Review

Exploration and Research on Key Technologies for Improving the Response Speed of Servo-Hydraulic Cylinders

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Abstract: The operating efficiency of the hydraulic system depends on the response speed and driving efficiency of the hydraulic components. Seeking various methods and technologies to improve performance and work efficiency is an important work for many scholars. In this paper, the development and performance improvement of four generations of hydraulic cylinders are analyzed to obtain the development of the drag reduction technology by examples such as sealing methods, microtextured hydrodynamic lubrication, manufacturing materials, drive methods, control methods, etc. The reviewed results show that the drag reduction and efficiency improvement of hydraulic cylinders are affected by many factors, and the new drag reduction theories, advanced drag reduction technology, and emerging materials point toward the direction of the acceleration of hydraulic cylinders. Finally, according to the higher requirements for future cylinders, four new ideas are proposed for improving the speed performance of hydraulic cylinders, including new material sealing ring with low friction coefficient or self-lubricating, internal leakage suppression from smart material, implementation of servo control techniques and algorithms, and digital hydraulic technology. These new viewpoints may provide some methods and references for the speed improvement of hydraulic cylinders.

Keywords: hydraulic cylinder; response speed; gap sealing; hydrodynamic lubrication

1. Introduction

The high-speed servo hydraulic cylinder is a core component of high-end manufacturing automation equipment and can provide complex motions [1]. It is an executive element in a hydraulic servo control system and can convert hydraulic energy into mechanical energy [2,3]. Similar to the traditional hydraulic cylinder, it is generally composed of main parts, such as an end cover, cylinder barrel, piston rod, piston assembly, and base. Additionally, control modules such as servo modules and sensing components are added, as shown in Figure 1. In order to ensure its dynamic responsiveness, the control modules are generally installed near the hydraulic cylinder. Then, the movement is determined by the control modules.

In addition, another servo hydraulic cylinder is also controlled by a servo motor and hydraulic pump [4,5], which is called the direct-driven servo-hydraulic actuator, also known as the pump direct-driven cylinder (PDDC), shown in Figure 2. PDDC systems do not use direction valves, and the direction in them is controlled by the rotation of the servomotor connected to the reversible pump. The controlling method can combine the benefits of hydraulic and electric drives and has many advantages, such as higher accuracy and dynamics of the servomotor, easier maintenance, and lower usage of hydraulic oil.
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Figure 1. A hydraulic servo control system: (a) an actual diagram of servo-hydraulic cylinder; (b) working principle diagram of the servo-hydraulic cylinder.

Figure 2. A servo-hydraulic cylinder with pump direct-driven system [4,5].

At present, there are many servo-hydraulic cylinders in the world, such as Parker, Hänchen, Boatke, etc. These are widely used in many large and heavy-duty metallurgical fields, such as continuous casting machines for crystal vibration, electric vibration tables, structural fatigue testing machines, steel rolling mills, and other important places of metallurgical production. Some working parameters of servo-hydraulic cylinders in some metallurgical equipment are listed in Table 1.

Table 1. Working parameters of servo-hydraulic cylinders in some metallurgical equipment.

| No | Application                              | Maximum Load (KN) | Maximum Frequency (Hz) | Acceleration (m/s²) | Speed of Piston (m/s) |
|----|------------------------------------------|-------------------|------------------------|---------------------|----------------------|
| 1  | Continuous casting machines [6]          | 100               | 20                     | /                   | 0.5–1                |
| 2  | Six DOFs electrodynamic vibration tables [7] | 25                | 2000                   | 1.3                 | 1.78                 |
| 3  | Structural fatigue testing machines [8]  | 10                | 100                    | /                   | 0.5–1                |
| 4  | Steel rolling mills [9]                  | 10                | 20                     | 0.2–0.4             | 0.5                  |

Although servo-hydraulic cylinders have a wide range of applications, similar to traditional hydraulic cylinders, they also suffer from leakage and friction, as shown in Figure 1b. The contradiction between the friction and leakage of the seal interface has always been a problem that restricts speed performance since the development and application of hydraulic cylinders. For example, under an oil pressure of 30 MPa, the internal
leakage of the Hänchen-306 hydraulic cylinder can reach 350 mL/min [10]. Therefore, less leakage and good sealing performance are key to improving the response speed of the servo-hydraulic cylinder. Domestic and foreign scholars have carried out much research on the sealing and leakage of hydraulic cylinders including the technology of sealing methods, structure optimization, and manufacturing materials, which have made significant progress and greatly improved the response speed performance of servo-hydraulic cylinders [11,12].

Higher performance and service life of servo-hydraulic cylinders have been required with the development of hydraulic transmission technology moving in the direction of high speed, high-frequency response, high efficiency, and low friction; that is, the frictional resistance of the hydraulic cylinder movement pair should not only be small but the internal leakage must also be effectively controlled.

In this paper, an in-depth analysis of the drag reduction technology through cases to obtain the advantages and disadvantages of different methods is conducted; then, based on the results, four new ideas are proposed for improving the speed performance of hydraulic cylinders, including new material sealing ring with low friction coefficient or self-lubricating, internal leakage suppression from smart materials, implementation of servo control techniques and algorithms and digital hydraulic technology.

It is composed of six sections, including the introduction, conclusions, and the main four methods for the improvements of servo-hydraulic cylinders, such as sealing methods, microtextured hydrodynamic lubrication, manufacturing materials, drive methods, control methods, etc.

2. Internal Leakage Minimization Based on Sealing Technology

Sealing technology is a key technology that determines the quality and performance of hydraulic cylinders. There are two main sealing methods, that is, elastic ring sealing and gap sealing (which includes constant gap sealing and variable gap sealing). The former is sealed by sealing elements, and the latter is sealed by the gap flow. We first introduce the sealing technology and summarize its improvement in this section.

2.1. Elastic Ring Sealing

The traditional mechanical elastic ring sealing is composed of a seal ring and a support ring [13]. This has the function of a good sealing effect and less leakage and has also the advantages of low cost and convenient replacement. Therefore, it is the most widely used in hydraulic cylinders. We call it the first generation hydraulic cylinder [14], and the cross-section of the elastic sealing ring is shown in Figure 3.

![Figure 3. Schematic diagram of elastic sealing ring: (a) O-ring seal; (b) V-ring seal; (c) Y-ring seal.](image)

According to the structure and shape of the elastic parts, they can be divided into O-ring seals [15], V-ring seals [16], and Y-ring seals [17]. Many scholars continue to improve the performance and life of seals through structural optimization and numerical simulation [18,19]. Some also use more than two materials or two different ring structures for combined sealing [20]. Taking the O-ring seal, for example, the friction between the hydraulic cylinder and the sealing ring can be calculated with the microelement method proposed by Li’s group [21]. The axisymmetric model of an O-ring and C-type combined
sealing ring was established in their study, and the friction resistance of the sealing ring under different pressures was calculated.

\[
f = \pi d \int_0^B p(b) \mu db
\]  

(1)

where the friction force is defined as \( f \) between the hydraulic cylinder and the sealing ring. The friction coefficient is defined as \( \mu \), and \( p(b) \) is the contact stress; its value will be changed by \( b \) (the term \( b \) is the width of the sealing groove, and its value ranges from 0 to \( B \)), and the diameter of the piston is \( d \), which is shown in Figure 4 and Equation (1).

\[p\ (b)\ , \ \mu\]

2.2. Constant Gap Sealing

Other alternative solutions are based on gap sealing of the hydraulic cylinder, and the tiny gap between the piston and the cylinder is used for sealing. As the sealing interface does not contact, the friction between the cylinder and the piston is greatly reduced. Therefore, the response speed of the piston is effectively improved. We call it the second generation hydraulic cylinder, as shown in Figure 5.

\[\text{Figure 5. Schematic diagram of the constant gap sealing: (a) support ring of constant gap sealing; (b) structure of constant gap sealing.}\]

In 1983, Hans-Dieter Fabrowsky and others improved the gap sealing technology and invented the annular gap seal (Servofloat) [23]. The floating ring was adopted to make the annular gap seal automatically centered against radial friction. The gap value was constant.
At the beginning of the 21st century, Gordon et al. [24] proposed a concept of gap sealing with end-face modification. It could change the lubrication condition between the end faces to achieve long-lasting operation of the mechanical seal by cutting various grooves on the seal’s end faces. In 2006, Herbert Busse [25] and others further improved the gap sealing technology, which prevented the gap amount change caused by the deformation of the annular gap seal. By processing multiple pressure-equalizing grooves on the surface of the piston, the lubrication effect was increased, and the speed of the piston was effectively improved. This can achieve the drag reduction lubrication (for example, the movement speed of the piston was increased from 0.1 m/s to 0.7 m/s).

However, there is serious internal leakage with the increasing pressure, which can result in low volumetric efficiency and also reduce the working efficiency. The internal leakage $q$ is related to parameters such as the sealing gap ($h_0$), the pressure difference between the two chambers of the hydraulic cylinder (the high-pressure chamber $p_1$ and the low-pressure chamber $p_2$), structure parameters (the length $L$ and diameter $d$ of the piston), and the properties of the oil (density $\rho$ and viscosity $\eta$), shown in Figure 6. Then, the internal leakage can be obtained by Equation (2) [26].

$$q = \frac{\pi dh_0^3 (p_1 - p_2)}{12\rho \eta L}$$

where the internal leakage is defined as $q$, and the term $h_0$ is defined as the sealing gap between the hydraulic cylinder and the piston. The symbols $p_1$ and $p_2$ are used to express, respectively, the two pressure of the high-pressure chamber and the low-pressure chamber. The length and the diameter of the piston are defined as $L$ and $d$, respectively. Meanwhile, the density $\rho$ and the viscosity $\eta$ are the physical properties of the hydraulic oil, which are shown in Figure 6 and Equation (2).

The above calculation formula (Equation (2)) is obtained when the hydraulic cylinder and the piston are coaxial. While the piston is off-center, and the relative eccentricity is defined as the term $\varepsilon$; then, its leakage will increase significantly and can be expressed by Equation (3) [26].

$$q = \frac{\pi dh_0^3 (p_1 - p_2)}{12\rho \eta L} (1 + 1.5\varepsilon^2)$$

where the term $\varepsilon$ is defined as the relative eccentricity, which is equal to $\varepsilon/h_0$. The term $\varepsilon$ is the eccentricity of the piston and the cylinder. The other parameters are the same as Equation (2).

Then, it can be concluded that the leakage of the annular gap is proportional to the relative eccentricity when the other parameters are not changed.

### 2.3. Variable Gap Sealing

On the basis of summarizing the advantages and disadvantages of the previous two generations of hydraulic cylinders, scholars such as Zhan Congchang and Jin Yao, among others, developed the third generation hydraulic cylinders with a new type of gap, that is,
a variable gap seal. The structural characteristics or material differences between the piston and the cylinder barrel were used in the cylinder to achieve a variable sealing gap.

2.3.1. Variable Gap Sealing Based on Structural Design

Congchang et al. [27] adopted the theory of elastoplastic deformation in metal materials and proposed a variable gap sealing technology based on the principle of automatic pressure compensation. When the pressure rises in the high-pressure working chamber of the cylinder, the lip will be slightly deformed under the action of the oil pressure difference between the inner and outer rings, which will reduce the sealing gap between the cylinder barrel and the piston, thereby reducing the leakage, as shown in Figure 7a. A pressure compensation mechanism was used in the hydraulic cylinder to establish a gap sealing flow field that can automatically adapt to pressure changes, reducing the pressure to 95 mL/min under 31.5 MPa.

![Figure 7. Schematic diagram of the variable gap sealing: (a) lip structure; (b) cavity structure.](image)

Subsequently, the variable lip structure was improved by Yao et al. [28], shown in Figure 7b, and a method was proposed to change the sealing gap by radially expanding the outer surface of the piston, which was close to the inner wall of the cylinder. The thin-walled sleeve was used as the deformed structure and fixed in the middle of the piston. Then, a cavity was formed, and the outer piston was tightly sleeved on the outside of the thin-walled sleeve. When hydraulic oil entered the cavity, the thin-walled sleeve expanded and deformed under the condition of increased pressure, which would cause the outer piston to deform. Therefore, the gap between the piston and the inner wall of the cylinder was reduced for less leakage.

However, the two kinds of variable gap structure seals mentioned above often failed due to plastic deformation. Meanwhile, the service life was short due to errors in the manufacturing and assembly. Thus, some scholars began to explore the possibility of achieving the variable gap sealing function from a material point of view. We introduce the realization of gap compensation from the material properties in the next section.

2.3.2. Variable Gap Sealing Based on Different Material Properties

Heterogeneous materials have superior physical, chemical, and mechanical properties and are widely used in various industries. The loading surface can deform at the position of the heterogeneous body due to the difference between the deformation of the matrix and the heterogeneous body.

Xianzhong et al. [29] designed a new type of heterogeneous ring structure based on the principle of equivalent inclusions, shown in Figure 8. The radial deformation was produced due to the difference in the matrix and heterogeneous ring materials, which was used to improve the sealing performance of the gap seal hydraulic cylinder. The mathematical model of the elastic deformation caused by the ring-shaped heterogeneous material was
established, and the heterogeneous ring model was numerically simulated. The results show that the soft ring structure can cause convex deformation on the surface of the piston, and the hard ring structure can cause concave deformation on the surface of the piston. Therefore, the gap in the hydraulic cylinder can be effectively reduced by reasonably setting the structure, distribution parameters, and material properties of the heterogeneous ring.

![Figure 8. Schematic diagram of the heterogeneous ring [29].](image)

Xiaolan et al. [30] proposed a variable gap sealing method for hydraulic cylinders based on a magnetic shape memory alloy (MSMA). This is a kind of smart material and will deform under a magnetic field, as shown in Figure 9. The amount of deformation is related to the size of the magnetic field. In their study, a plurality of annular grooves was designed on the outer surface according to the length of the piston, and several MSMA auxiliary support blocks were continuously arranged in the annular groove, thereby constructing a few gapped seal rings. When changing the coil current, the size of the magnetic field can be changed. Therefore, the gap is controllable and variable to achieve the purpose of reducing leakage.

![Figure 9. Schematic diagram of the variable gap based on MSMA.](image)

The above two methods change the sealing gap of hydraulic cylinders through the difference in deformation of heterogeneous materials or the flexibility of smart materials, which are still in the experimental stage and difficult to implement for application.

3. Drag Reduction Technology Based on Fluid Lubrication

Surface texture technology for dynamic pressure lubrication has been proven to be the most effective method for drag reduction and speed increase in high-speed and heavy-duty servo-hydraulic cylinders. The convex or concave pattern textures (microtextures) are constructed based on the wedge effect, which can improve the bearing capacity of the lubricating oil film on the sealing interface to reduce the friction coefficient.
The friction pair is regarded as a rigid contact for the surface texture lubrication, and the elastic deformation of the material is ignored. In fact, the contact stress between the piston and the inner wall of the cylinder is very high under heavy-load contact (under a large deflection force, it can reach 500 MPa). It will cause local elastic deformation of the contact surface, which can affect the film thickness and pressure distribution, and ultimately affect the performance of dynamic pressure lubrication.

3.1. Bionic Microtexture Dynamic Pressure Lubrication and Drag Reduction

There is a certain initial matching gap between the cylinder tube and the piston in a high-speed servo-hydraulic system, which can usually reach 10–50 μm, and the gap is filled with lubricant (hydraulic oil), so the type of friction between the moving pairs is determined as the complete fluid lubrication based on the state of fluid lubrication. When a certain bionic microtexture morphology is designed on the inner surface of the cylinder barrel, its effect on the interface of the moving pair can be regarded as the effect of a hydrodynamic bearing. When the texture morphology changes, the hydrodynamic lubrication effect will also be changed accordingly.

According to the characteristic of the grid and striped textures, Chen et al. [31] compared diamond-like textures and strip textures to determine the optimal textures by solving the Reynolds equation while considering the influence of multiple parameters simultaneously, including the axial length ratio, the diamond angle, and the area occupancy, as shown in Figure 10. The results show that the lift of the diamond texture is nine times greater than that of the striped texture under the same working conditions, while its friction coefficient is only one-quarter of the striped texture, which can greatly improve the friction and responsiveness of the hydraulic cylinder.

![Figure 10](image)

**Figure 10.** The hydraulic cylinder with diamond-like microtextures: (a) structure of hydraulic cylinder; (b) schematic diagram of a partially microtextured hydraulic cylinder.

It can be seen that dynamic pressure lubrication has a significant relationship with texture morphology. It depends on characteristic parameters such as the shape, depth, and distribution of the texture itself, in addition to depending on the influence of actual working parameters such as load–velocity, fluid temperature and viscosity, and contact surface roughness.

Zhang’s group [32] took the piston as the object and established single-textured and nine-textured models to compare and study their synergy based on the classical Reynolds equation, as shown in Figure 11. The simulation results reveal that the beneficial effect of the synergy firstly increases and then decreases as the area ratio of the texture increases. This is because the synergy of the textures acts as an “average pressure” and causes the pressure to decrease. As the area ratio of the texture increases, the beneficial effect from the synergy gradually increases and then decreases, which implies that there is an optimum area ratio—when the depth-to-area ratio is 0.009, and the texture depth is 10 μm, the synergy effect on the lubrication effect is best. Additionally, we can learn from the study that, for a hydraulic cylinder with a light load, the film thickness changes with speed, and...
the synergistic exists but does not result in a substantial change. Therefore, the synergy is still related to the loads, structure of microtextures, etc.

Figure 11. The hydraulic cylinder with micro textures [32]: (a) structure of hydraulic cylinder; (b) schematic diagram of single-textured and nine-textured piston.

Aiming at constraining the seal performance and friction of the piston, a drag reduction technology using a bionic non-smooth surface was presented by Xu et al. [33]. The seal ring of the cylinder was chosen as the research object, and there were many bionic textures on its outer surface, as shown in Figure 12. The piston speed and the bionic pit diameter for the drag reduction effect were studied. The simulation results demonstrate that the effective stress of the bionic non-smooth sealing ring meets the requirement of cylinder seal tightness when the compression rate is 20%. Moreover, it is able to reach the maximum drag reduction rate under a certain speed of the piston when the pit diameter is 1.5 mm. Meanwhile, the drag reduction rate increases with an increase in initial velocity and a certain diameter of the pit. The seal ring has a stable drag reduction rate when the speed reaches 0.6 m/s.

Figure 12. Bionic dimple feature of rubber sealing ring: (a) triangular element on the surface of the rectangular seal; (b) size and structure.

The drag reduction method of dynamic pressure lubrication plays a positive role in the early stage of use and is very effective in increasing the speed of the hydraulic cylinder. However, with the prolongation of use time, the textures on the surface of the friction pair will be gradually worn away, resulting in a greatly weakened drag reduction effect.

Nevertheless, exploring the general laws of texture drag reduction also needs to be further studied in the future, for example, how to make the texture wear-resistant and prolong its service life.

3.2. Gas and Coating-Assisted Drag Reduction

The existing textured gap seal is mainly based on the solid–liquid two-phase perspective, which can achieve the purpose of drag and wear reduction by generating a liquid film on the interface. Etsion and other scholars [34,35] found that the internal flow field of the texture was a simple two-phase state (that is, an existing solid and liquid), but micro–nanobubbles were also formed. Thus, how to reduce the wear resistance of the surface
textures and ensure the stability and durability of the dynamic pressure oil film between the moving pairs are the key factors in maintaining good lubrication characteristics of the textured hydraulic cylinder.

Mao et al. [36] studied the effect of the number of bubbles on the change in both fluid dynamic pressure and interface friction coefficient during the generation, development, and collapse of cavitation bubbles based on the boundary conditions of the conservation of mass, shown in Figure 13a. The mass flow parameters were selected as the conservation parameters to derive an improved Reynolds formulation. An analytic mathematic model was established to describe a uniformly distributed microtexture cavitation and address the variable density. The analytic solution of the cavitation characteristics was calculated coupled with the wedge effect, and the optimization results provided a reference for the gas–liquid mixed flow, which can be used to improve the performance of hydraulic components.

However, some researchers believe that bubbles have a negative influence on the cavitation process because the bubbles cause instability and noise in the hydraulic system. Furthermore, they localize high temperatures and pressure peaks, which leads to worse properties of hydraulic components [37–39].

Chen et al. [40] investigated the tribological performance of untextured and textured brass surfaces with TiN coatings by pin-on-disc experiments under oil lubrication, as shown in Figure 13b. They designed a dimple pattern with different diameters and depths for the transverse surfaces of brass pins. After texturing, they used a Ti target plating in pure nitrogen to obtain the TiN coatings, which were deposited through a pulsed-bias arc ion. Additionally, friction tests were carried out under different rotating speeds and loads, and then the interfacial adhesion was assessed by a scratch test. The results show that the textured surface can improve tribological behavior in mixed lubrication because it can generate hydrodynamic lift in the dimples, compared with the untextured one.

An epoxy-based nanocomposite for lubrication between the piston and the composite material was proposed by Scholz et al. [41]. It was theoretically proved that it can effectively resist wear. Under the actual working conditions of 0.4 Hz and 35 MPa, the nanocomposite materials were repeatedly operated for 50,000 cycles, and it was found that the average surface roughness was reduced from the original 1.5 μm to 0.29 μm, and the wear resistance was significantly improved. Therefore, it is revealed that the proposed coating structure has good wear resistance.

3.3. Elastohydrodynamic Lubrication with Particle-Reinforced Composite Materials

A type of particle-reinforced composite material was introduced for one of the components of a heavy-load contact pair based on the principle of microtexture dynamic pressure lubrication by Chen et al. [42,43], as shown in Figure 14. They constructed the Ree–Eyring model to analyze the performance improvement of elastohydrodynamic lubrication (EHL), considering the surface of the particle-reinforced composite material. Additionally, the minimum film thickness distribution under different loads, speeds, and initial viscosity
were also investigated. The results present the effects of different rough topographies combined with the related parameters of the particles on the EHL performance.

![Diagram](image.png)

Figure 14. Elastohydrodynamic lubrication with particle-reinforced composite materials: (a) simplified model of inclusion EHL problem; (b) EHL in line contact with different rough surfaces.

Drag reduction technology based on fluid lubrication essentially reduces the frictional resistance by constructing the oil film support force. However, the scale of the oil film is micrometers or even nanometers, which is greatly affected by external macroscopic and microscopic factors. The traditional macroanalysis is very limited, and it is necessary to introduce difficult microanalysis methods, such as molecular dynamics simulation.

4. Hydraulic Cylinders of Other Composite Materials

Carbon fiber composite materials are increasingly used in construction machinery and aerospace industries due to their low density, corrosion resistance, and high fatigue properties [44,45]. Many scholars have also put forward ideas on the lightweight of hydraulic cylinders. Hydraulic cylinders with improved performance from a material point of view can be called the fourth generation.

A hydraulic cylinder made of carbon fiber composite material was proposed by Zhou et al. [46], which can achieve lightweight and forming processing. It was made of high-strength carbon fiber strands, with a strength greater than 3500 Mpa as a reinforcing material and a thermosetting resin as a matrix, which can greatly reduce the weight of the hydraulic cylinder.

The team of Professor Xu Bing, of Zhejiang University, developed a carbon fiber composite hydraulic cylinder [47,48]. A mosaic connection method was proposed for the connection between the layers of different composite materials, which can reduce the weight of the whole machine by 30%, compared with the steel hydraulic cylinder. It is important to note that the hydraulic cylinder has been successfully applied. They proposed that the carbon fiber composite hydraulic cylinder can be improved by coating, processing, and post-processing to allow for better performance and higher efficiency and will serve better for the hydraulic system [49].

Hydraulic cylinders made of composite materials have been proven to have weight reduction and similar performance, compared with the traditional structural steel, through the FEM analysis and experiments by Solazzi et al. [50–52]. They designed a hydraulic cylinder with its piston rod made of composite material and the cylinder tube made of aluminum alloy tubular element wrapped in the composite material. The simulation and experimental results show that the new hydraulic actuator has a weight of about 12% of the one in traditional structural steel, and it is able to resist very common damage phenomena. Moreover, it also can be used for the evaluation of the stick–slip phenomenon for the
piston seals inside the cylinder, which is important for the speed improvement of the hydraulic cylinder.

5. Drive and Control Method

The above content describes the effect of drag reduction and acceleration from the aspects of the sealing method, component structure, and component material of the motion pair. However, the hydraulic cylinder is an integral part of the hydraulic system, and the performance of the internal control components and the use of the control method in the system will also affect its response speed performance [53,54].

The action of the hydraulic cylinder is mainly driven by the control elements. Therefore, its speed responsiveness can be indirectly enhanced by improving the precision of the control elements. In 1946, Tinsley of the United Kingdom developed a two-stage electrohydraulic control servo valve [55]. However, its control accuracy was not high because the spool and sleeve of the servo valve needed to be precisely matched. Then, electrohydraulic proportional valves were developed in the late 1960s, using proportional electromagnets as electromechanical converters, and electronic mechanical converters of valves were constantly updated and upgraded [56].

In recent years, servo-controlled valves made of smart materials have become a research hot spot. A specific driving method was proposed for electrohydraulic servo valves based on a large-inductance giant magnetostrictive actuator (GMA) by Zhaoshu et al. [57]. They set up a multi-coupled model for the overall servo valve and simulated it in a joint environment of Simulink and AMESim. Both the simulation and test results verified that it generated a smoother wave using fewer switch numbers and fewer switching losses, compared with the driving mode of traditional sinusoidal pulse width modulation (SPWM).

6. Conclusions

In summary, the elastic sealing ring is easy to replace with low costs in spite of high friction and was suitable for high-pressure hydraulic systems in the first generation. In the second generation, the fiction was reduced due to the non-contact moving pair, but there was more leakage. The microtextured dynamic pressure lubrication in the third generation greatly reduced the friction force, and the speed of the piston was significantly improved, but its internal leakage could increase with the increase in the working pressure. The use of smart materials and carbon fiber materials to design and manufacture fourth-generation hydraulic cylinders is a future development direction. Currently, the costs in the research and development stage are relatively high, and practical applications need to be promoted. Additionally, the control technologies of servo valves are important, and the response speed performance of servo-hydraulic cylinders can be ultimately improved through hardware upgrades and control methods. In addition, the properties of hydraulic oil and the manufacturing accuracy of hydraulic parts are not negligible factors. Therefore, there are many ways to improve their dynamic response.

Hydraulic cylinders have experienced a long period of development, from a purely mechanical structure to the integration of mechatronics, digital hydraulics technology, and a variety of communication technology. It is the goal of the continuous development of Industry 4.0. In the future, with the development of materials science and testing technology, hydraulic cylinders that are lightweight and have high pressure resistance, low leakage, low friction, fatigue resistance, and superior mechanical properties may be increasingly needed in the industry. Therefore, we can continue to explore and increase the response speed of servo-hydraulic cylinders in terms of the following aspects:

(i) For a period of time in the future, the sealing method used for the servo-hydraulic cylinder will still be dominated by the elastic ring seal due to its convenience in terms of replacement and operation. With the continuous advent of new materials, it is possible to develop new materials with low friction coefficients or new materials with their own lubricating function. In addition, changing the type of lubricant is a good
choice, such as the use of magnetic fluid and ionic liquids. Sealing rings made of these new materials or new lubricants can achieve a certain degree of lubrication.

(II) In terms of minimizing internal leakage from the material point of view, the use of emerging smart materials with a telescopic function effectively compensates for the clearance of the hydraulic cylinder. By controlling the amount of deformation of the smart material, the effective control of the sealing gap between the hydraulic cylinder and the piston can be realized, and finally, the purpose of reducing internal leakage and improving volumetric efficiency can be achieved.

(III) From the perspective of the control components of the hydraulic system, the control algorithms, such as PID, neural networks, genetic algorithms, and machine vision, are used to greatly improve the control accuracy and performance of the servo valve, and indirectly obtain a better response speed of the hydraulic cylinder.

(IV) With the continuous development of modern computer information and electronic technology, digital hydraulic technology has gradually emerged and can be used to achieve rapid development because it is very simple to operate, the control technology is also greatly simplified, and the control precision is higher.

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