INFOTEH-JAHORINA Vol. 9, Ref. A-24, p. 114-117, March 2010.

CROSS-COUPLING DIGITAL CONTROL OF MULTI INDEPENDENT SERVO-DRIVES

DIGITALNO UPRAVLJANJE SA UNAKRSNIM SPREZANJEM VIŠE NEZAVISNIH SERVO POGONA

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Abstract – *One of the most challenging problems in the motion control area has been synchronization control of multiple motion axes or drives. The basic idea presented in this paper is to apply the cross-coupling control strategy in order to enable the synchronous motion of several servomechanisms. The proposed control is based upon the simulation the effects that appear in a virtual mechanical link between the shafts of drives. Simulation and experimental results are presented to show the validity of the proposed control strategy on a system with three servo-drives.*

Sadržaj – *Jedan od najvećih izazova u oblasti upravljanja kretanjem je sinhronizacija višeosnog kretanja ili rada više pogona. Ideja prezentovana u ovom radu je primena strategije upravljanja sa unakrsnim sprezanjem kako bi se omogućilo sinhrono kretanje više servomehanizama. Predloženo upravljanje je zasnovano na simulaciji efekata koji bi se pojavili unutar virtuelne mehaničke sprege između razmatranih pogona. Prikazani rezultati simulacije, zajedno sa eksperimentalnim rezultatima, pokazuju validnost predložene upravljačke strategije na primeru sistema sa tri servo pogona.*

1. INTRODUCTION

The motion coordination in a system with multiple number of servomechanisms or axis has drawn much attention, especially in the modern manufacturing development. In early 1980s, the concept of cross-coupling control with a symmetrical structure was primarily introduced for the machine tool control [1]. Quite original structures of cross-coupling speed- and position-control of the shafts of two distant electromechanical drives based on the application of the concept of the so-called electrical shaft were introduced by the authors of this paper in mid 1990s. More concretely, the proposed cross-coupling control is accomplished by the digital simulation of stiffness and friction of a virtual twisting mechanical connection between the output shafts of the drives. Since then, a number of contributions in terms of the improvement of the suggested cross-coupling concept can be found in the literature, as shown in the paper [2].

In this paper, the synthesis of the structure of coordinated control in a multi drives positioning system is presented. The proposed structure is implemented in the case of three cross-coupling servomechanisms. Also, the control strategy is experimentally verified using the system for fast development and implementation of control algorithms dSPACE R&D DS1104 that provides a comfortable work in the MATLAB®/Simulink environment.

During the creation of the experimental platform, in the absence of three drives with similar characteristics, two drives are modeled in Simulink environment together with the control part of the cross-coupled servo system, while a real low power permanent magnet DC motor served as the third drive. The performances of the proposed structure of the cross-coupled observer-based control system are verified experimentally in the real conditions.

2. STRUCTURAL SYNTHESIS OF CROSS-COUPLING CONTROL SYSTEM

The functional block diagram of a positioning servo system with the proposed cross-coupling control is shown in Fig. 1. Angular positions $\theta_1(t), \theta_2(t), \dots, \theta_n(t)$ of n distant electrical drives represent controlled variables. In the steady-state, angular positions of drive shafts are to be the same and equal to the common reference θ_{ref}. In addition to the set point $\theta_{ref}(t) = \theta_{ref} \cdot h(t)$, the system is subjected to two kind of disturbances: load torques $T_{L1}, T_{L2}, \dots,$ and T_{Ln} acting on drives, as well as the disturbances in the form of the initial angular displacements $\Delta\theta_i(0) = \theta_i(0) - \theta_{i+1}(0)$, $i = 1, 2, \dots, n-1$.

Fig. 2 visualizes in details the structure only one part of the block marked in Fig. 1 by ‘digital regulator’, which corresponds to the $i-$th pair of drives. It consists of the common position regulator and of the cross-coupling mechanism for synchronization between $i-$th and $(i+1)-$th drive, where $i = 1, 2, \dots, n-1$. Note that the coupling is also established between the $n-$th and the first motor. In this way, through the signals of angular and speed differences, a special ring coupling is achieved. The angular positions $\theta_i(k)$, as well as the shaft speed signals of all n drives $\omega_i(k)$, $i = 1, 2, \dots, n$ are adopted as coordinates of the state vector $\mathbf{x}(k)$.

Each control channel of the considered multi-drive system has its main position feedback loop with the common position regulator, as it is shown in Fig. 2. The channels are coupled by two minor local feedback loops with proportional and derivative actions that electrically simulate the stiffness and friction of a virtual mechanical link (the so-called electrical shaft) between shafts of the drives. In such kind of link, the torsion tension, which is manifested in the form of difference between the steady-state values of angular positions of the distant servos in the presence of different load torque disturbances, is relaxed by the additional digital proportional-integral (PI) regulator in the local feedback loop that simulates the stiffness of the link [2].

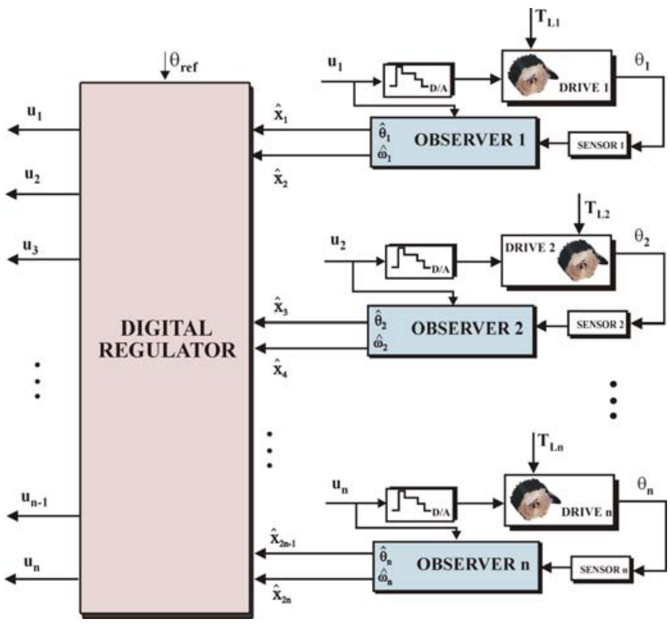

Fig.1. *Block diagram of a servo system with cross-coupling control*

Notice that the angular positions in system given in Fig. 1 are only measurable. It is suitable to apply PI^2 observers ([3], [4]), bearing in mind the implementation effects of the full observer from the viewpoint of filtering of measurement noise, as well as in order to enable the correct estimation of state variables in the presence of constant or slow varying load torque disturbances.

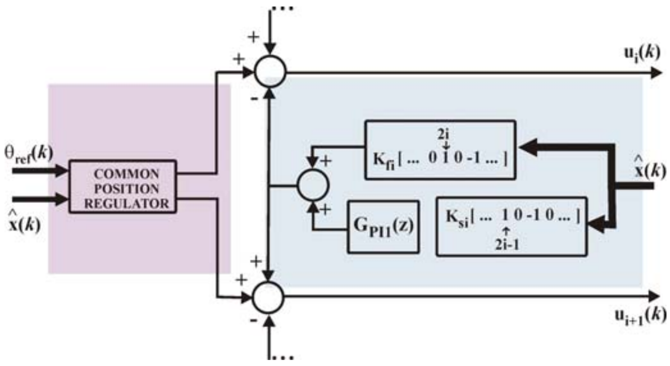

Fig.2. *Structure of the part of the digital regulator in the positioning servo system with cross-coupling control in Fig. 1*

3. PARAMETER SETTING IN DIGITALLY CONTROLLED POSITIONING SYSTEM WITH CROSS-COUPLING CONTROL

Notice that the coordination in the considered servo-system given in Fig. 1 is based on the assumption that the motion of all motors is coordinated if every pair of motors is coordinated in their motion. The proposed structure is analyzed in detail and verified in the previous papers of the authors. An extensive list can be found in the paper [2], where the structural synthesis of the coordinated control in a two-axis positioning system is presented in details. Recall that the considered system with cross-coupling control has a number of adjustable parameters – six control parameters and certain number of gain values of the applied observers.

It has been shown that in the case of identical drives, the cross-coupling control parameters (K_f , K_s) can be adjusted independently from the position regulator parameters. This property of decoupled effect of some parts of digital regulator given in Fig. 1, allows a relatively simple 3-step procedure for setting parameters of the digital regulator, while the observer gains are determined in the fourth step [2]. First, the parameters of common position regulator are calculated, afterwards the coefficients of stiffness and friction of the virtual mechanical link, and then the parameters of the additional PI regulator which serves to relax the torsion of the virtual coupling in steady-state. At the end, according to the separation principle, the structural observer synthesis and its parameter tuning may be accomplished.

4. EXPERIMENTAL SETUP FOR VERIFICATION OF CROSS-COUPLING CONTROL ALGORITHM

To illustrate and verify the effectiveness of the proposed cross-coupling control strategy given in Figs. 1 and 2, the example of three cross-coupling servomechanisms with quite different characteristics is considered. Fig. 3 visualizes the principal scheme of the experimental environment for rapid control prototyping.

The real system in Fig. 3 is composed of a DC motor with incremental encoder, and PWM power amplifier with power supply. The other two drives have been implemented in the MATLAB®/Simulink environment, and in this way the changes of parameter values in their transfer functions are enabled. Also, the control part of the proposed cross-coupled system and state observers are implemented in the same environment.

4.1 *Parameter setting in control part of the system*

The transfer function parameters (the gains and time constants) of the considered drives are given tabularly as follows:

K_{m1}	K_{m2}	K_{m3}	$T_{m1}\,[\mathrm{ms}]$	$T_{m2}\,[\mathrm{ms}]$	$T_{m3}\,[\mathrm{ms}]$
20.0	12.5	10.4	39.2	41.7	41.7

The parameters in the transfer function of the real system were determined on the basis of its experimentally recorded step response. Note that the gain factors of the other two drives are adopted to be approximately half the gain value of the real drive.

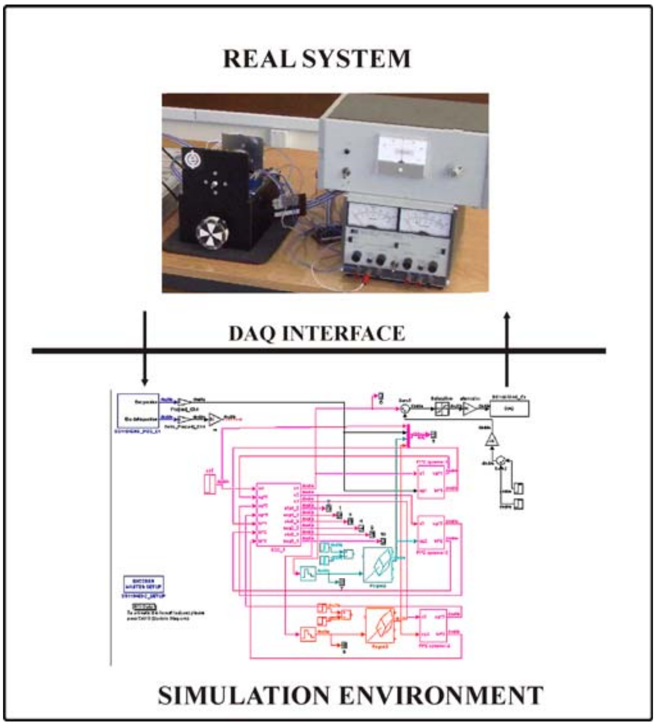

Fig.3. *Principal scheme of the experimental setup for rapid control prototyping*

For the sampling period the value $T = 0.001\text{ s}$ is selected. The speed of continuous-time closed-loop system responses and stability margin are specified by the dominant pole pair (the relative damping coefficient is $\zeta = 0.707$ and the undamped natural frequency is $\omega_n = 10\text{ rad/s}$) located in Nyquist frequency region.

As it is emphasized in the previous section, the coordinated motion in the system with multi independent servo-drives can be enabled if the synchronization of every pair of motors is provided. Recall that the efficiency of the special structure of two positioning servomechanisms with cross-coupling control was considered in details and experimentally verified already in the literature [2]. As presented, the control parameters may be adjusted by using a relatively simple procedure for control parameter tuning, that can be applied in both the similar and quite different servo drives. This is because certain parts of the control mechanism are weakly coupled or completely decoupled.

The desired quality of transient response is matched by the gains of the common position PI regulator $K_p = 0.52024$ and $K_I = 0.00129$. As it is shown in the literature [2], it is possible to select values of the coefficients of stiffness and friction (K_s, K_f) from the corresponding stable region that is determined in the parameter $\left(K_s, K_f\right)-$plane. In the considered case, the values $K_s = 500$ and $K_f = 0.7$ are adopted. Also, according to the procedure given in the literature [3], the gains of the digital PI^2 observers are set to values $g_1 = 0.0854$, $g_2 = 0.9214$ and $g_3 = g_4 = 0.0008$, insuring the bandwidth of 4.5 Hz. Unlike ordinary identity observer, these observers will recognize effects of constant or slow varying disturbances acting on the control objects.

4.2 *Experimental results*

After several digital computer simulation runs, that are used for verification of results of analytical investigation, the experimental research is carried out by using experimental setup that was described in the paper [2]. Note that the real control plant is the low power DC motor with some dry friction problems, which are especially expressive in the tasks of positioning.

The system is exited by the common step reference signal $\theta_{\text{ref}} = 10 \cdot \text{h}(t)\text{ rad}$. A constant load torque disturbance $T_{\text{L}1} = -0.1 \cdot \left\{\text{h}(t-6) - \text{h}(t-10)\right\}\text{ Nm}$, acting on the first drive in a certain period of time, amounts to 53% of the nominal torque value of the applied motor.

The traces of the angular positions of the drives in Fig. 4 show that the response quality is preserved. By using the cross-coupling strategy, the desired effect is achieved, i.e. the steady-state values of the angular positions of all three drive shafts are the same and equal to the common reference θ_{ref}. The achieved quality of continuous-time angular responses and speed of state estimation by the applied observers are in agreement with results expected in analytical design of the system.

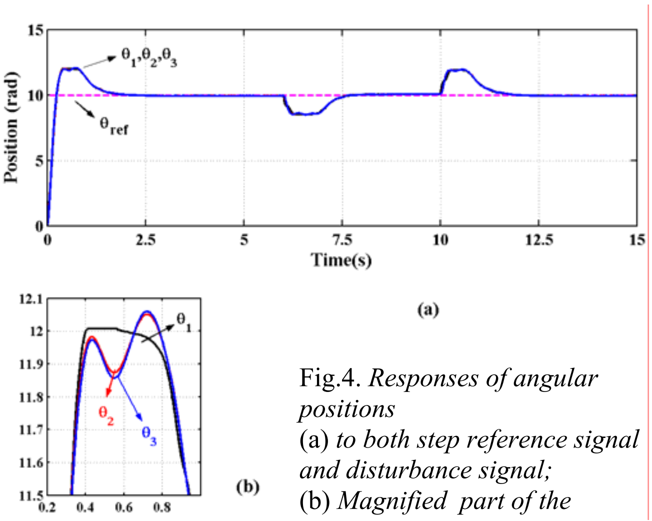

Fig.4. *Responses of angular positions*
(a) *to both step reference signal and disturbance signal;*
(b) *Magnified part of the responses given in* Fig. 4(a)

Also, the ability of observers to estimate both the shaft positions and speeds, when the constant load torque exists, is visualized in Fig. 4.

At the same time, the control variables u_1, u_2 and u_3 in Fig. 5 are without expressive chattering and in agreement with the results of the coordinated motion of the drives.

Under the same excitation conditions, both differences between the angular positions $(\Delta\theta)$ and the shaft speeds of the adjacent drives $(\Delta\omega)$ are recorded and shown in Fig. 6.

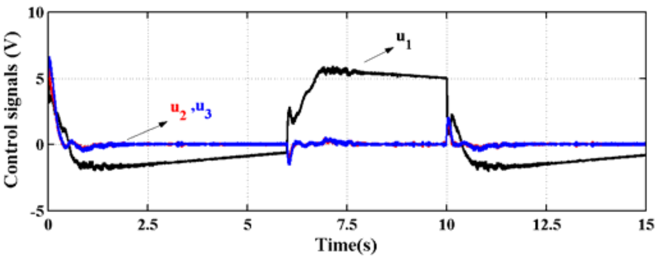

Fig.5. *Control signals*

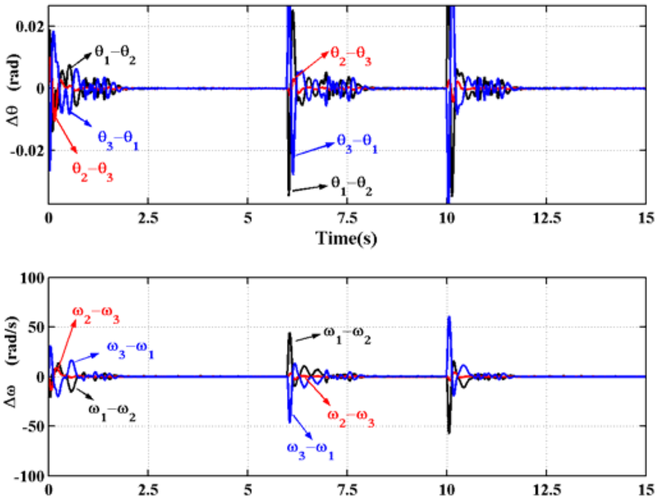

Fig.6. *Transient response and steady-state values of angular and speed differences*

5. CONCLUSION

The efficiency of the special structure of multiple positioning servomechanisms with cross-coupling control, proposed in this paper, is experimentally verified in the case of three cross-coupling servomechanisms. The considered control strategy is a type of the ring, based on the idea of parallel control and cross-coupling channels with compensation effects. Since the certain portions of controlling mechanism are decoupled or weakly coupled, the control parameters may be tuned by using a relatively simple procedure that can be applied in both the similar and quite different servo-drives. The results of some experimental runs in the environment for rapid control prototyping are presented to show the validity of the proposed control strategy.

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