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Hydraulic Synchronization Control Research Status and Outlook

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Author's contribution

The sole author designed, analysed, interpreted and prepared the manuscript.

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Review Article

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ABSTRACT

With the hydraulic synchronization control system in the industrial field of application is gradually widespread, synchronization control research is also more and more attention. Based on this background, this paper combines the current research status of hydraulic synchronization control system, from three aspects of the hydraulic synchronization system to discuss: 1) hydraulic synchronous drive system: analysis of the mechanical rigid synchronous drive system, hydraulic balance synchronous drive system, electro-hydraulic servo synchronous drive system three kinds of control, and summarize the advantages and disadvantages of the different control methods; 2) electro-hydraulic servo synchronization control strategy: master-slave synchronous control, equivalent synchronous control, cross-coupling synchronous control; 3) electro-hydraulic servo synchronous controller: PID control, adaptive robust control, neural network control; Finally, according to the analysis of the above three aspects of the research, the hydraulic synchronization control system outlook, the future of the hydraulic synchronization technology and electrical, Internet and other technologies integrated with each other, so that its control accuracy and response speed will be greatly improved and will gradually be applied to a number of applications. The future hydraulic synchronization technology and electrical, Internet and other technologies are

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integrated with each other, so that its control accuracy and response speed will be greatly improved and will be gradually applied to some high-precision industries, in order to promote the hydraulic synchronization control technology in the industrial field of research and application of reference.

Keywords: Hydraulic system; synchronous control mode; synchronous control strategy; synchronous controller.

1. INTRODUCTION

With the continuous development of modern industry, construction companies have put forward higher requirements on mechanical transmission, hydraulic transmission system with high mechanical efficiency, energy density, wear resistance, cooling and heat dissipation capacity and other advantages, in the field of engineering machinery transmission is in a leading position, widely used in engineering machinery, aerospace, shipbuilding and other fields [1]. Among them, hydraulic synchronization control is an important part of the hydraulic system, which plays a vital role in the development of the hydraulic field [2].

In recent years, in the process of mechanical construction, a single hydraulic cylinder has been unable to meet the project requirements, often requiring two or more hydraulic cylinders to complete the operation, in order to synchronize the hydraulic cylinder with good operating performance, the need to strictly ensure the accuracy and stability of the hydraulic synchronization control [3]. In response to this problem, the former proposed hydraulic synchronization control methods are: mechanical rigid synchronous drive control system, hydraulic counterbalance valve synchronous drive system, electro-hydraulic servo synchronous drive control system, of which the first two belong to the open-loop control, no feedback signals, and its control accuracy depends only on the accuracy of the hydraulic components to ensure that the synchronization of the control precision is relatively low; the latter belongs to the closed-loop control, with the output signal feedback to the input, to achieve the different hydraulic cylinders have good operational performance. The latter is a closed-loop control, with the output signal feedback to the input, to achieve the synchronization of different hydraulic cylinders to compensate for the error function, which can ensure the high precision control of hydraulic cylinders, so in the synchronization of high precision requirements of the project, most of the closed-loop synchronization control [4].

Based on this background, this paper firstly discusses the way of hydraulic synchronous drive system, then analyzes the development status of different electro-hydraulic servo synchronous control strategies as well as different controllers in the closed-loop control and summarizes the advantages and disadvantages of different control methods, control strategies, and finally, summarizes the outlook of the hydraulic synchronous control system to provide reference for the promotion of hydraulic synchronous control technology for research and application in the industry.

2. CURRENT STATUS OF RESEARCH ON HYDRAULIC SYNCHRONOUS DRIVE SYSTEMS

With the continuous development of multi-cylinder synchronous control, hydraulic synchronous drive mode has also been continuously improved, at present, the hydraulic synchronous drive mode is mainly divided into open-loop control, closed-loop control of the two drive modes, and closed-loop control is specifically developed from the open-loop control. The open-loop control mainly refers to the mechanical rigid synchronous drive mode and hydraulic balance valve synchronous drive mode, closed-loop control mainly refers to electro-hydraulic servo synchronous control drive mode. The following will be a detailed discussion of the different hydraulic synchronous drive control methods.

2.1 Mechanical Rigid Synchronous Drive System

Mechanical rigid synchronous drive refers to the use of guide rail slider, rack and pinion and screw nut and other mechanical constraints, as shown in Fig. 1 (guide rail slider), the rigid connection of the various executive elements to achieve synchronous control of the way, with a simple structure, strong reliability and other advantages. But its synchronization control accuracy depends mainly on the manufacturing accuracy and rigidity of the mechanism, the disadvantage is that the bias load cannot be too large, otherwise it is prone to the phenomenon of jamming, which is not conducive to the controllability of the mechanism. And mechanical rigidity synchronous drive cannot real-time control of the position of the hydraulic cylinder, and synchronization of high precision requirements of the project is not applicable.

2.2 Hydraulic Counterbalance Valve Synchronized Drive System

Hydraulic counterbalance valve synchronous drive refers to the use of various hydraulic synchronization control components, through the control of the hydraulic cylinder pipeline oil supply to achieve synchronous movement of multiple actuators, as shown in Fig. 2. The accuracy of its synchronous control mainly depends on the relevant performance of the hydraulic components and hydraulic oil, and the open-loop control used in this control mode does not have the ability to output feedback information, making it difficult to achieve high-precision synchronous control of hydraulic cylinders.

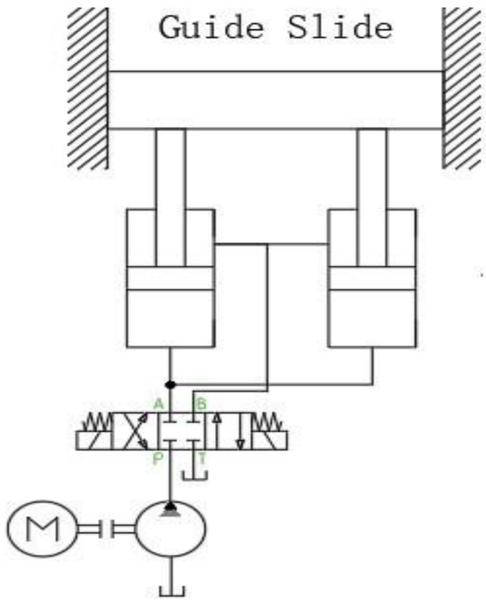

Fig. 1. Mechanical rigid synchronous control drive system

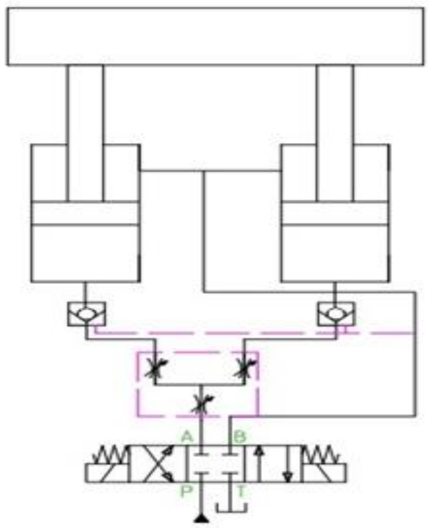

Fig. 2. Hydraulic counterbalance valve synchronized drive system

2.3 Electrohydraulic Servo Synchronous Drive System

Electro-hydraulic servo synchronous drive mainly refers to the use of a variety of proportional valves, servo valves or digital valves to form a closed-loop electro-hydraulic servo system, in order to realize the synchronous movement of multiple actuators, as shown in Fig. 3, which is the biggest difference with the first two synchronous drive methods is that the synchronous drive method can collect the signals at the output side, and through the synchronous controller, the collected output signals can be processed, and then finally the processed The signal is fed back to the input, through which real-time control of different actuators can be realized, so this control method has a high synchronization control accuracy. However, the control loop of this control method is complicated and the cost is high.

At the same time, the classification of electro-hydraulic servo synchronous drive system is more complex, according to the control variable can be divided into force synchronous control, speed synchronous control, displacement synchronous control; according to the control element can be divided into electro-hydraulic servo synchronous drive system, electro-hydraulic proportional synchronous drive system, etc.; according to the control of the executive element can be divided into hydraulic cylinder synchronous drive system and hydraulic motor synchronous drive system; the relationship between the diagram shown in Fig. 4.

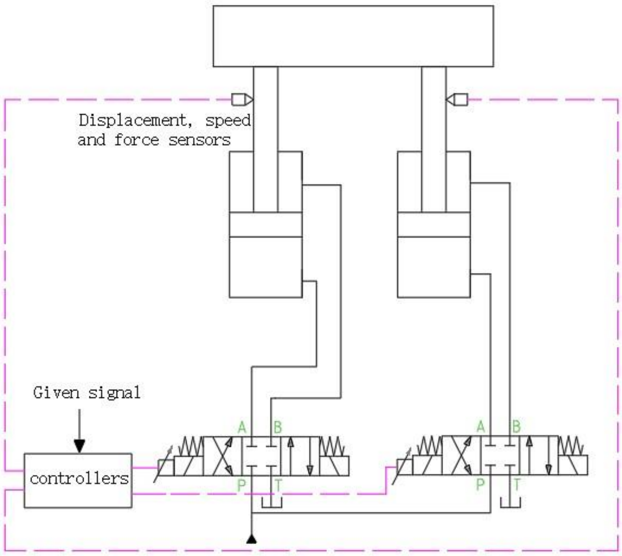

Fig. 3. Electro-hydraulic servo synchronized control drive system

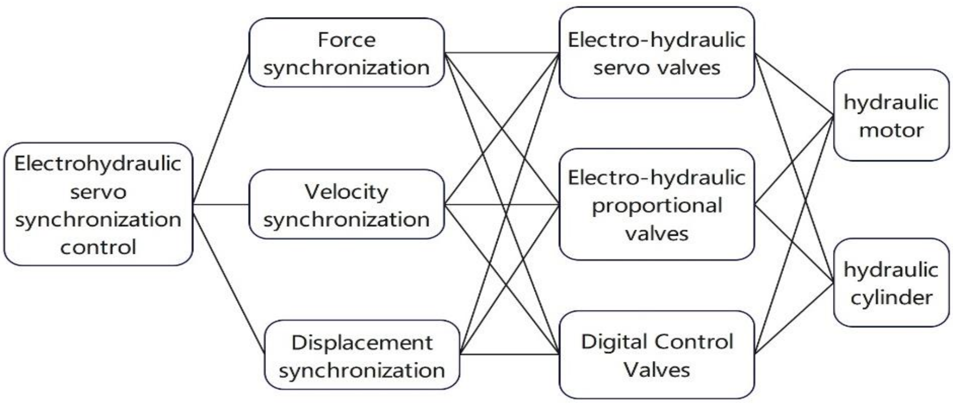

Fig. 4. Classification of electro-hydraulic servo-synchronous drives

Table 1. Comparison of synchronous drive performance

Control method	Driving method	Synchronization accuracy steady state case	Tracking Performance	System cost
Open loop control	Mechanical rigidity synchronized control	Centimeter scale	No	One
	Synchronized control of balancing valves	Millimeter scale	No	Two
Closed-loop control	Electro-hydraulic proportional synchronized control	Micron scale	Yes	Five
	Electrohydraulic servo synchronization control	Micron scale	Yes	Ten

According to the above analysis and summarizing the results of the current related engineering experiments [5-7], different synchronous drive systems are summarized, as shown in Table 1. It is concluded that the closed-loop control method is better than the open-loop control, but the cost of closed-loop control is higher, so in the construction of machinery, the appropriate synchronous control scheme should be selected according to the control accuracy required for the construction to avoid the problem of high cost.

3. RESEARCH STATUS OF ELECTRO-HYDRAULIC SERVO SYNCHRONIZATION CONTROL STRATEGY

In the closed-loop control in the existence of feedback regulation, the controller can realize the output and input of real-time feedback regulation, will be regulated to reduce the control deviation, improve the synchronization control accuracy. According to the different ways of feedback control of the hydraulic system synchronous control strategy can be divided into: single-channel model based synchronous control technology and multi-channel model based synchronous control technology, single-channel model can be subdivided into: master-slave control strategy and equivalent control strategy; multi-channel model can be divided into multi-channel decoupled synchronous control strategy and cross-coupling control strategy. At present, the multi-channel decoupled synchronization control strategy is not commonly used, so this paper mainly introduces the master-slave synchronization, equivalent synchronization and cross-coupling synchronization control strategy in detail. The relationship diagram is shown in Fig. 5.

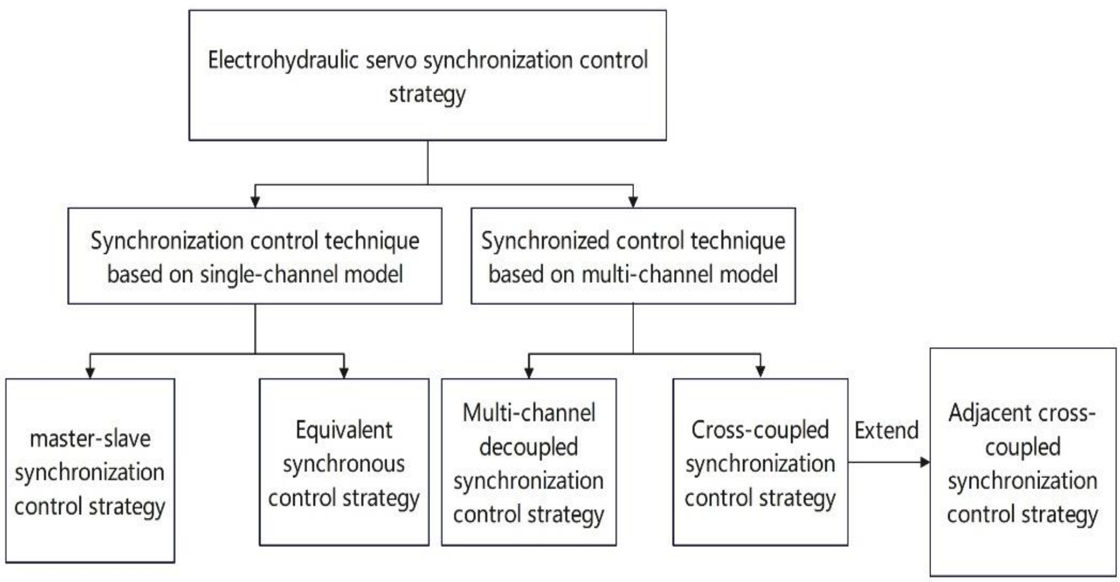

Fig. 5. Electro-hydraulic servo synchronization control strategy relationship diagram

3.1 Master-Slave Control Strategy

Master-slave control is similar to a series structure, the main working principle is: among multiple actuators that need to be synchronized control, the output of one actuator is selected as the ideal input, and the rest of the actuators are tracking this ideal input to achieve synchronized control. However, this synchronous control strategy has a certain hysteresis, especially in the start-stop phase of the system is more obvious, resulting in the master actuator has been with the slave actuator has a minimum error, and cannot achieve the complete synchronization of the actuators. The control block diagram is shown in Fig. 6.

Wang Nomu et al [8] used master-slave control to carry out a simulation study for the synchronization control accuracy of horizontal servo cylinders under extreme loads, firstly, the closed-loop control model of the valve-controlled servo cylinder was established in AMESim software, and finally, a reasonable PID parameter was found out by controlling the influence of different parameters on the response speed, accuracy, etc. The results show that the control system can meet the requirements of synchronization control accuracy.

Li Leyi et al. [9] proposed a synchronous control scheme of one master and three slaves for the problem of synchronous pressure of multiple hydraulic cylinders of roller straightening machine, simulated using Simulink software, and compared the simulation results with the experimental results, and concluded that this control method can better control the positional accuracy of the straightening machine and the straightening pressure compared with the traditional closed-loop control.

Dai Jianjun et al[10] for the hydraulic truck synchronization control problems, simulation verification controller using PID controller, control strategy selection “master-slave” synchronization control strategy, designed the CAN bus control system, through the real car experiments, verified that this control strategy can make the two cars to ensure good synchronization ability.

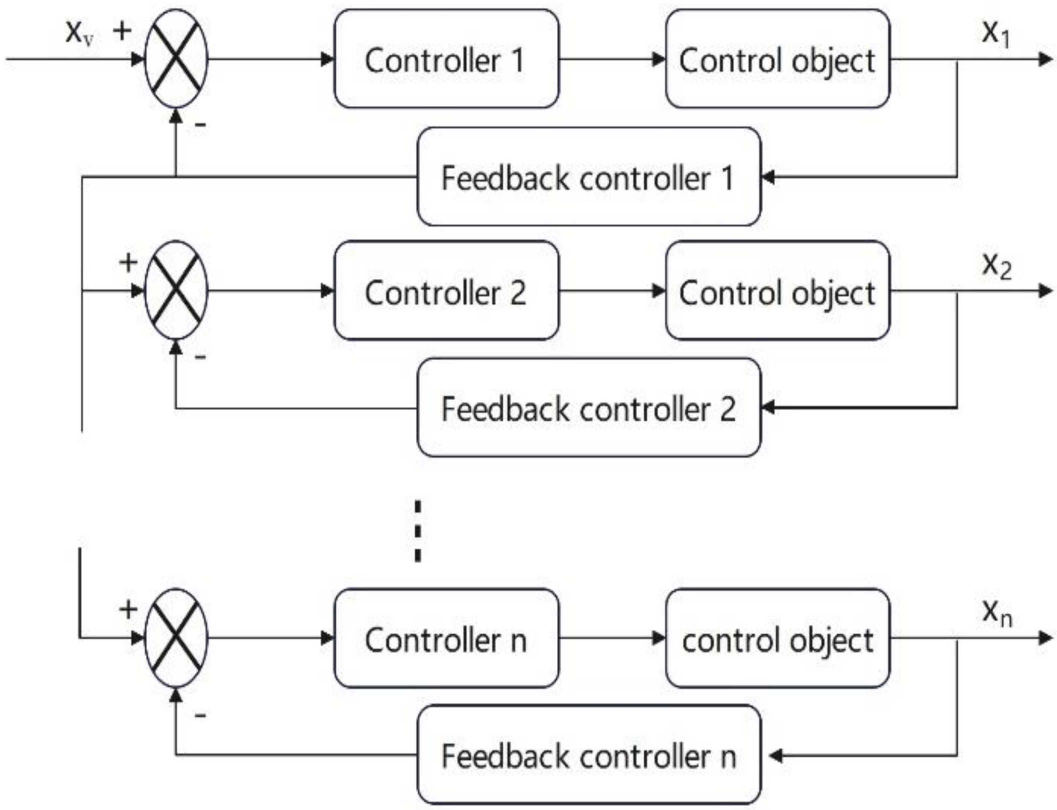

Fig. 6. Master-slave synchronization control strategy

3.2 Equivalent Control Strategies

Equal control, also known as equivalent control is similar to a parallel structure, and its working principle means that an ideal input value is given and this value is input to multiple actuators that need to be synchronized separately, so as to achieve the effect of synchronized control. However, this type of control is to use each actuator as a separate control loop, and mutual feedback cannot be realized between each loop, so the accuracy of this synchronous control mainly depends on the synchronous tracking error of each actuator. The block diagram of equivalent control is shown in Fig. 7.

Yunfei Wang et al. [11] for multi-cylinder synchronization control system, proposed a perturbation observer based position velocity dual constrained robust dynamic surface equivalent control method, using the obstacle Lyapunov to limit the position and velocity error of the system, the implementation results show that the designed synchronization controller has less fluctuation, stronger anti-interference ability and higher control accuracy.

Liu Haixing et al, [12] carried out an equivalent synchronization control study of a double-cylinder hydraulic cylinder based on the inverse step controller, the results of the study relative to the PID control, in the inverse step of the step error has been greatly improved, in the sinusoidal tracking aspect of the hysteresis has been reduced, due to the current research on the inverse step of the less, this paper in the parameter calibration of the larger lack, and did not join the adaptive control, therefore, the study of the inverse step control The research on backstepping control needs to be carried out.

3.3 Cross-Coupled Control Strategies

With the continuous development of industry, master-slave control and equivalent control gradually cannot accomplish some ultra-high precision control, so some scholars proposed the cross-coupling control strategy. The cross-coupling control strategy is mainly based on the control performance error compensation of each subchannel, the synchronization error generated by the nonlinearity of the system, external perturbations and mutual coupling between the channels is compensated, and the cross-coupling control block diagram is shown in Fig. 8.

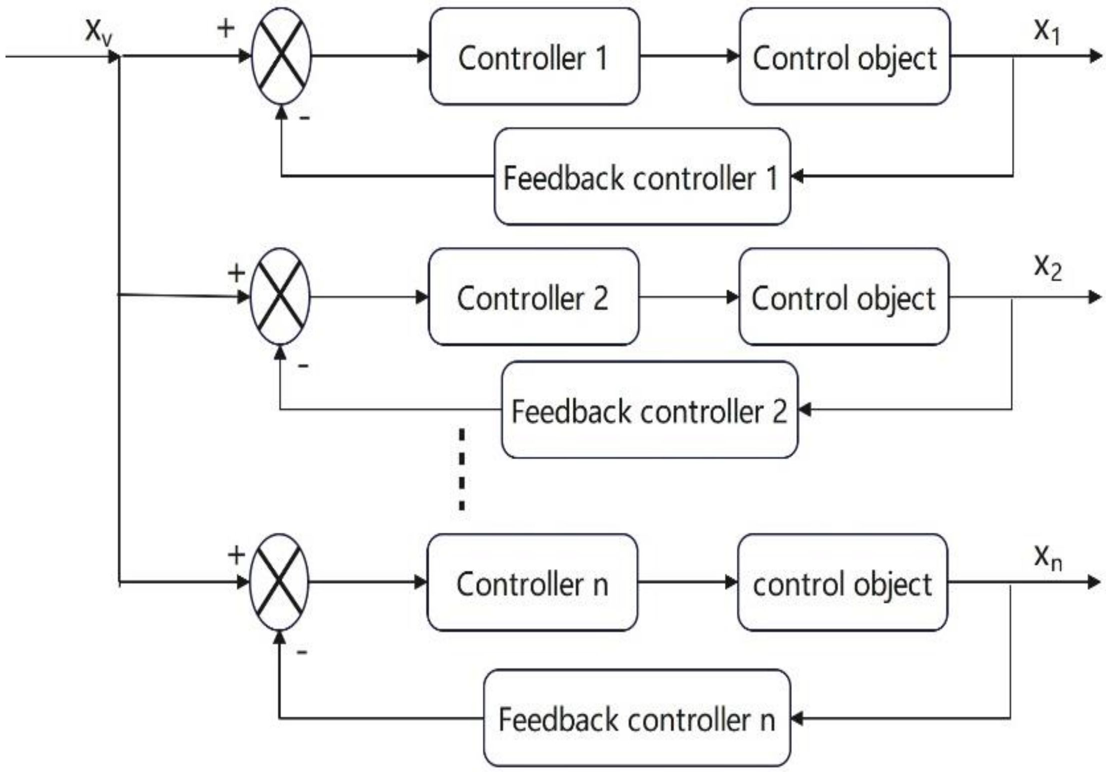

Fig. 7. Equivalent synchronization control strategy

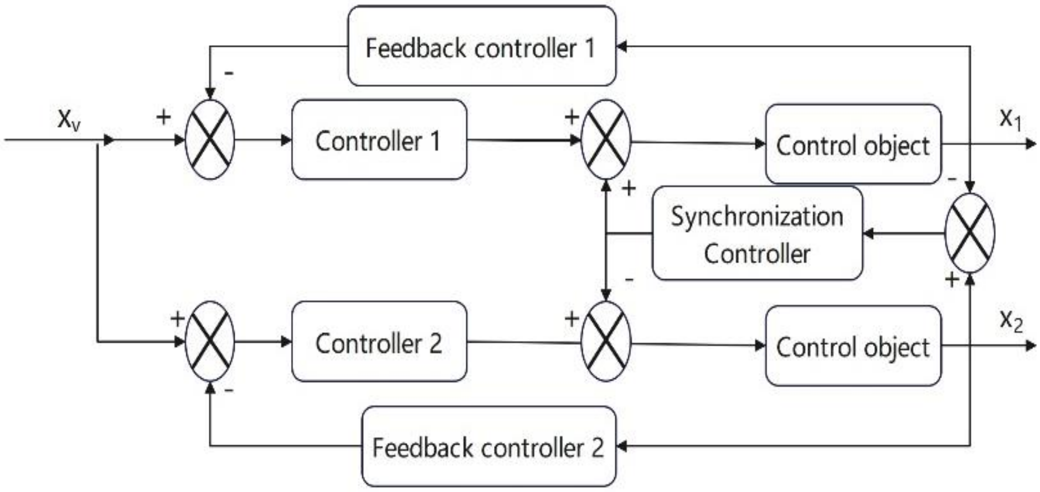

Fig. 8. Cross-coupled synchronization control strategy

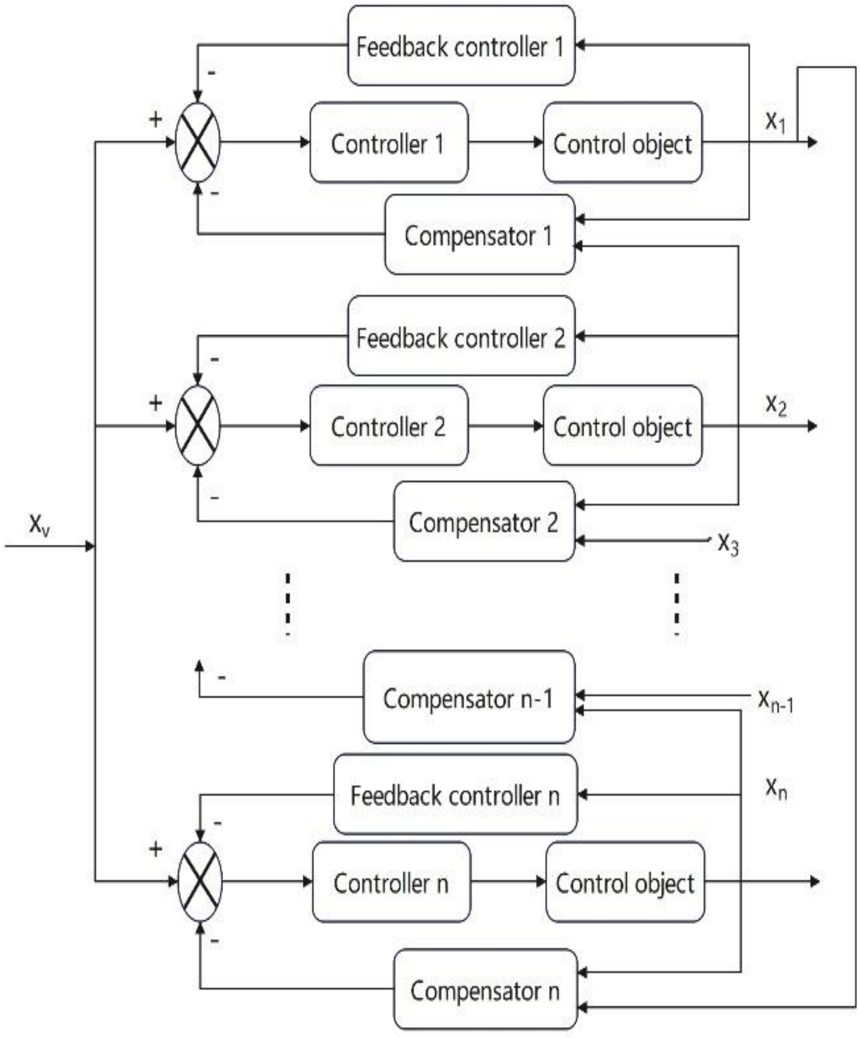

Fig. 9. Adjacent cross-coupling synchronization control strategy

Sun et al. [13] proposed a sliding film synchronization control method for the problem of improving the positional synchronization performance and interference immunity of the synchronization control of a hydraulic hoist with dual lifting points. On the basis of the method of cross-coupled synchronization control, a coupled sliding film surface containing the single bar following error and the double cylinder synchronization error is formulated, and at the same time, a sliding film synchronization controller is designed to ensure the convergence of the single cylinder following and synchronization errors. Finally Simulation results show that the synchronization controller has good performance under the condition of external interference.

Although cross-coupling has better accuracy and stability for two-cylinder control, it shows limitations for multi-cylinder control, which becomes too complex and the accuracy and stability of synchronized control deteriorate. Therefore, in order to solve this problem, more and more scholars began to study the neighbor cross control strategy. Adjacent cross-coupling is mainly a local synchronous control of the actuators, the controller in its own actuator output synchronization error feedback at the same time, but also to its neighboring hydraulic branch output synchronization error feedback, so as to control the output error compensation of the neighboring hydraulic branch, to achieve the synchronous control of the actuators, the control block diagram shown in Fig. 9.

Pan Mengting et al[14] roposed a control strategy combining generalized predictive control and adjacent cross-coupling control for the synchronous control of multiple cylinders of a lift-and-sink compensation platform, which ensures the stability of the position control of a single hydraulic cylinder while coupling the remaining five hydraulic cylinders with each other, realizing the precise and synchronous control of six hydraulic cylinders.

Duan Guoyuan et al. [15] proposed an indirect adaptive robust control study of adjacent cross-coupling for the synchronized control of electro-hydraulic multi-cylinders and verified it through simulink simulation, which proved that the strategy has high adaptability in electro-hydraulic multi-cylinders control and ensures the accuracy of synchronized control even when there is no bias load in the system.

Zhao Lijuan et al[16] For the synchronization control of vertically loaded hydraulic cylinders in the test bench of hydraulic stent with ultra-large mining height, fuzzy PID controller adjacent cross-coupling control strategy is adopted, and based on Adams-AMEsim-Simulink machine-hydraulic control integration co-simulation, the simulation results show that the fuzzy PID control has the characteristics of faster response speed, higher accuracy, etc., which provides a reference for the design of the hydraulic stent loading system. The simulation results show that the fuzzy PID control has the characteristics of higher response speed and accuracy, which provides a reference for the design of hydraulic support loading system.

4. CURRENT STATUS OF ELECTRO-HYDRAULIC SERVO SYNCHRONIZATION CONTROLLER RESEARCH

4.1 PID Control

At present, PID control has become one of the most commonly used methods in the field of hydraulic synchronous control by virtue of its own simple structure, easy to implement and other advantages, and has been applied in a number of hydraulic synchronous control machinery and obtained better robustness.

Li Qiang et al[17] proposed a synchronized hydraulic control system for the problem of unsynchronized hydraulic lifting cylinders of garbage compression trucks, which controls the flow rate of electro-hydraulic proportional valves to reduce the displacement deviation between the master and slave hydraulic cylinders by means of PID controllers, and the simulation results in AMEsim show that the proposed system has a faster response speed, higher synchronization accuracy, and better robustness. The mathematical model of the PID controller is shown below:

$$\mathrm{u}(t) = K_P\left[e(t) + \frac{1}{T_i}\int_0^1 e(t) + T_d\,\frac{de(t)}{dt}\right]$$

Wang Yaya et al. [18] for the crane luffing mechanism of the hydraulic cylinder asynchrony problem, first, the use of FLuidSIM software for the optimization of the parameters of the PID, and then, the establishment of the synchronous control simulation model with the PID control module in the AMEsim software, simulation, and the results show that: the PID control improves the synchronous control accuracy of the crane luffing mechanism.

Although some scholars use PID control to realize the synchronous control research of hydraulic system, but PID control has limitations in parameter adjustment, and PID control also relies on accurate mathematical model to achieve the desired control effect. Therefore, in response to this problem, some scholars began to combine PID control with analog control and intelligent algorithms, and proposed fuzzy PID control and intelligent algorithm PID control, which effectively solves the problem of PID parameter adjustment. The fuzzy PID control algorithm is based on the conventional PID control by adding a fuzzy controller, which performs fuzzy reasoning on the error and the rate of change of the error, so as to make real-time adjustments to the three parameters of K_p, K_i and K_d. Where the fuzzy PID mathematical model is shown below:

$$\mathrm{u}(t) = (K_P + \Delta K_P)e(t) + (K_i + \Delta K_i)\int_0^1 e(t) + (K_d + \Delta K_d)\frac{de(t)}{dt}$$

Bian Yongming et al. [19] proposed a PID parameter optimization method based on improved particle swarm algorithm for the problem of difficult adjustment of PID parameters of hydraulic synchronous control, and the optimized PID control parameters obtained have better control performance.

Liang Zhixin et al. [20] designed a dual hydraulic cylinder position synchronization control system, respectively, using conventional PID and fuzzy PID controllers for practical testing, the test results show that the use of fuzzy PID controllers compared to conventional PID control, fuzzy PID control has a strong robustness and high control accuracy.

4.2 Adaptive Robust Control

Adaptive robust control is a controller that combines the advantages of adaptive controllers and robust controllers, in which the adaptive controller can automatically adjust the parameters of the controller according to the changes in the parameters of the controlled object, so that the performance of the system remains unchanged, compared with PID, adaptive control does not require the model to be completely known, and it is a kind of “change to make change” control strategy. Compared with PID, adaptive control does not require the model to be completely known, and it is a kind of control strategy of “making changes with changes”. Robust control is a kind of control strategy for external perturbations, which “responds to changes with no changes”. Therefore, adaptive robust control can not only realize the controller parameters change with the controlled system parameters change at the same time can also be adaptive to the system's external disturbances to adjust, so as to achieve high-precision synchronous control.

Guo et al. [21] designed an adaptive sliding film synchronized position control strategy for the problem of hydraulic bracket drive synchronization, and developed an adaptive law to suppress the uncertainty generated by the subsystem after decoupling. The joint simulation platform and experimental results show that the proposed controller can effectively reduce the synchronization error between the two column positions, and has a control performance superior to that of PI and fuzzy PID controllers.

Wang Zhongwei et al. [22] for the closed pump-controlled servo system position of the control output process of the control algorithm debugging is difficult and other issues, put forward an adaptive backstepping control of the strategy, and in the Linux + Preempt semi-physical simulation of the platform to complete the experiments of the control of the different signals, the experimental results proved that the authors of the adaptive backstepping control strategy has a good tracking performance and robustness.

Sun et al. [23] proposed an adaptive robust cross-coupling strategy for high-performance trajectory tracking of a hydraulic leveling mechanism, which was verified by simulation and demonstrated to have a good synchronization control effect that can keep the inter-axis error within ±0.1mm.

4.3 Neural Network Control

Neural network is a kind of simulation of the human brain neural network in order to realize the artificial intelligence-like mechanical learning technology, can realize the rapid approximation of the nonlinear multi-input, output complex model, the control parameters can be adjusted with the changes of the environment and the load conditions, and has good robustness. With the continuous development of modern control theory, more and more scholars began to apply neural network technology to hydraulic synchronous control, and achieved better control results, commonly used in hydraulic synchronous control of neural networks such as BP neural network and inverse neural network.

Fanghua Liu et al. [24] proposed a master-slave control strategy with BP neural network for the lack of synchronization control strategy of pod thruster, which was verified by joint simulation of AMEsim and simulink, and the results showed that the strategy can achieve high-precision synchronization control of multiple hydraulic cylinders.

Li et al[25] for the synchronous control algorithm research of multi-hydraulic system, firstly established a nonlinear model of asymmetric hydraulic cylinders, then proposed an overall model solution using nonlinear model predictive control and cross-coupling control algorithms, and designed a new type of perturbation compensator based on the inverse neural network model, and finally compared with other controllers through the means of simulation, this controller have shown excellent control performance.

5. OUTLOOK

Hydraulic synchronization control technology as an important means of control in the field of industry and engineering, the control effect of the good and bad directly affects the performance of the whole device, its future development is full of another expected innovation and progress. And with the sensor technology, control algorithms and materials science continue to progress, hydraulic synchronization control will usher in unprecedented development opportunities.

With the construction machinery, aerospace, shipbuilding and other fields of precision requirements continue to improve, the future of hydraulic synchronization control will achieve a variety of algorithms organic and efficient combination, to achieve higher accuracy and faster response capability, the system can achieve micron or even nano level precision control will also become possible, for the development of high-end manufacturing industry to provide a solid support.

In the context of dual-carbon targets and increasingly constrained energy consumption, the improvement of energy efficiency will become an important direction of technological development. By optimizing the controller design and control strategy, the hydraulic system is able to minimize energy loss, improve the energy efficiency ratio, and contribute to the sustainable development of industrial production.

With the application of artificial intelligence and mechanical learning technology, the enhancement of the intelligent level of synchronous control is another key trend. The synchronous hydraulic system is able to achieve intelligent decision-making and implementation of adjustments through learning and optimization, improving the system's adaptive ability and work efficiency, so that it can better adapt to the complex and changing working environment and task requirements.

At the same time, the hydraulic synchronization control technology will also be with other advanced technologies such as electrical control, wireless communications and cloud computing and other deep integration not only to expand the field of application, but also to provide users with more intelligent and flexible solutions.

Hydraulic synchronous control technology in the future development path will continue to promote the overall improvement of precision, response speed, energy efficiency, intelligent level and application areas. This will not only bring new technological breakthroughs for industrial automation and intelligent manufacturing, but also inject more innovative power and development possibilities for global industrial development.

6. CONCLUSIONS

Hydraulic synchronization control is an important part of the hydraulic system, and plays a vital role in the development of the hydraulic field. This paper firstly analyzes different synchronous drive methods, and concludes that although the electro-hydraulic servo synchronous drive has high control accuracy, its construction cost is also far more than the open-loop control, so it should be based on the requirements of the control essence in the construction to choose the appropriate drive method; secondly, the control strategies and electro-hydraulic servo controllers for electro-hydraulic servo synchronous control are analyzed, which mainly include three kinds of master-slave control, equivalent control and cross-coupling control, and These three different control strategies and different controllers combined with each other to meet most of the synchronization control requirements; Finally, the hydraulic synchronization control technology outlook, the future of the hydraulic synchronization technology and electrical, Internet and other technologies integrated with each other, so that its control accuracy and response speed will be greatly improved and will be gradually applied to a number of high-precision industries, for the development of the global industrial development to inject more innovative power and development possibility.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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