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DYNAMICAL QUALITY IMPROVEMENT OF MECHATRONIC SERVO SYSTEM USING VARIABLE STRUCTURE VELOCITY CONTROLLER

Vilius Antanas Geleževičius

Department of Control Technology, Kaunas University of Technology
Studentu Str. 48, LT–51367 Kaunas, Lithuania
e-mail: vilius.gelezevicius@ktu.lt

Nerijus Šulčius

Department of Electrical engineering, Šiauliai University
Vilniaus St. 141, LT – 76353 Šiauliai, Lithuania

Abstract. A technique of dynamical quality improvement of the mechatronic servo system is presented in the article. Application of variable structure velocity controller, whose control law during the transient regime of the system can be automatically changed from the proportional-integrating (PI) to the proportional (P) law and vice versa, is the core of this technique. Two methods based on fuzzy logic and preprogrammed "Lookup Table" application, ensuring automatic change of velocity controller structure, are proposed and investigated. The simulation results of the servo system confirming suitability of the proposed dynamical quality improvement technique are presented and discussed.

Keywords: velocity control, dynamical quality, servo system, variable structure controller, fuzzy logic.

1. Introduction

The cascade control of the mechatronic servo drive ensuring the quantitative or the symmetrical optimum condition [1] is still widely used. The velocity control system of the mechatronic servo drive consists of the internal torque (current) control loop adjusted in accordance with the quantitative optimum condition and external velocity control loop adjusted according to the quantitative or to the symmetrical optimum conditions. The quantitative optimum condition requires the proportional (P) velocity controller and ensures optimum rapidity response to the step mode reference signal. However such a control mode distinguishes by a steady-state velocity error caused by the external load of the motor. In order to avoid a steady-state velocity error caused by this disturbance, the proportional-integrating (PI) velocity controller can be used. Usually, such a controller is adjusted according to the symmetrical optimum condition [1 2, 3]. However, the use of the PI controller declines the dynamical quality of the mechatronic servo system.

In order to coordinate the advantages and eliminate disadvantages of both the quantitative and the symmetrical optimum control methods, the variable structure velocity controller has been proposed [4]. The main peculiarity of such a controller is the possibility of automatic change of its control law from the proportional-integrating (PI) mode to the proportional (P) mode and vice versa during the transient regime of the servo drive. Two different methods of the velocity controller control law automatic change are proposed and investigated in [5]. The dynamical quality of the system regime has been evaluated with the help of the ITAE (Integral of Time multiplied by Absolute Error) quality criterion. Supposing that the best dynamical quality of the system corresponds to the minimum value of this criterion, the specific parameters of velocity controller structure switching from one control law to another have been defined.

In conformity with the obtained results [5], the following algorithm of the velocity controller control law change is proposed. In the initial phase of the transient regime of the servo drive, the velocity controller is adjusted according to the PI control law. At the time moment when the armature current reaches its maximum value the control law is switched to the P control law, corresponding to the quantitative optimum condition. Finally, after some delay time the control law is switched again from the P to the PI mode and remains unchanged up to the end of the cycle. This delay time depends on the load level of the servo drive and has to be defined on-line during the transient regime. Two control methods ensuring this delay time on-line estimation are investigated. The first method is based on the fuzzy logic methodology and the second one – on the preprogrammed "Lookup Table" application; both of them allow defining of necessary P control law duration in dependence of the static load level. The problem arises with the static load level definition. On purpose of acting load of servo drive estimation, the Luenberger observer is proposed. The results of investigation of the mechatronic servo system with variable structure velocity controller guided by Luenberger observer are presented in this article.

2. Discussion of mechatronic servo system with velocity controller of variable structure

The block diagram of the mechatronic servo system with velocity controller of variable structure is presented in Figure 1. The mechatronic servo system consists of the internal motor current control loop represented by the simplified transfer function

$$H_{CL}(s)=\frac{k_{CL}}{2T_C\cdot s+1}, \qquad (1)$$

the mechanical part of the system with transfer function

$$H_M(s)=\frac{k_M}{s}, \qquad (2)$$

a velocity feedback – k_Ω, the Luenberger observer block – LO and the variable structure velocity controller block – VSCB. The main parts of the VSCB are the variable structure controller VSC itself, which is able to turn proportional (P) control law

$$H_P(s)=k_{P\Omega}, \qquad (3)$$

to proportional-integrating (PI) control law

$$H_{PI}(s)=k_{P\Omega}(1+\frac{1}{8T_C\cdot s}), \qquad (4)$$

and vice versa, the control law switching block – SB, and the P control law delay time definition device – DTD (based on the fuzzy logic methodology or on the preprogrammed "Lookup Table" application). In the equations (1)– (4) the following notations are used: $k_{P\Omega}$ is a gain of the proportional (P) velocity controller, k_{CL} – a gain of the closed current control loop, k_M – a gain of the mechanical part of the system, T_c – a small time constant of the power converter.

Due to the static load level estimation of the servo drive, the Luenberger observer [6] has been developed and implemented. The structure of the observer in the form of the block LO is presented in Fig. 1, where H_{Mest} is an exact replica of the mechanical part of the mechatronic servo system – H_M. The transfer function of the observer compensator is chosen as

$$H_{OBS}(s)=k_{OBS}. \qquad (5)$$

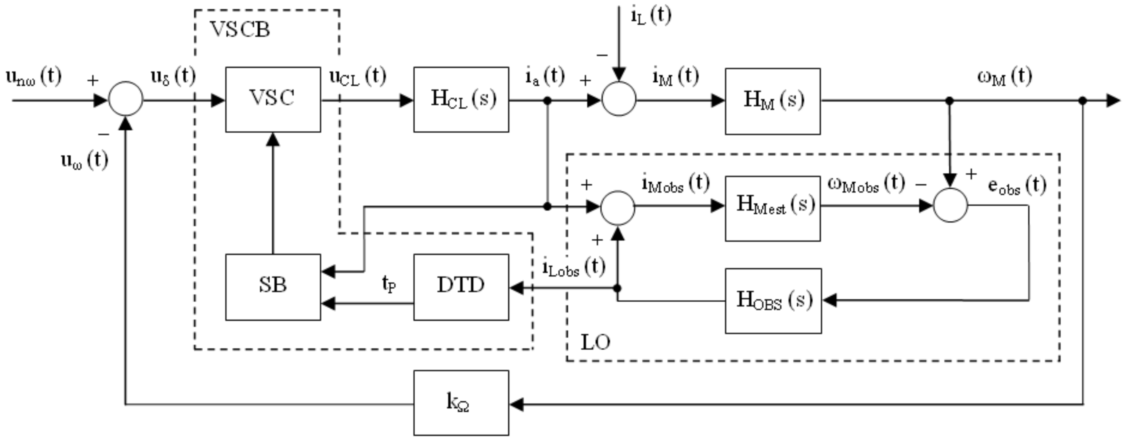

Figure 1. Block diagram of the mechatronic servo system with variable structure velocity controller block VSCB and Luenberger observer block LO

The response curve of observer provoked by the evaluated load step mode change is presented in Fig. 2. The curve named *Act* is the actual (settled) step mode nominal static load current. The curve named *Obs* is the estimated static load current obtained from the output of the developed Luenberger observer. It is seen that the evaluated value of the observed static load current asymptotically converges to the value of the actual (settled) nominal static load current. It is obvious from Figure 2 that the convergence time is shorter than the PI-P control law switching time (vertical ST line), thus the observed static load current obtains steady-state value (equal to the actual (settled) value) before the time when control law of the controller id to be switched from PI to P mode. Consequently, the derived static load current signal is suitable for passing from the Luenberger observer to the P control law delay time definition device.

3. Design of device for P control law delay time definition

Fuzzy logic-based delay time definition device. The first P control law delay time definition method is based on the fuzzy logic application. The architecture of the fuzzy logic device (FLD) is presented in Figure 3. The FLD has been designed using Fuzzy Logic Toolbox from MATLAB package [7] and has four common stages of the mapping from the input of the device to the output: *fuzzification*, *implication*, *aggregation* and *defuzzification*.

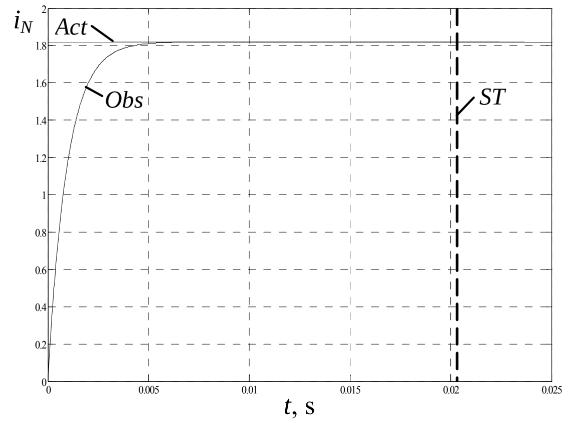

Figure 2. Curves illustrating static load estimation process

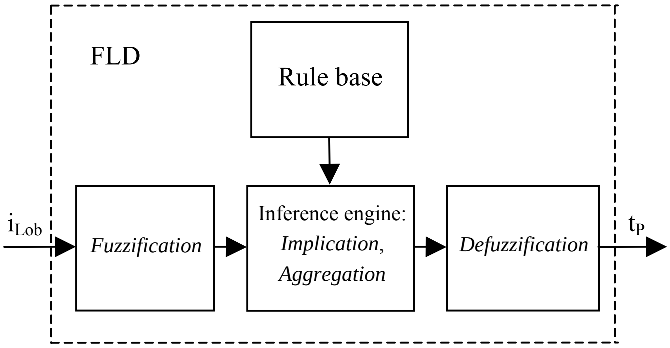

Figure 3. Architecture of the fuzy logic device

During the first stage – *fuzzification*, the input signal – the observed static load current value is taken and the degree to which it belongs to the appropriate membership functions is determined (Figure 4). Inference engine performs *implication* and *aggregation* functions and determines the aggregated fuzzy output in the dependence on the linguistic rules from the Rule base. The Rule base has been formed manually according to the investigation results [7] and consists of six IF-THEN linguistic rules :

$$\begin{cases} \text{IF } \textit{Load} \text{ is None THEN } \textit{Delay} \text{ is Longest,} \\ \text{IF } \textit{Load} \text{ is Very Small THEN } \textit{Delay} \text{ is Longer,} \\ \text{IF } \textit{Load} \text{ is Small THEN } \textit{Delay} \text{ is Long,} \\ \text{IF } \textit{Load} \text{ is Very Medium THEN } \textit{Delay} \text{ is Medium,} \\ \text{IF } \textit{Load} \text{ is Medium THEN } \textit{Delay} \text{ is Short,} \\ \text{IF } \textit{Load} \text{ is Nominal THEN } \textit{Delay} \text{ is Very Short;} \end{cases} \quad (6)$$

where *Load* is an input linguistic variable – the observed static load current i_{Lobs} with the range [0 ÷ i_{Nobs}], i_{Nobs} – the observed nominal static load current; *Delay* is an output linguistic variable – the proportional (P) control law duration time t_P with the range [0.01 ÷ 18.5 ms].

Six linguistic values – appropriate membership functions have been formed manually and assigned to the input and output linguistic variables (Figure 4). It has been chosen *product* implication method, which scales the fuzzy set. Modified fuzzy sets of each rule are then aggregated into a single output fuzzy set. Finally, the resulting set is defuzzified (solved) to a single (crisp) value – the proportional (P) control law duration time t_P. Two types of the fuzzy logic device (FLD) have been designed: Mamdani-type and Sugeno-type [7]. In the Mamdani-type FLD, after the *aggregation* process, the output membership function of the output variable (Fig. 4) is a fuzzy set. While a Sugeno-type FLD uses a constant value (singleton) as the output membership function (in our case it has six constant values (singletons): 0.01, 1.2, 3.0, 7.0, 13.0, 17.0 ms). In order to obtain a crisp output value – the P control law duration time, the *center of gravity* defuzzification method has been chosen in the Mamdani-type FLD while the *weighted average* method has been selected in the Sugeno-type FLD.

The input-output dependence of the delay time definition device – the $t_P = f(I_R) = f(I_L/I_N)$ diagram is presented in Figure 5, where t_P – the duration time of the proportional (P) control law, I_L – the settled load current value, I_N – the nominal load current value, I_R – the relative load current value (the ratio of I_L and I_N currents). The *Opt* curve (Figure 5) is obtained from the investigation results reported in [5] and demonstrates optimal $t_P = f(I_R)$ dependence. The SISO delay time definition device with the implemented optimal $t_P = f(I_R)$ dependence ensures the best dynamical quality (defined by the ITAE quality criterion) of the mechatronic servo system. The deviation of the duration time (t_P) from the optimal values (*Opt* curve) causes the decline of the dynamical quality of the mechatronic servo system. The quality region QR of the duration time (t_P) change is defined (Figure 5, unlined zone). Within the QR, the dynamical quality of the mechatronic servo system decreases up to 5% compared to the best dynamical quality. Nevertheless this possible decrease of the dynamical quality due to the duration time (t_P) change is considered as acceptable. Two curves have been derived from the fuzzy logic device and are presented in Fig. 5: *M* curve has been obtained from the designed Mamdani-type FLD, *S* curve has been obtained from the designed Sugeno-type FLD. The obtained *M* and *S* curves are located within the quality region QR (Fig. 5) and coincide with *Opt* curve in the range [0.5 ÷ 1] of the I_R, but differ a little from *Opt* curve in the range [0 ÷ 0.5) of the I_R. Consequently, both Mamdani-type and Sugeno-type fuzzy logic devices are suitable to use for the definition of the P control law duration time.

Programmable delay time definition device. The second P control law delay time definition method is based on the preprogrammed "Lookup Table" application. The programmable SISO delay time definition device has been built in the form of the "Lookup Table": the input variable – the load current value (obtained from the Luenberger observer) is mapped to the corresponding output variable – the duration time of the proportional (P) control law. Considering the defined quality region QR (Fig. 5), the input-output dependence of the programmable device – $t_P = f\,(I_R)$ curve (named *Progr* in Fig. 5) is defined and described by two linear functions:

$$Progr = \begin{cases} 0.0201 - 0.0402 \cdot I_R\ ,\text{if } 0 \le I_R < 0.5, \\ 0.00001,\ \text{if }\ 0.5 \le I_R \le 1\,. \end{cases} \tag{7}$$

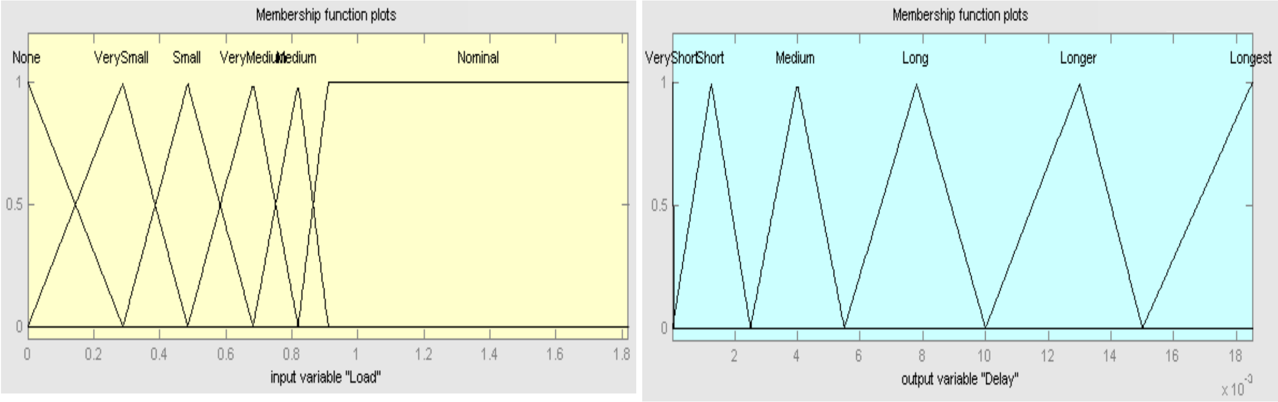

Figure 4. a – membership functions of the input linguistic variable *Load* in Mamdani-type and Sugeno-type FLD;
b – membership functions of the output linguistic variable *Delay* in Mamdani-type FLD

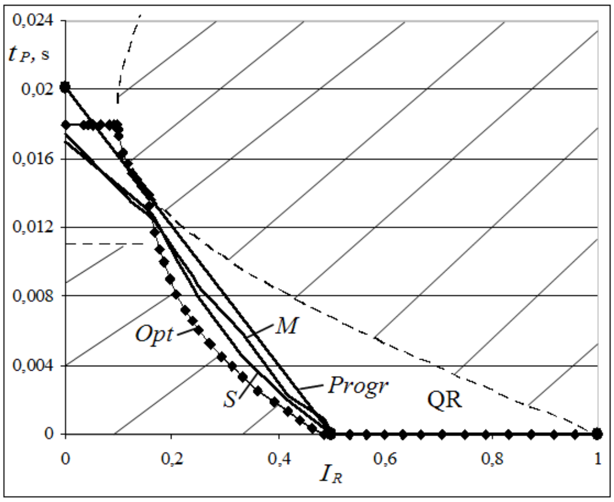

Figure 5. $t_P = f\,(I_R)$ diagram: input-output characteristics of the delay time definition device

The defined *Progr* curve is also located within the quality region QR (Figure 5) and coincides with *Opt* curve in the range [0.5 ÷ 1] of I_R (thus, the high dynamical quality of the mechatronic servo system should be achieved), but differ a little from *Opt* curve in the range [0 ÷ 0.5) of the I_R (thus, the dynamical quality declines up to 5% compared to the best dynamical quality of the mechatronic servo system). Consequently, the programmable delay time definition device with the described input-output dependence is also suitable for the definition of the P control law duration time.

4. Simulation of mechatronic servo system

The simulation has been performed using MATLAB/Simulink package [7]. It has been used the fifth-order Dormand-Prince numerical integration method with a fixed step size 0.00001. It has been applied the unit step control signal $u_{n\omega}\,(t) = 1\,(t)$. The modeling results obtained using variable structure and conventional velocity controllers are presented in Figure 6.

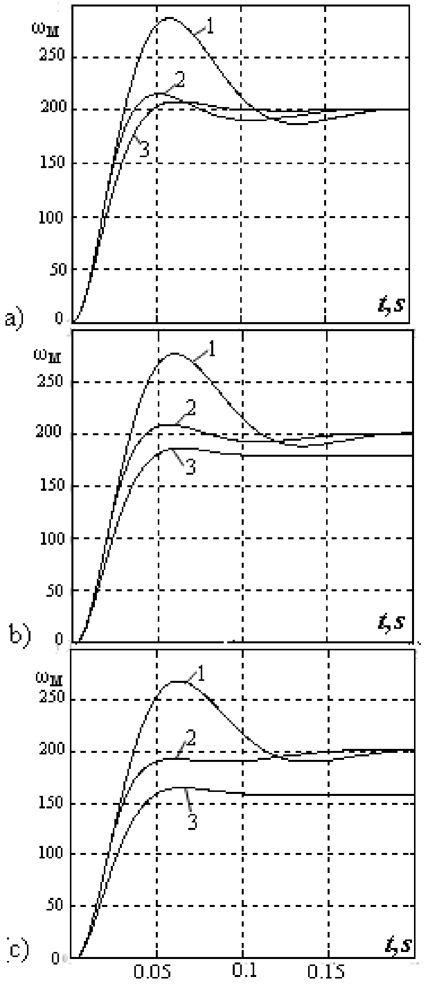

Figure 6. Comparison of dynamical response curves of the mechatronic system with different kinds of velocity controllers: a – in the idle case, b – in the static load $I_L = 0.5 \cdot I_N$ case, c – in the static load $I_L = \cdot I_N$ case

The curves obtained using velocity controller adjusted under the symmetrical optimum condition are denoted by number 1, in the case of using variable structure velocity controller VSC (with fuzzy logic based or programmable delay time definition device) – by number 2, and in the case of using velocity controller adjusted under the quantitative optimum condition – by number 3. It is seen from Fig. 6 that in all cases the rapidity of the mechatronic servo system with VSC has been increased comparing to the drives with conventional P an PI type velocity controllers. Hence the dynamical quality of the mechatronic servo system has been improved using VSC. Furthermore, the dynamical characteristics of the mechatronic system using VSC with fuzzy logic based delay time definition device are practically identical to the dynamical quality of the system using VSC with programmable delay time definition device. Consequently, both P control law delay time definition devices are suitable for the implementation of the proposed dynamical quality improvement technique.

5. Conclusion

The means of dynamical quality improvement of a mechatronic servo system based on velocity controllers of variable structure application are presented in this article. Two methods of the velocity controller structure change in dependence on the static load level of the system are proposed and investigated. The first method is based on the fuzzy logic methodology and the second one – on the preprogrammed "Lookup Table" application.

It is shown that the Luenberger observer could be applied for the static load current of the system estimation. The input-output dependences of the fuzzy logic based delay time definition device and programmable delay time definition device ensuring high dynamical quality of the mechatronic servo system independently on the static load conditions are defined. The presented simulation results of the mechatronic servo system confirm the suitability of the proposed dynamical quality improvement technique.

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