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Study on Dull-cylinder Synchronous Control Technology and its Application

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Abstract: The two-cylinder drive is one of many commonly used mechanical drive forms. Its synchronous control accuracy determines the movement accuracy of the working machinery. The study established the mathematical model for the two-cylinder electro-hydraulic servo synchronous drive system and revealed that the two-cylinder horizontal electro-hydraulic synchronous drive system has the cascade form of the linear system with the nonlinear system. Taking the band sawing machine and the broaching machine as the application object, the paper analyzed their compositions and synchronization CNC systems. Aiming at the dual-cylinder drive form for the broaching machine, the IPSO-PID synchronous controller of the two-cylinder system was designed. Through the digital simulation and actual testing, the results show that the IPSO-PID synchronous controller is faster in the tracking response speed and better in the synchronization performance than the conventional PID synchronization controller.

Key words: Electro-hydraulic servo, synchronous control, IPSO-PID, band sawing machine, broaching machine

INTRODUCTION

The band saw equipment has the fast cutting speed, the high dimensional accuracy, the little material loss, the high production efficiency, the strong adaptability of materials and so on. It has become the important processing equipment. In the 1960s, cutting 150 mm of No.45 steel needs 15-20 min. It only needs 1.5-2 min currently. In 30 years, the efficiency raises 10 times. The band saw equipment has obvious advantages in terms of material utilization. Cutting off 100 mm of No.45 in the band saw machine can reduce 56% material loss compared with the bow sawing machine and can reduce 87.5% material loss compared with the circular sawing machine. In addition, the band saw equipment has wide adaptability and low power consumption. It also is easy to operate and maintain and can do the angle cutting. Thereby it used more and more widely. But at present the homemade band saw equipment has the large gap in the sawing accuracy and efficiency compared with the foreign machine, in particular, the greater for the large band saw equipment. This is because the large band saw equipment is often driven by two cylinders as the feed movement. The synchronization accuracy of the double driven cylinders is a key factor of affecting the sawing accuracy. Therefore, studying the synchronization control methods for the servo two-cylinder drive of the large band saw equipment is the basis for the development of the large high-performance band saw equipment (Zhu *et al*., 2005; Chen *et al*., 2004).

The hydraulic broaching machine is a high-precision and high-efficiency machining method of the final shaping. It is the important machining equipment for the mass-production, long-size, high-precision and complex cross-section of key parts in the modern manufacturing industry of automobiles, aircrafts and so on. It has the compact structure, the high broaching force (generally above 40-100 KN), the quick broaching speed (up to 40 m min^{-1}), the high requirements to the motion accuracy and the short auxiliary time of the broach's movement back and forth. Nowadays the hydraulic broaching machine is mainly in the two forms of the single-cylinder drive and the two-cylinder drive. The single-cylinder drive has the simple structure and easy control but the "single-pole" form of the broaching drive is easily affected by the broaching load in the broaching process. Although the structure is relatively complex and the higher synchronization control precision is needed, the drive form of the dual-hydraulic cylinders can well balance the broaching load, reduce the sensitivity to the broaching load and thereby improve the broaching accuracy and efficiency. Because the drive form of the dual-hydraulic cylinders has the advantages, the hydraulic broaching machine at home and abroad is advancing in the direction of the dual-hydraulic cylinder's drive. Therefore, the high-performance synchronous servo-drive control technology of the dual-hydraulic cylinders is one of the core technologies for the broaching machine equipment (Wang *et al*., 2012; Li *et al*., 2011).

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MATHEMATICAL MODEL FOR TWO-CYLINDER ELECTRO-HYDRAULIC SERVO SYNCHRONOUS DRIVE SYSTEM

In order to establish the mathematical model of the two-cylinder electro-hydraulic servo synchronous drive system, without loss of generality, the load control problems for the two-cylinder horizontal-driver vehicle are considered, as shown in Fig. 1. Setting $x = [x_1, x_2]^T$, we can get the mathematical model:

$$\begin{cases} M\ddot{x} + B_p\dot{x} = \tau \\ \dot{p}_{iL} = \beta_e K_{iq}\Psi_i(x_i, p_{iL})\bar{x}_{iv} + \pi(x_i)p_{iL} + h_i(x_i)\dot{x}_i \end{cases} \quad i = 1, 2$$

$$M = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} = \begin{pmatrix} m_1 + \dfrac{Ml_2^2 + J_0}{L^2} & \dfrac{Ml_1l_2 - J_0}{L^2} \\ \dfrac{Ml_1l_2 - J_0}{L^2} & m_2 + \dfrac{Ml_1^2 + J_0}{L^2} \end{pmatrix}$$

$$B_p = \text{diag}([B_{1p}\, B_{2p}])$$

$$\tau = \begin{bmatrix} \tau_1 \\ \tau_2 \end{bmatrix} = \begin{bmatrix} A_{11}\, p_{1L} - F_{1c} - F_{4c} \\ A_{21}\, p_{2L} - F_{2c} - F_{3c} \end{bmatrix}$$

$$K_{iq} = C_d\, \omega_1$$

$$h(x_i) = \frac{\beta_e A_{i1}}{V_{ie}(x_i)}$$

$$\Psi(x_i) = \frac{1}{V_{ie}(x_i)}\sqrt{\frac{4(\alpha_{xv}p_s - \frac{x_{iv}}{|x_{iv}|}p_{iL}}{3\rho}}$$

$$\pi(x_i) = -\frac{C_{it}\,\beta_e}{V_{ie}(x_i)}$$

As the above formula, the two-cylinder electro-hydraulic synchronization and horizontal drive system has the cascade form of the linear system with the nonlinear system (Chen *et al*., 2011). Taking into account that the displacement feedback data collection for the hydraulic cylinders uses the magnetostrictive sensor of the high-frequency response, the response frequency greater than 1000 Hz and much higher than the frequency of the system response, the sensor channel modeling can been approximated as a unit feedback link (Chen *et al*., 2012).

So according to the above mathematical model, taking the conventional PID controller as an example, we can finally get the model of the electro-hydraulic servo system, as shown in Fig. 2. r_1 and r_2 in the figure are, respectively the desired control signal input channels.

From the above figure can be seen, various channels in the two-cylinder electro-hydraulic servo system are coupled with each other through the outputs. When the nonlinear or uncertain interference causes the desynchrony for the position outputs of the two hydraulic cylinders, the interactions between the two channels will exist. Such interactions may affect the performance of each channel and thereby generate the synchronization error of the system.

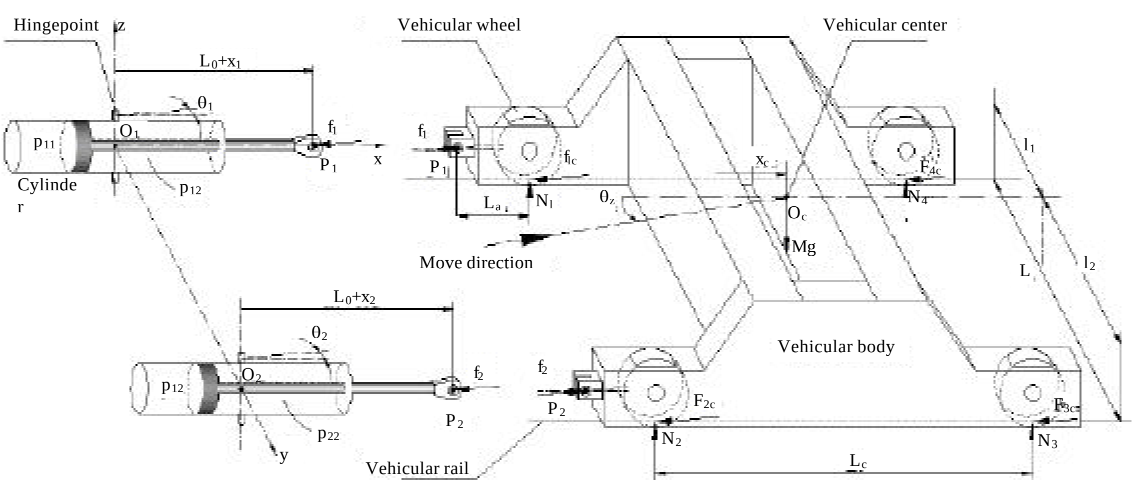

Fig. 1: Two-cylinder electro-hydraulic servo synchronous drive system

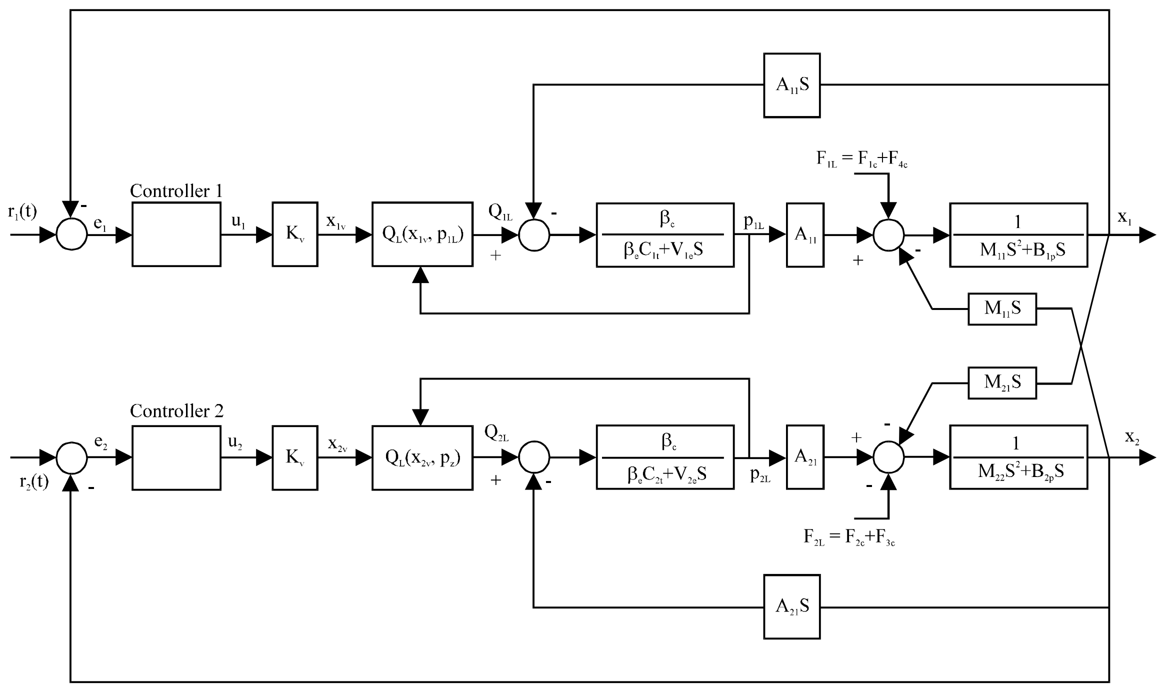

Fig. 2: Model of the electro-hydraulic servo system

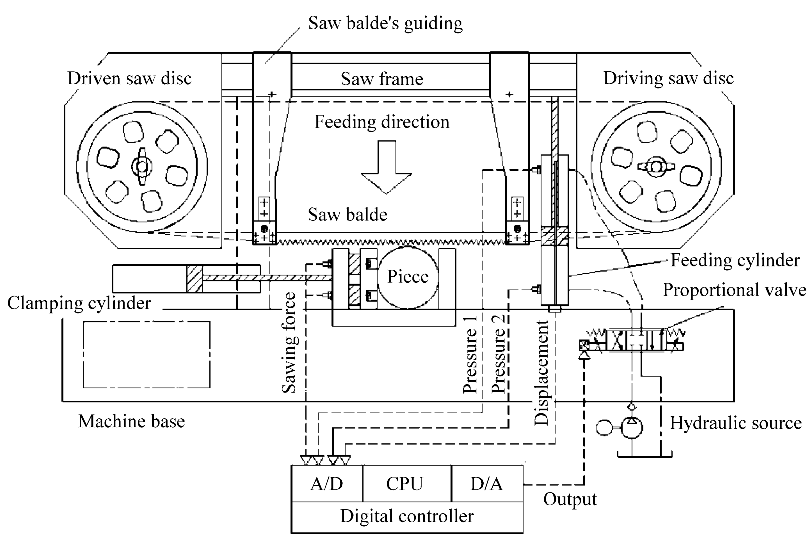

Fig. 3: Band sawing machine

APPLICATION OBJECTS-BAND SAWING AND BROACHING MACHINE

The band sawing machine is composed by the sawing base, the saw frame, the saw blade's guide part and the workpiece-clamping part, as shown in Fig. 3. The saw frame is supported by the hydraulic feeding cylinder and the pillar, on which is mounted the driving and driven saw pulley. The band saw blade is wound on the driving and driven saw pulley and is tensioned by the tensioning mechanism (hydraulic tensioning cylinder and slider). The workpiece-clamping part is responsible for griping the sawing workpiece (clamping cylinder and clamping block). The band saw blade is driven by the driving saw pulley (frequency conversion motor and worm gear reducer). The sawing movement of the specific workpiece is driven by a hydraulic feeding cylinder.

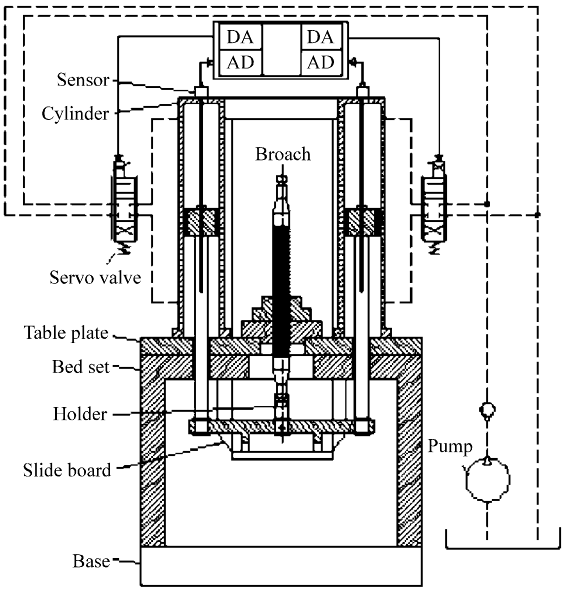

Fig. 4: Two-cylinder hydraulic broaching machine

This study studies the two-cylinder hydraulic broaching machine, as shown in Fig. 4. The hydraulic broaching machine of the two-cylinder electro-hydraulic servo drive system is composed by the base, the bed set, the table plate, the two hydraulic cylinders, the slide board, the holder, the workpiece, the broach and the electro-hydraulic servo drive system. The electro-hydraulic servo drive system is composed by the oil source, the hydraulic cylinders, the SSI displacement sensor, the proportional servo valve, the SSI module, the DA module and the controller. The working principle of the broaching machine: the broach is clamped on the slide board by the holder and the slide board is driven by two hydraulic cylinders in the servo synchronization form to realize the broaching processing.

STUDY ON TWO-CYLINDER SYNCHRONOUS DRIVE SYSTEM FOR BROACHING MACHINE

Designing ipso-pid synchronous controller for two-cylinder system: According to analyzing the control strategy, the intelligent PID controller for the hydraulic broaching machine of the two cylinders is simplified, as shown in Fig. 5.

Practical application research: The actual electro-hydraulic servo synchronous drive system for the hydraulic broaching machine of the two cylinders is studied. Its major system parameters: the hydraulic working pressure 10 MPa, the working flow 400 L min^{-1}, the hydraulic cylinder Φ130/63-1900 mm, the hydraulic cylinder displacement sensor MTS RH1900 (25-bit precision output type), the Rexroth proportional servo valve 4WRZE25, the location acquisition module, the DA module and controller. The selected operating conditions for the actual system simulation and the application research: the two-cylinder drive stroke 100-1000 mm, the constant speed 100 mm sec^{-1}, the acceleration and deceleration time 0.5 sec, the broaching load f = 100 kN.

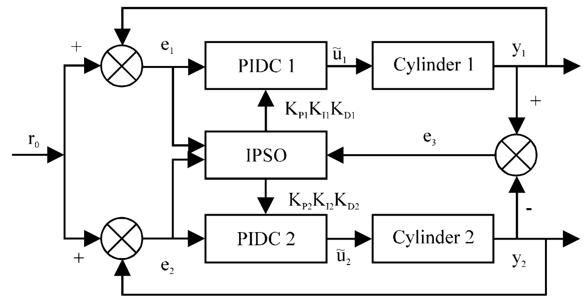

Fig. 5: Intelligent PID synchronous controller based on IPSO-PID

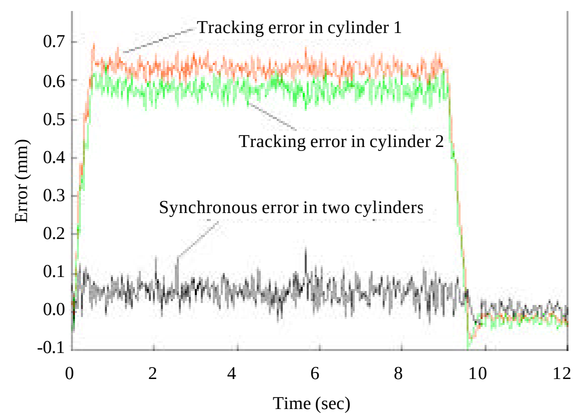

Fig. 6: Simulation for PID control

In order to test the validity of the IPSO-PID-based synchronous controller, the conventional PID synchronous controller is taken as the comparison object. In the two control strategies, the actual parameters for the conventional PID synchronous controller and the intelligent IPSO-PID controller are shown in Table 1.

The practical application results of two control strategies are shown in Fig. 6-9. The Fig. 6 and 7 are the simulation and practical application results for the conventional PID synchronous control. The Fig. 8 and 9 are the simulation and practical application results for the IPSO-PID synchronous control.

Table 1: Controller parameter

Parameter	Parameter symbol	IPSO-PID parameter	Conventional PID parameter
Proportion parameter	K_{pi}, $\tilde{K}_{pi}$	5.0 (initial value)	5.0
Integration parameter	K_{Ii}, $\tilde{K}_{Ii}$	0.3 (initial value)	0.3
Differential parameter	K_{Di}, $\tilde{K}_{Di}$	0.1 (initial value)	0.1
Maximum inertia coefficient	w_{max}	2	--
Minimum inertia coefficient	w_{min}	0.1	--
Number of particles	M	50	--
Number of iterations	k_T	100	--
Tracking error weighting coefficient	α_i	0.25	--
Synchronous error weighting coefficient	β_1	0.5	--
Control interval	T_s	10 m sec	10 m sec

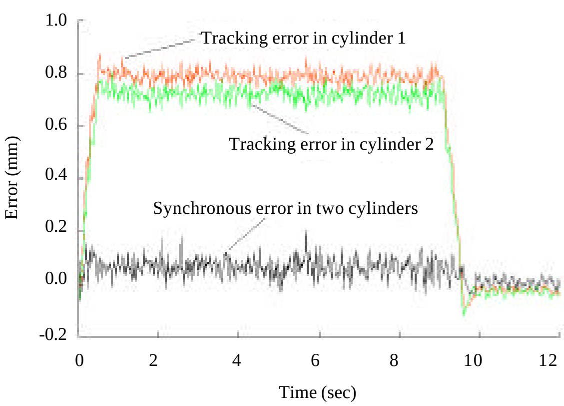

Fig. 7: Application for PID control

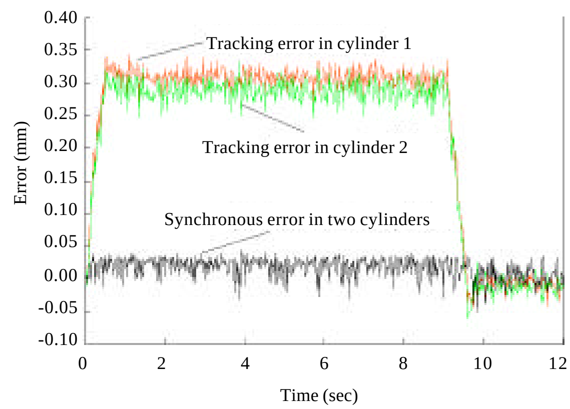

Fig. 8: Simulation for IPSO-PID control

Comparing the Fig. 6 with the Fig. 7 can see that in the simulation and practical application for the conventional PID synchronous control, the cylinder 1 and the cylinder 2 have basically the same tracking error (a difference of less than 0.2 mm) and the synchronous error of the cylinder 1 and cylinder 2 is basically the same (within ±0.1 mm). Comparing the Fig. 8 with the Fig. 9 can see that in the simulation and practical application for the IPSO-PID synchronous control, the cylinder 1 and the cylinder 2 have basically the same tracking error (a difference of less than 0.1 mm) and the synchronous error of the cylinder 1 and cylinder 2 is basically the same (within±0.03 mm). Those show that the established system model is effective.

Comparing the Fig. 6 with the Fig. 8 can see that in the system simulation control case, the tracking errors for the IPSO-PID synchronous controller of the cylinder 1 and the cylinder 2 are reduced by about 0.35 mm and the synchronization error is about±0.03 mm. In comparison with the conventional PID synchronous controller, the tracking error of each cylinder is decreased by 0.3 mm and the two-cylinder synchronization error is reduced by 0.07 mm. These simulation control results show that the IPSO-PID synchronous controller is faster in the tracking response speed and better in the synchronous performance than the conventional PID controller.

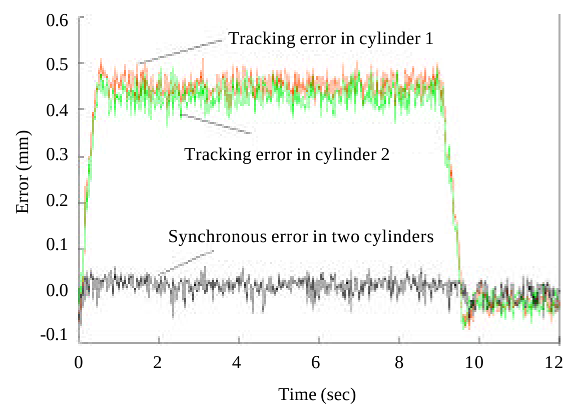

Fig. 9: Application for IPSO-PID control

Comparing the Fig. 7 with the Fig. 9 can see that in the actual system control case, the tracking errors for the IPSO-PID synchronous controller of the cylinder 1 and the cylinder 2 are reduced by about 0.45 mm, the synchronization error by about ±0.03 mm and compared with the conventional PID synchronous controller, the tracking error of each cylinder is decreased by 0.5 mm, the two-cylinder synchronization error is reduced by 0.07 mm. Those actual control results indicate that the IPSO-PID synchronous controller is faster in the tracking response speed and better in the synchronous performance than the conventional PID controller.

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