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Review

Review of Research and Development of Hydraulic Synchronous Control System

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Abstract: Hydraulic synchronous control systems are widely used in various industrial fields. This paper deeply analyzes the research status and development trend of the hydraulic synchronous control system. Firstly, it gives a brief introduction of the research significance control theory and control methods of the hydraulic synchronous control system. Secondly, the hydraulic synchronization control system is classified, the synchronization error is analyzed, and some solutions to synchronization error are given. Then, according to the classification of the hydraulic synchronous control system, relevant research is carried out. In this paper, three control modes (equivalent, master–slave and cross-coupling) and related control algorithms (fuzzy PID control, sliding mode control, robust control, machine learning control, neural network control, etc.) of closed-loop hydraulic synchronous control systems are studied in detail. Finally, the development trend of the hydraulic synchronization control system is predicted and prospected, which can provide some reference for promoting the research and application of hydraulic synchronization technology in the future industrial field.

Keywords: hydraulic synchronization; closed loop control; synchronization error; control mode; control algorithm

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Citation: Li, R.; Yuan, W.; Ding, X.; Xu, J.; Sun, Q.; Zhang, Y. Review of Research and Development of Hydraulic Synchronous Control System. *Processes* **2023**, *11*, 981. https://doi.org/10.3390/pr11040981

Academic Editors: Francisco Ronay López-Estrada and Guillermo Valencia-Palomo

Received: 4 March 2023
Revised: 17 March 2023
Accepted: 21 March 2023
Published: 23 March 2023

1. Introduction

Hydraulic transmission has the advantages of large output power, stability and reliability, fast response speed, compact and flexible installation, and can achieve a wide range of stepless speed regulation. It is often widely used in large-scale mechanical equipment, metal processing equipment, large-scale metallurgical equipment, agricultural machinery equipment, aerospace, and other related industrial fields [1–4] and has become an important technical force to promote the development of mechanical equipment. Additionally, the hydraulic synchronous control system is an important component in the field of hydraulic transmission, which has a great influence on the research and development of this field.

The development of the hydraulic synchronous control system has gone through a long process. With the unremitting efforts of many scholars and experts, the hydraulic synchronous control system is also developing and progressing [3,5–8]. Joseph Bramah [9], an Englishman, invented the world's first hydraulic press in 1795, and the hydraulic field began to develop gradually. Around the 1870s, the steam engine-driven water pump was gradually applied to hydraulic equipment such as extruders and shears. In the 1930s, the integrated hydraulic system composed of a pump, valve, and actuator was gradually applied to the hydraulic synchronization equipment, and the hydraulic synchronization control system developed rapidly. In the late 1970s, the feedback element began to be applied in the hydraulic closed-loop synchronous control system. Compared with the previous open-loop control, the synchronization accuracy and response speed have been significantly improved. At the same time, the first fuzzy controller developed by the University of London in the United Kingdom was gradually applied to the hydraulic synchronous control system, which effectively solved the control problem of the nonlinear system. However, the fuzzy rules and system design methods are completely based on experience, and it is difficult to accurately and stably control the complex system. In 1981, Canadian scholar G. Zames [10] first proposed H∞ optimal control, and then robust control was widely used in electro-hydraulic servo systems and multi-cylinder hydraulic synchronous systems. Since the 20th century, with the development of electronic components and artificial intelligence, adaptive fuzzy PID, robust control, neural network and other algorithms have been gradually applied to hydraulic synchronization systems. Because of its adjustable control parameters and strong adaptability, it can achieve high-precision synchronization accuracy and good robustness in the control of complex nonlinear hydraulic synchronization systems.

The hydraulic synchronous control system usually requires the actuators in the hydraulic transmission mechanical equipment to operate synchronously with the same displacement or speed at the same time [11]. Generally, due to the existence of nonlinear factors such as leakage, impurities, machining error, and component wear in the hydraulic synchronization control system, it is difficult to ensure the accuracy of the hydraulic synchronization system. Although the existing conventional and simple hydraulic synchronization system is low in cost, it cannot meet the requirements of high-precision synchronization equipment. In order to make the hydraulic synchronization equipment have good operation performance, some relevant scholars have optimized the hydraulic components and hydraulic circuit, but the synchronization accuracy improved by this method is limited. Other scholars have used closed-loop control to apply relevant intelligent control algorithms to the hydraulic synchronization control system, and the control accuracy and reliability and stability have been greatly improved.

Gu et al. [12] focused on the phenomenon that the synchronous open-loop hydraulic synchronous control system of two hydraulic cylinders has no feedback regulation, and there is a constant accumulation of errors and low control accuracy. Through comparing several improvement schemes, the hydraulic synchronous circuit was optimized, and finally the scheme of reasonable configuration of the one-way valve by the synchronous motor for flow compensation was adopted. Through repeated optimization of the opening of the one-way valve, the synchronous error of the two cylinders in the full stroke of 500 mm was not more than 3 mm. Chen et al. [13] proposed a fuzzy control method for piston motion trajectory synchronization aiming at the synchronization error caused by the load imbalance of dual hydraulic cylinders. Based on the fuzzy control, two fuzzy controllers were introduced to eliminate the track tracking error of hydraulic cylinders and the synchronization error between hydraulic cylinders. The experiment shows that the composite control method can control the synchronization error within ±10 mm. Yang et al. [14] proposed a single neuron PID cross-coupling control strategy for the synchronization error caused by the uneven stress of the two hydraulic cylinders of the hydraulic bending machine during the working process, and compared it with the PID control effect under master–slave and cross-coupling. The simulation results showed that the maximum synchronization error of the master–slave PID control was 0.9 mm, and the maximum synchronization error of the cross-coupling PID control was 0.79 mm. The two-cylinder system controlled by neuron cross-coupling PID had a faster response, and the maximum synchronization error was 0.27 mm.

Traditional PID control needs to rely on accurate mathematical models because its parameters are not adjustable. It can achieve a good control effect in a linear system. For complex nonlinear hydraulic systems, some scholars combine PID control with fuzzy control and adaptive control to achieve high synchronization control accuracy. Zhang et al. [15] proposed a synchronization control strategy based on fuzzy PID control, which uses fuzzy rules to realize the real-time adjustment of PID control parameters. Taking the piston displacement of a hydraulic cylinder as an indicator, the joint simulation of AMESim and Simulink shows that the synchronization accuracy of double hydraulic cylinders under this control strategy is between 0 and 0.66 mm, which meets the operation requirements of the shear-type synchronous lifting mechanism. Liu et al. [16] investigated the hydraulic pin type lifting system of the jack up wind power installation ship, a two-stage hydraulic synchronous control system. The speed tracking and displacement coupling synchronization control strategy was adopted for single pile legs to improve the synchronization accuracy, and the fuzzy PID control algorithm was adopted to improve the robustness of the system. The joint simulation of AMESim and Simulink software showed that the maximum synchronization error of the sensor was still less than 0.3 mm when it was disturbed, the system had a higher synchronization accuracy, and had the advantages of stable operation, no overshoot and higher reliability. Li et al. [17] designed a fuzzy adaptive PID controller to be used in the steel plate hydraulic synchronization technology. The joint simulation of AMEsim and Simulink software showed that the displacement synchronization error of the two hydraulic cylinders was always less than 0.1 mm, and the proposed control strategy had a faster response speed, stronger stability, and a higher control accuracy. Zhao et al. [18] proposed a fuzzy PID controller based on particle swarm optimization to solve the problem of synchronization error caused by friction and uneven stress of a new type of hydraulic fan barring drive cylinder group. The particle swarm optimization algorithm was used to iteratively optimize the quantization factors Ke, Kec, and scale factor Ku of the fuzzy controller. Simulation analysis by Simulink software showed that the hydraulic synchronization system under particle swarm composite PID control had a higher synchronization accuracy than traditional PID control, and that fuzzy PID control had the advantages of smaller overshoot, shorter adjustment time, and stronger adaptive ability. Wang et al. [19] proposed a control method combining adaptive robust error sign integration control and extended state observation (ESO) control and combined them with cross-coupling control. The simulation results showed that the control strategy can achieve good synchronous tracking performance in the double hydraulic cylinder actuator system. Fang et al. [20] introduced fuzzy PID control into the hydraulic servo system of a C32 friction welding machine, which improved the closed-loop control characteristics of the welding process. However, due to the small design tonnage, the difficulty of multi-cylinder synchronous control was not considered. In order to solve the difficulty of multi-cylinder synchronization control accuracy, Wang et al. [21] proposed a synchronization controller based on a neural network to solve the synchronization error caused by the difficulty of the coordinated operation of the hydraulic multi-actuator synchronization system. Through the backstepping technology, the synchronization accuracy of multiple hydraulic cylinders was greatly improved. Finally, the effectiveness of the control strategy was verified by simulation and experimentation.

According to the above research, closed-loop control is often used in the hydraulic synchronization control system to improve the accuracy of the hydraulic synchronization control system. This is because there is no feedback signal regulation in the hydraulic synchronous control system under open-loop control, and its control accuracy depends entirely on the accuracy of the hydraulic components to control the actuator. In addition, the synchronization error of the hydraulic system will continue to accumulate under long-term operation, so its synchronization accuracy and anti-interference are poor. The hydraulic synchronous control system under closed-loop control adds online detection and feedback of the actuator displacement and speed between the controller and the controlled object, and the feedback value is compared with the preset control parameters. The controller outputs the signal adjustment amount to compensate the synchronization error of the hydraulic system, which can significantly improve the synchronization accuracy and stability of the hydraulic synchronous control system [22–25].

This paper analyzes the development process and research significance of the hydraulic synchronous control system, studies three control modes and related intelligent control algorithms of the closed-loop hydraulic synchronous control system of the hydraulic synchronous control system, summarizes the causes of synchronization errors, and puts forward some corresponding solutions to improve the control accuracy of the hydraulic synchronous system, Finally, based on the above research, the development trend of hydraulic synchronous control system is predicted and prospects are proposed. With guaranteed control accuracy of the hydraulic synchronization system, the research in this paper can provide some measures to reduce the synchronization error, and has certain reference significance for the selection of control methods and control algorithms.

2. Research Significance of the Hydraulic Synchronous Control System and Development History of Control Method

2.1. Research Significance of the Hydraulic Synchronous Control System

Hydraulic synchronous control systems are a branch of hydraulic systems, and their research direction mainly includes hydraulic synchronous control methods and control algorithms. The hydraulic synchronous system has the advantages of high control accuracy, fast response speed, and easy application in high-power equipment, so it has a pivotal position in synchronous control systems [26], and its research significance has the following aspects.

(1) It can improve the synchronization control accuracy and maintain the good performance of mechanical equipment.
(2) It can reduce the torsional force and friction between the actuators due to the synchronization error, reduce the wear and torsional deformation of the mechanism, and extend the service life of the hydraulic equipment.
(3) It can increase the efficiency of the hydraulic system, thus saving more energy.

2.2. Development History of Hydraulic Synchronous Control Method

With the development of modern control technology, all kinds of hydraulic equipment require a higher and higher accuracy of the hydraulic synchronous system. According to the development process of the synchronization control method, it can be divided into the first, second, and third generations of the synchronization control method [27].

The first generation of the hydraulic synchronization control method mainly adopts open-loop control to regulate the output of the actuator, using hydraulic components to change the pressure change in the hydraulic system to control the output of the hydraulic source and change the flow and pressure of the fluid in the hydraulic line, so as to control the synchronization movement of the actuator. The first-generation control method is low cost, simple, and practical, but the synchronization accuracy of the control system is not high and is generally used for industrial equipment with low control accuracy requirements.

With the social demand for high-precision machining and the improvement of sensor and control technology, the requirements for hydraulic synchronous equipment have gradually increased. The second-generation hydraulic synchronization control method widely uses the electro-hydraulic control method, introducing a signal (speed, load, displacement, etc.) feedback link, detecting feedback on the output quantity of the controlled object, comparing the feedback signal value with the ideal target value, and outputting the regulation electric signal to the electro-hydraulic valve by the controller, thus regulating the actuating element to reduce the synchronization error. The second generation of hydraulic synchronization control method adopts closed-loop control, mostly used for hydraulic system control using an electronic component system-hydraulic pilot control-hydraulic actuator, which regulates the synchronization error and increases the synchronization accuracy of hydraulic actuator.

With the further improvement of automation technology and control technology, higher requirements for hydraulic synchronization accuracy have been put forward. The third-generation hydraulic synchronization control method mainly uses a microprocessor combined with different control algorithms, introduces sensors (force sensors, displacement sensors, angle sensors, speed sensors, etc.) to compare the actual control accuracy and ideal control accuracy of the system, uses a microprocessor as the control unit, all kinds of sensors to detect and feedback the hydraulic synchronization control system, and combines different pairs of control algorithms to reduce synchronization interference and error.

The third generation hydraulic synchronization control method has higher automatic intelligence, but its regulating actuators have a certain lag. In the future, the hydraulic synchronization control system can be digitized and intelligently controlled through the construction of a hydraulic characteristic information network, the collection of flow and pressure at the important nodes of the hydraulic circuit, and the active real-time regulation of the hydraulic synchronization control system by making full use of intelligent algorithms and information-variable technology.

3. Analysis of Synchronization Error of Hydraulic Synchronous Control System

To achieve synchronous control of the hydraulic system, ideally it is only necessary to allow equal pressure and equal amount of hydraulic oil to flow through the actuator with identical structural parameters. Generally, the hydraulic synchronization system has synchronization errors due to oil pollution and leakage in the hydraulic synchronization system, uneven friction and load of the actuators, asymmetrical arrangement, back pressure of the actuators, oil pressure fluctuation, manufacturing and installation errors of components, and other factors. Even if closed-loop control is adopted, the hydraulic synchronization system under actual working conditions is complex and nonlinear due to its control hysteresis. It is difficult to establish its accurate mathematical model to achieve high-precision control, so the generation of synchronization error is inevitable [28–33].

At present, the hydraulic synchronous control system mainly uses the error feedback correction method to reduce the error accumulation of the hydraulic actuator, so as to improve its synchronization accuracy, but the method has a certain lag. In the future, with the continuous development of artificial intelligence and big data, active feedback adjustment is expected to solve this problem. There are many reasons for synchronization error of the hydraulic synchronization control system, which are mainly summarized in the following 10 aspects.

(1) There is a fluid leak in the hydraulic synchronous control system. Due to the different manufacturing accuracy of hydraulic components and the clearance caused by long-time movement friction, the connection of hydraulic pipelines becomes loose, resulting in the leakage of hydraulic oil, thus affecting the synchronization accuracy of hydraulic systems.

(2) The friction of hydraulic actuators is uneven. The uneven friction of the hydraulic actuator will lead to the uneven force in the movement process, which will affect the synchronization accuracy of the hydraulic synchronization control system.

(3) Uneven load of the hydraulic synchronous system. When the load on the same hydraulic actuator end is different, synchronization error will occur, and the hydraulic cylinder or hydraulic motor with a large load has a small oil intake and a slow movement speed.

(4) Asymmetrical arrangement of the hydraulic synchronization control system. The asymmetric arrangement of hydraulic components and pipelines will make the hydraulic power and hydraulic impact of each branch in the hydraulic synchronization control system different, so that the force is different in the start stop phase, which will cause certain errors to the synchronization accuracy. Symmetrical arrangement can be adopted to make the hydraulic resistance of each hydraulic branch equal, thus improving the synchronization accuracy of the hydraulic system.

(5) Back pressure of actuators. When the hydraulic oil flows along the pipeline in a closed container, due to the obstruction of the actuating element, the flow direction of the oil will be rapidly changed, resulting in a pressure opposite to the movement direction. If the back pressure valve is installed on the actuators, due to the influence of various factors, the back pressure value on each branch is often different, which affects the accuracy of the hydraulic synchronous control system. The oil pipes at the oil return port of each actuator can be collected first, and then flow through the back pressure valve, thereby reducing the influence of back pressure on hydraulic synchronization accuracy.

(6) There are manufacturing and installation errors in hydraulic components. Manufacturing and installation errors can cause initial unsynchronized errors in the hydraulic system, resulting in different friction resistance and oil resistance of hydraulic components. To reduce the initial asynchronous error, the following measures can be taken to reduce the manufacturing and installation errors of hydraulic components, and compensate the synchronization error of the hydraulic synchronization control system.

(7) Pressure fluctuation of hydraulic oil. The source of pressure fluctuation is mainly the pressure fluctuation generated by the hydraulic source and the pressure fluctuation generated by the throttle valve (hydraulic resistance) due to the load change, which can affect the dynamic characteristics of the hydraulic branch and the synchronization accuracy of the hydraulic system. The following measures can be taken to reduce the pressure fluctuation of hydraulic oil: (1) choose a hydraulic source with a small pressure fluctuation or add an accumulator at the outlet of the hydraulic source; (2) add a pressure compensation (load sensitive) device at the proper position in the hydraulic system to effectively control the pressure fluctuation in the hydraulic synchronous control system.

(8) Insufficient rigidity. Mechanical equipment with insufficient rigidity can produce obvious stress and deformation after being stressed; insufficient rigidity of the hydraulic medium can cause the fluctuation of the oil in the hydraulic pipeline, and the ambient temperature will affect the viscosity and compressibility of the fluid, which can result in insufficient rigidity of the hydraulic system and hydraulic synchronization error, even out of tolerance. The following measures can be taken to reduce the insufficient rigidity: (1) use mechanical equipment with better rigidity or optimize the structure of mechanical equipment to increase its resistance to stress and deformation; (2) optimize the connection form of the components and reasonably simplify the structure to increase its rigidity; (3) select a hydraulic medium with strong rigidity to reduce the influence of fluid viscosity and compressibility on hydraulic synchronization accuracy; (4) choose a working environment with relatively stable ambient temperature, or add equipment to keep the hydraulic oil temperature constant, so as to stabilize the viscosity and compressibility of the oil.

(9) The oil is mixed with gas. Gas in the hydraulic oil can affect the compression ratio of the oil and the dynamic performance of the hydraulic system, thus affecting the normal oil supply required by the hydraulic system, resulting in synchronous accuracy errors of the actuating elements. The following measures can be taken to reduce the gas in the oil: (1) use reliable seals to ensure good sealing at the oil suction; (2) add an inclined metal mesh to the tank to float up and release the air in the oil; (3) add an automatic air release device to the hydraulic synchronous system.

(10) The oil is mixed with impurities. Impurities in the oil cause a flow error at the flow regulating valve port, which affects the synchronization accuracy. The following measures can be taken to reduce the impurities in the oil: (1) sealing the oil tank with a more reliable device to prevent small impurities from entering the hydraulic system; (2) cleaning the filter regularly to reduce impurities in the oil.

4. Research on Hydraulic Synchronous Control System

The hydraulic synchronization control system is widely used because of its advantages such as easy control, simple structure, and being able to adapt to high power and complex environments. At the same time, the continuous improvement and optimization of the hydraulic synchronization system has always been a research hotspot in the hydraulic field [34]. According to the different application fields, control modes and tasks, the hydraulic synchronization system can be classified into several categories [35–37].

According to whether there is feedback in the hydraulic synchronization control system, it can be divided into "open-loop synchronization" or "closed-loop synchronization". Open-loop synchronization is on a simple scale, has low control accuracy, and poor robustness. Closed-loop synchronization can be widely used in various hydraulic equipment; because of the feedback regulation of its intelligent controller, its synchronization accuracy is significantly improved, its complexity and processing scale become larger, and the robustness of the system is better. In addition, different intelligent control algorithms can be combined in closed-loop control to select the best control scheme, but the closed-loop control system under complex machine learning and a neural network often has the phenomenon of over-learning, which increases the control cost of the system. In addition, the closed-loop hydraulic synchronization control system can be subdivided into "equivalent synchronization", "master–slave synchronization" and "cross-coupling synchronization", according to the different control modes.

According to whether the hydraulic synchronous control system has compensation, it can be divided into "uncompensated synchronization" and "compensated synchronization". The uncompensated hydraulic synchronous system is simple, has low control accuracy and poor robustness, while the compensated hydraulic synchronous control system timely compensates the synchronization error, so its control accuracy is high, and its robustness is strong. In addition, the compensated hydraulic synchronization system can be divided into "pre-valve compensation hydraulic synchronization" and "post-valve compensation hydraulic synchronization" according to the different compensation positions.

According to the different control elements, the hydraulic synchronization control system can be divided into "pump-controlled synchronization" and "valve-controlled synchronization". The pump-controlled synchronization efficiency is high, the response speed is slow, the control accuracy under constant load condition is high, and the valve-controlled synchronization efficiency is low, but the robustness is good, the response speed is fast, and the synchronization accuracy under dynamic load condition is high. In addition, according to the different types of control valves, the valve-controlled hydraulic synchronization control system is divided into "flow synchronization", "electro-hydraulic proportional synchronization", and "electro-hydraulic servo synchronization".

In addition, other hydraulic synchronization systems are divided into "hydraulic cylinder synchronization" and "hydraulic motor synchronization" according to the different actuating elements. According to different control tasks, it can be divided into "position synchronization" and "speed synchronization". According to the number of actuators, it can be divided into "double actuator synchronization" and "multiple actuator synchronization". According to different installation methods, it can be divided into "horizontal synchronization" and "vertical synchronization". The classification of hydraulic synchronization control systems is shown in the following Figure 1.

This paper will carry out a detailed study on the hydraulic synchronization system according to the relevant classification in Figure 1 above.

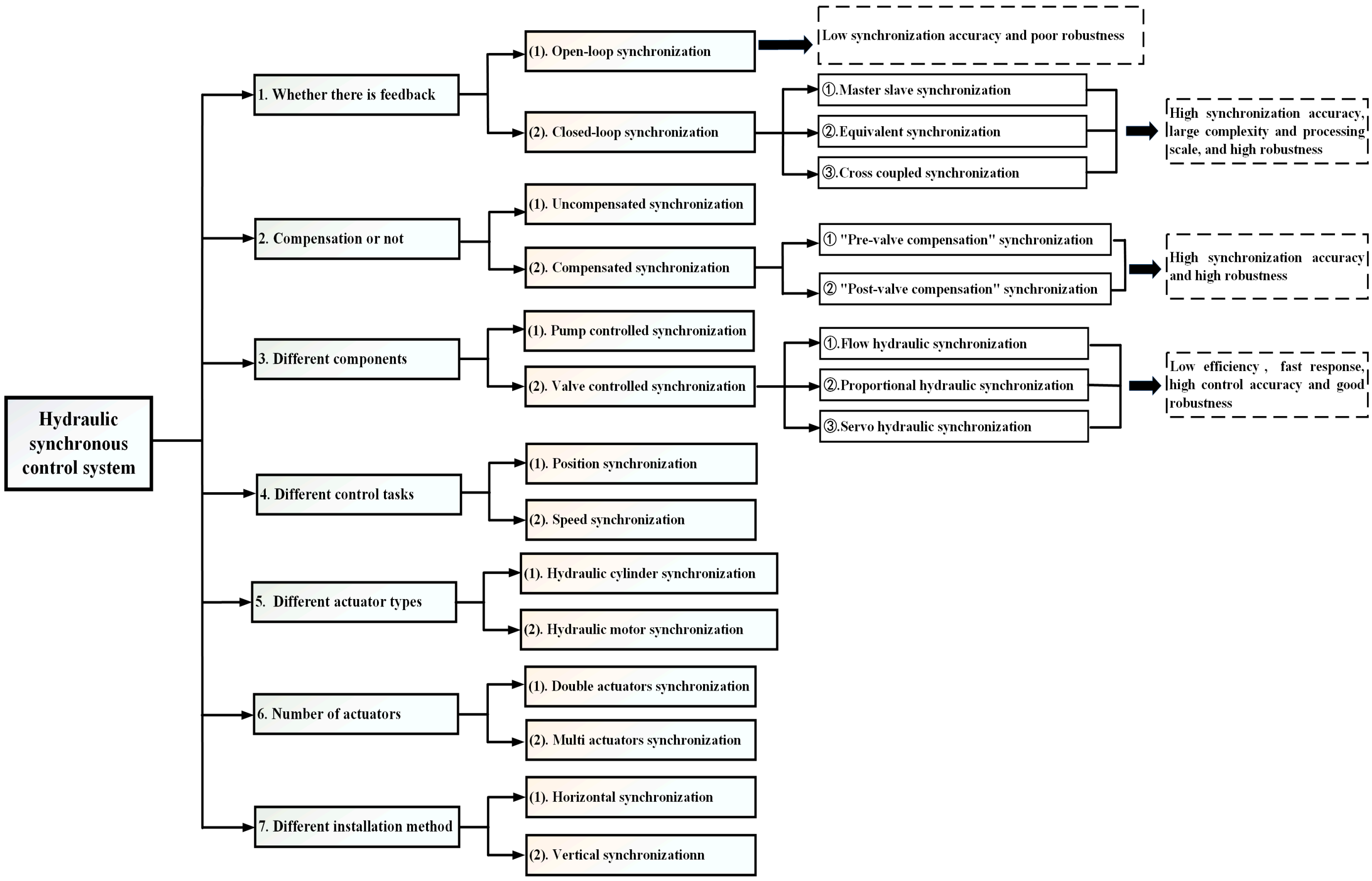

Figure 1. Classification diagram of hydraulic synchronous control system.

4.1. Open-Loop and Closed-Loop Hydraulic Synchronization Control System

The hydraulic synchronous control system can be divided into open-loop hydraulic synchronous control systems and closed-loop hydraulic synchronous control systems according to whether there is feedback signal adjustment [38].

4.1.1. Open-Loop Hydraulic Synchronous Control System

There is no feedback signal regulation in the hydraulic synchronization system of open-loop control, and its synchronization control accuracy depends entirely on the accuracy of the hydraulic components (such as step valve, throttle valve, and speed regulating valve) to control the actuator. The output signal of the actuator is not detected and fed back in the open-loop control hydraulic synchronization system, so the accuracy and anti-interference of the open-loop control are poor. Common open-loop synchronous control circuits include a mechanical rigid synchronous circuit, flow control valve synchronous circuit, series cylinder synchronous circuit, synchronous cylinder synchronous circuit, parallel motor, or parallel pump synchronous circuit. Generally speaking, because of its low cost and simple structure, the open-loop control hydraulic synchronization control system is widely used in situations with small load, low synchronization accuracy requirements, simple control loop, and close synchronization distance. The open-loop control of the hydraulic synchronization system, due to the absence of feedback compensation, will make the synchronization error gradually accumulate and increase, and cannot eliminate the errors caused by hydraulic oil leakage, load angle bias, and the manufacture and installation of hydraulic components.

To make the hydraulic synchronization control system under open-loop control realize accurate synchronization, Ding et al. [39] proposed a load sensing synchronization control method consisting of a load sensing unit and a synchronization valve. The load sensing unit consists of a load sensing pump and a load sensing valve. The load sensing pump provides the pressure and flow required by the system through the pressure-closed-loop control. The load sensing valve can improve the ability to resist offset load through pressure compensation. The synchronizing valve is located between the load sensing pump and the load sensing valve to achieve an even distribution of the flow supplied by the pump. The experimental results show that compared with the traditional synchronous valve control, this control mode has stronger control accuracy, efficiency, and synchronous speed regulation capability.

4.1.2. Closed-Loop Hydraulic Synchronous Control System

With the development of modern control theory and control technology, various closed-loop hydraulic synchronous control systems are widely used in high-precision hydraulic synchronous drive equipment [22,40,41].

The hydraulic synchronous control system under closed-loop control has a high synchronization accuracy because of the feedback regulation. The controller can conduct online feedback comparison between the output value and the ideal setting value and reduce the control deviation after regulation. The control modes of the hydraulic synchronous control system can be divided into master–slave control, equivalent control, and cross-coupling control according to the different feedback control modes of output values [42,43].

Lorenz et al. [44] proposed two synchronous control modes: equivalent control and master–slave control. Equivalent control [45–47] is a parallel structure, in which multiple hydraulic actuators form a closed loop independently, tracking the target output value signal set by the control system, so that each actuator can achieve synchronous control. Since each actuator in the equivalent control synchronizes the feedback signal independently and tracks the motion error, the synchronous tracking error of each actuator determines the error of the equivalent control. The equivalent control block diagram of the hydraulic synchronization control system is shown in Figure 2.

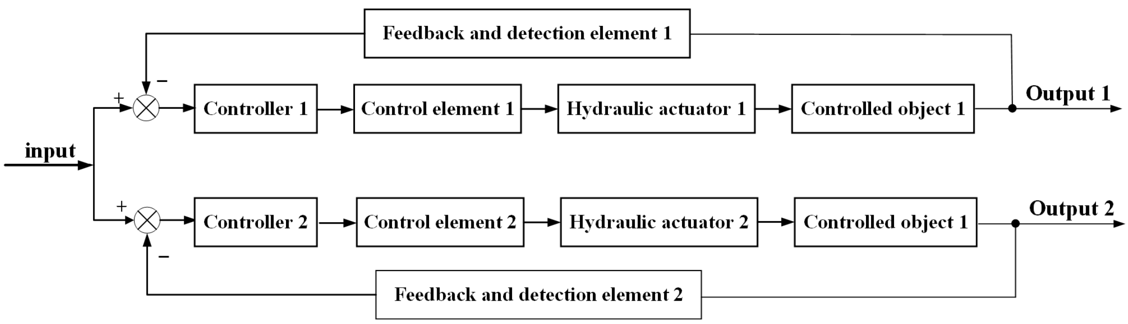

Figure 2. Equivalent control block diagram of hydraulic synchronous control system.

Equivalent control requires that each hydraulic component and electrical component of the hydraulic synchronization system must have a high matching consistency, and if the consistency of each component is good, the hydraulic system with equivalent control has a high synchronization accuracy.

The master–slave control [48–50] is a series structure. First, the output of an actuator is selected as the ideal output signal in the master–slave controlled hydraulic synchronization system; that is, one actuator is the main hydraulic oil circuit, and the other actuator is the slave hydraulic circuit. Then, the error feedback signal in the main circuit is input to the other slave hydraulic circuits through the feedback detection elements in the main hydraulic circuit. The master–slave control has a delay feedback that means the slave hydraulic circuit follows the signal of the main hydraulic circuit; especially in the start stop phase of the hydraulic synchronous control system, this delay is more significant. The slave actuating element has a large tracking lag to the master actuating element, which will cause the master–slave control error. The master–slave control block diagram of the hydraulic synchronization control system is shown in Figure 3.

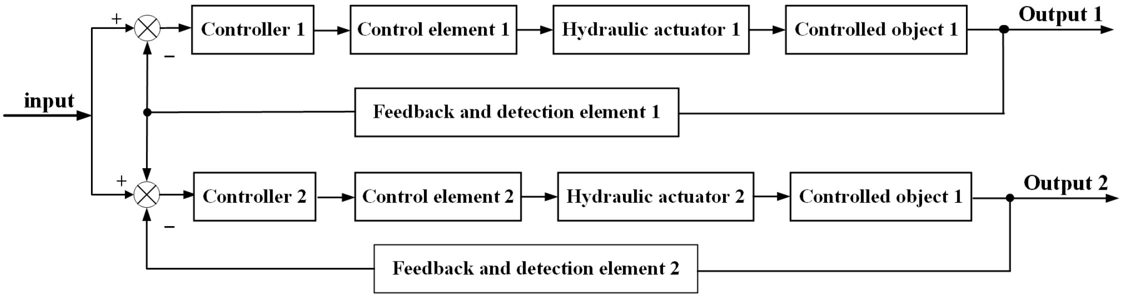

Figure 3. Master–slave control block diagram of hydraulic synchronous control system.

There is a certain delay error in the master–slave-controlled hydraulic synchronization system, and to reduce the tracking delay error of the master–slave-controlled hydraulic circuit, a front feedback device needs to be added to feed back the synchronization error signal of the system to the control link [51].

There is no coupling relationship between the master–slave control and the hydraulic branches of the same control, so the controller is relatively simple, and the synchronization accuracy is relatively general. Therefore, the cross-coupling control is gradually studied and applied in the hydraulic synchronization control system by scholars. Cross-coupling control [52,53] establishes a coupling relationship between hydraulic branches, detects the output deviation values of multiple hydraulic branches, and feeds them back to the controller. When the synchronous deviation exceeds a certain range, the synchronous controller immediately compensates for the coupling of two hydraulic actuators, thereby effectively reducing the synchronous error. The cross-coupling control combines the advantages of master–slave control and equivalent control, and the synchronization accuracy is further improved. The cross-coupling control block diagram of hydraulic synchronization control system is shown in Figure 4.

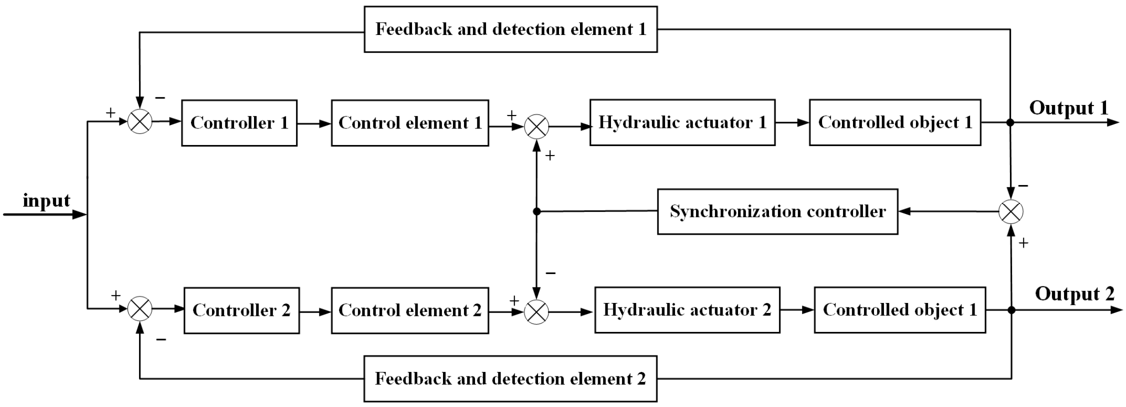

Figure 4. Cross-coupling control block diagram of hydraulic synchronous control system.

However, the cross-coupling control has certain limitations for any hydraulic system with more than two hydraulic branches. When there are many controlled hydraulic actuators, the control mode will become too complex, and the robustness, stability, and synchronization of the hydraulic synchronization control system will become worse. To solve the synchronization accuracy of multiple actuators, adjacent cross-coupling is gradually being studied by more and more scholars. Adjacent cross-coupling hydraulic synchronization control [54,55] is to locally synchronize the actuating elements. When the controller synchronizes each hydraulic branch, it outputs synchronization error feedback for its own hydraulic branch and outputs synchronization error feedback to its adjacent hydraulic branch, to control the output error compensation of adjacent hydraulic branches and achieve synchronization control of each hydraulic branch. The adjacent cross-coupling control block diagram of the hydraulic synchronization control system is shown in Figure 5.

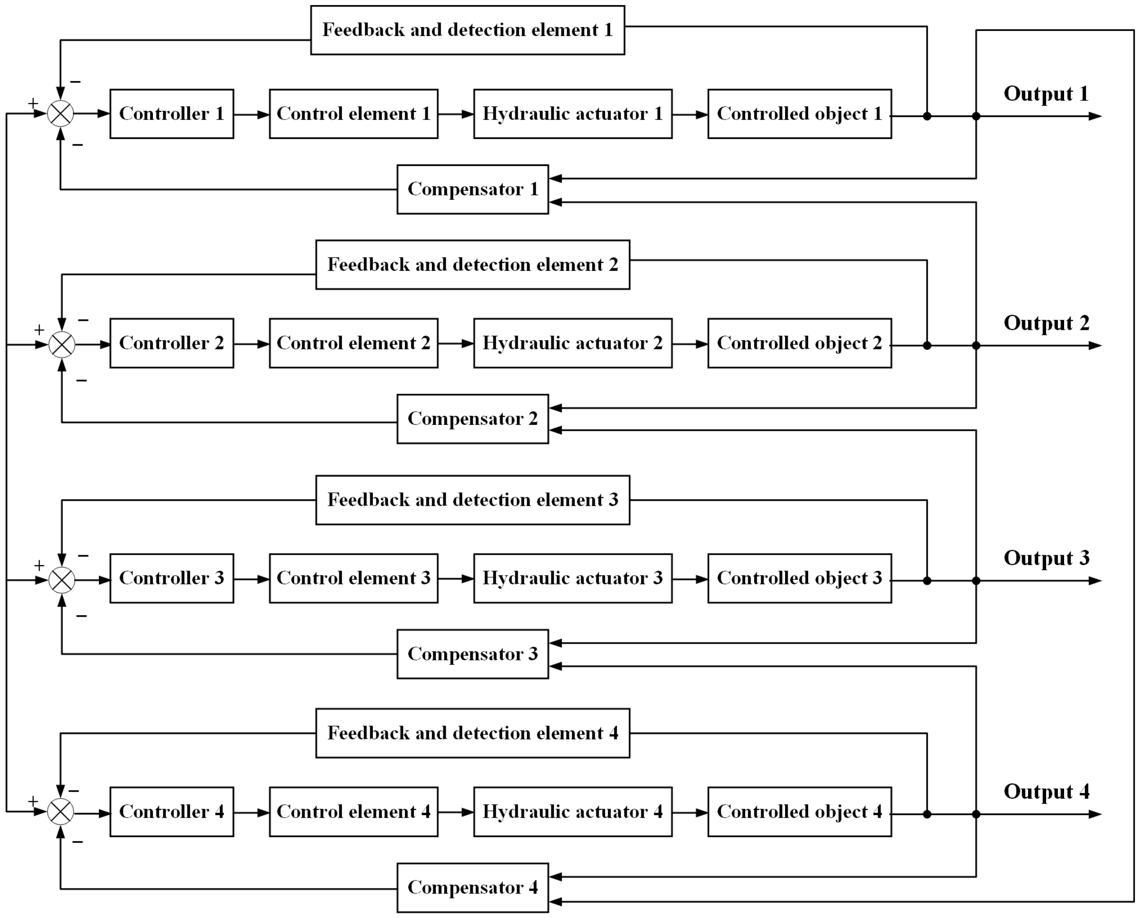

Figure 5. Adjacent cross-coupling control block diagram of the hydraulic synchronization control system.

Wu et al. [56], based on the adjacent cross-coupling synchronization control, designed the adjacent cross-coupling fuzzy self-tuning integral separation PID synchronization controller by combining fuzzy control with integral separation PID control, combined with three hydraulic synchronous closed-loop control modes (master–slave, equivalent, and adjacent cross-coupling). Through the joint simulation with AMESim and Simulink software, the three closed-loop synchronous control methods were compared and analyzed. The results show that in the four cylinders synchronous control system, the overshoot under the master–slave synchronous control mode is 6%, and the maximum synchronous error is 0.26 mm; the overshoot under the same synchronous control mode is 4.2%, and the maximum synchronous error is 0.15 mm; the overshoot of adjacent cross-coupling synchronization control mode is 2.8%, and the maximum synchronization error is 0.12 mm. The reason for the above phenomenon is that the master–slave synchronous control first sets a main hydraulic branch, and the output of the other slave hydraulic branches should follow the set main hydraulic branch, so there will be some hysteresis in the control process. All controllers of equivalent synchronous control follow the same set ideal output value, and the actuating elements of each hydraulic branch are not regulated by synchronous controller. The adjacent cross-coupling synchronous control can not only track and control the given ideal output value, but also compensate the synchronous error of the actuating elements of different adjacent hydraulic branches. Therefore, the control accuracy of adjacent cross-coupling synchronous control under closed-loop control is higher than that of master–slave control and equivalent control.

Compared with master–slave control and equivalent control, cross-coupling control can obtain a higher accuracy in the hydraulic synchronous system. Therefore, more and more scholars are combining cross-coupling control with other control methods to further develop the field of cross-coupling control. Sun et al. [57] proposed an adaptive robust cross-coupling control strategy by combining the cross-coupling control mode with the adaptive robust control, and its maximum synchronization error is not more than ±0.1 mm, which further improves the synchronization accuracy of the hydraulic press slide leveling electro-hydraulic control system. Liu et al. [58] proposed a control method based on fuzzy adjacent coupling for synchronous control of multiple hydraulic cylinders to be leveled, designed an adjacent coupling controller, fed back the position synchronization error of two adjacent hydraulic cylinders to the synchronous controller, and used the fuzzy controller to obtain the parameters that are difficult to obtain. The simulation and experimental results show that the fuzzy adjacent coupling control can quickly reduce the synchronization error of the hydraulic cylinder in the acceleration and deceleration phase.

Through the above research on the equivalent, master–slave, cross-coupling, and adjacent cross-coupling control of closed-loop hydraulic synchronous control systems, it can be concluded that their control effects and characteristics are shown in Table 1 below:

Table 1. Comparison of the effects of four control methods for closed-loop hydraulic synchronization systems.

Control Mode	Control and Control Effect	Characteristic
equivalent	Zhang [45] adopted PID equivalent control, with good synchronization control effect; Tian [46] adopted PID equivalence and master–slave control, which reduces the maximum synchronization error by 80.649% and steady-state error by 30.306% compared to master–slave control.	Each actuator independently synchronizes the feedback signal without coupling, and the synchronization accuracy is relatively high. However, it requires that each element have a high matching ability.
master–slave	Li [49] adopted a master–slave synchronous control scheme of one master and three slaves to synchronously control four hydraulic cylinders. The average displacement fluctuation of the hydraulic cylinder is 0.189 mm, and the maximum fluctuation is 0.273 mm	There is a tracking lag error between the main hydraulic circuit and the slave hydraulic circuit, especially during the startup and shutdown stages; there is no coupling and the synchronization accuracy is average.
cross-coupling	Koren [52] used cross-coupling to synchronize the dual axis hydraulic system. The results show that cross-coupling improves synchronization accuracy, but the response speed of each axis will be slightly lower.	The compensation hydraulic circuit can be coupled, combining the advantages and disadvantages of master–slave and equivalent control, with high synchronization accuracy, robustness, and stability. However, for complex multi-hydraulic circuit-synchronous systems, there are limitations, and the control accuracy is general.
adjacent cross-coupling control	Wu [56] adopted a PID controller with fuzzy self-tuning integral separation under adjacent cross-coupling for the synchronous control of four hydraulic cylinders. The results show that the overshoot of adjacent cross-coupling synchronization control is 2.8%, and the maximum synchronization error is 0.12 mm. Sun [57] adopted a robust adaptive cross-coupling strategy, with the maximum synchronization error not exceeding ±0.1 mm.	It can solve the high-precision control problem of complex multiple hydraulic circuits, with high robustness and reliability.

4.2. Hydraulic Synchronous Control System without Compensation and with Compensation

The hydraulic synchronization control system can be divided into the "compensated hydraulic synchronization control system" and "non-compensated hydraulic synchronization control system", according to whether there is compensation in the hydraulic circuit.

4.2.1. Hydraulic Synchronous Control System without Compensation

In the hydraulic synchronous control system without compensation, the actuator is not compensated, and the accuracy of the hydraulic synchronous control system is determined by the manufacturing and installation errors of the hydraulic components. Generally speaking, the control accuracy of the hydraulic synchronous control system without compensation is relatively low, and it is mostly used in situations where the load is not large, and the synchronous accuracy is not required to be too high.

4.2.2. Compensated Hydraulic Synchronous Control System

In the hydraulic synchronous control system with compensation, when the load changes, the hydraulic oil flow from the hydraulic pump to the actuator via the hydraulic valve will change, affecting the control accuracy of the hydraulic synchronous system. The compensated hydraulic synchronous system introduces the compensation valve to regulate the flow, or through the sensor to feedback the error value to the control signal. Through the corresponding control algorithm, the signal to be compensated and adjusted is input to the hydraulic pump/hydraulic motor and control valve to compensate and regulate the flow and pressure in the hydraulic circuit. The control system belongs to closed-loop control. Because it can adjust the flow and pressure of the synchronous control system, the control accuracy of the hydraulic synchronous control system is significantly improved. According to different positions of the compensation valve and control valve, it can be divided into either a “pre-valve” compensation or “post-valve” compensation hydraulic synchronous control system [59,60].

The pre-valve compensation hydraulic synchronization control system is to set the pressure compensation valve at the front of the control valve port. The spring chamber of the pressure compensation valve receives the outlet pressure of the control valve port, and the non-spring chamber is connected to the inlet pressure of the control valve port. The differential pressure before and after the two control valves for valve front compensation is equal and both are constant. The flow that can be achieved is only related to the opening of the control valve and is not affected by the load change.

The post-valve compensation hydraulic synchronization control system is to arrange the pressure compensation valve behind the throttle valve. The spring chamber of the pressure compensation valve receives the maximum load pressure selected by the shuttle valve, and the non-spring chamber is connected to control the pressure behind the controllable throttle valve. The differential pressure before and after the two control valves in the post-valve compensation is equal but not constant; when the flow provided by the pump cannot meet the requirements, the flow of the two branches will be reduced in equal proportion. The actuator with the large load will not stop working, and the function of anti-flow saturation can be realized. The schematic diagram of the hydraulic synchronous control system for “pre-valve” compensation and “post-valve” compensation is shown in Figure 6 [59].

With the development of electro-hydraulic control and hydraulic energy-saving technology, more and more scholars have studied the compensated hydraulic synchronous control system and made a series of achievements. Li [61] established an integrated platform for the synchronous test of sunken ships, analyzed the synchronous hydraulic system of active compensation and passive compensation of sunken ships, further designed the overall hydraulic system of the hydraulic heave compensation test platform, and verified the accuracy of platform synchronous motion and the effectiveness of active compensation through tests. Zheng [62] studied the hydraulic synchronization system for lifting and fishing operations, designed a semi-active wave hydraulic cylinder synchronization compensation system with hydraulic cylinders in series–controlled by using double closed-loop PID and compared and analyzed through Matlab software simulation: master–slave PID synchronization control, parallel PID control and cross-coupling PID synchronization control. The results show that the error decay rate of master–slave PID synchronization control is 47.26%, the error decay rate of parallel PID synchronization control is 16.81%, and the error decay rate of cross-coupling PID control is 69.56%. It further proves that the cross-coupling PID synchronization control can quickly reduce the synchronization error and achieve stable conditions, and its control effect is the best.

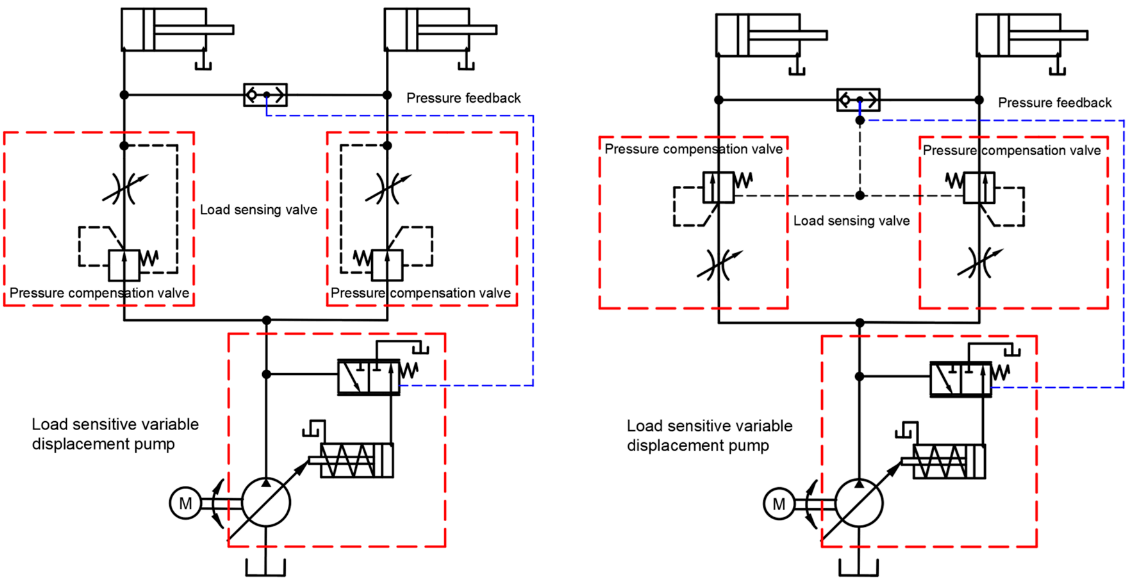

Figure 6. Schematic diagram of compensated hydraulic synchronous control system. (**a**) Schematic diagram of pre-valve compensation hydraulic synchronization control system; (**b**) Schematic diagram of post-valve compensation hydraulic synchronization control system.

Zhou et al. [63] studied the valve-controlled asymmetric hydraulic cylinder synchronization system, proposed a two-layer fuzzy controller to improve the response speed of the hydraulic cylinder, and designed a feedforward compensation control mode under cross-coupling to reduce the synchronization error. The simulation results show that the tracking accuracy and synchronization accuracy of the hydraulic cylinder with dual compensation under uneven load have been greatly improved.

4.3. Pump-Controlled and Valve-Controlled Hydraulic Synchronous Control System

Hydraulic synchronization control systems can be divided into "pump-controlled hydraulic synchronization control systems" and "valve-controlled hydraulic synchronization control systems", according to different control modes and control valve components [64].

4.3.1. Pump-Controlled Hydraulic Synchronous Control System

Pump controlled is also called volume controlled [65]. The pump-controlled hydraulic synchronous control system controls the synchronous movement of the actuating elements by changing the displacement of the hydraulic pump to make each actuator input the same amount of oil. Compared with the valve-controlled hydraulic synchronization system, the pump-controlled hydraulic synchronization system adopts the way of pump controlling the actuating elements, which reduces the number of hydraulic valves and the layout of hydraulic pipelines, significantly reduces the overflow throttling loss of the hydraulic system, the leakage of hydraulic oil, the friction heat of the system and other energy loss, and improves the efficiency of the system. However, under the same conditions, the natural frequency of the pump control system is much lower than that of the valve control system, which makes the response speed of the pump control system not high. The volumetric efficiency of the pump-controlled hydraulic synchronization system is high, and a low synchronization error can be obtained under the condition of constant load or small load change.

Peng et al. [66] designed a closed-loop digital PID control algorithm to control the speed of the hydraulic pump-controlled motor due to the synchronization error problem during its operation, and verified the good stability and rapidity of the system by optimizing the PID control parameters through simulation. Zhang et al. [67] put forward a loader lifting device with closed pump-controlled three chamber hydraulic cylinder, which adds a potential energy recovery chamber connected with the accumulator, and changed the original asymmetric two chamber hydraulic cylinder of the boom into a symmetric hydraulic cylinder. The simulation proved that the valve control system can not only significantly reduce energy consumption, but also significantly improve the response speed and control accuracy of the boom.

4.3.2. Valve-Controlled Hydraulic Synchronous Control System

The valve-controlled hydraulic synchronization control system realizes synchronization by controlling hydraulic valves (proportional valves, servo valves, pressure compensation valves, synchronization valves, diverter valves, etc.) and specially designed valve blocks. The valve control system usually selects proportional and servo valves as its control components, which can be known from the basic formulas of pump control system and valve control system [68]: in the case of the same controlled object, the natural frequency of the valve control system is greater than that of the pump control system. The valve control system has faster response and better dynamic characteristics. Therefore, the valve control system is mostly used under the working condition of dynamic load. The components of the valve-controlled hydraulic synchronous control system are arranged separately, which does not affect the performance of the system and is more convenient for maintenance. Due to the throttling speed regulation of the throttle port and overflow valve and the centralized oil supply of the system, the valve-controlled hydraulic synchronous system has the disadvantages of large throttling loss, large pressure loss, large hydraulic oil leakage, and low system efficiency, resulting in large system power loss.

The valve-controlled hydraulic synchronization control system can be divided into "flow hydraulic synchronization control systems", "electro-hydraulic proportional hydraulic synchronization control systems" and "electro-hydraulic servo hydraulic synchronization control systems" according to different types of control valves.

The flow hydraulic synchronization control system [69,70] regulates the flow in the hydraulic circuit through the flow control valve to make the flow into and out of the hydraulic cylinder/hydraulic motor equal, thus realizing the synchronization of the hydraulic system. The flow hydraulic synchronous system often uses a speed-regulating valve, diversion and collection valve, and throttle valve to control the hydraulic circuit. The synchronization accuracy of the hydraulic synchronization system of the speed-regulating valve is generally less than 4–5%, which is often used in situations where the flow is not very large, the speed change is small, and the synchronization accuracy is required to be high. The synchronization accuracy of the hydraulic synchronization system of the diverter and collector valve is generally 1–3%, its deviation correction capability is large, its use is simple, and its cost is low. It is often used in situations where the hydraulic circuit is simple and the flow and load change range are not large. The hydraulic synchronizing system of the throttle valve has low synchronization accuracy, but its cost is low, adjustment is simple, and multi cylinder synchronization can be achieved. It is often used in situations where the synchronization accuracy is not high, the flow is small, the load is not large, and the load is stable.

The electro-hydraulic proportional hydraulic synchronization control system [71,72] is controlled by the electro-hydraulic proportional valve. The electro-hydraulic proportional valve is a new type of electro-hydraulic control element, which is mainly composed of a proportional electromagnet and a working valve core, which can change the displacement of the working valve core according to the size of the electrical signal of the system, to adjust the flow and pressure at both ends of the electro-hydraulic proportional valve. Compared with the traditional hydraulic synchronization control system, the electro-hydraulic proportional hydraulic synchronization system has greatly improved the response speed, low cost, strong anti pollution ability, and high control accuracy. The electro-hydraulic proportional hydraulic synchronous control system is generally composed of a controller, electro-hydraulic proportional unit, actuator, controlled object, etc. Its control block diagram is shown in the following Figure 7.

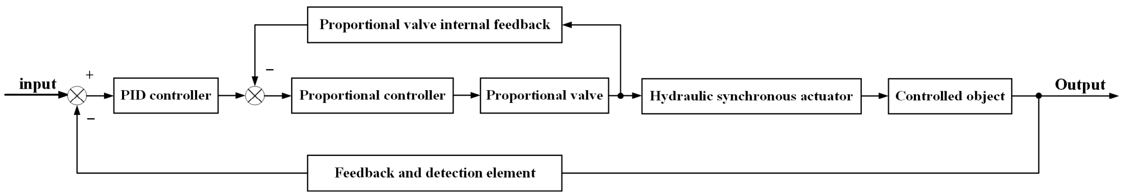

Figure 7. Block diagram of electro-hydraulic proportional hydraulic synchronization control system.

The electro-hydraulic servo hydraulic synchronization control system [73,74] is controlled by the electro-hydraulic servo valve. The electro-hydraulic servo valve has the advantages of small dead zone, zero covering, fast dynamic response, and high oil cleanliness. The electro-hydraulic servo hydraulic synchronous control system can adjust the flow into the hydraulic actuator at any time, with good dynamic characteristics and high control accuracy [75]. The electro-hydraulic servo hydraulic system has the characteristics of intrinsic nonlinearity and parameter nonlinearity. Intrinsic nonlinearity mainly refers to the dead zone characteristics of control elements and the coupling characteristics of flow in the system, while parameter nonlinearity mainly refers to the uncertainty of temperature change, load change, and oil leakage. The synchronization error caused by the above nonlinear factors can be reduced by selecting an effective control algorithm. The electro-hydraulic servo hydraulic synchronization control system is generally composed of a servo amplifier, controller, electro-hydraulic servo valve, and actuating element. Its control block diagram is shown in Figure 8.

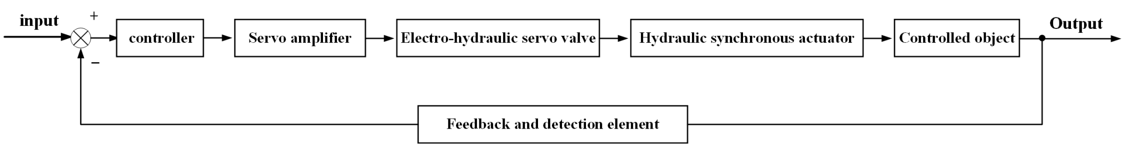

Figure 8. Block diagram of electro-hydraulic servo hydraulic synchronization control system.

With the development of modern control, more and more scholars have carried out research related to hydraulic synchronous control systems under valve control and pump control. Prabhakar et al. [76] compared the dynamic performance of pump control and valve control for a hydraulic motor, and the results show that the valve-controlled hydraulic motor system is more sensitive. Zhao et al. [77] established the control model for the four-motor hydraulic synchronous control system controlled by an electro-hydraulic proportional valve based on a fuzzy self-tuning PID control strategy. AMESim/Simulink software simulation analysis showed that the electro-hydraulic proportional valve-controlled four-motor hydraulic synchronous control system has a fast response and high synchronization accuracy.

In addition, some scholars combine valve control with pump control. The new synchronous control system with pump control as the main and valve control as the auxiliary can integrate the respective advantages of valve control and pump control, making the system have the characteristics of both control accuracy and response speed. Dong et al. [78] applied valve control and pump control to the synchronous system of a hydraulic excavator to improve the response speed and control accuracy of the system, designed the flow pressure to match the independent control of the inlet and outlet, applied it to the hydraulic excavator system to reduce the pressure fluctuation of the hydraulic excavator boom during operation from 6.9 Mpa to 1.7 Mpa, and at the same time, the energy consumption of one working cycle of the boom was reduced by 15%. The control strategy significantly reduces the working pressure difference at the valve port and improves the system stability and energy utilization.

4.4. Other Hydraulic Synchronization Control Systems

According to the different actuators [79], the hydraulic synchronization control system can be divided into the "hydraulic cylinder synchronization" and "hydraulic motor synchronization" systems. The hydraulic motor synchronization control system can be divided into "gear motor synchronization system" and "plunger motor hydraulic synchronization system" according to the type of hydraulic motor. Ideally, by comparison, the synchronization accuracy of the plunger hydraulic synchronous motor can reach more than 99%, and the synchronization accuracy of the gear hydraulic synchronous motor is about 95%, and the external load has a great impact on it.

According to different motion states [80], the hydraulic synchronization control system can be divided into "position hydraulic synchronization control system" and "speed hydraulic synchronization control system". Position synchronization requires that different hydraulic actuators have the same position at the same time during movement or when static. Speed synchronization requires that different hydraulic actuators have the same speed.

According to the number of actuators [81], the hydraulic synchronous control system can be divided into "double actuator" and "multi-actuator" hydraulic synchronous control systems. The hydraulic synchronous system with double actuators has less synchronous error accumulation due to fewer actuating elements. The synchronous system of multiple actuators has many components in the circuit, and there are manufacturing, installation, and leakage errors among the hydraulic components, which makes the accumulation of synchronous errors among its mechanisms relatively large. To improve the synchronization accuracy of multiple actuators, closed-loop control and flow compensation are often used.

According to different installation position [82], the hydraulic synchronization control system can be divided into "horizontal" and "vertical" hydraulic synchronization control system. The actuating element of the horizontal hydraulic synchronous system is fixed horizontally, as the hydraulic cylinder synchronous control system is not affected by its own gravity, and the change in the hydraulic cylinder's own gravity will not affect the synchronization accuracy. In comparison, the vertical hydraulic cylinder synchronization system has its own load under the vertical installation of the hydraulic cylinder, and the uneven change of the oil quality in the hydraulic cylinder also has a certain impact on the synchronization accuracy of the system.

5. Research Status of Control Algorithms of Hydraulic Synchronous Control System

With the development of modern control methods, hydraulic synchronous systems are more widely used in the engineering field, and at the same time, people also put forward higher requirements for hydraulic synchronization accuracy, anti-interference, stability, and response speed. The hydraulic synchronous system mostly adopts closed-loop control, and the simple closed-loop control can no longer meet the requirements of high-precision synchronous control due to the hysteresis of error feedback and the influence of nonlinear factors. Therefore, scholars at home and abroad combine different control algorithms with the hydraulic synchronous system to further improve the accuracy, stability, and anti-interference ability of the hydraulic synchronous system. The control algorithms of the hydraulic synchronous control system mainly include fuzzy control, PID control, fuzzy PID control, auto disturbance rejection control, sliding mode control, robust control, adaptive robust control, machine learning control, neural network control, and networked control, etc.

5.1. Fuzzy Control

Fuzzy control makes the control variables of the hydraulic synchronous system fuzzy, uses fuzzy rules, and finally defuzzles to simulate human reasoning and decision-making, to realize the control of the hydraulic synchronous system. The fuzzy control block diagram of the hydraulic synchronization control system is shown in Figure 9.

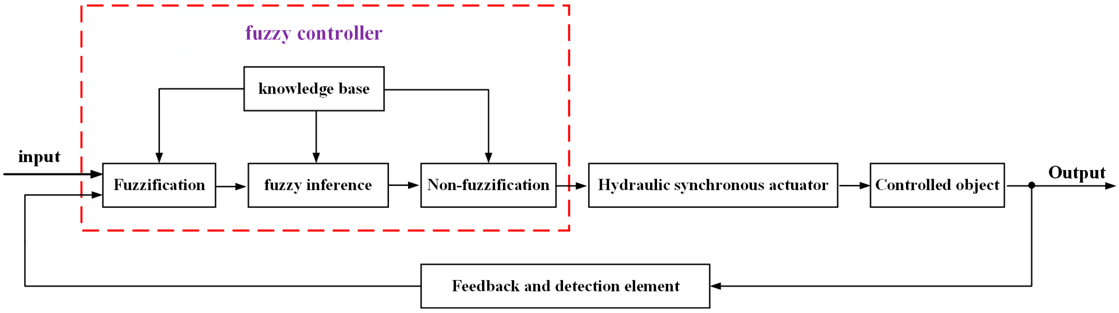

Figure 9. Fuzzy control block diagram of hydraulic synchronization control system.

Fuzzy control is mostly applied to hydraulic synchronous systems that are difficult to establish accurate mathematical models. However, this control algorithm will have a certain steady-state error, which requires researchers to summarize a lot of experience. The accuracy of the control system needs to be guaranteed by establishing complete fuzzy control rules. Liu et al. [83] established a fuzzy feedforward controller for symmetric double hydraulic cylinders, and simulation results show that the synchronization error between the two cylinders is within 15 mm, which verifies the feasibility of the dual hydraulic cylinder synchronization control system under fuzzy control. Chen et al. [84] designed a dual-integrated fuzzy controller based on fuzzy control, in which the fuzzy coordinator is used to process the synchronization error signal of the dual hydraulic cylinders, and the fuzzy tracking controller is used to detect the tracking error of the tracking dual hydraulic cylinders. The test results show that the maximum synchronization error of the two hydraulic cylinders is stable within ± 4 mm under the working conditions of unbalanced load, system uncertainty, and large change of system interference.

The synchronization error of the hydraulic synchronous system under the fuzzy control is relatively large, and to make it have a higher synchronization accuracy, it needs to combine other algorithms and control methods to optimize. Li et al. [85] proposed a cross-coupled hydraulic fuzzy synchronization control strategy based on the fuzzy control principle and applied it to the two plug-in main valves of the plug-in electro-hydraulic servo valve, and the simulation results show that the control strategy can effectively compensate the synchronization error. Jia [86] designed a fuzzy-PID controller for the multi-stage hydraulic cylinder synchronization control system by combining fuzzy control and PID control in Simulink. The joint simulation of AMESim and Simulink shows that the synchronization accuracy of the multi-stage hydraulic cylinder synchronization system under fuzzy PID control is more stable and higher than that under fuzzy control.

5.2. PID Control

The PID algorithm [45,46,87,88] is widely used in hydraulic synchronous systems in recent years due to its simplicity, easy implementation, simple algorithm, and good robustness. Compared with fuzzy control, PID control has a better control effect in linear systems. PID control is composed of a proportional factor P, integral factor I, and differential factor D, and when these three parameters are adjusted properly, the hydraulic synchronous system can obtain a good control effect. The block diagram of PID control of the hydraulic synchronization control system is shown in Figure 10.

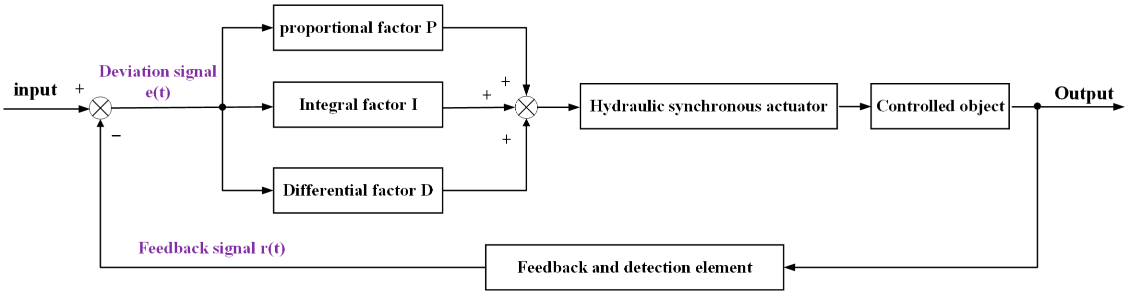

Figure 10. PID control block diagram of hydraulic synchronization control system.

Wei et al. [89] studied the step response of the four-cylinder synchronous platform under different parameters based on PLC control and the PID algorithm, and the results showed that the top mold hydraulic system under the PID control algorithm had a faster response speed, stable operation, and no overshoot. Li et al. [90] compared and analyzed the dynamic control effects of conventional PID and fractional PID on the motion of hydraulic cylinders based on the synchronous control strategy and method of double-cylinder four-column hydraulic press, and the simulation results show that the fractional PID controller has better anti-interference ability and robustness.

PID control has certain limitations in the control of hydraulic synchronous system because its parameters are not adjustable, and it depends on accurate mathematical models. Therefore, some scholars combine PID control with fuzzy control, adaptive control, neural network control, and other algorithms to further improve the control accuracy of the hydraulic synchronous system. Huang et al. [91], based on the control mode of deviation coupling, used an algorithm to optimize the PID control parameters, and studied the synchronization performance of multi-channel hydraulic cylinders with different parameters. The simulation results show that the control strategy has the characteristics of rapid system response, no overshoot, and a high steady-state accuracy. Yu et al. [92] combined the fuzzy adaptive control and PID control to realize the real-time adjustment of PID control parameters, and adopted the master–slave control mode for the hydraulic lifting synchronization system. The simulation shows that the improved control strategy can make the system respond faster and become more stable when the synchronization error is within the allowable range.

5.3. Fuzzy PID Control

Some scholars have combined fuzzy control and PID control to apply them to the hydraulic synchronous control system. First, the fuzzy controller performs fuzzy inference on the input control quantity, and then adjusts the parameters of the PID controller according to the working conditions of the hydraulic synchronous system. Then, the PID controller regulates the hydraulic synchronization system based on the deviation signal, thereby controlling the hydraulic actuator to synchronize the movement. The fuzzy PID control block diagram of the hydraulic synchronization control system is shown in Figure 11.

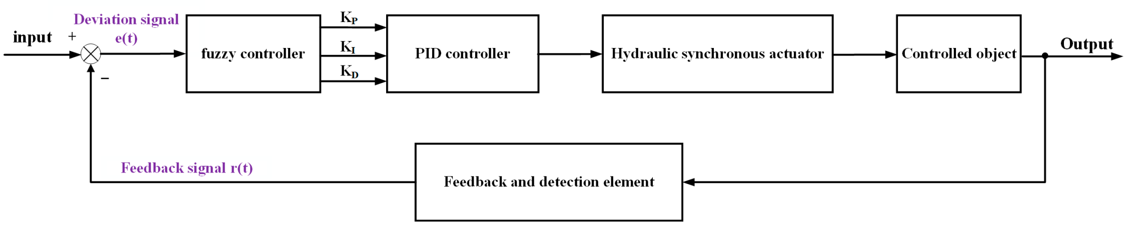

Figure 11. Fuzzy PID control block diagram of hydraulic synchronization control system.

Compared with traditional PID control, fuzzy PID control [93] combines the advantages of fuzzy control and PID control. It can not only realize the real-time adjustment of PID control parameters, but also apply to nonlinear systems. Moreover, the hydraulic synchronous system under this control strategy has a higher control accuracy and better control effect. Liu et al. [94] used the fuzzy PID control strategy to control the two-way electro-hydraulic dual-cylinder synchronous drive system. The PID control parameters can be automatically adjusted according to the change in the working condition error during the control process; the simulation results show that there is a small following error between the slave cylinder and the active cylinder under the fuzzy PID control, and the synchronization accuracy is high.

To make the synchronization control effect better, some scholars have proposed multiple fuzzy PID control strategies. Based on the dual fuzzy PID control with compensation factors, Mu et al. [95] proposed an adaptive fuzzy controller based on a model reference to control the hydraulic circuit of three hydraulic cylinders synchronization control, which reduced the impact of the hydraulic synchronization system due to the changes in the nonlinear friction, load, and operating parameters.

The combination of fuzzy PID control, adaptive control, neural network control, and other algorithms can further improve the control effect of the hydraulic synchronous system [96]. Mu et al. [97] designed a fuzzy parameter adaptive PID synchronization control strategy based on master–slave synchronization control for the hydraulic synchronization system of the inclined gating machine and added an accumulator pressure maintaining circuit at the outlet of the hydraulic pump of the hydraulic synchronization system. The simulation results of Simulink and AMESim software show that the control strategy has better synchronization accuracy and was more energy saving than the traditional PID hydraulic synchronization control strategy. Wu et al. [56] compared the synchronization control accuracy of the fuzzy PID controller and the fuzzy self tuning integral separation PID controller. The test showed that the overshoot amount of the fuzzy PID control algorithm was 4.8%, and the maximum synchronization error was 0.19 mm; the overshoot amount of fuzzy self-tuning integral separation PID control algorithm was 2.8%, and the maximum synchronization error was 0.12 mm. The reason for this phenomenon is that the fuzzy self-tuning integral separation PID controller integrated with the integral separation strategy can close the integral link when the synchronization error is large to prevent the control flow from supersaturation, so its control accuracy is higher than the fuzzy PID control.

5.4. Auto Disturbance Rejection Control

Active disturbance rejection control (ADRC) [98,99] can effectively solve the problem of system disturbance; the algorithm can estimate and compensate the disturbance to the hydraulic synchronous control system in real time, and the system response is more rapid and accurate. Compared with PID control, ADRC is more convenient to adjust parameters and has better control accuracy.

Ren et al. [100] designed an auto disturbance rejection controller to counteract the internal and external disturbances to the speed system, and added PID control in the feedback loop, which enhanced the dynamic adjustment ability and anti-interference ability of the system under disturbances. This significantly improved the synchronization accuracy of the dual electro-hydraulic position servo hydraulic synchronization control system. Lu et al. [101] introduced the auto-disturbance rejection control method into the hydraulic suspension multi-cylinder synchronization system based on the adjacent cross-coupling control method, and compared it with the PID control strategy based on the adjacent cross-coupling. The simulation shows that when the adjacent cross-coupling and auto-disturbance rejection control method is used, the synchronization error of the suspension system group is within ±0.2 mm. When the adjacent cross-coupling and PID control method is used, the synchronization error range of the suspension system group is −2~4 mm, Thus, it is verified that the designed control strategy has strong robustness and adaptability, and has high synchronization accuracy.

5.5. Sliding Mode Control

In the hydraulic synchronous control system, the sliding mode control sets the corresponding sliding plane according to the dynamic characteristics of the system, and then makes the system gradually converge to the sliding plane through the control function. When the state of the controlled object reaches the sliding plane, the system will move along the plane under the control of the equivalent function. Sliding mode control has the advantages of simple structure, insensitivity to parameter disturbances and changes, and is a nonlinear control strategy based on switching characteristics. Synovial membrane control has higher accuracy and robustness than PID control [102,103].

Guo et al. [104] designed an adaptive sliding film synchronous position control strategy with a feedforward compensator based on the improved sliding film approach law, and through the joint simulation of the dual hydraulic cylinders of the hydraulic support used in mining by Matlab and AMESim, and the comparative analysis with PI control and fuzzy PID control, the superiority of the control strategy was further verified. Zhang et al. [105] studied the performance of master–slave synchronous control of hydraulic support and proposed an adaptive sliding film control method based on sliding film control and fuzzy control. The simulation results show that compared with the fuzzy PID control, the adaptive sliding film control has better stability, synchronization, and higher synchronization accuracy, and can better overcome the problem of large fuzzy PID steady-state error.

5.6. Robust Control

Robust control [106] is based on the system state space model, which can solve nonlinear control problems without an accurate mathematical model. Robust control is applied to hydraulic synchronization equipment because it can ensure stability after the model and parameters of hydraulic synchronization system change, and has high robustness.

Zhou et al. [107] designed a robust controller composed of a stabilizing compensator and a servo compensator to solve the problem of small suppression and poor robustness of the multi-cylinder synchronous drive control system of a giant die-forging hydraulic press to system parameter changes. The simulation results show that the multi-cylinder hydraulic synchronous system still has good synchronization accuracy and response speed even in the case of large parameter changes. Liu et al. [108] established the mathematical model of the synchronization system of the giant die-forging hydraulic press, and designed a robust controller for the synchronization control of the giant die-forging hydraulic press. The simulation results show that the system synchronization error increases with the increase of the eccentric load, but the steady state error is basically close to 0, which proves that the robust controller has a good inhibition effect on the nonlinear fluctuation of the synchronization system, and can effectively solve the problem of multi-cylinder synchronization control.

5.7. Adaptive Robust Control

Robust control is applicable to hydraulic synchronous control systems with a large variation range of uncertain factors and a small stability margin. Because it generally does not work in the optimal state, the steady-state control accuracy of the system is poor. Therefore, in order to make the system work in the optimal state, some scholars have proposed adaptive robust control. Adaptive robust control [109,110] combines the advantages of robust control and adaptive control. Based on robust control, parameter adaptive control is added to the feedforward link of the hydraulic synchronous control system to enable the system to work in the optimal state and ensure that the hydraulic actuator has high-precision motion tracking performance and high synchronization accuracy when moving.

Dou [111] studied the synchronization of unsymmetrical hydraulic cylinders, designed a robust adaptive tracking controller based on the nonlinear coupling model, selected the adaptive backstepping design method, and combined it with the parameter adaptive law to solve the uncertainty of some parameters of the system. The simulation in Amesim software shows that the maximum synchronization error of the two hydraulic cylinders is about 1.4 mm, and this control method has good synchronization. Liu et al. [112] designed an adaptive robust controller based on the new integrated actuator electro-hydraulic composite cylinder to compensate the continuous friction it suffered, introduced the robust integral of the error signal into the controller to compensate the approximate error caused by the external disturbance, and the simulation verified the effectiveness of the control method. Li et al. [113] designed an adaptive robust H∞ control and proposed an adaptive controller to update the parameters to control the influence of uncertain parameters and external disturbances during the movement of double hydraulic cylinders. The good control ability of the control system was verified through simulation, which provided a reference for the synchronous control of multiple hydraulic cylinders.

5.8. Machine Learning Control

Machine learning [114,115], as an artificial intelligence algorithm with multiple fields, is dedicated to studying how computers simulate and realize human learning behavior and gradually improve and perfect their own performance through autonomous learning. The process of machine learning modeling is to divide the data into training sets and test sets. The test set is the independent data of the training set. It does not participate in the training at all, but is only used for the final evaluation of the model. With the continuous development of artificial intelligence, machine learning is now gradually being applied to the hydraulic synchronous control system.

Compared with traditional control, machine learning control is more stable and reliable, with higher control accuracy. Fu et al. [116] proposed a control method combining fuzzy PID control and feedforward control based on machine learning to solve nonlinear problems such as a sluggish and dead zone in the electro-hydraulic system of the boom of a mainstream pump truck, and fitted the machine learning and fuzzy PID to obtain the control algorithm that can be applied in PLC. The test results show that the control algorithm can greatly improve the tracking control synchronization accuracy of the boom. Wei [117] studied the control method based on the fusion of machine vision, machine learning and the fuzzy model and established the prediction model of slab bending based on machine learning. Subsequently, the author introduced the differential evolution algorithm and Bayesian optimization algorithm to select the optimal parameters of the machine learning algorithm in order to realize the high-precision detection and prediction of slab bending, and the synchronous and accurate compensation of the roll gap tilt compensation value for the hot strip rolling process. The experiment shows that the accuracy of the stochastic forest prediction model based on differential optimization is 96.3% in the range of ±3 mm, and the accuracy of the prediction model based on Bayesian optimization support vector is 99.25% in the range of ±2 mm. The machine learning model can meet the accuracy requirements.

5.9. Neural Network Control

Neural network is based on simulating the structure and function of the biological brain, and quickly approximates the complex model of nonlinear multi-input and multi-output. Its control parameters can be adjusted continuously with the changes in environment and load conditions, so it can achieve good control accuracy. However, neural networks are prone to over-learning, and their control cost is high. With the development of modern control theory, more and more scholars have applied neural network control to hydraulic synchronous systems and achieved good control results. The relevant neural network control algorithm can automatically adjust the control parameters online, which gives the hydraulic synchronization system a strong anti-interference ability. The neural networks commonly used in the hydraulic synchronization system include the BP neural network and immune neural network.

The BP neural network [118,119] (error return neural network) is widely used in hydraulic neural network synchronization control. The BP neural network uses a nonlinear continuous transformation function to make neurons in the hidden layer have a learning ability. Its core idea is to use error to reverse correct the control system, so that the system has a strong learning ability, memory ability, and nonlinear mapping ability. Liu et al. [120] proposed the master–slave synchronization control strategy of the BP neural network for the four-cylinder pod thruster installation platform that needs synchronization control, and designed a PID controller based on the BP neural network in combination with the PID controller. The simulation verified that the synchronization error of the smooth operation of the four hydraulic cylinders was within 0.1 mm, and the PID control principle under the BP neural network was shown in Figure 12.

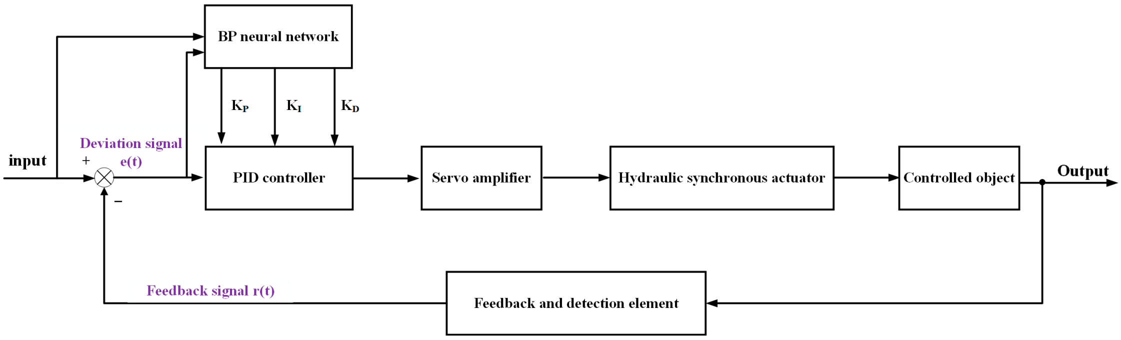

Figure 12. PID control principle under BP neural network.

The immune neural network [121] is a control algorithm formed by studying the immune algorithm based on the working principle of the biological immune feedback mechanism and applying it to a neural network. Its key is the approximation of antibody suppression function. Based on the property that a neural network can approach any nonlinear function, Liu [122] used the BP neural network to approach the antibody suppression regulation function, and combined it with a PID controller to design an immune neural network control method. This uses the output of the actuator to approach the antibody suppression regulation function in real time, thus realizing the self-adjustment of proportional integral differential parameters, and further improving the control effect of the dual hydraulic cylinders. The simulation results show that when the system damping is 0.1, the maximum synchronization error of two hydraulic cylinders is 0.014 mm, which further verifies that the control algorithm can meet the control requirements of a high precision double-cylinder forging machine.

Neural network control is often combined with fuzzy control, PID control, and adaptive control because of its strong robustness, high control accuracy, and the ability to solve the control of complex, uncertain, nonlinear, and time-varying systems, which further significantly improves the control accuracy of hydraulic synchronous system. Xu et al. [123] combined a neural network and fuzzy control to form a fuzzy neural network synchronization control algorithm, applied it to a double-cylinder forging hydraulic press, and established a mathematical model of the double-cylinder synchronization control. The experiment shows that the fuzzy neural network control algorithm has good synchronous control accuracy.

5.10. Networked Control

With the continuous development of Internet technology, the hydraulic synchronization control system is gradually developing to wireless network control. Some scholars have used sensors and a wireless network signal transceiver to achieve hydraulic synchronization control, so that it has a faster response speed and higher synchronization accuracy.

To solve the problem of a long-distance hydraulic pipeline and signal line in hoisting a hydraulic lifting system, Dong et al. [124] proposed an intelligent hydraulic synchronous lifting scheme based on a wireless network communication module, and designed a distributed iterative learning controller, which can effectively overcome the impact of communication time delay and saturation. AMESim simulation verified the effectiveness of the control strategy, and the six hydraulic-cylinder system can achieve accurate synchronization control in a short time. Lu et al. [125], based on the robust control theory, set the sensor and actuator nodes as time-driven, set the controller as event-driven, used the wireless networked synchronization system to connect the distributed subsystems that needed synchronous output, and established the error model of the hydraulic synchronization system that could reduce the network delay function. The simulation shows that the displacement of the active cylinder and the slave cylinder can be gradually synchronized, and the experiment shows that the displacement synchronization error of the driving cylinder and the slave cylinder is within ±1 mm.

After the above research on hydraulic synchronization control algorithms, their control effects and characteristics can be summarized as shown in Table 2.

Table 2. Comparison of Different Control Algorithms for Hydraulic Synchronization System.

Control Algorithm	Control and Control Effect	Characteristic
fuzzy control	Liu [83] used a fuzzy feedforward controller to synchronize symmetric dual hydraulic cylinders, and the synchronization error between the two cylinders is within 15 mm; Chen [84] used a dual integrated fuzzy controller to synchronize the dual hydraulic cylinders, and the maximum synchronization error of the hydraulic cylinders did not exceed ±4 mm.	Researchers need to summarize and establish complete fuzzy control rules to ensure synchronization accuracy, commonly used in hydraulic synchronization systems that are difficult to establish accurate mathematical models. Synchronization control accuracy is poor and is often used in combination with other control algorithms.
PID control	Wei [89] used a PID controller to synchronously control four hydraulic cylinders. The results show that the system has fast response speed, stable operation, and no overshoot, but the control accuracy is average.	The control is simple, easy to implement, has good robustness, and has high control accuracy in linear systems. However, the control parameters are not adjustable, the adaptability is weak, and the synchronization accuracy is general. Often used in conjunction with other algorithms.
Fuzzy PID control	Mu [97] used a fuzzy parameter adaptive PID synchronization controller to synchronize the tilting pouring machine. The results show that this control strategy has higher synchronization accuracy and more energy saving compared to PID control; Wu [56] used a fuzzy PID controller to synchronously control 4 cylinders drive hydraulic press. The experiment shows that the overshoot of the fuzzy PID control algorithm is 4.8%, and the maximum synchronization error Is 0.19 mm.	Combining the advantages of fuzzy control and PID control, it can not only adjust PID control parameters in real time, but also be applicable to nonlinear systems. High control accuracy and good control effect.
auto disturbance rejection control	Lu [101] adopted an active disturbance rejection control and adjacent cross-coupling control method to synchronize the suspension hydraulic cylinders. Simulation results show that the synchronization error of the suspension system group is within ±0.2 mm.	It can estimate and compensate the disturbance of hydraulic synchronous control system in real time, and improve the response speed of the system. High synchronization control accuracy, high robustness, and strong adaptability.
sliding mode control	Zhang [105] proposed an adaptive sliding film control method based on sliding film control and fuzzy control for synchronous control of hydraulic supports. Compared with fuzzy PID control, adaptive sliding film control has better steady-state performance and higher synchronization accuracy.	Simple structure, insensitive to parameter disturbances and changes, and higher control accuracy and robustness compared to PID control.

Table 2. *Cont.*

Control Algorithm	Control and Control Effect	Characteristic
robust control	Liu [108] designed a robust controller for synchronization control of giant die forging hydraulic presses. The simulation results show that the system synchronization error increases with the increase of eccentric load.	Nonlinear control problems can be solved without the need for accurate mathematical models, but hydraulic systems typically do not work in optimal conditions and have poor control accuracy.
adaptive robust control	Dou [111] designed a robust adaptive tracking controller based on a nonlinear coupled model to synchronize asymmetric hydraulic cylinders. The results show that the maximum synchronization error of the two hydraulic cylinders is about 1.4 mm.	Combining the advantages of robust control, it can also make the hydraulic synchronous system work in the optimal state, with strong robustness and high steady-state control accuracy.
machine learning control	Wei [117] used a control method that combines machine vision, machine learning, and fuzzy models to synchronously and accurately compensate the roll gap tilt compensation value. Experiments show that the accuracy of the prediction model reaches 99.25% within the range of ±2 mm, meeting the requirements of high-precision synchronous control.	It is more stable and reliable than traditional control, and can self-tune control parameters, resulting in higher synchronization control accuracy.
neural network control	Liu [120] used a PID controller based on BP neural network, simulation shows that the synchronization error of the four hydraulic cylinders is less than 0.1 mm during smooth operation. Liu [122] adopted an immune neural network control method combined with a PID controller, and when the system damping is 0.1, the maximum synchronization error of the two hydraulic cylinders is 0.014 mm.	Synchronous control has high accuracy, strong anti-interference ability, and can self-tune control parameters, but it is prone to excessive learning and high control cost.
networked control	Lu [125] used a wireless networked synchronization system based on robust control to connect distributed subsystems that require synchronous output, with the synchronization error of the active cylinder and the slave cylinder being less than ±1 mm.	Fast response speed and average synchronization accuracy.

6. Discussion

The hydraulic synchronization control system has the characteristic of nonlinearity and is time-varying, and the adoption of an appropriate control algorithm is an important research direction of the hydraulic synchronization system. Common advanced control algorithms include fuzzy control, fuzzy PID control, adaptive robustness control, machine learning control, and neural network control, etc., but they have their own advantages and disadvantages. For a nonlinear, easily disturbed, time-varying hydraulic synchronous control system, a single control algorithm often cannot achieve a good control effect, so some scholars have organically combined multiple control algorithms and thus achieved a good control effect.

With the development of hydraulic synchronization control systems towards automation, low energy consumption, low leakage, low noise, high response, anti-interference, intelligence, and high accuracy, higher requirements are put forward for the control strategy and hydraulic components. The designed hydraulic synchronous system first must meet the requirements of high precision, needs to have fast response, overshooting, strong anti-interference ability and other characteristics, and the selected control strategy can ensure that the system has a good control effect when it is subjected to external disturbance. The prediction and prospect of the development trend of the hydraulic synchronous control system [22,126–133] can be summarized as follows.

(1) Reliable and safe. On the premise of ensuring the accuracy of hydraulic synchronization, with the improvement of control technology, new technology, and processing technology, the hydraulic synchronization system will develop towards more safety and reliability in the future.
(2) Energy conservation and environmental protection. An intelligent control algorithm and hydraulic components with new structure will be adopted to improve the efficiency and response rate of the hydraulic system, thus reducing the system energy consumption and oil leakage and further improving the energy utilization rate.
(3) Automation. The new intelligent control strategy will be adopted to enable automatic regulation and further improve the control effect of the hydraulic synchronization control system.
(4) Digitalization. Rational use of mechanical and computer controllers will further improve the hydraulic system, will be further combined with new control technology to form the integration of a "mechanical-electrical-hydraulic-controller", and then realize digital control. A discrete digital signal will be used to control the discrete hydraulic fluid, and then the digital control of the hydraulic synchronous control system will be realized.
(5) Integration. The integrated hydraulic components can make the structure of the hydraulic synchronization control system more compact, without the connection of hydraulic pipe fittings, thus effectively eliminating the vibration and oil leakage at the oil pipes and joints.
(6) Intelligence. In the future, intelligent new hydraulic pumps, intelligent electro-hydraulic (digital) valves, intelligent electronically controlled synchronous cylinders, etc., can make the accuracy of hydraulic synchronization control system higher.
(7) Neural network. The use of a neural network and other related control algorithms will become the development trend of hydraulic synchronization control systems in the future due to its advantages of continuous self-learning, fast approaching to nonlinear complex models, and high control accuracy.
(8) Innovation. With the continuous development of science and technology, the new pressure compensation synchronous control systems, the new valveless hydraulic synchronous control systems and the new hydraulic synchronous control systems with wireless monitoring function will continue to enrich the hydraulic field.
(9) Initiative. With the continuous development of artificial intelligence and big data, the future hydraulic synchronous control system can slowly realize the functions of active prediction and active flow distribution, so as to self-diagnose and control the hydraulic system, which will further improve the system response speed and synchronization accuracy.
(10) Networking. The wireless network transceiver will be added to the hydraulic synchronization system, and the distributed sub-hydraulic branch system that needs synchronous operation will be connected through the Internet, which can realize data acquisition, communication, and control of electro-hydraulic valve at low cost, making the hydraulic synchronization system respond faster, and effectively solving the control problem of the hydraulic synchronization control system at a long distance.

7. Conclusions

The hydraulic synchronous control system is the core of hydraulic synchronous motion machinery and equipment, which determines the function and technical performance of these machines and equipment. The main problems of the hydraulic synchronization system under the current closed-loop control are: there is a feedback adjustment lag, it is difficult to combine between different control algorithms, it is difficult to achieve accurate synchronization under eccentric load and other problems, and with the improvement of control accuracy, the requirements and costs of hydraulic components are getting higher and higher. It is believed that with the continuous development of artificial intelligence and control algorithms in the future, the above problems can be gradually solved. With the continuous development of control theory, the improvement of computer level and the continuous improvement of new intelligent manufacturing methods and processes, the cost of the hydraulic synchronization system will be gradually reduced, and its combination with intelligent control algorithms will also be closer. Digitalization, integration, intelligence, neural networking, innovation and networking are gradually becoming the future development trend of the hydraulic synchronous control system, among which the more promising development is neural network and networking, which can significantly improve the control accuracy of the hydraulic synchronous system and reduce the time of the feedback adjustment. At the same time, more scholars are also required to carry out relevant research on the hydraulic synchronous control system, so as to continuously promote the progress and development of the hydraulic field.

Author Contributions: Conceptualization, R.L. and W.Y.; methodology, X.D.; software, J.X.; validation, W.Y., Q.S. and Y.Z.; formal analysis, R.L.; investigation, X.D.; resources, W.Y.; data curation, X.D.; writing—original draft preparation, W.Y.; writing—review and editing, R.L.; visualization, J.X.; supervision, X.D.; project administration, Q.S.; funding acquisition, R.L. All authors have read and agreed to the published version of the manuscript.

Funding: 1. Key R&D plan of Shandong Province, China, grant number 2021CXGC010207; 2. Creation Project of Key Components Of High Performance Sowing and Harvesting and Intelligent Work Tools, grant number 2021CXGC010813; 3. General project of Shandong Natural Science Foundation, grant number ZR2021ME116; 4. Key R&D plan of Shandong Province, China, grant number 2020CXGC011005.

Acknowledgments: We would like to thank our tutor, Ruichuan Li, for all his support and guidance. I would like to thank my colleagues for their care and help in my daily work.

Conflicts of Interest: The authors declare no conflict of interest.

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