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A Fuzzy-Logic Based Tuning for a Velocity Controller of the DC Servo Drive

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Abstract. The paper presents a methodology of designing a velocity control system for a DC motor servo drive that is widely used in CNC power transmission systems. There are presented both: the algorithm for tuning the velocity controller for a specified value of overshoot and a fuzzy-logic based tuning of PID controller procedure.

Usage of a method called PID-OVR, which ensures the assumed overshoot in a control loop, allows one to chose initial settings of the controller. This algorithm is used with assumptions that the load of motor is equal to zero and that the electrical T_{em} and mechanical T_{mm} parameters (time constants) are known accurately. Since all this parameters are always encumbered with errors and the load torque of motor during its work is greater than zero the initially assumed controller settings may not ensure well enough quality of the velocity regulation. Overshoot and damping factor of a step response in a velocity control loop, both of these parameters are used in a fuzzy-logic based tuning of PID controller procedure. This procedure do not require any active identification experiments to be carried out, thanks to which the control performance is not affected.

Introduction

One of the most difficult problem in the process of designing the power transmission system of the CNC is a correct tuning of the velocity control loop. The problem has been considered for many years [1–4]. A great number of works in this field present methods that use detuning of PID controllers, feed-forward systems or controllers based on artificial intelligence methods [4, 5].

In the paper we present a methodology of designing a velocity control system for a direct current motor servo drive that is widely used in CNC power transmission systems. The paper is a partial result of an on-going research program. There are being developed new procedures for designing and tuning control systems for synchronous permanent magnet AC servo drives with electronic commutation. These have recently won great popularity in contemporary CNC feed systems since currently only brushless electronic commutation servo drives with encoders fixed on the shaft are used. There are two versions of such servo drives: BLDC (*BrushLess DC*) and PMAC (*Permanent Magnet AC*).

In the process of designing the power transmission system of the CNC one meet a few basic problems which were enumerated in [3]. One of them is to provide the stiffness of the DC motor servo drive, especially at a small velocity and with the varying load of the shaft. Another problem is to tune correctly a velocity loop, particularly when the motor mechanical time constant is comparable with the electromechanical one. Then the control loop of the DC motor can be treated as an oscillatory second order element without delay. In this case it is important that the step response in the control loop be overshoot-free, as any oscillatory transient state in the velocity control loop cause inaccuracy and long settling times in the position loop.

The paper presents both: the algorithm for tuning the velocity controller for a specified value of overshoot and a fuzzy-logic based tuning of PID controller procedure.

Usage of a method called PID-OVR, which ensures the assumed overshoot in a control loop, allows one to chose initial settings of the controller. The proposed in the paper fuzzy-logic based tuning of PID controller procedure allows one to adjust the control system to the changing machining conditions thanks to which it ensures both high quality of tracking of the reference value (velocity) and significant increase in stiffness of the servo drive in the presence of motor parameters perturbations and varying load torque. The procedure minimize value of overshoot in the control loop. This algorithm has already been considered in previous papers [6, 7].

In the paper a few assumptions have been made, which allows us to present clearly the essence of methodology for tuning the DC motor velocity control systems. Similarly, we purposely omit in the motor scheme the current loop, which is used for security purposes, rather than to improve the control performance.

The paper is rounded off with numerical examples and results of simulation experiments that illustrate the main assumptions of the proposed here algorithms. In the following papers, on which work is underway, this method is going to be developed to be applied to other types of motors used in CNC machines.

Model of the DC Servodrive

Fig. 1 shows the simplest model of the direct current motor [3], for which accessibility of the controllable DC source is assumed. It is represented by the power supply u_m (values of variables presented in Fig. 1 and in the following equations are relative).

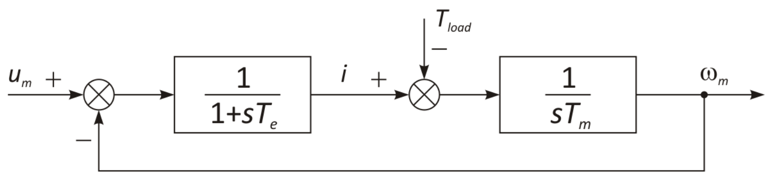

Fig. 1. DC motor simplified model

The electro-mechanical relations of the DC motor take the form

$$\begin{cases} T_e \dfrac{di(t)}{dt} + i(t) = u_m(t) - \omega_m(t) \\ T_m \dfrac{d\omega_m(t)}{dt} = i(t) - T_{load}(t) \end{cases} \tag{1}$$

It is obvious that during work of the motor not only the load (T_{load} = var), but also motor parameters may vary and be perturbed. In the paper the unknown changes of the electrical and mechanical motor parameters are simplified to the form

$$\begin{aligned} T_e &= T_{em} + \Delta T_e \\ T_m &= T_{mm} + \Delta T_m \end{aligned} \tag{2}$$

where $\Delta T_e, \Delta T_m$ are the electrical (electromechanical) and magnetic time constants variations respectively. For the nominal model $T_{load} = 0, \Delta T_e = 0, \Delta T_m = 0$.

Equations (1) may be transformed to the form:

$$T_e T_m \frac{d^2\omega_m(t)}{dt^2} + T_m \frac{d\omega_m(t)}{dt} + \omega_m(t) = u_m(t) - T_{load}(t) - T_e \frac{dT_{load}(t)}{dt} \tag{3}$$

Assuming the value of load is zero and performing the Laplace transform with the zero initial conditions, equation (3) assumes the form

$$\left[s^2 T_e T_m + s T_m + 1 \right] \omega_m(s) = u_m(s) \tag{4}$$

In real constructions with DC motors an AC/DC converter (rectifier) with controllable voltage amplitude is needed [3]. There are modeled as a pure delay τ. Then for a motor in an open loop the following transfer function is in force

$$\frac{\omega_m(s)}{u_m(s)} = \frac{1}{s^2 T_{mm} T_{em} + s T_{mm} + 1} e^{-s\tau} \tag{5}$$

where T_{em}, T_{mm} denote unperturbed electrical and magnetic time constants respectively.

PID-OVR Design for Oscillatory Plus Time Delay Model

Initial settings of the velocity PID controller may be chosen by usage of the PID-OVR method, which was proposed in [8]. This abbreviation denotes a method for synthesis of the PID controller that ensures a specified value of the overshoot occurring in the closed-loop system. The overshoot χ (OVR) is defined by equation (see denotation in Fig. 2)

$$\chi = \frac{A_1}{A} \tag{6}$$

The method consists in the following assumptions:
– the equivalent transfer function of the closed-loop system is given by

$$\widetilde{M}(s) = \frac{k\omega_n^2 e^{-s\tau}}{s^2 + s2\beta\omega_n + \omega_n^2} \tag{7}$$

– the process itself is approximated by the oscillatory model

$$\widetilde{P}(s) = \frac{k_m e^{-s\tau}}{T_m^2 s^2 + 2\beta_m T_m s + 1} \tag{8}$$

– the controller $C_1(s)$ is a PID one given by

$$C_1(s) = k_{cm}(1 + sT_{dm} + \frac{1}{sT_{im}}) \tag{9}$$

Also, the following approximation

$$e^{-s\tau} \approx \frac{1 - s\tau/2}{1 + s\tau/2} \tag{10}$$

is adopted here.

For a given closed-loop overshoot value (OVR) we get the following approximate relationship related to eq. (7)

$$\beta_{assumed} \approx \frac{\ln \frac{1}{OVR}}{\sqrt{\pi^2 + \left[\ \ln\left(\frac{1}{OVR}\right)\right]^2}} \tag{11}$$

With this assumptions the calculating procedure comprises the following steps:

1. Specifying the value of overshoot χ (OVR); thus the damping ratio $\beta_{assumed}$ for the closed-loop is derived;

2. On the basis of $\beta_{assumed}$ and plant parameters (8) k_m, β_m, T_m and τ calculating values of parameters of the PID controller (9) k_{cm}, T_{im}, T_{dm} which ensures satisfying the criterion. For the process approximated by the oscillatory model (8) one has to assume: $T_{im} = 2\beta_m T_m$, $T_{dm} = T_m / 2\beta_m$ and the gain k_{cm} evaluated with the inequality

$$k_{cm} \le \frac{4\beta_m T_m}{k_m \tau}\left(1 + 2\beta_{assumed}{}^2 - 2\beta_{assumed}\sqrt{1+\beta_{assumed}{}^2}\right). \tag{12}$$

A Fuzzy-logic Based Tuning of PID Controller

The presented in the previous chapter PID controller tuning procedure, with assumption that the motor load equals zero, allows one to tune the velocity control loop in a way that ensures satisfying the assumed overshoot criterion. However is assumes that both electrical and magnetic time constants are unperturbed and known accurately. Since all the above mentioned parameters are always encumbered with errors and the load torque of motor during its work is greater than zero the initially assumed controller settings may not ensure well enough quality of the velocity regulation. Uncertainties of the servo drive model and the load torque may cause deterioration of the quality of control: changes of the assumed overshoot and damping factor of a step response in a velocity control loop. All this changes cause a necessity of retuning the controller, which means the necessity to use a self-tuning and/or adaptation methods.

Papers [6, 7] present a fuzzy-logic based tuning of PID controller method that is used after a jump of the reference signal. Observation of the step response (regulated signal) during the transient state allows one to evaluate among other things:

- overshoot χ of the regulated signal

$$\chi = \frac{A_1}{A}, \tag{13}$$

- rapidity of regulation α defined as

$$\alpha = \frac{t_1}{t_r} \tag{14}$$

- damping factor

$$\zeta = \frac{A_3 - A_4}{A_1 - A_2}. \tag{15}$$

Parameters of the equations (13) - (15) are denoted in Fig. 2.

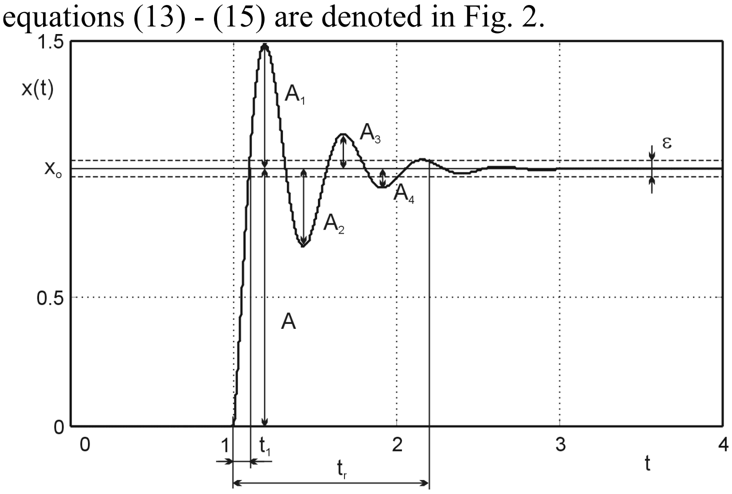

Fig. 2. Measurements for the fuzzy-logic tuning procedure

The presented in the paper algorithm in a decision-making process makes use of two parameters: overshoot χ of the regulated signal and either rapidity of regulation α ratio or damping factor ζ. The choice between this two parameters α and ζ may come from the individual preferences and experience of the machine operator. It may be as well done during the step response analysis, especially, that usage of one of the above factors may decide about termination time of the tuning procedure. E.g. for a periodic processes, in a case of an inaccurate tuning of the controller, usage of the damping factor allows one to finish the procedure and retune the controller more quickly.

Apart of the values of the parameters χ and $\alpha\,(\zeta)$ the algorithm takes advantage of value of the reference signal. It is obvious that in the case of numerous constraints imposed on signals in a real control system it is not possible for instance to achieve high values of the overshoots when the reference signal is close to the maximal possible values of the controlled signal. So the structure of the fuzzy logic algorithm is shown in Fig. 3.

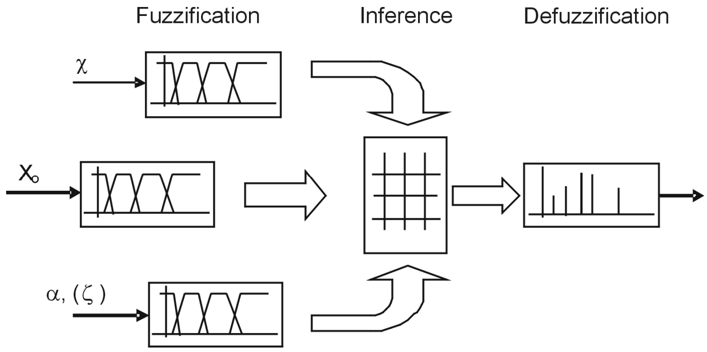

Fig. 3. Structure of the fuzzy-logic block in a tuning procedure

All this parameters are fuzzified into four fuzzy sets, which member functions are taken as trapezoidal ones. Then we infer a fuzzy output, which means a fuzzy value of the correction coefficients for the particular controller settings. The rule bases are organized in tables, which cells instead of the usually used names of the fuzzy sets contain direct values of the correction coefficients. For such form of the “fuzzy” outputs the most convenient (very fast) defuzzification method is a Singelton one. Change of the controller settings are then made according to the rule

$$N_{Ni} = p_i N_{Oi}\,, \tag{16}$$

where N_{Ni} and N_{Oi} denote a new and old value of i-th setting respectively.

Trapezoid shape of the membership functions for the input, large number of the output sets together with many various fuzzy operators, which are available in the algorithm allows one to match the algorithm precisely to a peculiarity of the process. It allows one to shape flexibly output inference surfaces Since the procedure may lose its sensitivity to changes of the checked factors χ and $\alpha\,(\zeta)$ so if all their values are within some acceptable ranges then no alterations of the controller settings are made.

Illustrative Example

Opportunities available from application of the presented above algorithms will be presented on the basis of a velocity control for a DC motor drive. We assume that its electrical and magnetic time constants have values T_{em} = 0,15[s] and T_{mm} = 0,153[s] respectively.

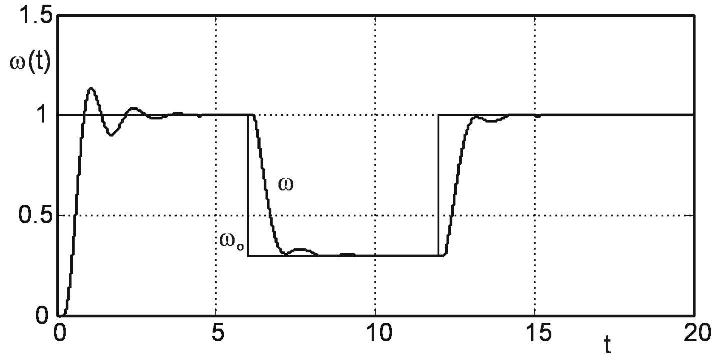

Fig. 4. Velocity control of the servo drive with a retuned PID controller

Results of simulation are presented in Fig. 4. It is clearly seen that due to perturbations of the electrical time constant the controller, tuned initially under a PID-OVR procedure with assumption of the overshoot close to zero, had to be retuned. A fuzzy logic procedure rectified its parameters in such way, that the control performance after next changes of the reference value was significantly improved.

Summary

Results of the so far done research into presented in the paper fuzzy logic based PID controller tuning procedure confirm its usefulness and improvement of the regulation quality. This procedure do not require any active identification experiments to be carried out, thanks to which the control performance is not affected.

Application of the presented algorithms in industrial controllers surely requires a number of experiments, however, positive results achieved so far show, that fuzzy logic tuning procedures may be one of the effective ways in building a simple and effective velocity controller for the servo drives, which could be accepted by consumers.

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