Fuzzy Controllers Simulation for CNC Feed Drives

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Abstract: - The paper presents some researches about feed drives using induction motors. An integrated approach is presented starting with the building of the feed drive model. An induction motor feed by frequency inverter model was chosen as actuation system for the feed drive. After the building the model, a simulation process was performed in order to test the system's behaviour and to tune the system's controllers. PI classic controllers and PD fuzzy controllers were compared by means of simulation.

Key-Words: - computer simulation, controllers, feed drives, fuzzy, simulation

1 Introduction

Servo-driven contouring systems are capable of producing accurate movements on various trajectories. Tracking and/or contouring errors often limit the accuracy of such systems [3]. Tracking errors result from various kinds of sources, including mechanical hardware deficiencies, manufacturing process effects and drives dynamics [1], [5].

Vector control is the independent control of the magnetizing and torque-producing components of current in an AC cage motor, the aim is to create a drive for induction motor that gives a degree of control equal or better than a DC motor plus a variable speed drive [4], [6].

The only way to provide effective independent control over the stator and rotor currents is to use a complex mathematical model to work out what is happening inside the motor.

The model must operate in real-time, something which has only recently become realistically possible with the introduction of a new generation of powerful low-cost microprocessor-based DSP controllers.

The microprocessor treats the field and torque producing components separately. This technique enables an AC motor to produce a linear and rapid control of motor torque for high-performance positioning.

The approach intended in this paper is to simulate a system based upon vector controlled AC motors and to test different speed controllers for the system, such as PI digital controllers and fuzzy PD controllers.

2 Motion control of CNC feed drives

Although machine tools designs, both for cutting and sheet metal industry vary immensely, the electro-mechanical configuration of their feed drive is largely standardized. In almost all cases the re-circulating ball screw has established itself as the solution for converting the rotary motion of the servomotor into linear slide motion.

The ball screw bearing takes up all axial forces of the slide. The servomotor and ball screw drive are usually directly coupled. For position measurement of feed axes on CNC machine tools it is possible to use either linear encoders or re-circulating ball screws in conjunction with rotary encoders. Because of the trend toward digital axes in drive technology, a large share of new servomotors feature rotary encoders, which can serve together with the feed screw for position control. With such a drive configuration the decision must be made as to whether to ad a linear encoder or simply to use a ball screw working in combination with the already existing motor encoder.

As for the actuation solutions used for feed drives, DC servomotors were for many years the standard. These types of motors were mostly replaced these days by AC permanent magnet synchronous servomotors. The synchronous AC motor having a permanent magnet can be transformed into a system like DC motor with separately excited field control having linear behaviour under field-oriented control accompanied with an inverter controlled by current hysteresis.

However, market analysis shows that most of all industrial motor applications use AC induction motors. The reasons for these include high robustness, reliability, low prices and high efficiency (up to 80%). The use of this motor in motion control systems, such as main or feed drives of machines, became realistically possible with the introduction of vector controlled voltage/frequency inverters equipped with powerful low-cost microprocessor-based motion control cards.

3 The model of the system

A motion control systems based upon induction motor, as actuating system and a rotary encoder as position feedback system was taken into consideration for this approach.

In order to test the systems behaviour, a simulation diagram was built, using the Matlab & Simulink software package (fig 1). The diagram is based upon the model of vector controlled induction motor with speed control, presented in [4], modified by the authors to be used in the CNC machine tools positioning systems.

The main modifications of the model presented in [4] involved the introduction of the positioning loop, and the introduction of the effects of the mechanical part of the system (transmission system, friction, cutting forces). The numerical character of a CNC feed drive was also taken into consideration. The structure of the subsystems from figure 1 was detailed in [1]. It is here to notice the fact that the system model was built taken into consideration both the numerical and analogical character of the system. The transfer functions used were both continuous (s-variable) and discrete (z-variable). One can say that the speed and flux control loops have mostly an analogical character while the position control loop has mainly a numerical one. However, the control algorithms used on all the three control loops are numerical ones and subsequently the system controllers are PI discrete controllers.

The next step after building the simulation diagram was to tune the three system controllers: the position controller, the flux controller and the speed controller. The tuning of the flux controller was done according to the relations:

$$K_{P\Psi} = \frac{\tau_r}{L_m} \quad (1)$$

respectively:

$$K_{I\Psi} = \frac{1}{L_m} \quad (2)$$

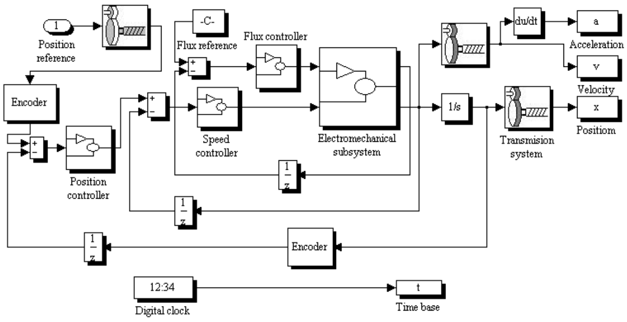

Fig. 1. The simulation diagram

where:

$K_{P\Psi}$ - the proportional gain factor of the flux controller;

$K_{I\Psi}$ - the integration factor of the flux controller;

τ_r – time constant of the induction motor's rotor;

L_m – mutual inductivity.

For the position controller the following relations were used:

$$\begin{cases} K_{PP} = 2\xi\,\omega_0 T_s \\ K_{IP} = \omega_0^2 T_s^2 \end{cases} \quad (3)$$

where:

K_{PP} - the proportional gain factor of the position controller;

K_{IP} - the integral factor of the position controller;

ω_0 – the own frequency of the system;

ξ – the damping factor;

T_s – the sampling period of the control loops.

The following relationship is recommended between ω_0 and T_s:

$$\omega_0 = \frac{1}{4T_s} \quad (4)$$

It was chosen T_s = 0,0001 s, thus ω_0 = 25000 s^{-1}. Replacing these values in (3) and imposing an optimum damping factor of ξ = 0.707, we obtain K_{PP} = 0,35 şi K_{IP} = 0,0625. It is here noticeable the fact that the position controller factors are independent from the motor characteristics.

The tuning of the speed controller was performed by a trial and error method until a satisfactory behaviour (through simulation) was obtained. Even if the find of some analytical relationships for K_{PV} and K_{IV} is theoretically possible, because of the high number of phenomenon which cannot be analytically defined with precision (such as friction) which are involved in the system's behaviour, a trial and error simulation process was considered as the best tuning method for this controller.

The use of Matlab and Simulink software package facilitates the study by means of simulation, due to the ease of parameters changing within the program.

4 Reference inputs

In order to drive the machine slide, reference inputs for the motion control system have to be generated. For a single axis movement, a typical set of cinematic inputs involves the use of the trapezoidal velocity profile. Other profiles to be used are, for example, the parabolic profile, or even profiles defined by spline-curves, for highly sophisticated applications.

The trapezoidal velocity profile has some drawbacks, such as the apparition of the “jerk” phenomenon, due to the shape of the acceleration (rectangular profile), but it is widely used because of the ease of implementation.

Furthermore, the “jerk” phenomenon is to be taken into consideration only when large loads have to be moved. Also, the lags, which normally appear in the control loops, lead to smother output acceleration profiles, different from the rectangular one and consequently, the possibility of apparition of the “jerk” are significantly reduced.

Figure 2 shows a typical set of simulated reference inputs used for simulating the system behaviour. Because of the numerical character of the system, the reference inputs had to be also generated in a discrete way. A sampling time for generating these inputs was chosen equal to 0.001 seconds, which is ten times larger as the sampling time of the control loops.

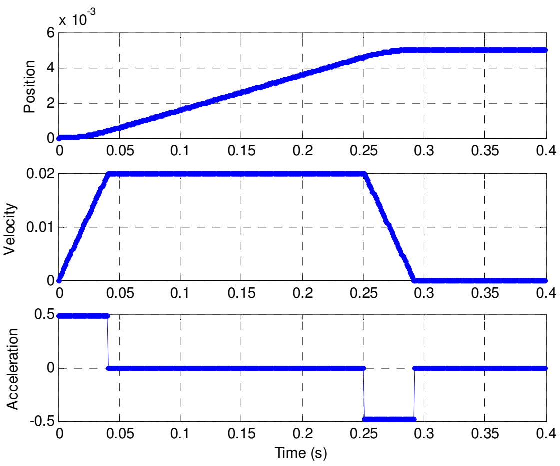

Fig. 2. Typical set of simulated reference inputs based on trapezoidal velocity profile.

5 Fuzzy controller

In order to compare various controlling strategies, a two inputs fuzzy controller was implemented. The first input of the controller was the variable „speed error (error)” and the second input was „derivative of the speed error (error variation)”. Three triangular membership functions named negative, zero, positive were used to fuzzyfy the two inputs

Five triangular membership functions named negative big, negative medium, zero, positive medium, and positive big were used for the output.

The rules for the fuzzy controller were:

- if error is negative and error variation is negative then command is negative big;
- if error is negative and error variation is zero then command is negative medium;
- if error is negative and error variation is positive then command is zero;
- if error is zero and error variation is negative then command is negative medium;
- if error is zero and error variation is zero then command is zero;
- if error is zero and error variation is positive then command is positive medium;
- if error is positive and error variation is negative then command is zero;
- if error is positive and error variation is zero then command is positive big;

The main purpose of the fuzzy regulator with two inputs is to reduce the speed and acceleration oscillations. According to the classic controllers, this implies the use of a derivative effect. Thus, the fuzzy controller has to be designed as a proportional-derivative controller. The internal structure of the controller is presented in figure 3.

Three proportional factors K_1, K_2 şi K_3 are involved in the structure. One can determine the value of these factors starting with the fact that command signal C is a non-liniar function of error (er) respectively of error variation (var_er):

$$C = f(K_1 \cdot er, K_3 \cdot \text{var\_}er) \cdot K_2 \tag{5}$$

Using linear approximation:

$$K_1 \cdot e + K_3 \cdot \text{var\_}er \tag{6}$$

we obtain:

$$C = (K_1 \cdot e + K_3 \cdot \text{var\_}er) \cdot K_2 = K_1 \cdot K_2 \cdot (er + \frac{K_3}{K_1} \cdot \text{var\_}er) \tag{7}$$

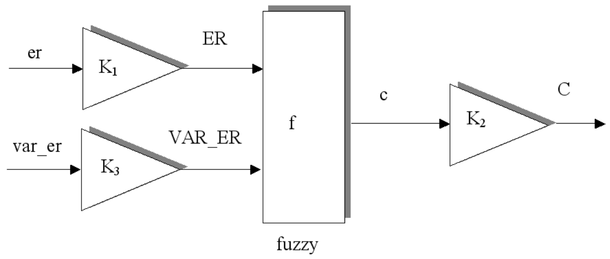

Fig. 3. The internal structure of the fuzzy controller

By analogy with the PD classical controller we obtain:

$$K_P = K_1 \cdot K_2$$
$$K_D = K_2 \cdot K_3 \qquad (8)$$

Because the speed controller is a PI one without D component, we will fix only K1 and K_2, and will determinate K_3 by a trial and error process.

Figure 4 presents a comparison of position, speed and acceleration outputs for the PI speed controller and for the PD fuzzy controller.

The reference data for simulation were:

- cutting force with step variation at 0.2 seconds, maximum value 2000 N
- maximum distance 0.005 m
- maximum speed 0.02 m/s
- maximum acceleration 0.1 m/s^2

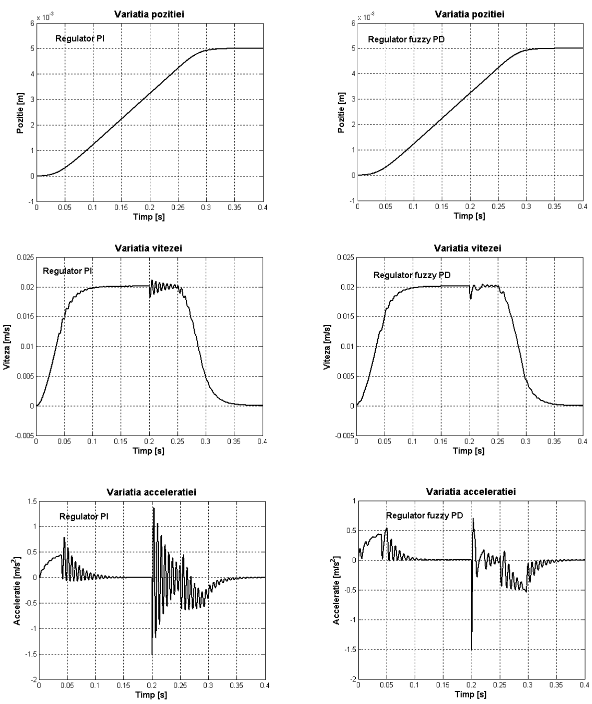

Fig. 4. Comparison between digital PI and fuzzy PD controllers

5 Conclusions

From figure 4 it is noticeable the fact that the fuzzy PD controller performs better than digital PD controller with regards of the oscillatory behavior of speed and acceleration.

Positioning error of the simulated feed drive is also reduced from 7µm (PI controller to 0.87 (fuzzy PD controller).

The obtained results validate the use of the fuzzy controller, however one has to keep in mind the fact that these kinds of controllers are quite hard to be implemented in practice. Another drawback of the fuzzy controllers is the saturation phenomenon, which appears quite rapidly if the controller is not tuned correctly.

These problems will be the subject of further research. Researches will also be performed in order to improve the contouring behaviour of the system.

A future approach will involve the use of the parabolic velocity profile instead of the trapezoidal one, in order to reduce the "jerk" phenomenon, which may have great influence when great masses of machine slides are involved.

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