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A successful application of an intelligent hybrid controller for feed drive control of CNC Machine tool

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Abstract— Successor effect of error that displays integrator part of PID controller in application of this controller for closed loop control of feed drive mechanism often can cause high overshoots and delays in the stability of the system. In this paper we have made a detailed study of this effect. Eliminating these overshoots by raising artificially the input of the controller, cannot be done without sacrificing the settling time. In terms of work with high speed CNC machines, the length of this time causes the reduction of productivity and precision machines. As a model we have chosen the closed loop system of feed drive control of CNC machines. To keep the limits required for the rise time without sacrificing settling time, we propose to remove the integral part from PID, and replacing its role by a hybrid controller with fuzzy logic. The new controller gives fast loop response stability, reducing the steady state error, increasing the rising time and decreasing the settling time.

Index Terms— PID control, error, Fuzzy logic, feed drive, CNC, control, intelligent control,

1 Introduction

Generally these feed drives are designed using a rotary servomotor and a ball screw [1]. The most common motors used in the feed drive are dc motors since they allow a wide range of operating speed with a sufficiently large torque delivery required by machine tools [2].

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 [3]. This torque produced by the motor is spent in acceleration of inertia reflected in the motor shaft [2] 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.

Before selecting the controller types, is to see which is he manipulated variable and working conditions on which that operates. So, 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.

The Fuzzy logic control has proven advantages of its application to cases where mathematical modeling of the dynamic system is difficult with very unsafe working conditions followed by nonlinearities and external disturbances and always unpredictable. However, its effective implementation depends primarily by the adequately chosen field of its application. Also, the performance of conventional fuzzy logic systems depends on the mode of filing the linguistic values of variables, predefining of fuzzy sets and by the way of establishing the fuzzy rules. All these require the need of expert knowledge in the area where control is applied and those experiences intertwine at the same time with knowledge of fuzzy logic reasoning.

Simulated results made by using MATLAB/ SIMULING shows the relevant effectiveness of its applications by errors comparison between conventional and applied controller.

2 The Feed drive

The feed drive mechanisms of a three-axis vertical milling machine consist of a DC motor and a lead-screw with recalculating balls. The DC servomotor which is directly connected to lead-screw shaft drives the table and work piece. [3] 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.

In order to model the feed drive for control purposes, we have simplified the system in a two degree of freedom

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structure. For this servomechanism, the transfer functions of the individual system components are usually known or have to be calculated. The electrical part, it is presented by a transfer function (1) according to [1] 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 [4] [5].

$$F_m(t) = 2/s^2 + 8s + 12 \qquad (1)$$

For simulations purposes, the dynamic characteristics of the mechanical components of feed drive of are calculated based on the laws of physics and are modeled using higher mathematics, according to [4]. The Mat Lab implementation is made by a program of S-function.

3 PID Control strategy

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

$$u(t) = K_p e(t)dt + K_i \int_o^t e(t)dt + K_d \frac{de(t)}{dt} \qquad (2)$$

Firstly we will see effects integral part to replace them then on new controller. We have found that to gain a transient response with zero steady state error we must have oscillations due to the integral part (fig.1):

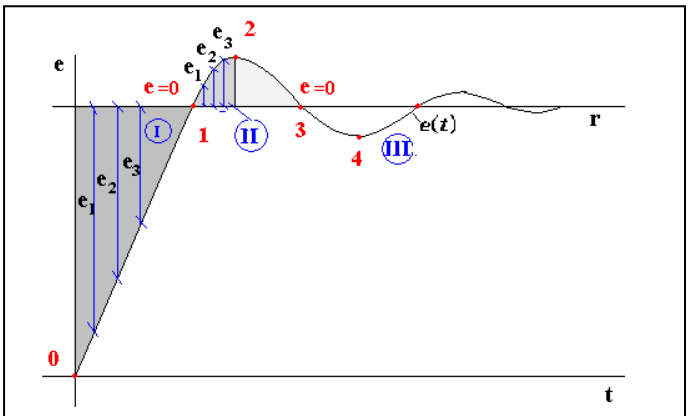

Fig.1. Error zones

On the zone-I the error is positive and tends to decrease. The proportional part Kp*e also is positive and is going to decrease due to the reduction of error. The integral part is positive but it is increasing so long as the outlined area is increasing.

$$e_1 > e_2 > e_3 > \ldots\ldots > 0$$

$$K_p e_1 > K_p e_2 > K_p e_3 > \ldots\ldots$$

$$K_I \int_0^{e_1} e_1 dt < K_I \int_0^{e_2} e_2 dt < K_I \int_0^{e_3} e_3 dt < \ldots\ldots \quad K_I \int_0^{e_I} e_I dt > 0 \qquad \ldots\ldots\ldots(3)$$

At the point 1 when the error becomes zero, is the integral part that drives the motor, because:e=0, Kp*e=0,

and $K_I \int_0^{e_I} e_I dt > 0$ so, u=0+Ki=Ki

Namely, the area I present a kind of error accumulation which pushes the curve away from the set point causing overshoot.

Going above 1-2 zone, the proportional part becomes negative but with an upward trend

$$e_1 < e_2 < e_3 \ldots\ldots$$

$$K_p e_1 > K_p e_2 > K_p e_3 > \ldots\ldots$$

$$K_I \int_0^{e_1} e_1 dt < K_I \int_0^{e_2} e_2 dt < K_I \int_0^{e_3} e_3 dt < \ldots\ldots K_{II} \int_0^{e_{II}} e_{II} dt < 0 \qquad \ldots\ldots(4)$$

But, the amount of the error is still positive so integral controller output continues to generate input for motor:

$$I = K_I \int_0^{e_I} e_I dt - K_{II} \int_0^{e_{II}} e_{II} dt > 0 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(5)$$

The impact of part of the accumulated error causes overshoot beyond the value of the set point and then creates a diversion in the opposite direction. In the case of step changes of the disturbances this will cause problems. This means that every time you have the reprogramming of the value of the set point, will have high overshoot and oscillations variable, while negative integrals canceled by those positive (surfaces under the set point line, ex the zone III). So the stabilization time will be increased under the influence of an integral part.

Elimination of the overshoot we can do by adding more input by increasing the slope of the line, but, it hurts other performance, increases the rise time. We see new curve in fig.2.

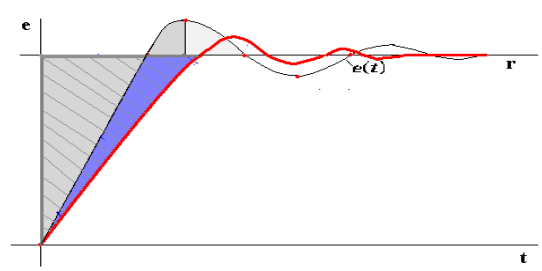

Fig.2. Iput and slope of line

But, we don't want to sacrifice the time of the establishment which is very important to the tool or work table positioning of CNC machine. We will remove an integral part of the PID and quick return to reprogrammed state will do with fuzzy logic. By integral part removal will try to eliminate the increasing of the settling time and overshoot.

Rise time decreases with increasing Kp factor, which action will do also steady state error reduction. Elimination of overshoot will be done by derivative part with very short of rise time. Rapid return direction from the direction of oscillation will do with the careful placement of fuzzy rules.

To examine the effects of removing an integral part in the model we only take member proportional and derivative. Signal coming out from this controller will be amplified with a KP1 factor (fig.3).

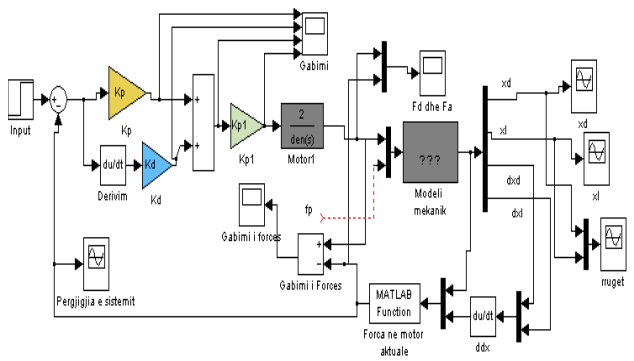

Fig.3. PD close loop

Since this does not have a integration member, error reduction will do by choosing the value of Kp factor that gives the smallest steady state error.
Manually adjust the factors starting with real requirements of the system. We see that for a step input value of 1, the output of the system is very weak features and we have a gain 1/13 to reach. That's why should go with values higher than 13 for Kp factor, in order to have better growth time. On the closed loop we start with increasing Kp value until the value closer to 1 (fig.4).

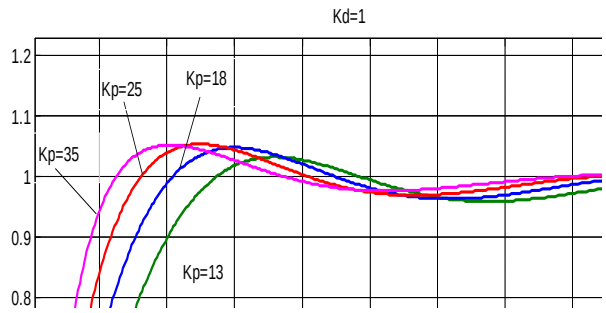

Fig.4.Kp Influence

It is seen that for large values the rise time upgrades and SSE error decreases but increases overshoot us and growing oscillations and settling time. Overshoot will be decreased with the derivative factor by decreasing its value (fig.5).

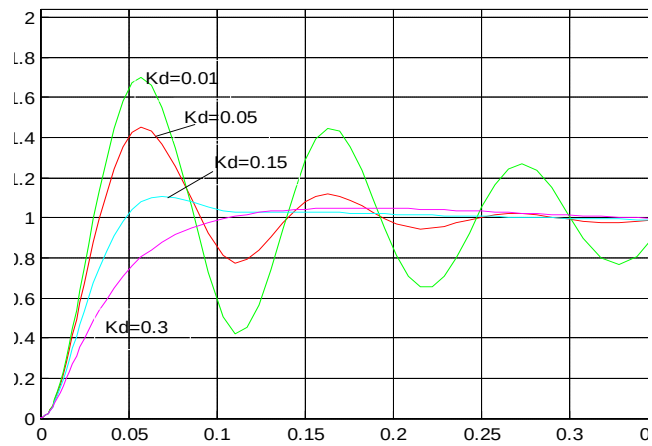

Fig.5.FLC transient response

So the compromise we have to do is rise time not to have high overshoot, or do eliminate overshoot with any other element does not increase the rise time (fig. 6). According to this logic, the most appropriate values are the values Kp = 13 and Kd = 0.3, which rise good time but has high overshoot and oscillations repeat T1> T2> T3 …(fig.7).

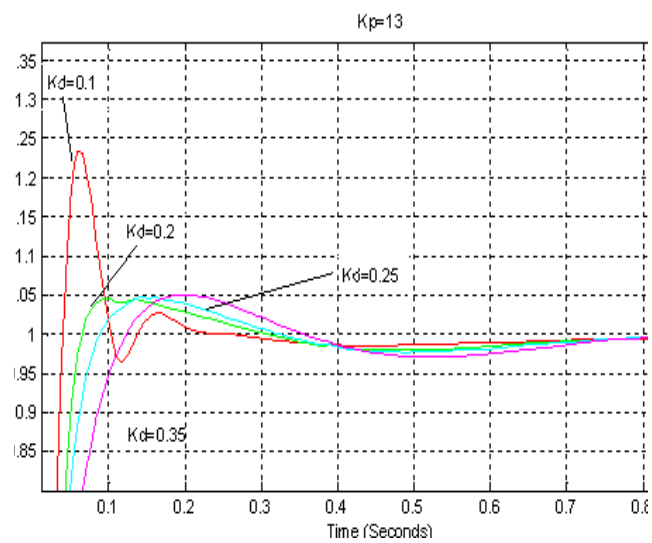

Fig.6.Kd Influence

We consider that a good transient response which offer the smallest rise and settling time conform our work condition limitations.

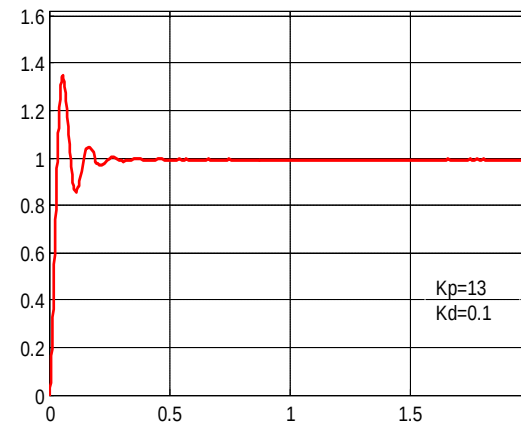

Fig.7.PD transient response

4 Fuzzy Logic Rules

In relation to this response all others have lower overshoot but greater rise time and do not have the same period repetitive oscillations (fig.8).

We will make a separation of the areas overpasses and underpasses to explore the establishment of fuzzy logic rules (fig.9).

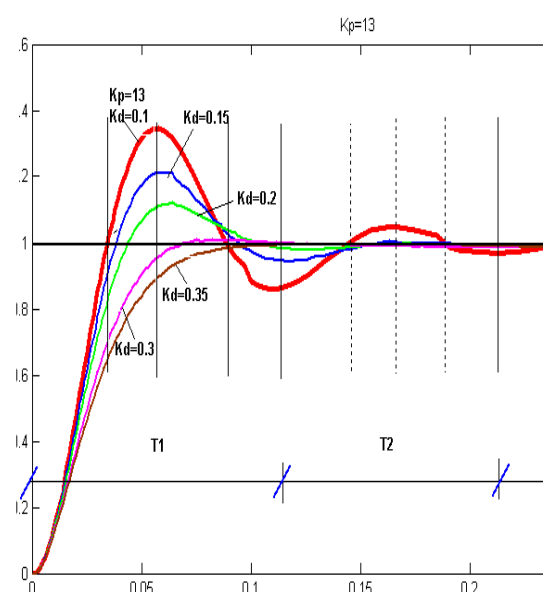

Fig.8.PD response oscillations

We distinguish the most important areas of transient response:

Zone 1: $e > 0$ *and* $de < 0$

Zone 3: $e < 0$ *and* $de > 0$

In both these areas, we notice that the curve claims set point and controller is correcting error and curve moves toward its reduction. In these areas do we need to do corrective action or it may be very small.

Zone 2: $e < 0$ *and* $de < 0$

Zone 4: $e > 0$ *and* $de > 0$

In these two areas the error do not correcting themselves and should therefore seek an executable element action, which means additional speed to opposite direction depending of the amplitude error and change of error.

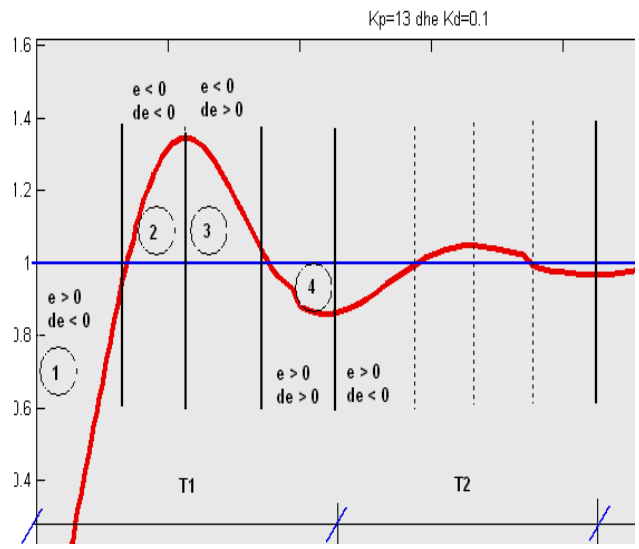

Fig.9.FLC important zones

The zone 5 it is the area where the error is approximately zero and its change is approximately zero. Correctional action should be zero or very small.

Table 1.

The Fuzzy Sets

	de	*de<0*			*de=0*	*de>0*		
e	action	**NB**	**NM**	**NS**	**Z**	**PS**	**PM**	**PB**
e<0	**NB**	NB	NB	NB	NB	NB	NM	NS
	NM	NB	NB	NB	NM	NM	NS	Z
	NS	NB	NB	NM	NS	Z	Z	PS
e=0	**Z**	NM	NM	NS	Z	PS	PM	PM
e>0	**PS**	NS	Z	Z	PS	PM	PB	PB
	PM	Z	PS	PM	PM	PB	PB	PB
	PB	PS	PM	PB	PB	PB	PB	PB

While in zones 2 and 4, where the error and its derivative have the same sign, the action must be rude, ie if e and de are negative (zone 2), the variables increases with speed and should operate with negative speed in the actuator, namely to slow down a speed in order to reduce their amplitude. Moreover, when both are positive (zone 4), then we decrease the desired variable speed, therefore, we must increase faster the speed of the motor, in order to stabilize the controlled variable. In both areas 1 and 3, control

actions should be very small or zero because the change of error tends to reduce the error that is of opposite sign.
That is, even though the error is high, the rate of change of error is satisfactory. Adequate regulation of the level of the "satisfaction" by activating careful action makes linearization. This forces us to make the redefinition of the scope of the error and its rate of change in quality levels type: small error, medium positive, large negative, etc[6].
Motor reaction quantity will be the range of the sum $e + de$.
Simulation will be in the same schema where fuzzy block will be decided after PD block. After this conclusion, we have reconstructed the fuzzy system and simulated the loop with fuzzy file FLC.

5 Results of simulations

After simulation process on Mat Lab, we can see considerable improvements in term of reducing the rise time, settling time, overshoot an steady-state error (fig.10). Comparing with PID, the FLC controller with symmetric triangular membership functions, can reduce rising and settling time, but not the overshoot either. To do that we need to determine well the grade for every membership function by using asymmetric triangular sets. This will be treated in another paper.

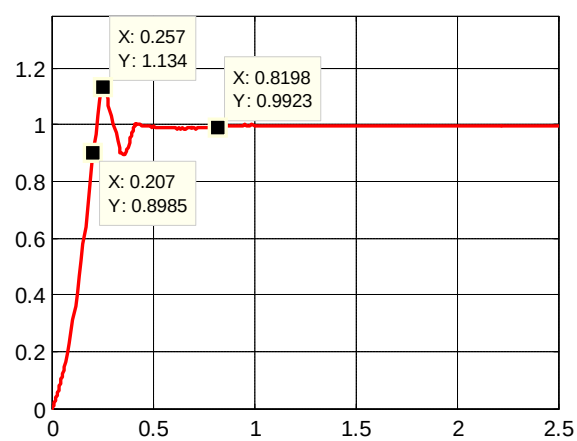

Fig.10. FLC-step response

Table 2.
The Performance comparison

	Rise time	Overshot	Settling time	Peak
PID	0.7667	0.0005	1.877	1.0005
FLC	0.207	0.134	0.82	1.134

6 Conclusion

By implementation of fuzzy reasoning on control systems we can improve some of the performances of the system. The PID control of feed drive gives as more stability but slower response, so, we have to make a compromise in favor of rise time which can be reached by fast response of the system. According to the results of simulation we can conclude that the hybrid controller gives as the acceptable stability which is not the best stability but offers us the faster response.
By placing a Fuzzy control algorithm we expand the scope of the change of control coefficients. Changes are frequent and rapid and the adaptation is done through the Fuzzy control. Fuzzy logic enhances the quality of the system and manages the nonlinearities leaved effect from time delays and uncertainty, and the uncertainty of the system too.

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