Two Distant Cross-Coupled Positioning Servo Drives: Theory and Experiment

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Abstract—**The special structure of two distant speed-controlled or positioning servo drives with cross-coupling control, proposed in previous papers of the authors, enables synchronous motion of the servomechanisms. The considered cross-coupling control is based upon the idea of simulation the effects that appear in a virtual mechanical link between the shafts of drives. In this paper, the suggested structure was implemented and experimentally verified using the dSPACE R&D DS1104 system, which works within MATLAB®/Simulink environment. Both numerical simulations and real-time experimental results show good properties of the proposed structure of the cross-coupled observer-based control system.**

Index Terms—**Cross-coupling digital control, Synchronous motion of drives, Rapid control prototyping.**

I. Introduction

DIFFERENT types of cross-coupling controllers are met in many practice applications in which motions of two or more drives are to be coordinated in a certain sense. The synchronous operation of the drives is particularly important in paper making and processing machines, in numerically-controlled machines for metal, in nonlinear path control in automated vehicle and robot guidance, as well as in flexible systems in general.

In order to achieve a cooperation control, that since the eighties became more attractive, many different control structures have been developed. Two basic approaches can be distinguished. The first approach is the conventional distributive control where each robot is controlled separately by its own local controller, while the interactions between the robots are measured by sensors. The second approach is based on the idea of so-called cross-coupling of control systems of two distant independent servomechanisms. The first system of cross-coupling type was proposed by Sarachik and Ragazzini (1957, [1]) and had a “master-slave” structure (y follows x). Namely, the error in the y-axis affects both the x- and y-control loops, but the error signal in the x-axis is not generated. Such nonsymmetrical cross-coupled structure, however, requires a substantial difference in the gains for each axis, resulting in a contour error.

The concept of cross-coupling control with a symmetrical structure was primarily introduced by Koren (1980, [2]) for the machine tool control. In machine tool servo control, the main idea of cross-coupling control is based on calculation of the actual contour error, multiplying it by a controller gain, and feeding the result back to the individual loops. Later, many structures based on the application of cross-coupling control scheme have been proposed and tested in numerous engineering applications: biaxial control of machine tools [3], automatic guidance system of self-controlled vehicles [4], computer-controlled mobile platform for nursing or household robots [5], cross-coupling motion controller for mobile robots [6], etc.

Quite original structures of cross-coupling speed- and position-control of shafts of two distant electromechanical drives based on the application of the concept of electrical shaft are proposed in papers [7] and [8], respectively. Namely, the 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. The schematic diagram presented in Fig. 1 shows the relationship between design and testing activities in the case of considered structure of servo system with cross-coupling control. This is the well-known V-cycle that is an internationally recognized development standard for IT systems. The results of a research lasting many years at the level of modeling, design and simulation, in order to improve the structure of cross-coupling, are presented in the papers of authors and contributors [9]-[18]. Thus, an effective procedure of parameter setting in digital position regulator is formulated in the paper [9]. The special observer-based structures of the system with two digitally controlled and cross-coupled servomechanisms, with induction and DC motors as actuators, are considered in papers [10]-[12]. A novel structure of the observer-based system for two manipulators which are cooperatively handling the same object in the presence of slow varying load torque disturbances is proposed in [13]. Note that two servomechanisms with cross-coupled control can be treated as a multivariable control system and then designed using different approaches [10], [15].

In this paper, the synthesis of the structure of coordinated control in a two-axis positioning system is presented. The proposed structure is implemented and experimentally verified

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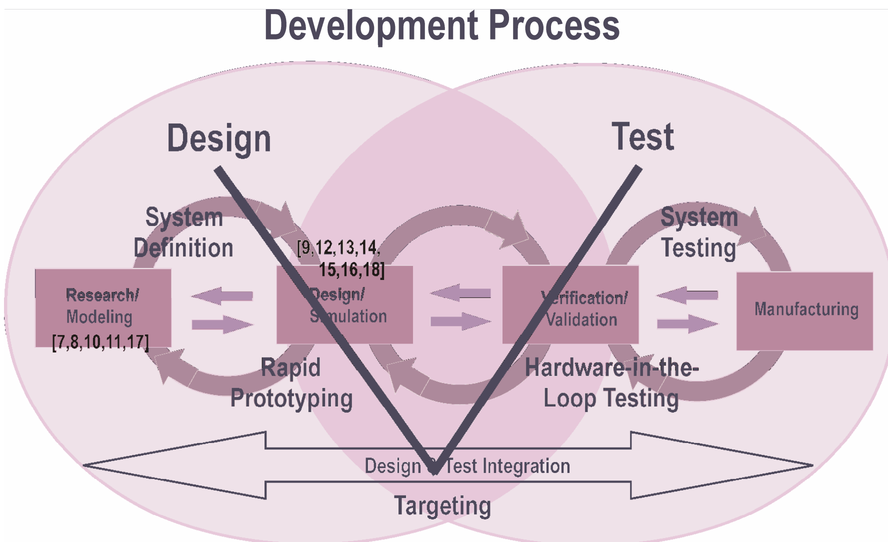

Fig. 1. Implementation of design functions of cross-coupled servosystem according to V-Cicle.

using the system for fast development and implementation of control algorithms dSPACE R&D DS1104 that provides comfortable work in the MATLAB®/Simulink environment.

During the creation of the experimental platform, in the absence of two drives with similar characteristics, one drive is 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 other drive. The performances of the proposed structure of the cross-coupled observer-based control system are verified by digital computer simulation, as well as experimentally in real conditions.

II. 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. 2 [13]. Angular positions $\theta_1(t)$ and $\theta_2(t)$ of two 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 $\theta_{ref}(t) = \theta_{ref} \cdot \mathrm{h}(t)$, the system is subjected to two kind of disturbances: load torques T_{L1} and T_{L1} acting on first and second drive, respectively, and disturbance in the form of the initial angular displacement $\Delta\theta(0) = \theta_1(0) - \theta_2(0)$.

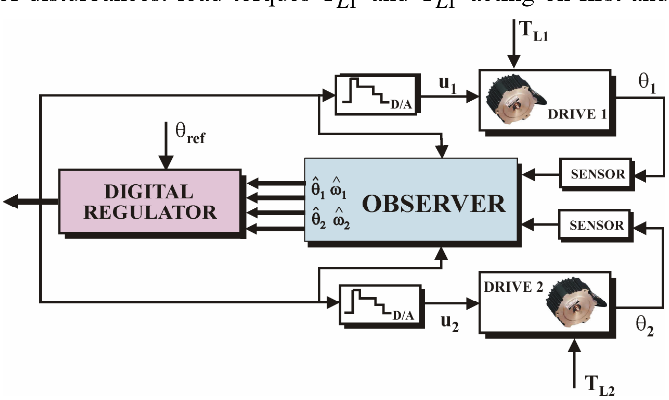

Fig. 2. Block diagram of a servo system with cross-coupling control.

Fig. 3 visualizes in details the structure of digital regulator, which consists of common position regulator and elements of cross-coupling mechanism. The angular positions $\theta_i(k)$, as well as the shaft speed signals of both drives $\omega_i(k)$, $i = 1, 2$ are adopted as coordinates of the state vector $\mathbf{x}(k)$.

Each control channel of two drive system given in Fig. 2 has its main position feedback loop. 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 (electrical shaft) between shafts of the drives. In such kind of link, the torsion tension, that 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 PI regulator in the local feedback loop that simulates the stiffness of the link.

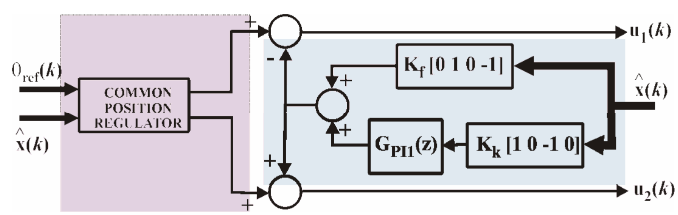

Fig. 3. Structure of digital regulator in the positioning servo system with cross-coupling control in Fig. 2.

The angular positions in system given in Fig. 2 are only measurable. It is suitable to apply PI^2 observers [19], bearing in mind effects of full observer implementation 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.

III. Parameter Setting in Digitally Controlled Positioning System with Cross-Coupling Control

Note that the considered system with cross-coupling control has ten adjustable parameters – six control parameters and four gain values of the reduced-order observers.

In the case of identical drives, the pole spectrum of the considered control system is decoupled; it consists of two pole pairs that can be placed separately. This means that 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. 3, which has been described in detail in earlier papers [8]-[12], allows a relatively simple 3-step setting parameters of the regulator, while the observer gains are determined in the fourth step. First, we calculate the parameters of common position regulator, 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 observer structural synthesis and its parameter tuning may be accomplished. A summary of the procedure for setting fourteen parameters
($K_p, K_I, K_f, K_k, K_{p1}, K_{I1}, g_{ij}$, $i=1,2$, $j=1,2,3,4$)
of the digital regulator and two observers in the servo system shown in Fig. 2 is given in Table I.

TABLE I
PROCEDURE OF PARAMETER SETTING FOR THE SYSTEM SHOWN IN FIG. 2

Suppose that the transfer function of both servo drives are identified in the form

$$W_i(s)=\frac{\Theta_i(s)}{U_i(s)}=\frac{K_i}{s(1+sT_{mi})}\,,\quad i=1,2\ , \tag{1}$$

where K_i and T_{mi} , $i=1,2$ are gains factors and mechanical time constants of the considered drives, respectively.

1° Calculate the parameters of position PI regulator (K_p and K_I) using

$$\begin{bmatrix} 0 & d_1 & 0 & -1 \\ -d_1 & -d_2 & -1 & z_1+z_2 \\ d_2 & -d_3 & z_1+z_2 & -z_1z_2 \\ d_3 & 0 & -z_1z_2 & 0 \end{bmatrix}\begin{bmatrix} P_1 \\ P_2 \\ A_0^* \\ A_1^* \end{bmatrix}=\begin{bmatrix} -(z_1+z_2)+2+A+B \\ z_1z_2-1-2A-2B-AB \\ A+B+2AB \\ -AB \end{bmatrix}, \tag{2}$$

where

$$P_1=K_p\ ,\ P_2=K_p+K_I \tag{3}$$

and

$$\frac{\Omega_1(z)}{U_1(z)}=\frac{K_1(1-A)}{z-A}\,,\quad \frac{\Omega_2(z)}{U_2(z)}=\frac{K_2(1-B)}{z-B}\,,\qquad d_1=\frac{1}{2}(b_{01}+b_{02})\,,$$

$$\frac{\Theta_1(z)}{U_1(z)}=\frac{b_{01}z+b_{11}}{(z-1)(z-A)}\,,\quad \frac{\Theta_2(z)}{U_2(z)}=\frac{b_{02}z+b_{12}}{(z-1)(z-B)}\,,\qquad d_2=\frac{1}{2}[(Bb_{01}-b_{11})+(Ab_{02}-b_{12})]\,,\quad d_3=\frac{1}{2}(Bb_{11}+Ab_{12})\,; \tag{4}$$

2° Choose a pair of cross-coupling parameter values (K_s and K_f) that belongs to the determined stable region of (K_s, K_f) -plane;

3° Calculate the parameters of the additional PI regulator in the local feedback loop as:

$$K_{p1}=1 \quad \text{and} \quad K_{I1}=\frac{K_I}{K_p}\ ; \tag{5}$$

4° Set gain values g_{ij}, $i=1,2$, $j=1,2,3,4$ of digital PI^2 observers yielding the poles to be real and equal to $\sigma_z=\exp(-2\pi f_0 T)$, where f_0 is bandwidth of the observers, as follows:

$$\det\begin{bmatrix} z-1+g_{i1} & -e_{i1} & -1 & 0 \\ g_{i2} & z-e_{i2} & 0 & -1 \\ g_{i3} & 0 & z-1 & 0 \\ 0 & g_{i4} & 0 & z-1 \end{bmatrix}=\left(z-\sigma_z\right)^4\ , \tag{6}$$

where

$$e_{11}=T_{m1}(1-A)\,,\ e_{12}=A\,,\ e_{21}=T_{m2}(1-B)\ \text{ i }\ e_{22}=B\,. \tag{7}$$

IV. Experimental Setup for Verification of Cross-Coupling Control Algorithms

To illustrate and verify the usefulness of the procedure of independent setting of parameters of the proposed structure given in Fig. 3, the example of two cross-coupling servomechanisms with quite different characteristics will be considered. Fig. 4 visualizes the structure of the experimental environment for rapid control prototyping that was realized during the PhD thesis research [20].

On the basis of the experimentally recorded step response of the servo drive with low power permanent magnet DC motor given in Fig. 5, the parameters in transfer function (1) can be determined as: $K_1=22.065$ and $T_{m1}=0.0348\ \text{s}$. In the MATLAB®/Simulink environment are implemented the control part of the cross-coupled system, as well as the other servo drive with the posibility of varying the parameter values in its transfer function.

A. Parameter setting in control part of the system

The sampling period $T=0.001\ \text{s}$ was adopted. The speed of continuous-time closed-loop system responses and stability margin are specified by the dominant pole pair ($\zeta=0.707$ and $\omega_n=10$ rad/s) located in Nyquist frequency region. The desired quality of transient response is matched by the gains of

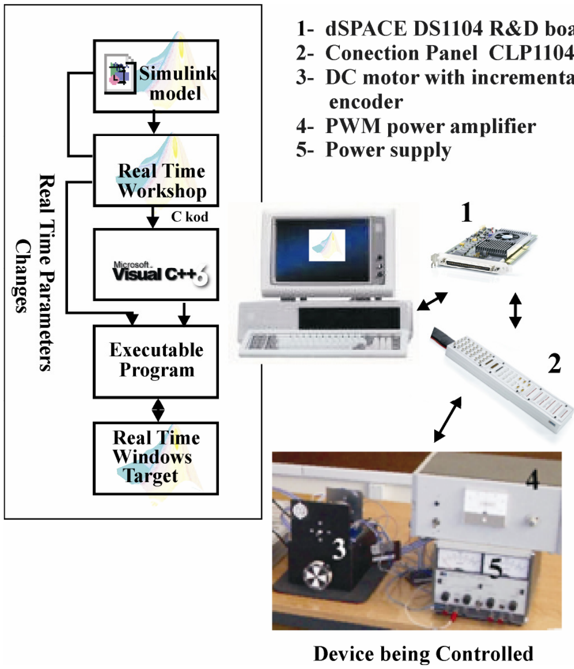

Fig. 4. Schematic representation of experimental setup.

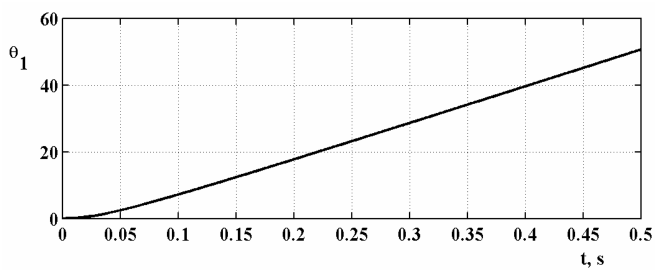

Fig. 5. Step response of servo drive angular position which is measured by using incremental encoder with 1000 pulses per revolution; input signal is $u_1(t) = 10 \cdot \mathrm{h}(t)$.

the common position PI regulator $K_p = 0.445$ and $K_I = 0.002$ obtained by solving matrix equation (2). In papers [8]-[13], [15] it has been shown that it is possible to adopt values K_s and K_f from the corresponding stable region shaded in the parameter plane and given in Fig. 6. In the considered case the values $K_s = 110$ and $K_f = 0.6$ are adopted.

According to relations (6) and (7), the gains of digital PI[2] observers were set to values $g_1 = 0.0854$, $g_2 = 0.9214$ and $g_3 = g_4 = 0.0008$ insuring bandwidth of 4.5 Hz. Unlike ordinary identity observer, these observers will recognize effects of constant or slow varying disturbance on control plants.

B. *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 of Fig. 4. Note that the considered control plant is the low power DC motor with dry friction problems, which are especially expressive in the tasks of positioning. Under the same excitation conditions, both differences between the angular positions $\Delta\theta$ and the shaft speeds of the drives $\Delta\omega$ are recorded and shown in Fig. 7. Control variables u_1 and u_2 in Fig. 8 are without chattering and in agreement with the results of synchronous motion of drives.

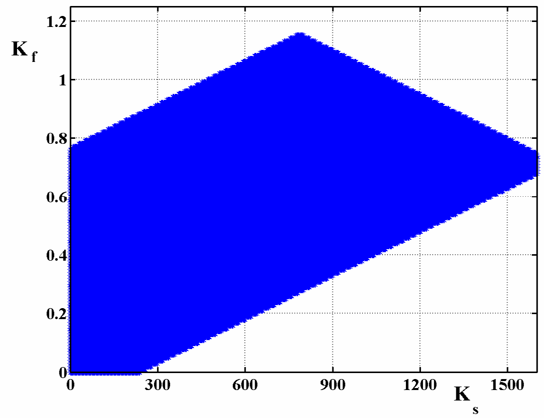

Fig. 6. Stable region in (K_s, K_f) - plane.

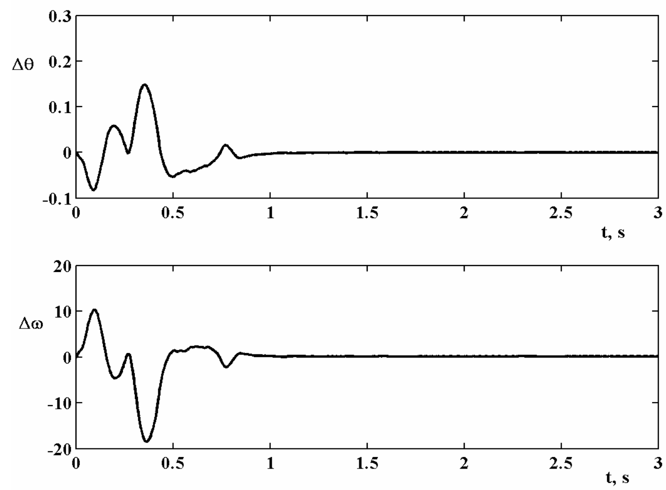

Fig. 7. Transient response and steady-state values of position and speed differences.

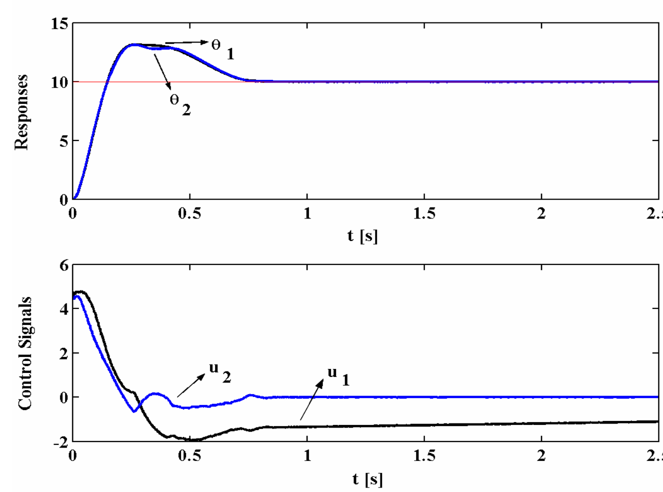

Fig. 8. Responses of angular positions and control signals of digital regulator after step reference signal.

V. CONCLUSION

The efficiency of the special structure of two positioning servomechanisms with cross-coupling control, considered in this paper, is experimentally verified. Since the certain portions of controlling mechanisms 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 servodrives.

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