very frequent when a CNC new command is given, the torque acceleration has to overcome the reflected moment of inertia as a result of the system dynamic loads.

$$J_e = \frac{J_{cw}+J_v}{i_R^2} + J_m$$

$$J_{tw} = \left(\frac{h_p}{2\pi}\right)^2 (m_t + m_w)$$

$$J_l = \frac{1}{2} m_l \left(\frac{d_p}{2}\right)^2$$

J_l-moments of inertia of lead screw,

J_{tw} -table and work piece, and

J_m -inertia of the motor

d_p-pitch diameter

m_l-mass of lead screw

The entire moment of inertia is divided in two parts: the mechanical moment of inertia of the motor and the load inertia.

The inertia ratio (JL/Jm) defines the motor capacity to overcome the load inertia which consists of components used in the mechanical drive design of motion. For high-speed machining purposes the motor shaft it i is directly spoiled by the bolls-crew with the table.

The dynamic required torque to accelerate the reflected Inertia J_e and viscous friction and static torque is:

$$T_d = J_e \frac{\Delta\omega}{\Delta t} + B\omega + T_s$$

The motion profile in CNC control, the inertia reflected the speed and acceleration profile determines the choice of DC motor. All the variables gains used on the modeling procedures have to be tuned to have desired velocity or position loop gain.

In the mechanical side we have the motor moment of inertia as a factor, the damping element for the friction on the motor's bearings and the stiffness of the shaft. All the inertia comes from outside of the motor is treated as load inertia. So, the mathematical model gives as the relationship of electrical part and mechanical system. The required transfer function for simulations purposes uses the B EMF equation:

$$V_b = K_e * \theta'_m$$

For simulation purposes we used the equation as a transfer functions were are included also the equations the armature voltage of DC and mechanical part:

$$\frac{\Omega(s)}{V_a(s)} = \frac{K_t}{(L_a s + R_a)(Js+b) + K_t K_E}$$

After substitutions of the values for DC, we get the transfer function: `G=2/(s^2+12*s+24);`

IV. Servo Requirements for the Control 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. The amplifier will increase the control voltage in order to achieve the sufficient torque range to overcome the static and dynamic loads to accelerate the table. Usually the mechanical actuators uses rolling elements which have low friction, high load capacity and stiffness, but with low structural damping too. That why the feed drive servo system requires the rapid response. The system response does not fellow always the desire profile of the speed (fig,1)

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. This is known as proportional servo control.

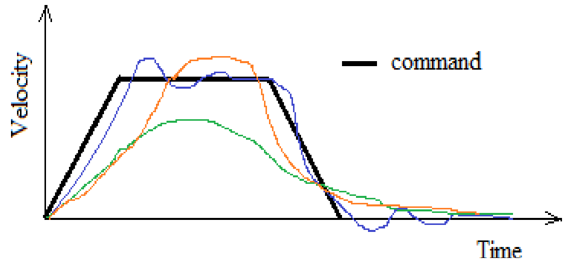

Figure 1. Different types of the responses

The actual torque respond of the system depends of the gain parameter which shows that how strongly the error signal is amplified. The gain must be adjusted conform the dynamics of the mechanical the system.

-if the gain is too low, the motor does not obtain the desired performance level

-otherwise the over level of gain results on overshoot and oscillation

The PID control algorithm involves three separate parameters P, I and D, and, the control strategy is based on calculation of control action as a sum of these tree factors.

$$u(t) = P + I + D$$

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

This same torque amplifier it is used current control amplifier in the velocity servo system where the input control voltage is proportional to motor speed. The motor speed sensor tachometer sends a feedback signal and closes the loop, where the controller determines the velocity error. To stabilize the system the error must be set to zero, so the proportional gain determine the system response. The velocity loop includes also the tachometer gain adjustment.

V. PID Tuning

The first tuning method was the MatLab Manual and results with: Kp =50; Ki = 40; Kd = 9;

Empirical method is also the manual but it offers a lot of possibilities to see the impact of changing values manually. Usually when we are working with second order system it is almost best to start tuning the proportional gain and that with the derivative ones. The integral part has gives the effect of destabilizing so it is better to left it in the end.

Firstly we define the relation between Kp and Kd in term of using the increase of gain in a form of geometric array of:

10^x, x=0, 1, 2, 3, 4….

We started with open loop of the system:

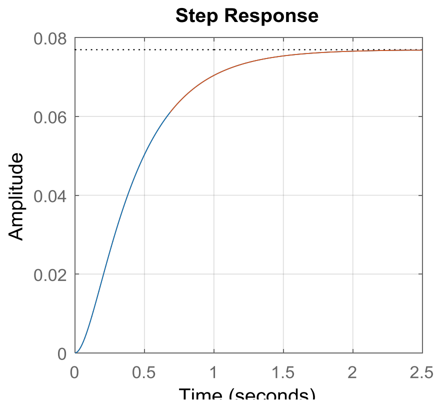

Figure 2. Open loop responses

Manually adjusting the factors starts with real requirements of the system. We see that the response of the system it is so far from desired set point. Then we increase stiffness by the Kp, starting from value 1 until we reach the set point.

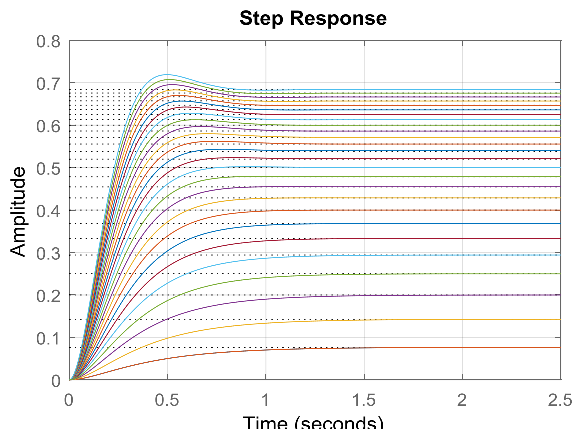

Figure 3. Proporcional amplification

For Kp=400 the transfer function is G =800/s^2 + 12 s + 824

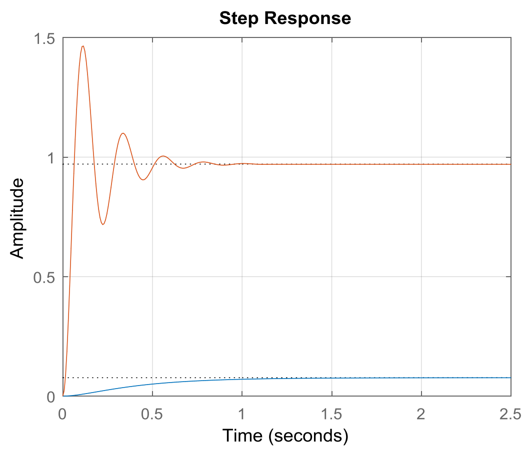

Figure 4. Proporcional and open loop response

We stop rising the Kp add starts giving the system more damping effect by derivative part:

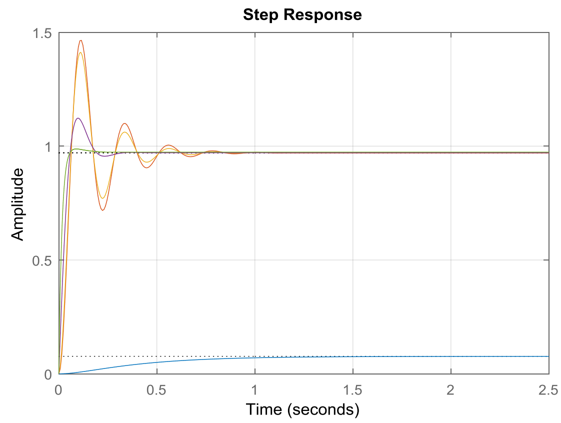

Figure 5. Proporcional oscilation

Were it is clear that the overshot decreases obviously:

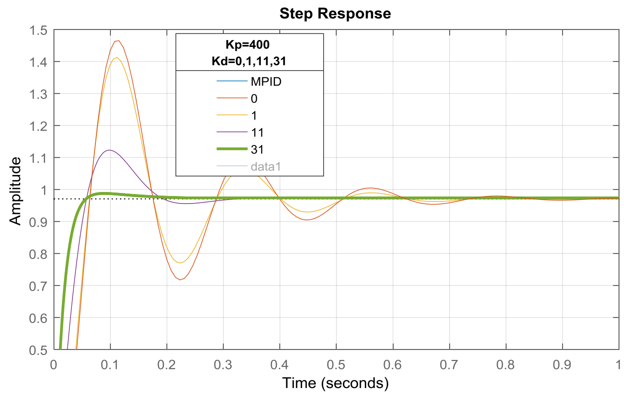

Figure 6. The derivative part effect

To stop with a T=400 Kd=47 and Ki=10. The steady state error around 0.03

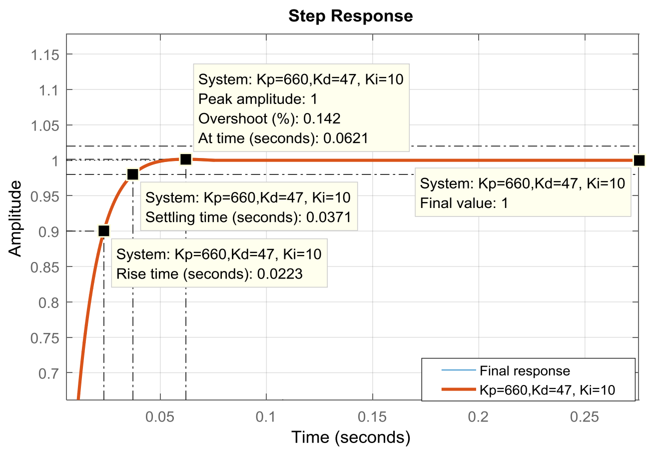

Figure 7. The derivative part effect

So, the feedback loop transfer function is:

G= (94 s^2 + 1320 s + 20)/ (s^3 + 106 s^2 + 1344 s + 20)

The genetic algorithm tuning is based on ITAE error optimization by objective of min function value and it is done in two phases.

The first one is GA1 with180 and GA2 after 300 interactions. The Mat Lab code is shown below:

```
function [GA]=pid_optimSH1(x)
G=2/(s^2+12*s+24);
Kp=x(1)
Ki=x(2)
Kd=x(3)
cont=Kp+Ki/s+Kd*s;
dt=0.01;
t=0:dt:1;
step(feedback(cont*plant,1));
e=1-step(feedback(G*cont,1),t);
%ITAE
GA=sum(t'.*abs(e)*dt);
end
```

Figure 8. The fitness function used for GA

The first tendency was to see if there a tuning by rules of genetic algorithm may resulting the low levels of absolute error, so we tried with 180 interactions and got the result:

Kp =73.0117;Ki=99.4928;Kd=3.2217;

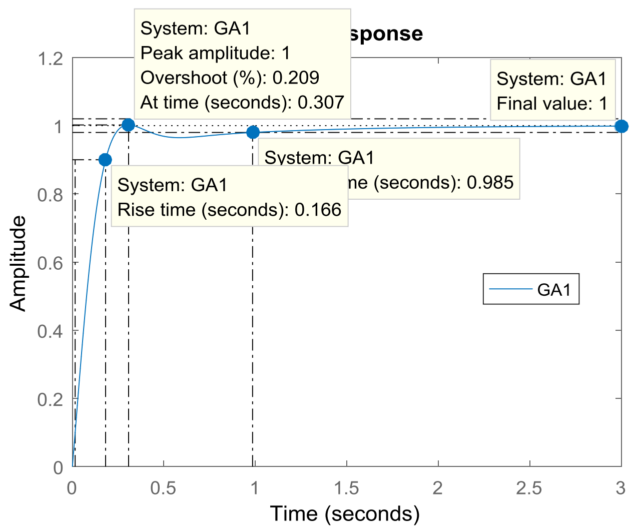

Figure 9. The GA tunning with 180 interations

The second variant was GA2 with 300 interactions and the result is elimination of overshot and smoother damping:

Kp =55.2628; Ki = 98.9995; Kd = 3.7851;

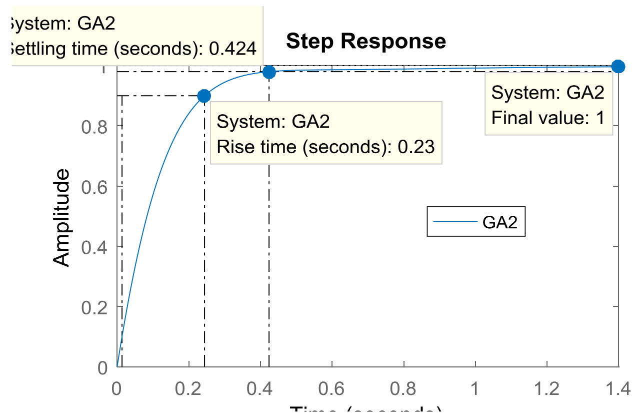

Figure 10. The GA tunning with 300 interations

From the automatic MatLab tuning algorithm for PID we can highlight the result: Kp =25.8322 ; Ki =82.1288; Kd =1.9612;

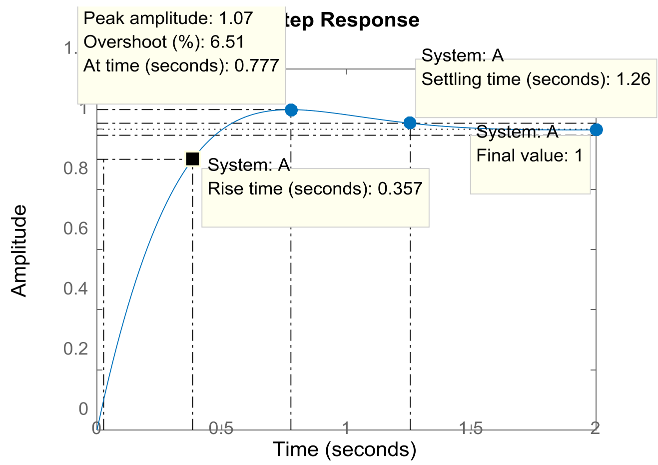

Figure 11. The Mat Lab tunning algoritham result

VI. COMPARISONS

The comparison of these methods shows that genetic algorithm tuning method GA1 and GA2 gives better performances according to the requirements of the feed drive, which means faster response without overshoots.

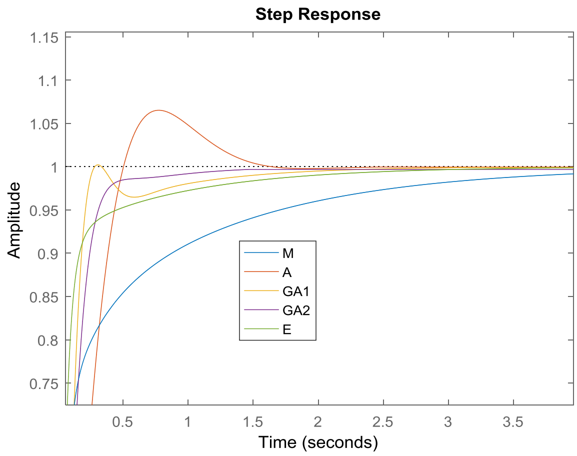

Figure 12. The Mat Lab tunning algoritham result

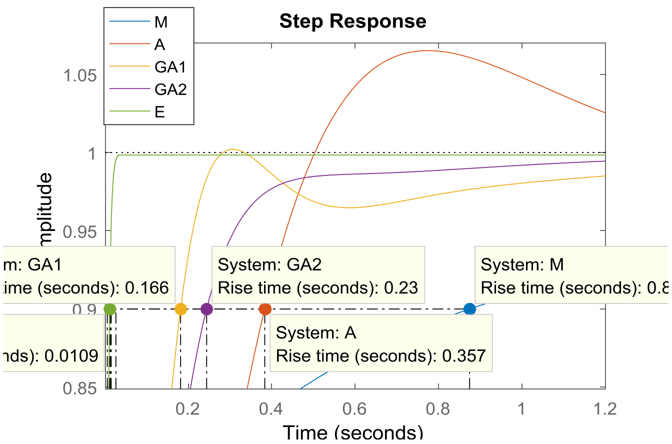

Figure 13. Rise times comparasion

In the table below we can see differences between methods with a clear dominance of Empirical and GA tuning.

TABLE I. COMPARISON OF DIFFERENT TUNING METHODS

	Tr	Ts	Overshot	ESS
M	0.877	4.42	0	0
A	0.357	1.8	0.07	0
GA1	0.166	0.985	0.209	-
GA2	0.23	0.424	0	0
E	0.0109	0.0193	0	0

VII. CONCLUSIONS

Given the fact that we are investigating to find the most appropriate controller for feed drive control system for milling process, the results are satisfactory. The idea was to find the best controller suitable for feed drive of milling machine with respect of working conditions and often set-point changes. Even that controller has nature of intelligent controller, the basis of its feasibility it is fast tuning PID controller.

We notice that if we have experience we can manually come to a fast tuning method with a minimal number of rules. The empirical method gives as fastest and easiest method.

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