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Study on the relationship between structure and properties of electro-hydraulic positioning actuators

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In this work, a novel perspective is proposed to develop schematics solutions for electro-hydraulic positioning actuators. The basis of the design approach has been established, which includes: a set of possible desired properties of actuators; a series of defined typical positioning methods; variants of schematic structures; a quantitative assessment method for specific properties based on influencing factors; the quantitative relationship between the structure and properties of actuators, as well as the method for overall evaluation of the actuator's performance based on the total score. The results obtained can serve as the basis for an effective design approach, which allows for reducing the number of iteration cycles while developing new electro-hydraulic positioning actuator schematic solutions.

1. Introduction

The term "actuator" refers to a technical device that converts energy into mechanical motion according to the input control signals [1]. It is typically utilized to control and drive the working body to perform various desired actions. There are many types of actuators, which can be categorized as electric actuators, hydraulic actuators, and pneumatic actuators according to the different energy sources. There are also actuators that combine different types of energy, such as electro-hydraulic actuators. The electro-hydraulic actuator combines the advantages of both electric and hydraulic actuators, making them capable of achieving better performance.

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Electrohydraulic actuators are used in technical facilities for various purposes. Among them, positioning actuators are also widely used, which ensure the movement of the working body to specified positions. For example, such actuators are used to make positioning movements in multi-axis manipulators [2] and electro-hydraulic forklifts [3]. Digital hydraulic actuators [4] are utilized to move milling machine tables. Adjustable hydraulic positioning actuators [5] are used to perform positioning movements in continuous casting and rolling machines of steel plants. Positioning actuators [6] are applied in control systems of non-road mobile machines. Electro-hydraulic actuators with proportional control [7] are employed in the equipment of shield tunneling machines and other applications.

Electro-hydraulic positioning actuators must be designed with different characteristics based on the tasks to be performed, which in turn affects their structures and control methods.

The variety of requirements for the positioning actuators, numerous variants of schematic solutions, and the specificity of control methods, lead to the complexity of the design. To a large extent, developing schematic structures relies on the intuition and experience of developers, who have limited information to make reliable decisions. The improvement of widely applied electrohydraulic positioning actuators and the demand for increasing development efficiency have led to relevant scientific studies focusing on different aspects. These studies include the definition of certain technical characteristics, determining the influence of internal and external factors, or the search for new solution schemes. For example, in electro-hydraulic servo drives with closed-loop control systems [2, 8], the researchers studied the positioning accuracy, as well as the influence of factors such as temperature, load, and elements' defects on the dynamic characteristics. Examples of new solutions for electro-hydraulic actuators include multi-position actuators [5, 9] aimed at improving dynamic characteristics, or technical solutions [10, 11] designed to reduce costs and working fluid requirements. Studies on these aspects are aimed at improving the characteristics of positioning actuators rather than revealing the reasons for their intrinsic shortcomings, which appear at the level of the fundamental technical solutions.

There is another aspect of the research on technical objects for various purposes, aimed at laying the design foundations, namely, clarifying the relationship between the technical object's schematic structure and its properties. For example, in the literature [12], the relationship between the structures of different leg modules of hydraulic quadruped robots and the properties such as design complexity, motion control, and robot performance was researched. This made it possible to construct quadruped robot structures rational in terms of control easiness and improved performance. In the work [13], the relationship between the airbag structure solutions and properties of the soft pneumatic actuator was studied. This led to a wider choice of influencing parameters in the development process. In the study [14], it was found that the crystal structure, rather than the geometrical parameters of the ceramic element, has a significant influence on the mechanical characteristics of piezoceramic actuators. The article [15] presents the relationship between the structure solutions of the collecting pipe and the properties of the roto-jet pump. This makes it possible to improve the efficiency of the pump.

Through the studies on this aspect, it is possible to qualitatively and quantitatively assess how the object's structure influences its properties. It also points out a promising direction in the search for new and effective technical solutions to obtain the desired properties. In addition, this aspect of the research also shows a proper direction in the development of technical objects with desired properties. However, it is necessary to go deeper into research in order to establish the theoretical basis for the design of electrohydraulic positioning actuators. It should also be mentioned that the relationships between the structure of the actuator, the desired functions, the requirements for characteristics, and the operating conditions are not sufficiently represented in the known studies of electro-hydraulic actuators.

In our opinion, by generalizing different types of positioning actuators, analyzing the interaction of actuator components in the positioning process, comparing the effectiveness of different types of actuators, and revealing the relationship between the structure and actuator's properties, a promising direction for the design of positioning actuators can be formed.

In this paper, firstly, the basic properties of electro-hydraulic positioning actuators are defined and the terms involved are explained. Then, the main analysis results of the known actuators are presented, and the basic positioning methods employed in the actuators are described. A detailed analysis of the components and their interaction state diagrams is performed for the actuators based on specified methods. In the next part, the properties of actuators are evaluated and their decisive factors are given. The following are evaluation results that represent the relationship between the structure and properties of positioning actuators. Finally, the results are compared with known studies.

2. The main properties of positioning actuators and their positioning methods

Application fields of positioning actuators, applied objects, functions of objects, their characteristics, as well as operating conditions determine the requirements for actuators and their properties. The main properties of positioning actuators include discreteness (positioning resolution), positioning accuracy, achievable speed, working force, response speed, stability, speed controllability, cost, and cleanliness of the working fluid. Depending on the positioning method of actuators, these properties may have different qualities.

The meaning of the above terms is as follows. Discreteness (positioning resolution) is the achievable minimum displacement value of the rod within a single action; positioning accuracy refers to the achievable stable minimum difference between the specified and actual position of the rod when executing commands to move to a set position within a stroke; achievable speed – the maximum speed of the rod; working force – the maximum force on the rod under the same conditions; response speed – the time in which the set speed is reached after sending the control signal; stability – continuous operation of an actuator in a certain mode while keeping the actuator's functional properties unchanged; speed controllability – the movement speed of the rod can be changed through control signals; cost – required costs for manufacturing the actuator; the cleanliness of the working fluid – limitations on the size and quantity of particle contamination in the test volume of the working fluid. The property "stability" of actuators is not considered in this paper, because it is determined by the relationship between the parameters in each actuator and cannot be determined without performing a dynamical analysis.

It is known that two basic control methods are used in hydraulic systems – throttling control and volumetric control. The structure of positioning actuators is also based on such methods, which are found in various technical solutions. Despite the diversity of these technical solutions, they may share common features. Moreover, they are based not only on basic control methods, but also on more complex methods consisting of basic methods. The revelation of these methods will deepen the understanding of modern positioning actuators and will provide opportunities for further improvement.

The studies of known electro-hydraulic positioning actuators showed that they have certain structural features and are based on different positioning methods. Positioning actuators [2, 8] are based on servo or proportional valves. Positioning actuators [16, 17] are based on digital components with a specific discreteness. Positioning actuators [5, 9] have a structure consisting of switching valves and an executive mechanism with multiple working windows. Positioning actuators [18–25] are based on special chambers, which cyclically supply portions of the working fluid.

The structure analysis of the specified positioning actuators shows that they are based on four positioning methods, which are the following: M1 – analog control of fluid supply to reach a preset position; M2 – discrete control time of fluid supply to reach a preset position; M3 – discrete control of fluid supply to reach a preset fixed position; M4 – discrete control of portioned fluid supply to reach a preset position. Next, the specified positioning methods are based, in detail, on the analysis of the schematic diagrams of the positioning actuators. The presented diagrams are highly simplified, for instance, the diagram (Fig. 1) does not show proportional electromagnets for controlling the spool position and possible amplifier stages. This is because the simplified diagrams allow us to focus on the positioning method, which is independent of the above-mentioned drive elements.

2.1. Method 1 – analog control of fluid supply to reach the preset position

This positioning method is used in positioning actuators with servo or proportional valves [2, 8]. The set control program initiates the control unit (Fig. 1) to send analog signals to the valve, and then the spool of the valve is displaced

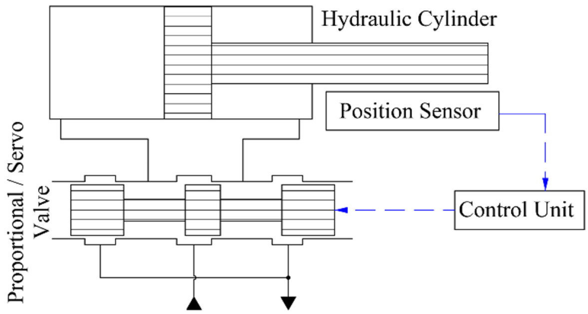


Fig. 1. Schematic of the actuator based on analog control of fluid supply applied to reach the preset position

and the valve opening reaches the corresponding size. The working fluid enters the chamber of the hydraulic cylinder through the valve, and the rod starts to move. At the same time, the position sensor detects the current position of the rod and transmits position signals to the control unit. As the rod nears the set position, the control unit adjusts the signal to the valve. Once the rod reaches the set position, the valve spool is set to the neutral position.

In order to understand how the actuator components interact during the positioning process, the logic of the positioning process was analyzed in detail and presented in a state diagram within the execution of the given program. The positioning process is determined by variable parameters that reflect the states of the components. In all state diagrams, the variable parameter for components like hydraulic cylinders, containers, or executive mechanisms is the position of their rods. For the control valve, it is the current position of the spool. For the sensor, it is the output electrical signal. For the control unit, it is the control signal. The desired rod positions are set via the control program. The variable parameters are presented as absolute values at the qualitative level. Fig. 2 depicts the state diagram showing the position changes of the valve spool, hydraulic cylinder rod, and the electric signal value from the position sensor. These changes occur when control signals are transmitted from the control unit, corresponding to the set control program.

The opening size of the servo or proportional valve is controlled by analog signals from the control unit. In order to achieve the positioning function, such actuators require a closed-loop control system, therefore a position sensor is necessary. Actuators with this type of positioning method have the following advantages: (1) because the opening size of the valve can be large, the flow rate through the valve is also high, so the rod movement speed can be very fast; (2) because the response frequency of the valve is high, so the response speed is fast; (3) because hydraulic drive has great rigidity against load, and the electronic control system is a closed loop, so the positioning accuracy is high; (4) the movement speed of the rod can be continuously controlled since the opening size of the valve can be set continuously by means of control signals. Disadvantages include the following: (1) because the

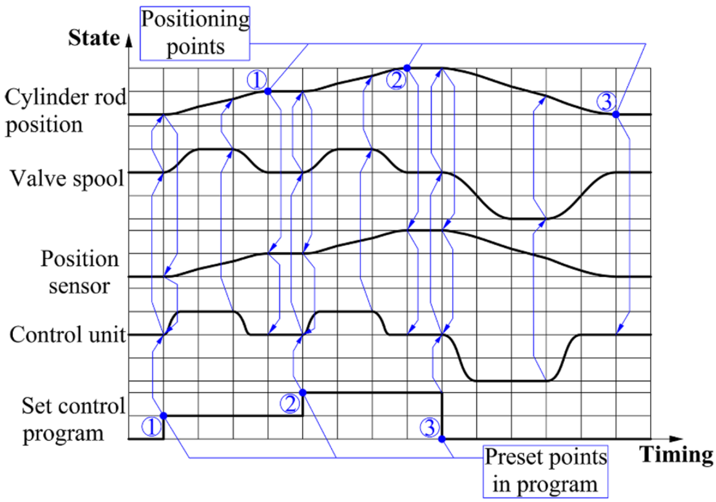


Fig. 2. The state diagram for components of the actuator based on positioning method 1 according to the set program

machining accuracy of the valve's parts is high, the cost is high; (2) the small radial gaps in the valve result in high requirements for fluid cleanliness.

2.2. Method 2 – discrete control the time of fluid supply to reach the preset position

This positioning method is used in positioning actuators presented in [16, 17, 22, 23]. According to the definition [22], this type of actuator (Fig. 3) is classified as the digital hydraulic actuator. In order to employ the positioning method, the control unit sends discrete signals to control the opening and closing time of the discrete valves, where each opening means that a portion of fluid enters the chamber of the hydraulic cylinder. Each portion of the fluid corresponds to one unit movement

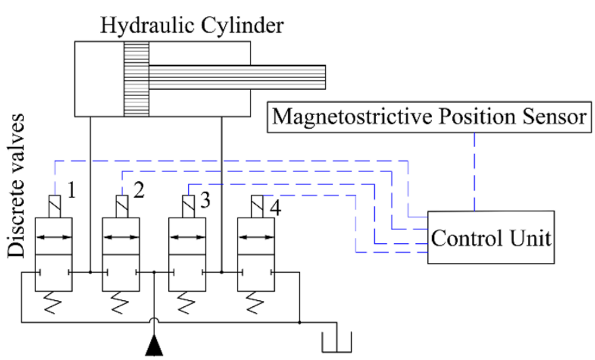


Fig. 3. Schematic of the actuator based on discrete control of the time of fluid supply applied to reach the preset position

of the rod, so the positioning function can be implemented. The states diagram in Fig. 4 illustrates the interaction of the actuator's components during the execution of the set control program. According to the set control program, the control unit sends signals to change the working position of the discrete valve, which results in changes in the cylinder rod position. At the same time, the magnetostrictive position sensor feeds back the rod position as an electrical signal to the control unit, which sends the correction signals to return the discrete valve to the closed state.

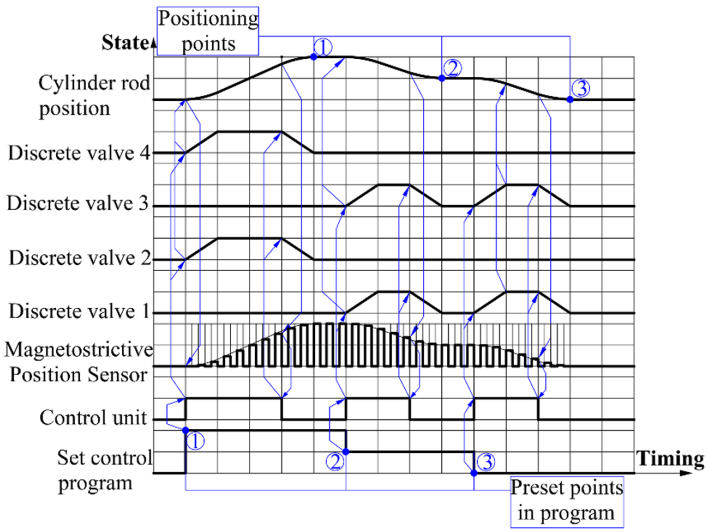


Fig. 4. The state diagram of components for the actuator based on positioning method 2 according to the set program

Due to the small effective orifice area of the discrete valves, it is possible to supply a tiny portion of the working fluid into the cylinder chamber and the unit displacements of the rod can be very small, so the positioning discreteness is very good. This makes it possible to realize the positioning function with an open-loop control system without a position sensor when the accuracy requirement is not very strict and the external load does not significantly vary.

Several discrete valves can also be connected in parallel to form a combination valve, and each discrete valve is independently controlled by the control unit. In this way, more diverse flow rate combinations can be obtained. Thus, the actuator based on time control of discrete valves can be implemented to control the rod's positioning speed.

Compared to the actuators based on analog control of fluid supply to reach preset position, such actuators have the following advantages: (1) since the requirements for the machining accuracy of discrete hydraulic valves are not high, the cost is lower; (2) considering the relatively large size of the orifice in the open state of the valve, the actuator is not sensitive to fluid contaminations. The disadvantages are as follows: (1) lower positioning accuracy in the case of the use of an open-loop control system without a position sensor; (2) discrete valves with relatively large mass of spools have low oscillation frequency. In the case of high discreteness required, this leads to small amplitude of spool motion, which limits the flow through the orifice. As a result, the speed of the rod's movement is lower.

2.3. Method 3 – discrete control of fluid supply to reach the preset fixed position

Actuators with this positioning method have two types of structures of the executive mechanism. As shown in Fig. 5 and Fig. 7, both of them have some fixed positions determined by special structures. The positioning actuators known from [5, 9] use a structure like Fig. 5, while the positioning actuators known from [10, 11, 26–29] use a structure like Fig. 7.

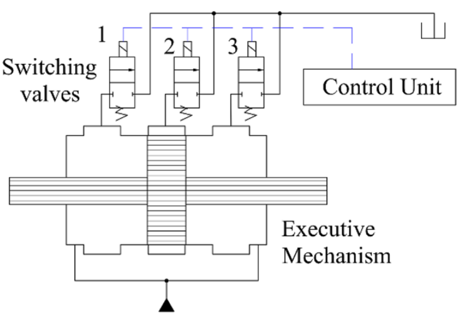


Fig. 5. Schematic of the actuator based on discrete control of fluid supply applied to reach the preset fixed position

The positioning function of the actuators (Fig. 5) is realized as follows. The executive mechanism has several working windows in the structure. The fluid is supplied to the chambers on both sides of the piston of the executive mechanism and then returned to the tank through the working window and its corresponding switching valve. Depending on the status of the switching valves, the rod of the executive mechanism will move to a position corresponding to the open working window. When a switching valve is activated, the piston of the executive mechanism moves a fixed distance and closes the corresponding working window of the switching valve, thus the purpose of positioning is achieved. The state diagram in Fig. 6 shows changes in the state of the switching valves and the rod's position of the executive mechanism when the control unit sends control signals corresponding to the set control program.

The actuators shown in Fig. 7 have a multi-chamber configuration, which can either be built into the executive mechanism as shown in Fig. 7a [10, 26, 27] or can be external to it, as shown in Fig. 7b [11, 28, 29]. For the actuators in Fig. 7a, the pistons are equipped with equidistant x limiters, which stop the movement of

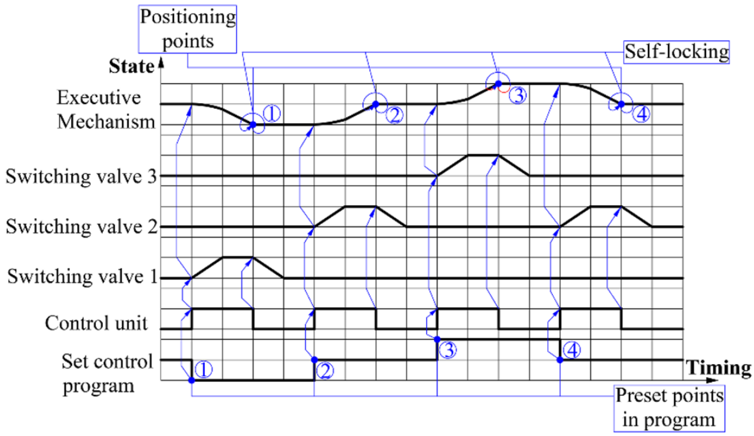


Fig. 6. The state diagram for components of the actuator based on positioning method 3 according to the set program

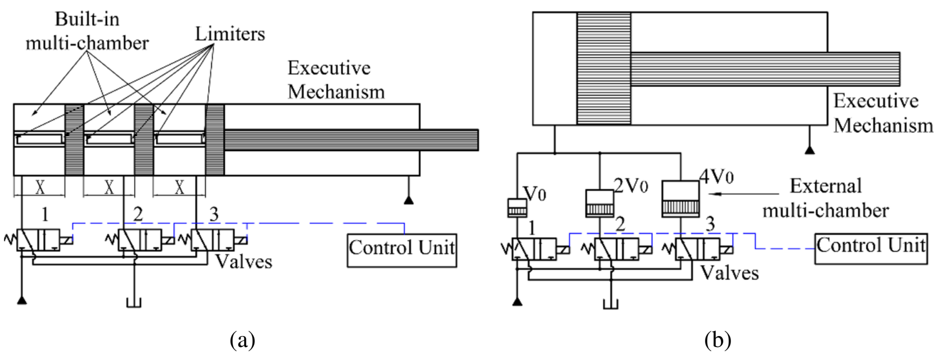
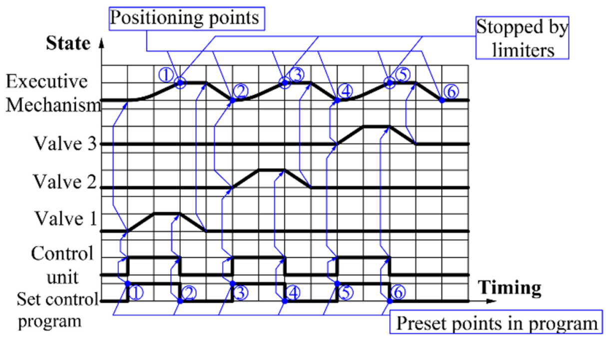


Fig. 7. Schematic of the actuator based on discrete control of fluid supply applied to reach the preset fixed position (a-built-in multi-chamber structure; b-external multi-chamber structure)

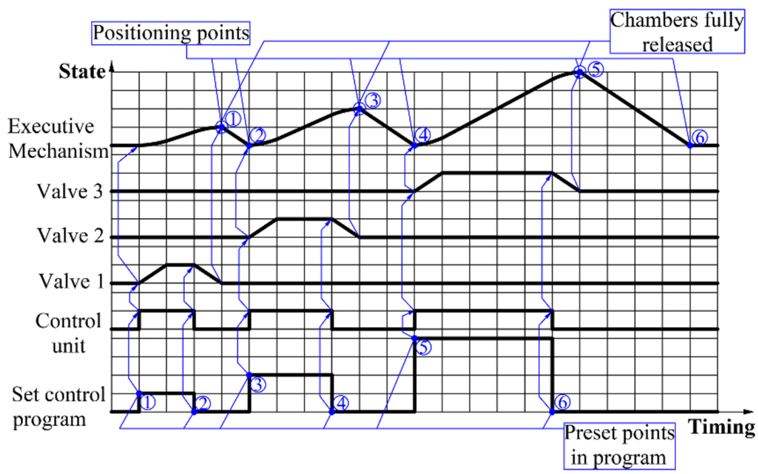
pistons, so that chambers form several fixed maximum volumes. For the actuators (Fig. 7b), they have separate chambers with a multiplicative volume V0 relationship. To achieve the positioning function, the working fluid is filled into chambers with a fixed volume. Then, this fixed volume of working fluid acts on the piston of the executive mechanism causing the rod to gradually move to the preset fixed position. The status diagram in Fig. 8 depicts the positioning process of the actuator shown in Fig. 7 under the set control program. It shows the changes in signals from the control unit, the valves' working positions, and the rod's positions of the executive mechanism.

Since the actuator based on the positioning method M3 has fixed positions, the positioning function can be achieved without a position sensor.

Positioning actuators using method M3 have several advantages: (1) high response speed because the valve opening can quickly reach the fully open state;



(a)



(b)

Fig. 8. The state diagram for components of the actuator based on positioning method 3 according to the set program (a) built-in multi-chamber structure; (b) external multi-chamber structure)

(2) high working speed of the rod in the case of large size of the valve's orifice; (3) low cost because of the simple structure and low requirements for machining accuracy of the components; (4) low requirements for fluid cleanliness because of the large size of the valve's orifice. The disadvantages are: (1) because the number of fixed positions is directly related to the number of working windows and multi-chambers, which are limited, the positioning discreteness of such actuators is low; (2) the positioning accuracy of actuators in Fig. 5 is poor because the control system is an open-loop one, so it is difficult to precisely position the piston over the whole working window. However, in the case of the actuator from Fig. 7a, the rod fixed positions are determined by limiters, so the positioning accuracy is higher; (3) the overall size of the actuators shown in Fig. 7 is large because of their multi-chamber configuration; (4) for the actuators in Fig. 7b, the response speed, the speed of rod movement and positioning are low due to the low speed of filling the chambers and

releasing the working fluid from the chambers. It is worth mentioning that with the same size of the executive mechanism or hydraulic cylinder and the same fluid pressure, the actuator based on positioning method M3 has a lower working force than the actuator based on positioning methods M1 and M2. The reason lies in the fact that in Fig. 5 both sides of the piston are supplied with the same pressure of fluid, and in Fig. 7 the chamber with the rod is always supplied with the fluid, whereas the chambers with the rod of the actuator based on the positioning methods M1, M2 are connected to the tank.

2.4. Method 4 – discrete control of portioned fluid supply to reach the preset position

The schemes of positioning actuators based on this method of positioning can be divided into several categories. The main difference between them lies in their components that generate discrete portions of fluids. For example, two slave cylinders and valves [18, 19], pneumo-hydraulic multiplier [20, 30], piezoactuator-driven pump [21, 25], hydrostatic double cylinder with the same dimensions [24], and so on. These positioning actuators have different structures, but the key idea of positioning methods is the same, which can be explained in Fig. 9.

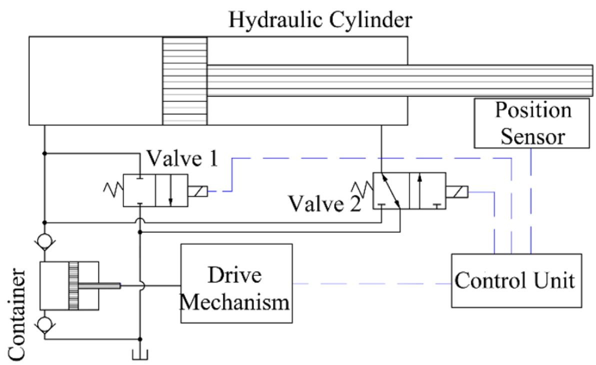


Fig. 9. Schematic of the actuator based on discrete control of portioned fluid supply to reach the preset position

The actuator shown in Fig. 9 has a container(s) that can be cyclically filled with a fixed portion of the working fluid, or the fluid can be cyclically released. The container(s) can be formed in different ways, and the drive mechanism is the main difference from the previous type of positioning actuator. The positioning function is executed by cyclically filling the fixed portion of working fluid into container(s), and then these portions of the fluid act on the piston of the cylinder, thereby the rod is gradually moved to the preset position.

The state diagram in Fig. 10 illustrates the positioning process of the actuator under a set control program, which shows the setting of the rod positions in the control program, the change in the signals from the control unit and from the

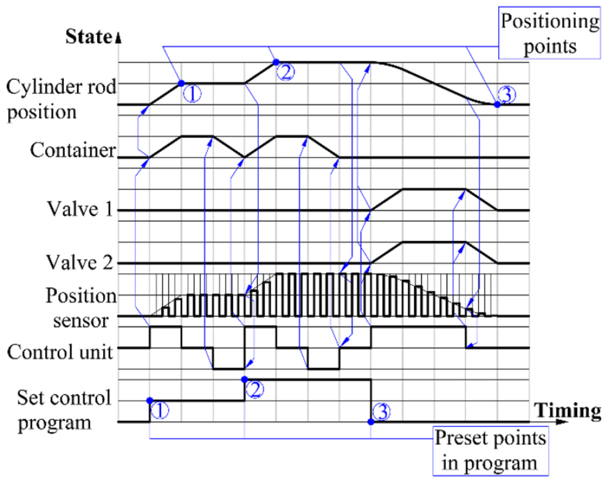


Fig. 10. The state diagram for components of the actuator based on positioning method 4 according to the set program

position sensor, the change in the valve's position, and the change in the position of the rod and the container.

The volume of fluid in the container in Fig. 9 is the same for each cycle, and the discreteness corresponds to it. The smaller the volume of the container, the better the discreteness that can be achieved, but the rod's movement will be slower. The main differences between the actuators of Fig. 9 and Fig. 7b concern the container and its working mode. The container of the actuator in Fig. 9 has a constant volume and the fluid can be supplied to the hydraulic cylinder in multiple cycles during each positioning process.

Compared to actuators based on positioning methods M3, the actuators based on positioning methods M4 have the following advantages: (1) because the volume of the container(s) can be made very small, better discreteness can be achieved; (2) because the discreteness is better, there are more locations that can be positioned; (3) positioning accuracy is higher due to a closed-loop system with position sensor. The disadvantages are as follows: (1) because a certain time is needed to fill into- and release the fluid from the container(s), the speed of movement and the response of the rod is lower.

3. Determination of the relationship between the structure and properties of positioning actuators

We have analyzed the structures and positioning methods of electro-hydraulic positioning actuators based on their typical schematics. The next question is what factors determine the properties of the actuators and what results are achieved. Considering the structures and positioning methods of actuators, these factors must be determined for each type of the actuator. Due to the fact that the form of the actuator structures is the result of the applied positioning method, it makes sense to consider the factors associated with the positioning method. So, for the above-mentioned properties and positioning methods of positioning actuators, the influence of various factors on the potential effectiveness of actuators is analyzed, substantiated, and evaluated, as shown in Table 1.

In each cell of Table 1, the main factors that determine the property performance for actuators based on different positioning methods are listed. By comparing these factors, scores are given to quantitatively assess the potential of the corresponding actuators to achieve the property. For example, for the actuator based on method M1, the "positioning speed" property is determined by the potential of the valve's throttling opening to reach its maximum value. The same property for the actuator based on method M4 is determined by the refilling time of fluid into a metering container. When comparing the achievable maximum speed achieved in different actuators under the same conditions such as fluid pressure, loads, rod displacement, etc., one can see that the actuator based on method M1 can achieve a higher maximum speed than that of the actuator based on method M4. This is because the time needed for the valve spool to move and to start the fluid supply is much shorter than the time taken to periodically fill the container. As a result, the scores of the "positioning speed" property of the actuators based on methods M1 and M4 are estimated as 5 and 3, respectively. As far as the actuator based on method M3 (Fig. 7a) is concerned, its maximum speed is lower than that of the actuator based on method M1 under the same conditions. This is due to the differential connection of its hydraulic cylinder. However, the maximum speed of the actuator based on method M3 (Fig. 7a) is higher than that of the actuator based on the M4 method. This is because the fluid can enter the cylinder chamber without a time delay when filling the container. Therefore, the estimated score for the actuator based on the method M3 is 4 for the "positioning speed" property. The properties of other positioning actuators were evaluated in the same way.

The relationship between the structure and properties of positioning actuators is determined by comparing the properties of actuators of different structures based on specific positioning methods. In order to quantitatively evaluate the achievable effectiveness of each property of the actuator, it is proposed to use a score scale in the range $-5\sim0\sim+5$. A score of 5 means the best positive impact on effectiveness, and a score of –5 means the worst negative impact. The total score of the actuator based on a certain positioning method is defined as the algebraic sum of the scores obtained for each property. In general, the actuator scores can be rated up to 30 when maximum effectiveness is achieved.

Based on the obtained data from the analysis of the properties of positioning actuators with different positioning methods and taking into account the influence factors, the following comparison results are shown in Table 2.

In Table 2, the total score of positioning actuators based on a specific positioning method is close to maximum and can serve as a criterion for assessing the

Table 1. Factors determining the properties of actuators based on different positioning methods, and the predicted scores for the possible achievable results

Property	Structure of the actuator based on positioning method			
	M1 – analog control of fluid supply to reach the preset position	M2 – discrete control the time of fluid supply to reach the preset position	M3 – discrete control of fluid supply to reach the preset fixed position	M4 – discrete control of portioned fluid supply to reach the preset position
Positioning speed (0...5)	High, the opening size of the valve can be large. score 5	High, discrete valves can work at high frequency. score 5	Fig. 5 – High, the opening size of the valve can be large. Fig. 7a – Upper-middle, the opening size of the valve can be large. The rod chamber is connected with high-pressure oil. Fig. 7b – medium, the filling and releasing of the working fluid in the chamber takes time. score 5/4/3	Medium, the filling and releasing of working fluid into container(s) takes time. score 3
Positioning accuracy (0...5)	High, closed-loop control system. score 5	High, the unit fluid volume corresponding to the unit rod's displacement is small and closed-loop control system. score 5	Fig. 5 – Low, large radial clearance between cylinder and piston. Fig. 7a – High, rod's positions are determined by limiters. Fig. 7b – Middle, fixed volume of chambers directly related to the positioning, and open-loop control system. score 3/5/3	Upper-middle, a fixed volume of container(s) directly related to the positioning, and the closed loop system. score 4
Requirements for cleanliness of the working fluid (–5...0)	High, small clearance in the valve. score –5	Low, the valve has a large size of orifice. score 0	Fig. 5 – Low, the valve has a large size of orifice, and large radial clearance between cylinder and piston. Fig. 7 – Low, the valve has a large size of orifice. score 0/0/0	Low, the valve has a large size of orifice and the container has a large working channel size. score 0
Discreteness (positioning resolution) (0...5)	High, the opening size of the valve can be set very small. score 5	High, the unit fluid volume corresponding to the unit rod's displacement is small. score 5	Fig. 5, 7 – Low, limited number of chambers and working windows. score 1/1/1	Medium, the volume of the container(s) can be small. scores 3

Table1 [cont.]

Property	Structure of the actuator based on positioning method			
	M1 – analog control of fluid supply to reach the preset position	M2 – discrete control the time of fluid supply to reach the preset position	M3 – discrete control of fluid supply to reach the preset fixed position	M4 – discrete control of portioned fluid supply to reach the preset position
Cost (–5. . . 0)	High, the parts of the valve require high machining accuracy. score –5	Upper-middle, the parts of the valves do not require high machining accuracy, but there are many valves. score –4	Medium, simple structure and moderate requirements for the machining accuracy of components. score –3/–3/–3	Medium, a large number of complex components are required but not high requirements for the machining accuracy of components. score –3
Response speed (0. . . 5)	High, valve opening can quickly reach a large size. score 5	High, the valve opening can quickly reach maximum size. score 5	Fig. 5, 7a – High, the valve opening can quickly reach maximum size. Fig. 7b – Low, filling and releasing of the working fluid to the chamber is slow. score 5/5/2	Low, filling and releasing of the working fluid to the container(s) is slow. score 2
Speed controllability (0. . . 5)	Yes, the valve opening can be continuously adjusted score 5	Yes, by changing the amplitude and frequency of control signals. score 3	No, score 0/0/0	Yes, by changing the frequency of filling and releasing the working fluid. score 1
Limitation of locations that can be positioned (–5. . . 0)	No, defined by discreteness score 0	No, determined by the working frequency of the valve. score 0	Yes, High, determined by the number of working windows and multi-chambers. score –5/–5/–5	Yes, Medium, determined by the volume of container(s). score –3
Working force (0. . . 5)	High, the chamber with rod is connected to the tank. score 5	High, the chamber with rod is connected to the tank. score 5	Fig. 5 – Low, the chambers on both sides of the piston are supplied with pressure fluid. Fig. 7 – Low, the rod chamber is supplied fluid with pressure. score 2/2/2	High, the chamber with rod is connected to the tank. scores 5

Table 2. Relationship between the structure and properties of actuators based on different positioning methods

Property	Structure of the actuator based on positioning method			
	M1 – analog control of fluid supply to reach the preset position	M2 – discrete control the time of fluid supply to reach the preset position	M3 – discrete control of fluid supply to reach the preset fixed position	M4 – discrete control of portioned fluid supply to reach the preset position
Positioning speed	5	5	5/4/3	3
Positioning accuracy	5	5	3/5/3	4
Requirements for cleanliness of working fluid	–5	0	0/0/0	0
Discreteness (Positioning resolution)	5	5	1/1/1	3
Cost	–5	–4	–3/–3/–3	–3
Response speed	5	5	5/5/2	2
Speed controllability	5	3	0/0/0	1
Limitation of locations that can be positioned	0	0	–5/–5/–5	–3
Working force	5	5	2/2/2	5
Total score	20	24	8/9/3	12

effectiveness of the desired set of properties. Based on the criterion, the dependence of the properties on the effectiveness of the corresponding positioning method is presented in Fig. 11.

In Fig. 11, the horizontal axis represents the total effectiveness score of positioning actuators based on different positioning methods, and the vertical axis displays the total score of each positioning method for all properties. Colored blocks represent properties with positive scores, and black-and-white blocks indicate properties with negative scores. The score given for the positioning methods for each property is denoted by the thickness of the blocks and the number in their area.

It is obvious that the effectiveness scores of the positioning actuator based on the positioning methods M1 and M2 are the higher ones. However, M1 scored the lowest in terms of the two properties – cost and requirements for cleanliness of the working fluid. Therefore, overall, the actuator structure based on the positioning method M2 shows the best performance when all properties are evaluated.

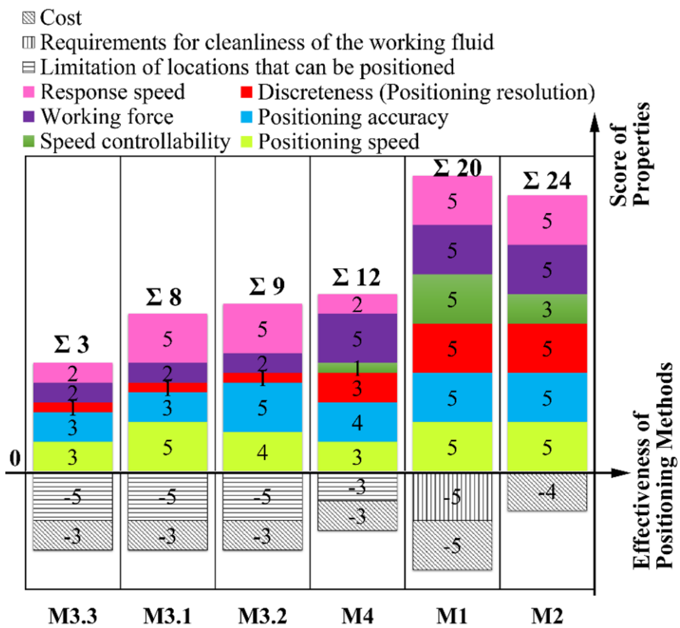


Fig. 11. Dependence between properties and effectiveness of positioning methods. M1 – analog control of fluid supply to reach the preset position; M2 – discrete control of the time of fluid supply to reach the preset position; M3.1 – discrete control of fluid supply to reach the preset fixed position (Fig. 5); M3.2 – discrete control of fluid supply to reach the preset fixed position (Fig. 7a); M3.3 – discrete control of fluid supply to reach the preset fixed position (Fig. 7b); M4 – discrete control of portioned fluid supply to reach the preset position

The relationship between the structure and the properties of actuators is reflected in Table 2 and Fig. 11. Using the positioning method that corresponds to the actuator's structure one can determine the effectiveness of actuator properties.

For some actuator applications, the required properties are high positioning accuracy and positioning speed, low cost, low requirements for the cleanliness of the working fluid, high discreteness, and controllability of the positioning speed. So, each of these properties should achieve the highest score in its corresponding score range. Based on the data in Table 2 and Fig. 11, one can identify promising structures for positioning actuators. In terms of positioning accuracy, positioning speed, discreteness, response speed, controllability of positioning speed, working force, and unlimited number of locations, the structure of the actuator based on positioning method M1 is the best. However, if considering the cost and the requirements for the cleanliness of the working fluid, the structure of the actuator based on positioning method M2 is the best choice. Due to the obvious lack of positioning accuracy, limited number of locations, and poor positioning discreteness, the structures of actuators based on positioning methods M3 and M4 are not a promising choice. Considering all the properties, one can consider the structure of the positioning actuator based on the positioning method M2 as the most promising option. At the same time, although discrete valves are critical, one may also take into account the advantage of the structure of the actuator based on positioning method M1 – which is the controllability of positioning speed.

3.1. Substantiation of the obtained results

The state diagrams of the component interaction in each type of electro-hydraulic positioning actuator were obtained by analyzing the cause-and-effect relationships in the actuator's positioning process. The correctness of state diagrams is confirmed by compliance with the logic of step-by-step changes in the components state, and their interaction through the working fluid under the influence of the control signal.

The study is based on the known actuator schematics, the feasibility of which has been declared and confirmed inprevious research works. The evaluation of influence of certain specific factors on the properties of actuators is based on determining the causes and effects, taking into account well-known physical laws. Under normal operation conditions, according to the physical laws, one can predict that the effect caused by changes in certain factors can be evaluated on the qualitative level. Evaluation of specific scores within a given scale is performed by comparing the potential of each property when changing the influential parameters of each type of actuator. The quantitative scale used for evaluation, as well as the specific scores for evaluation of each factor of the influence materiality, allows one to approximately assess actuator's properties. The positive effects of application of these tools also confirm the reliability of the results obtained. The determined relationships between the structure and properties of actuators allows the researchers to develop a new scheme solution for positioning actuators with the desired properties, which is the direction of further research.

4. Discussion

In the study [2, 8], the influence of actuators' specific parameters on their characteristics was determined. In this paper, the component interaction processes in the known electro-hydraulic actuators in the positioning process were analyzed. These were illustrated with the detailed state diagrams for each type of actuator. The research direction of this paper is the same as that presented in the literature [12–15], but the subject of our research are electro-hydraulic positioning actuators. The generalized analysis of the actuator structures reveals several specific positioning methods, on which the actuator are based. Such methods include M1 – analog control of fluid supply to reach the preset position, M2 – discrete control of the time of fluid supply to reach the preset position, M3 – discrete control of fluid supply to reach the preset fixed position, M4 – discrete control of portioned fluid supply to reach the preset position. A new approach to the comparative evaluation of actuators based on different positioning methods is also proposed, which makes it possible to reveal the relationship between the structure and properties of actuators. The obtained results have deepened the understanding of the schematic structure of electro-hydraulic positioning actuators and the dependence between their properties, the positioning method and the components involved.

The development of schematic structures, such as the positioning actuators shown in Figs. 3, 5, 7 and 9, usually relies on intuition and experience. Obviously, this makes it impossible to quantitatively assess the performance of the properties of the developed schematics. The novelty of this work lies in creating a new perspective for the design of electro-hydraulic positioning actuators at the stage of developing the basic schematic structure. It is at this stage that the potential properties of actuators are established.

It is proposed that the schematic structure of an electro-hydraulic positioning actuator should be developed according to its desired properties. The basis for the implementation of the proposed principle has been presented in our work, that is, we have shown the quantitative relationship between the properties and the schematic structure that determines the positioning method of the actuator. Such a development approach is clearly more reasonable and formal than that only based on intuition and experience. Therefore, the development efficiency can be improved by reducing the number of iteration cycles needed when designing a positioning actuator close to the desired ones.

5. Conclusions

In this paper, known electro-hydraulic positioning actuators have been studied from the viewpoint of improving their design efficiency. Various types of schematic solutions were analyzed, in which the applied positioning method, the set of properties, the influencing factors and the relationship between structure and properties were taken into account. The results obtained can serve as the foundation for an iterative approach to designing electro-hydraulic positioning actuators with desired properties and characteristics, in which a lower number of iterations is needed. The main contributions can be summarized as follows:

1. A new perspective is proposed for developing schematic structures of electro-hydraulic positioning actuators, which involves the formation of the actuator structure accommodated to the required properties.
2. The factors affecting actuator properties are identified, and a quantitative assessment method for the properties and the performance of structural solutions is proposed.
3. The understanding of the actuator structure and the interaction processes between its components has been deepened, and some specific positioning methods have been revealed.
4. The relationship between the structure and properties of electro-hydraulic positioning actuators has been determined.

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