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COMMITTEE OF MECHANICAL ENGINEERING

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SPIS TREŚCI

ROBUST MODEL-FOLLOWING CONTROL FOR THE DC SERVO DRIVE

Krzysztof Pietrusewicz, Paweł Dworak
Bogdan Broel-Plater

Summary

The goal of this paper is to present a new method that ensures stiffness of the mechanical characteristic of the direct current motor servo drive, which means lack of influence of the varying load torque on quality of the velocity control. Additionally, usage of the new MFC-V (Model-Following Control for Velocity control) system allows one to shape the servo drive transient response, ensuring, among other things, an overshoot free step response in the velocity control loop. The proposed solution exemplifies a possible approach to designing a DC motor servo drive of a CNC power transmission system.

Keywords: PID control, Model-Following Control, robust control, overshoot, speed control, drive stiffness

Odporna regulacja MFC serwonapędu prądu stałego

Streszczenie

W artykule zaprezentowano nową metodę projektowania serwonapędu silnika prądu stałego. Zapewnia wysoką sztywność charakterystyki mechanicznej, rozumianą jako brak wpływu zmian momentu obciążenia na jakość regulacji prędkości. Dodatkowo, wykorzystanie nowego układu MFC-V (Model-Following Control for Velocity control) pozwala kształtować zachowanie serwonapędu w stanach przejściowych. Zapewnia odpowiedź bez przeregulowania wartości wyjściowej w pętli regulacji prędkości. Zaproponowane rozwiązanie stanowi przykład możliwego podejścia do projektowania serwonapędu prądu stałego układu napędowego obrabiarek CNC.

Słowa kluczowe: regulacja PID, regulacja nadążająca za modelem, regulacja odporna, przeregulowanie, regulacja prędkości, sztywność napędu

1. Introduction

The problem of velocity control has been considered for many years [1-8]. 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 [9-14].

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In the paper we present a methodology of designing a velocity control system for a direct current motor servodrive that is widely used in CNC power transmission systems (Fig. 1). In Fig. 1 classification of electrical constructions of the power transmission systems of CNC feed systems is shown [4]:

Electrical servodrives of the CNC feed systems

Direct Current	Alternating current
- controller	- controller
- DC feeder	- rectifier
- **rotary**/linear motor	- inverter
- displacement transducer	- rotary/linear motor
	- displacement transducer

Fig. 1. Electric motor drives used in CNCs

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 servodrives: BLDC (*BrushLess DC*) and PMAC (*Permanent Magnet AC*).

In the paper a few assumptions have been made, which allow 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.

In the process of designing the power transmission system of the CNC one meet a few basic problems which were enumerated in [4, 15]. 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 is overshoot-free, as any oscillatory transient state in the velocity control loop cause inaccuracy and long settling times in the position loop.

The proposed in the paper robust control structure MFC-V allows one to avoid these two basic problems and the presented therein method of tuning of control loop parameters 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.

In the paper there are presented both the algorithm for tuning the velocity controller for a specified value of overshoot [16, 17] and a new two degrees of freedom robust structure of the velocity controller that applies the principle of tracking the nominal internal model of the control system by the disturbed and perturbed process [18].

The paper is rounded off with numerical examples and results of simulation experiments that illustrate the main assumptions of the algorithms proposed here. 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.

2. Robust Model-Following PID control

In a classic feedback system the controller $C_1(s)$ has been designed using the process model as the base in full consciousness that the model M may differ from the process P by perturbations. The perturbations may originate from different sources, such as errors in identification, errors in modeling, deliberate model simplification, process nonlinearities, fluctuations and variations of process parameters, etc.

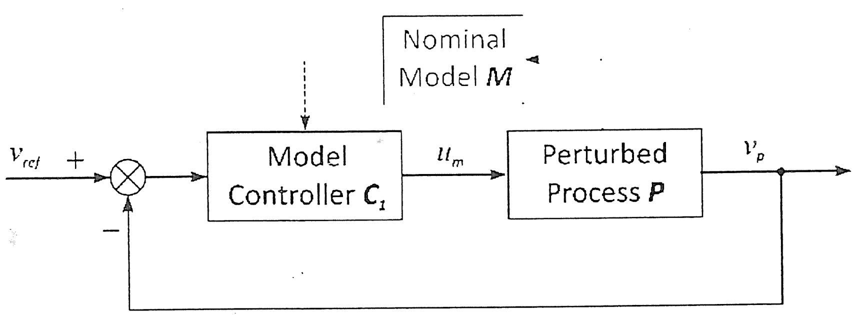


Fig. 2. Classic single-feedback control loop with PID controller designed with the use of model M

The presence of perturbations $\Delta(s)$ makes that the process $P(s)$ has to be treated as unknown. On the other hand the precise form of the model $M(s)$ can be assumed, no matter how accurate it is. Thus, the process $P(s)$ can be represented by its model

$$P(s) = [1 + \Delta(s)]M(s) \tag{1}$$

In the following, it will be assumed that perturbations are limited, i.e. they are subject to the condition:

$$\left|\Delta(s)\right|_{s=j\omega} \leq \Delta_{\max} < 1,\ \omega \in [0,\infty) \tag{2}$$

The MFC structure shown in Fig. 3 will be regarded as a part of a more general class of systems called Model Based Control. The essential component of the plant input signal in the MFC structure is generated in an auxiliary control system containing a model of the plant $M(s)$ and its controller $C_1(s)$ in the feedback loop. In the case of DC servo drive the perturbations involved in the process refer to change in electrical and mechanical time-constants. Torque load of the driven shaft is typically treated as the input load of the process to be controlled.

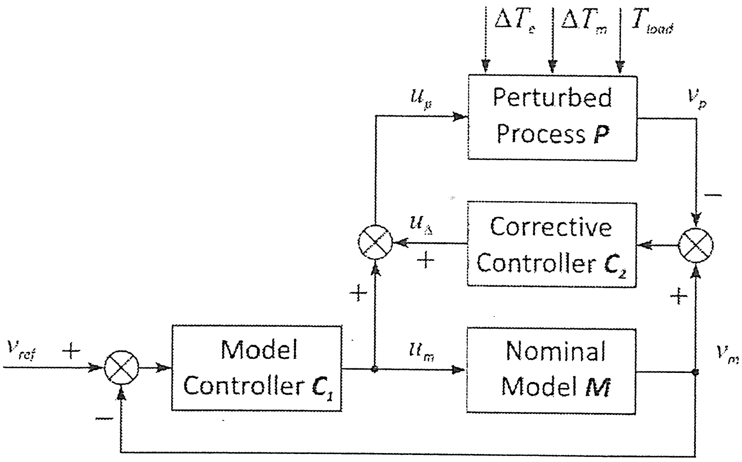


Fig. 3. Model-Following Control system

The output of the model controller $C_1(s)$ actively forms the input of the actual process plant $u_p(s)$. The second control loop of the MFC structure contains the auxiliary controller $C_2(s)$ and the actual process $P(s)$ disturbed by the signal $T_{load}(s)$, as well as perturbed, where the difference between the plant output velocity $v_p(s)$ and the model output velocity v_m(s) is processed. Thus, the summed result of actions of both controllers, i.e. $C_2(s)$ and $C_1(s)$, excites the input of the actual plant $P(s)$. Note that for $C_2(s) = C_1(s)$ the MFC structure is equivalent to the classic single-loop feedback system.

Features exhibited by the MFC structure have been discussed in [18] and [20] in detail. In the paper [19] a significant improvement of robustness of the MFC control system applied to the perturbed plants in comparison with the classic single loop PID control system has been shown.

The system presented in Fig. 3 achieves an outstanding quality of robustness, however the procedures of tuning of the controllers are not as simple and obvious as in the case of the single-loop system shown in Fig. 2. It is customary to tune the controller $C_1(s)$ for a specified phase and amplitude margin [16, 20], while the auxiliary controller $C_2(s)$ has been chosen experimentally. In the case of the structure presented in Fig. 3 the following condition has to be satisfied

$$\left|C_1(s)\right|_{s=j\omega} \leq \left|C_2(s)\right|_{s=j\omega}, \omega \in \left[0, \omega_{3dB}\right] \tag{3}$$

where '3dB' denotes a maximum value of the working frequency. A method called PID-OVR that in a simple manner satisfies condition (3) is presented in [17].

3. PID-OVR design for Second Order Plus Time Delay model

The PID-OVR 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 (OVR) is defined, as shown in Fig. 4.

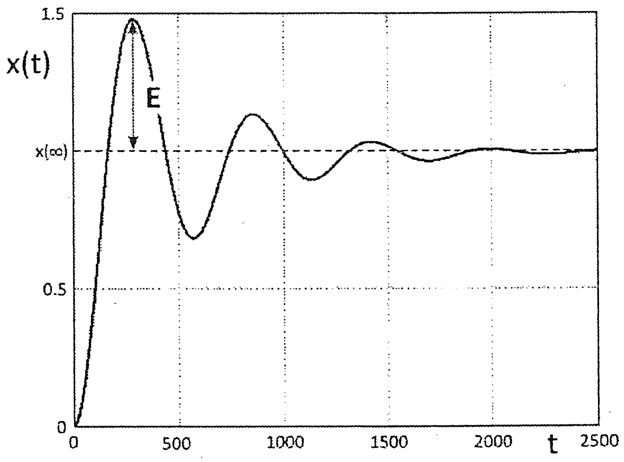


Fig. 4. OVR definition

The following relation defines the overshoot taken into consideration in the presented here methods PID-OVR

$$OVR = \frac{E}{x(\infty)} \tag{4}$$

The presented method was proposed by Skoczowski in [16]. The method consists of the following assumptions:

- the equivalent transfer function of the closed-loop system is given by

$$\tilde{M}(s) = \frac{k\omega_n^{\ 2} e^{-s\tau}}{s^2 + s2\beta\omega_n + \omega_n^{\ 2}} \tag{5}$$

- the process itself is approximated by the second order model

$$\tilde{P}_2(s) = \frac{k_p e^{-s\tau}}{(1+sT_1)(1+sT_2)}, \quad T_1 < T_2 \tag{6}$$

- the controller $C_1(s)$ (Fig. 2) is a PID one given by

$$C_1(s) = k_{cm} \frac{(1+sT_{dm})(1+sT_{im})}{sT_{im}} \tag{7}$$

Also, the following approximation

$$e^{-s\tau} \approx \frac{1 - s\tau/2}{1 + s\tau/2} \tag{8}$$

is adopted here.

With these simplifications, the denominator of the closed-loop transfer function becomes a second-order polynomial

$$s^2 + s\frac{\left(1 + k\dfrac{T_d}{T_{im}} - k\dfrac{\tau}{2T_{im}}\right)}{\dfrac{\tau}{2}\left(1 - k\dfrac{T_{dm}}{T_{im}}\right)} + \frac{k}{\dfrac{T_{im}\tau}{2}\left(1 - k\dfrac{T_{dm}}{T_{im}}\right)} \tag{9}$$

where $k = k_{cm}k_p$.

By equating the polynomial (9) with the denominator of (5) we get an approximate equation that links the damping factor β with parameters of the controller (7) and those of the model (6)

$$\beta \approx \frac{1}{2\sqrt{\frac{k\tau}{2T_{im}}\left(1-k\frac{T_{dm}}{T_{im}}\right)}}\left[1+k\left(\frac{T_{dm}}{T_{im}}-\frac{\tau}{2T_{im}}\right)\right] \tag{10}$$

For a given closed-loop overshoot value (OVR) we get the following approximate relationship related to eq. (6)

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

Hence, the gain k can be found from eqs. (10) and (11) by taking a specified OVR value for the controller to be designed.

In the case the model (6) is known, the PID controller can be designed. One has to assume the values $T_{dm}=T_1, T_{im}=T_2$ of the controller (7), and the gain can be evaluated with the inequality

$$k \le \frac{2T_{im}}{\tau}\left(1+2\beta_{assumed}{}^2-2\beta_{assumed}\sqrt{1+\beta_{assumed}{}^2}\right) \tag{12}$$

4. DC servo control problem

Figure 5 shows the simplest model of the direct current motor [4, 9], for which accessibility of the controllable DC source is assumed. It is represented by the power supply u_m. In real constructions with DC motors an AC/DC converter (rectifier) with controllable voltage amplitude is needed [4]. In the paper we purposely omit this aspect of modeling – being aware of the effects on the control performance it can have – focusing on the designing and tuning of the velocity controller procedure.

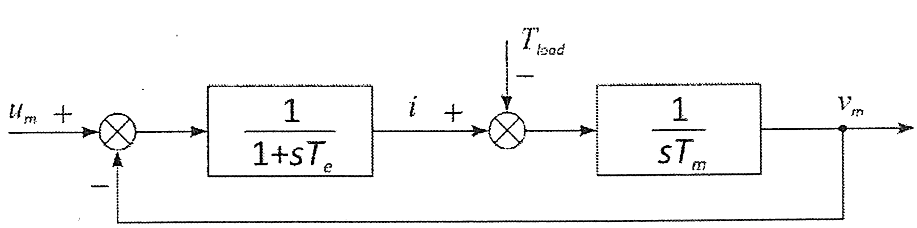


Fig. 5. DC motor simplified model

In the course of the on-going research the model is going to be verified and successively supplemented by some additional elements.

The electro-mechanical relations of the DC motor are described by the following equations

$$\begin{cases} T_e \dfrac{\mathrm{d}i(t)}{\mathrm{d}t} + i(t) = u_m(t) - v_m(t) \\ T_m \dfrac{\mathrm{d}v_m(t)}{\mathrm{d}t} = i(t) - T_{load}(t) \end{cases} \tag{13}$$

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:

$$\begin{cases} T_e = T_{em} + \Delta T_e \\ T_m = T_{mm} + \Delta T_m \end{cases} \tag{14}$$

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 (13) may be transformed to the form:

$$T_e T_m \frac{\mathrm{d}^2 v_m(t)}{\mathrm{d}t^2} + T_m \frac{\mathrm{d}v_m(t)}{\mathrm{d}t} + v_m(t) = u_m(t) - T_{load}(t) - T_e \frac{\mathrm{d}T_{load}(t)}{\mathrm{d}t} \tag{15}$$

Assuming the value of load is zero and performing the Laplace transform with the zero initial conditions, equation (15) assumes the form:

$$\left[s^2 T_e T_m + sT_m + 1\right] v_m(s) = u_m(s) \tag{16}$$

In the next section of the paper a new method of tuning the velocity controller with respect to the specified value of overshoot in the closed loop is presented.

5. PID-OVR-V design for Second Order model

Most of the currently known tuning methods for PID controllers assume a delay in the process model [21-23]. So, it turns out that despite that delay may cause problems deteriorating the control performance, its existence makes the process of tuning much more simple, especially for high order processes.

Below a proposal of a tuning method for the auxiliary controller is given. Owing to it – with assumptions that the load of motor is equal to zero – it is possible to tune the controllers in the velocity control loop so that the specified value of overshoot in the closed loop is achieved. This method is highly useful, the more so because it employs signals that are usually available for being measured, i.e. velocities or accelerations of the motor shaft. Figure 6 shows the velocity control system under consideration.

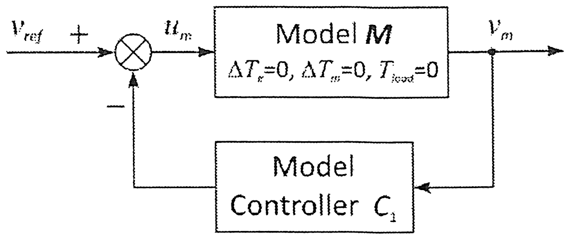


Fig. 6. Velocity control loop tuned for the specified value of the overshoot (PID-OVR-V)

If it is assumed that the load torque in the plant model equals 0 ($T_{load} = 0$) and that the electrical and mechanical parameters are known accurately ($\Delta T_e = 0,\ \Delta T_m = 0$), then the open loop transfer function of the motor has the form

$$v_m(s) = \frac{1}{s^2 T_{mm} T_{em} + s T_{mm} + 1} u_m(s) \tag{17}$$

where T_{em}, T_{mm} denote electrical and mechanical time constants free of perturbations respectively. The natural frequency ω_{0m} and damping ratio ξ_m are defined by

$$\omega_{0m} = \sqrt{\frac{1}{T_{mm} T_{em}}}, \quad \xi_m = \frac{1}{2}\sqrt{\frac{T_{mm}}{T_{em}}} \tag{18}$$

Equation (17) may then be written in the form

$$v_m(s) = \frac{1}{\frac{s^2}{\omega_{0m}^2} + s\frac{2\xi_m}{\omega_{0m}} + 1} u_m(s) \tag{19}$$

The transfer function of the $C_1(s)$ controller is given by

$$C_1(s) = sT_{dm} \tag{20}$$

which allows one to write the closed-loop transfer function for the system presented in Fig. 6 in the following form

$$v_m(s) = \frac{1}{\frac{s^2}{\omega_{0m}^2} + s\left(\frac{2\xi_m}{\omega_{0m}} + T_{dm}\right) + 1} v_{ref}(s) \tag{21}$$

If the closed-loop is to satisfy the overshoot criterion, then equating the transfer function (21) with the assumed equation describing the closed loop transfer function

$$\hat{M}(s) = \frac{1}{\frac{s^2}{\omega_{0assumed}^2} + s\frac{2\beta_{assumed}}{\omega_{0assumed}} + 1} \tag{22}$$

analogous to (5), we get:

$$\frac{1}{\frac{s^2}{\omega_{0m}^2} + s\left(\frac{2\xi_m}{\omega_{0m}} + T_{dm}\right) + 1} \stackrel{\Delta}{=} \frac{1}{\frac{s^2}{\omega_{0assumed}^2} + s\frac{2\beta_{assumed}}{\omega_{0assumed}} + 1} \tag{23}$$

Thus, it is possible to derive the value of gain T_{dm} for the specified value of the overshoot OVR (damping ratio $\beta_{assumed}$):

$$T_{dm} = f\left(\beta_{assumed}\right) = \frac{2\left(\beta_{assumed} - \xi_m\right)}{\omega_{0m}}, \quad \omega_{0m} = \omega_{0assumed} \tag{24}$$

Hence, the calculating procedure comprises the following steps:

1. specifying the value of overshoot OVR; thus the damping ratio $\beta_{assumed}$ for the closed-loop is derived;
2. calculating the gain T_{dm}, which ensures satisfying the criterion.

6. MFC-V for DC servo control

Figure 7 presents the classic one-loop PID control system for the DC motor velocity. Numerous works [4, 11-14] show its imperfection. Tuning PID controller in such a way as to obtain overshoot-free step responses results in significant changes in the control performance at the moment of load variation – thus the servodrive stiffness is low. In the case of tuning the controller $C_1(s)$ of Fig. 7 for good control performance after load T_{load} changes, we observe large overshoots in transition states.

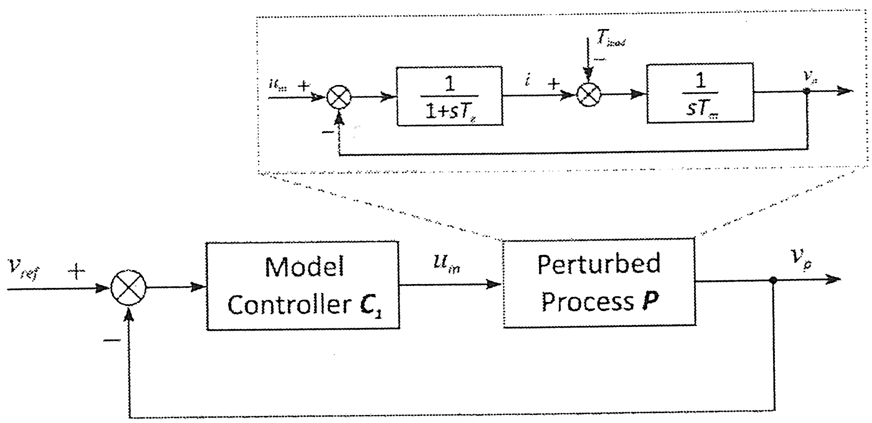


Fig. 7. Typical PID control of the perturbed process

Taking into consideration a structure presented in Fig. 6 there is proposed a new velocity control system MFC-V, which makes use of the method for synthesis of the PID controller for the admissible overshoot. The block diagram of the MFC-V system is presented in Fig. 8.

In the system presented in Fig. 8 one can distinguish two control loops:

- model loop – tuned for the specified overshoot by the PID-OVR-V method;

• process loop, where the goal of the PID auxiliary controller $C_2(s)$, such that it satisfies the condition (3), is to compensate the effect produced by process parameter perturbations and varying load on the control performance.

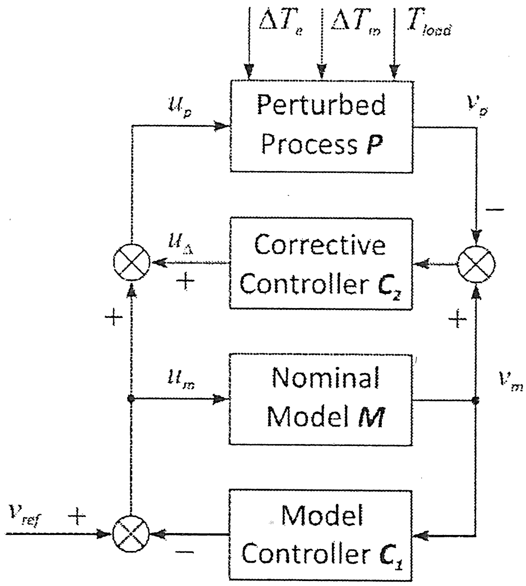


Fig. 8. Model-Following Control system
for velocity control

7. Stiffness of MFC-V control system

The transfer function of the closed-loop control system presented in Fig. 7 is given by:

$$v_p(s) = \frac{C_1(s)}{1 + C_1(s) + sT_m + s^2 T_m T_e} v_{ref}(s) - \frac{1 + sT_e}{1 + C_1(s) + sT_m + s^2 T_m T_e} T_{load}(s) \tag{25}$$

Then the stiffness of the classic system is as follows

$$\frac{v_p(s)}{T_{load}(s)} = -\frac{1 + sT_e}{1 + C_1(s) + sT_m + s^2 T_m T_e} \tag{26}$$

For classic systems the greater is the magnitude $C_1(s)$, the greater is the servodrive stiffness. It also undergoes changes with the variations of the motor parameters (14).

By analogy, for the MFC-V system of Fig. 8 one can write:

$$v_p(s) = \frac{1 + C_2(s) + sT_{mm} + s^2 T_{mm} T_{em}}{\left[1 + C_1(s) + sT_{mm} + s^2 T_{mm} T_{em}\right]\left[1 + C_2(s) + sT_m + s^2 T_m T_e\right]} v_{ref}(s) +$$

$$-\frac{1 + sT_e}{1 + C_2(s) + sT_m + s^2 T_m T_e} T_{load}(s) \tag{27}$$

Thus the load influence on the control performance depends on:

$$\frac{v_p(s)}{T_{load}(s)} = -\frac{1 + sT_e}{1 + C_2(s) + sT_m + s^2 T_m T_e} \tag{28}$$

One should notice that for $C_2(s) = C_1(s)$ equation (27) is reduced to

$$v_p(s) = \frac{1}{1 + C_1(s) + sT_m + s^2 T_m T_e} v_{ref}(s) - \frac{1 + sT_e}{1 + C_1(s) + sT_m + s^2 T_m T_e} T_{load}(s) \tag{29}$$

which means that for changes of the reference variable the system is equivalent to the one presented in Fig. 6, whereas the changes in load affect the velocity control identically to that they do in the classic system presented in Fig. 7 (see eq. (25)).

From equations (26) and (28) it is seen that the MFC-V system, owing to the appropriately tuned corrective controller $C_2(s)$, ensures significantly higher stiffness of the mechanical characteristic of servodrive.

8. Robustness of MFC-V control system

To analyze the robustness of the proposed MFC-V structure to perturbations (14) – electromagnetic and mechanical DC motor properties – a multiplicative description of the perturbations (1) with condition (2) satisfied has been used. Moreover, the load torque $T_{load}(s)$ has been assumed to equal zero. To simplify the notation in the following equations the operator s has been omitted.

For the classic system we have:

$$v_{pPID} = \frac{C_1 P}{1 + C_1 P} v_{ref} = \frac{C_1 (1+\Delta) M}{1 + C_1 (1+\Delta) M} v_{ref} \tag{30}$$

Analogously to a MFC-V system it may be written:

$$v_{pMFC-V} = \frac{(1+C_2 M)P}{(1+C_1 M)(1+C_2 P)} v_{ref} = \frac{(1+C_2 M)(1+\Delta)M}{(1+C_1 M)\left[1+C_2(1+\Delta)M\right]} v_{ref} \tag{31}$$

Rearranging equation (30) gives:

$$v_{pPID} = \left[1 - \frac{1}{1+C_1(1+\Delta)M}\right] v_{ref} \tag{32}$$

while eq. (31) may be transformed to the form:

$$v_{pMFC-V} = \frac{M}{1+C_1 M}\left[1 + \frac{\Delta}{1+C_2(1+\Delta)M}\right] v_{ref} \tag{33}$$

Thus, from equations (32) and (33) we can draw the following conclusions:

- for the classic system, the controller $C_1(s)$ is responsible for both shaping the step responses for the reference variable changes and rejection the influence of the varying motor load;
- in the case of the MFC-V system, the controller $C_2(s)$ allows one to eliminate the influence of perturbations and to maintain high stiffness of the load characteristic.

9. Illustrative example

In the first of the presented examples, the methodology of designing a PID-OVR-V controller for the system shown in Fig. 6 is presented.

For the DC motor, which parameters have been estimated on the basis of its mechanical and electrical properties T_{em} = 0.070 s, T_{mm} = 0.153 s, the controller in the PID-OVR-V system has been chosen in such a way as to achieve the overshoot OVR value near to zero. It turns out that (as shown in Fig. 9, despite it is of no practical use) the methodology described in section 3 of the present paper gives equally good results in the case when the specified overshoot and thereby the parameter $\beta_{assumed}$ of the closed-loop is greater than ξ_m.

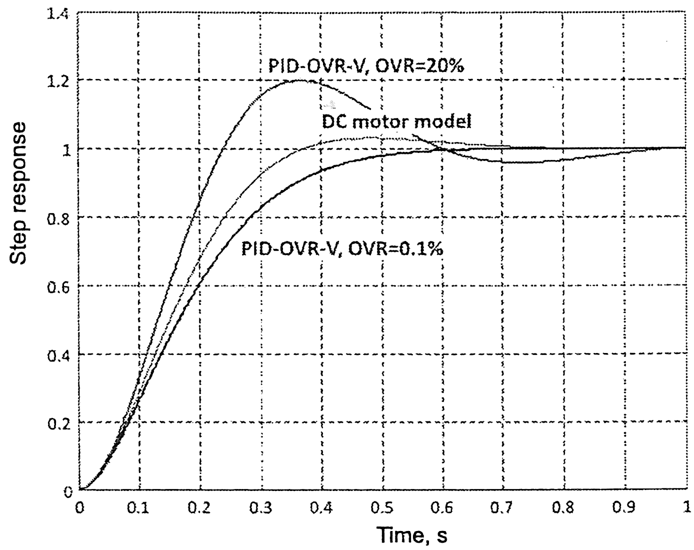


Fig. 9. Closed-loop tuning with the use of PID-OVR-V method – example of MFC-V model loop tuning

Simulation results presented in Fig. 10 show significantly greater robustness of the MFC-V system to perturbations of the mechanical time constant. The PID controller in the classic single-loop system has been tuned by experiment to obtain, in the nominal case (i.e. without perturbations), a start-up being comparable to the one achieved in the MFC-V system.

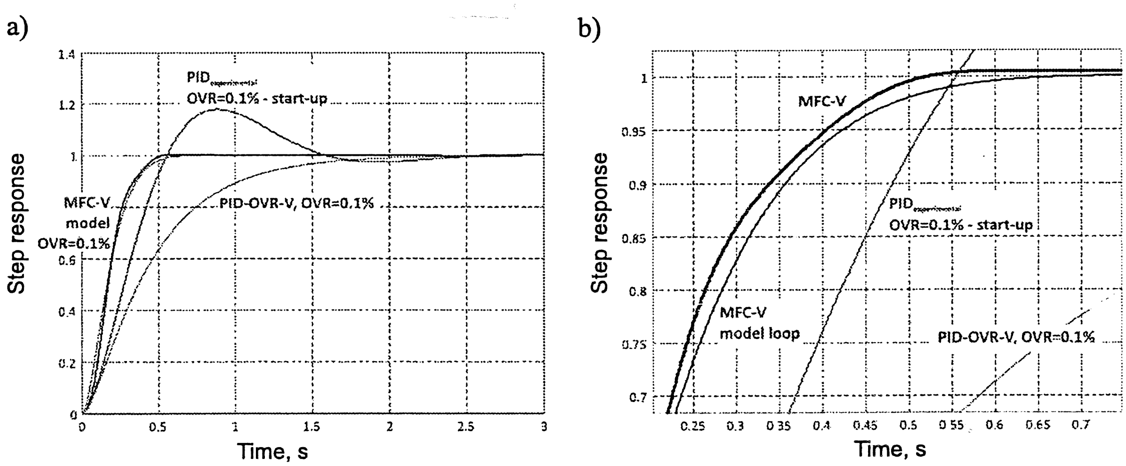
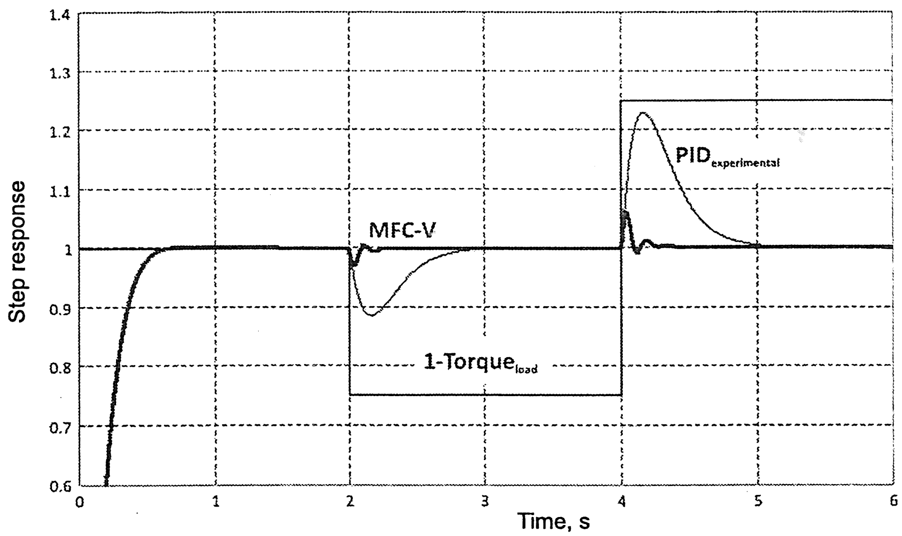


Fig. 10. Robustness of MFC-V control system

Figure 10 shows clearly that the proper tuning of the controller in the model loop (see Fig. 9), the corrective controller in the MFC-V system reduces the effect of perturbations on the control quality. Figure 10b shows on an enlarged scale how the plant output signal in the MFC-V system keeps up with the output of the model loop.

Results of simulation presented in the last figure (Fig. 11) demonstrate considerably greater stiffness of the mechanical characteristic in the case of using an MFC-V control system than in the case of using the single-loop system with the PID controller (see Fig. 2) tuned as in the simulation, the results of which are presented in Figs. 10a and 10b.

a)



b)

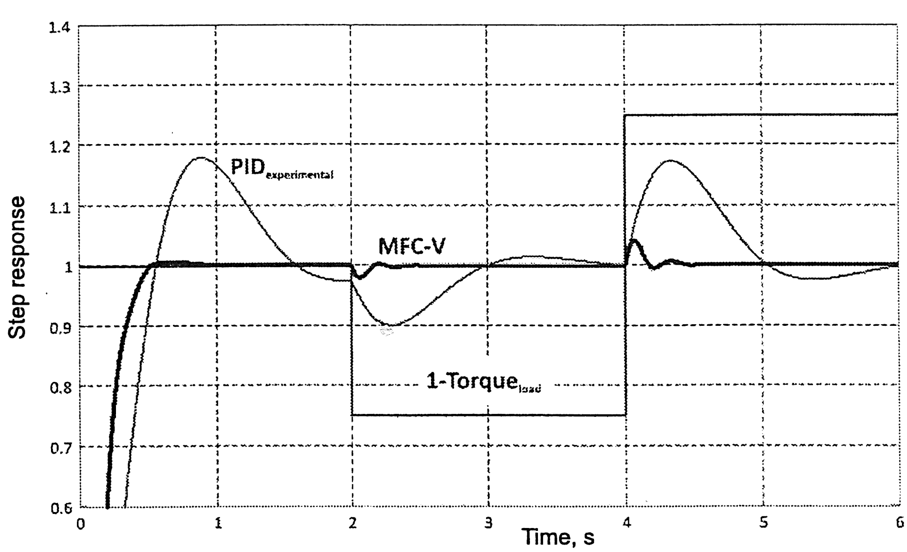


Fig. 11. Stiffness of the proposed system for nominal (a) and perturbed process (b)

10. Conclusions

In the paper a control system that provides greater stiffness of the mechanical characteristic of AC motor servodrive compared to the classic single-loop PID control system is shown. Application of the two-loop MFC-V structure with its PID having been tuned according to the PID-OVR-V method ensures additionally that some specific requirements concerning transient states of work of the servodrive are satisfied.

Work is underway to study the effect produced by constraints imposed on control signals on the control performance exhibited by CNC servodrives. Also, employing artificial intelligence in the MFC-V structure to improve the servodrive properties appears to have considerable promise.

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References

[1] N. MOHAN: First course on power electronics and drives. MNPERE, 2003.

[2] R. KRISHNAN: Electric motor drives. Modeling, analysis and control. Prentice Hall, 2001.

[3] C.T. KILIAN: Modern control technology: components and systems. Delmar, Cengage Learning, 2005.

[4] J. KOSMOL: Servo drives of the numerical control machine tool. Wydawnictwa Naukowo-Techniczne, Warszawa 1998.

[5] B.K. BOSE: Power electronics and motor drives. Advances and trends. Elsevier, 2006.

[6] B.K. BOSE: Modern power electronics and AC drives. Prentice Hall, 2002.

[7] N. MOHAN, T.M. UNDELAND, W.P. ROBBINS: Power electronics. Converters, applications and design. John Wiley and Sons, 1995.

[8] R.H. BISHOP: Mechatronics: An introduction. Taylor & Francis, 2006.

[9] M. NAKAMURA, S. GOTO, N. KYURA: Mechatronic servo system control. Problems in industries and their theoretical solutions. Springer-Verlag, Berlin 2004.

[10] G.W. YOUNKIN: Industrial servocontrol systems. Fundamentals and applications. Marcel Dekker, 2003.

[11] F. ANTRITTER, J. TAUTZ: Tracking control of the angular velocity of a DC-motor via a BOOT-converter. Proc. 7th IFAC Symposium on Nonlinear Control Systems, 2007 South Africa, 880-885.

[12] G. FERRETTI, F. LUCCHINI, G. MAGNANI, P. ROCCO: A mechatronic approach to the control of machine tools, IFAC World Congress 2007.

[13] G. TAPIA, A. TAPIA: Sliding-mode control for linear permanent-magnet motor position tracking, IFAC World Congress 2007.

[14] G. ELLIS, R.D. LORENZ: Comparison of motion control loops for industrial applications, Proc. IEEE IAS Annual Meeting, **4**(1999), 2599-2605.
[15] M. KAŹMIERCZAK, A. KOLKA, J. KOSMOL, H. SŁUPIK: Numerical control programming. Wydawnictwo Politechniki Śląskiej, Gliwice 2007.
[16] S. SKOCZOWSKI: Model following PID control with a fast model. Proc. 6th Portuguese Conference on Automatic Control, Faro, Portugal: 2004, 494-499.
[17] S. SKOCZOWSKI, K. PIETRUSEWICZ: New method of simplified identification for PID-OVR design. Proc. First Inter. Conference on Modeling, Simulation and Applied Optimization, Sharjah, U.A.E., 2005.
[18] S. SKOCZOWSKI: Robust model following control with use of a plant model, *Journal of Systems Science*, **32**(2001), 1413-1427.
[19] S. SKOCZOWSKI: Feedback systems architectures and their robustness (in Polish), Proc. 14th National Control Conference, Zielona Góra 2002, 507-514.
[20] S. SKOCZOWSKI, S. DOMEK, K. PIETRUSEWICZ, B. BROEL-PLATER: A method for improving the robustness of PID control. *IEEE Trans. on Industrial Electronics*, **52**(2005)6, 1669-1676.
[21] A. O'DWYER: Handbook of PI and PID Controller Tuning Rules. Imperial College Press, 2006.
[22] G.J. SILVA, A. DATTA, S.P. BHATTACHARYYA: PID Controllers for Time Delay Systems, Birkhauser, 2005.
[23] A. VISIOLI: Practical PID control. Springer-Verlag, Berlin 2006.

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