Dividing and Conquering: Engineering Measures for the Storage Life Extension of Electro-Hydraulic Servo Mechanism in Natural Storage Conditions

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Abstract. In recent times, there has been a growing interest in examining the reliability and service life of electro-hydraulic servo mechanisms under natural storage conditions. Notably, extensive research has been conducted on the topic of prolonging the storage life of these mechanisms. However, due to the diverse components involved in electro-hydraulic servo mechanisms, determining accurate influencing factors through whole-machine accelerated storage methods has proven to be difficult. As a result, individual component accelerated storage methods have been employed in the past to estimate the storage life of the entire machine. Nonetheless, this approach lacks an understanding and verification of the actual lifespan and performance changes under natural storage conditions. This paper aims to explore the performance changes of electro-hydraulic servo mechanisms under natural storage conditions. A divide-and-conquer approach is employed to analyze the hydraulic circuit and control circuit's performance changes separately. The research investigates each component in corresponding circuits to identify how its performance changes under different natural storage times and suggests appropriate measures to extend their service life. Actual sample test results demonstrate that the proposed engineering measures can effectively prolong the period during which electro-hydraulic servo structures can be utilized under natural storage conditions.

Keywords: natural storage · electro-hydraulic servo mechanism · performance change rule · storage life extension

1 Introduction

In the 1960s, the development of electro-hydraulic servo valves led to the rapid adoption of electro-hydraulic servo systems as the primary choice for control system actuators in aviation, aerospace, and navigation due to their precise control and high power characteristics [1–4]. Recently, there has been a growing urgency in the field of aerospace to study the performance variation of electro-hydraulic servomechanisms under natural storage conditions. Such research is useful for understanding the performance change

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law of electro-hydraulic servomechanisms under specified storage conditions, which can lead to the formulation of corresponding storage life extension strategies in advance and ultimately improve the economic benefits of the product. While some research results and application information on the accelerated storage life test of components and raw materials are available [5, 6], few reports exist on the accelerated storage life test of the whole machine [7, 8]. The complexity of the electro-hydraulic servo mechanism, which is composed of components and parts from various professional fields such as machinery, electronics, and hydraulics, presents challenges for carrying out accelerated storage test research on the complete mechanism as the test object. Although some studies have focused on the accelerated storage test method by selecting representative components, this method lacks an understanding of the actual service life of the servo mechanism under natural storage conditions. Therefore, this paper utilizes a divide-and-conquer approach to analyze the performance changes of key components in the control and hydraulic circuits of the electro-hydraulic servo mechanism under natural storage conditions. Corresponding engineering measures are proposed to extend the storage life, and the effectiveness of these measures is validated through the results of measured samples.

2 Two Components of the Electro-Hydraulic Servomechanism

The electro-hydraulic servo mechanism is a highly complex product, which integrates mechanics, electronics, and hydraulics, and uses a large number of components and parts belonging to different professional fields, including servo motors, oil pumps, servo valves, and feedback potentiometers, pressure sensor, oil level potentiometer, various valves, various seals and non-metallic materials, etc.

In this section, the main components involved in the hydraulic circuit and the control circuit are briefly introducted:

1) Hydraulic circuit

In the hydraulic circuit of the electro-hydraulic servo mechanism, the servo motor drives the oil pump to rotate and draw low-pressure oil from the oil tank. The oil is then compressed into high-pressure oil and outputted to the high-pressure oil circuit. The hydraulic circuit is equipped with various valves and oil filter components such as check valves, overflow valves, high-pressure safety valves, low-pressure safety valves, and magnetic oil filters to regulate the working pressure of the system and ensure its safety and reliability. Additionally, an accumulator is installed in the high-pressure oil circuit as an auxiliary energy source to maintain system pressure stability and provide backup pressure for the oil tank. The high-pressure oil is directed to one side of the cylinder via servo valve control, while the oil on the other side flows back into the oil tank, thus completing the hydraulic circuit's closed loop. Therefore, the key components in the hydraulic circuit include servo motors, oil pumps, various valves, oil filter, metal structures, and seals.

2) Control circuit

In the control circuit of the electro-hydraulic servo mechanism, a small command current signal is received by the servo mechanism, which amplifies it into a high-pressure flow with a certain power through the servo valve. This flow enters the actuator cylinder to achieve the telescopic movement of the piston rod, and the displacement sensor in the actuator cylinder moves synchronously with the piston rod to provide feedback on the position signal to the control system, forming a position closed-loop control. Additionally, the servo control strategy also involves closed-loop control using machine speed or velocity as the closed-loop control quantity. It should be noted that various sensors play an essential role in the closed-loop control process, as they collect the status information of the servo mechanism and feed it back to the control system. Therefore, the components involved in the control circuit of the electro-hydraulic servo mechanism include the servo valve, displacement sensor, and various other sensors.

3 Analysis of Performance Change Law of Components Under Natural Storage

After conducting visual inspections, performance tests, and statistical analyses on servo mechanism samples with varying natural storage times, it was observed that prolonged storage time led to various issues in the entire servo mechanism. These issues included shell corrosion, insulation resistance reduction, oil and air leakage, and potentiometer linearity tolerance violations, among others. Shell corrosion accounted for a relatively large proportion of problems, but did not affect the overall machine performance. Conversely, while other problems were less frequent, they still caused a negative impact on the entire machine as the storage environment influenced its components. In general, performance degradation of components was delayed, meaning that the system's performance did not immediately deteriorate; a certain degree of degradation was needed to cause performance deterioration. Hence, this section aims to analyze the performance of hydraulic circuit and control circuit components during natural storage.

3.1 Performance Analysis of Hydraulic Circuit's Components Under Natural Storage

Servo motor.

The servo motor is a vital component of the electro-hydraulic servo mechanism, responsible for converting electrical energy into mechanical energy to power the load pump and facilitate precision control of the servo mechanism. The motor's construction consists of three primary components: the stator, which comprises the motor housing and magnetic poles, the armature, consisting of the armature winding and commutator, and the brush device. The armature, composed of a combination of metal parts and insulating materials, plays a pivotal role in influencing the motor's electrical performance.

During long-term storage, it is generally believed that the metal parts in the armature do not undergo significant changes, but the insulating materials such as paint leather, impregnated varnish, insulating varnish, and insulating cloth may age. The grease in the servo motor armature support bearing may also volatilize or dry up, leading to the bearing running under no lubrication conditions and increasing the friction torque. An increase in frictional torque results in an increase in current and temperature, which directly affects the reliability of the scroll spring in the motor and can even cause the motor to burn out. Additionally, long-term storage may result in debonding of stator

Table 1. Retest data of motor performance at different storage times

Items	**Storage Time (Years)**					
	0	***4***	***8***	***12***	***16***	***20***
Load torque/(N·m)	1.68	1.68	1.68	1.70	1.72	1.82
Rotational speed/(r·min^{-1})	5308	5304	5282	5274	5078	5055

magnets and wear of the rotor commutator, as well as poor contact between the brush and armature due to brush wear.

The main performance parameters of a motor are its load torque, speed, and other related factors. After conducting tracking tests on motor samples with different storage times, it was observed that the motor's performance deteriorated to varying degrees over time. Table 1 presents the motor performance data under various storage times. Specifically, the load torque of the motor increased with an increase in storage time, while the rotational speed decreased, which aligns with the theoretical condition of brush wear under long-term work. Notably, the motor's performance changed significantly after 15 years of storage, possibly due to the armature support bearing being in a non-lubricated state at this point.

Oil pump.

During long-term storage and use, the plunger rods in the seat and plunger of an oil pump experience wear, resulting in an increase in their total axial clearance value. This clearance value reflects the closing quality of the plunger assembly, which is a critical factor in the reliability of the pump. If the closing quality is poor, the plunger may pull off, leading to pump failure. The gaps between the plunger rod and the seat, and the plunger rod and the plunger, are crucial indicators of closing quality. These gaps should allow for flexible movement without jamming or freezing, and their values must be controlled within a specific range to ensure pump life and reliability. With continued use, the friction pair will experience wear, leading to increased axial clearance of the plunger assembly.

Another issue that can arise during long-term storage of hydraulic servo products is oil leakage in the oil pump. This issue is caused by the various sealing forms present in the pump structure, particularly the mechanical seal pair which belongs to the contact seal. As the oil pump operates, the moving ring rotates with the transmission shaft at high speed, creating an oil wedge on the contact surface that prevents oil from flowing from the outside of the driven ring to the inside, achieving a dynamic sealing effect. However, over time, the seals will age, leading to a decrease in sealing performance and potentially causing severe oil leakage that can result in pump failure.

The rated flow rate of an oil pump under the same pressure and speed conditions is an indicator of its performance. Assuming a working pressure of 14 MPa, retesting of oil pump samples with different storage times showed that the longer the storage time, the greater the decrease in the rated flow rate. Table 2 presents the retest data for the rated flow rate of the oil pump at different storage times.

Table 2. Retest data of oil pump performance at different storage times

Items	Storage Time (Years)					
	0	***4***	***8***	***12***	***16***	***20***
Rated flow rate/(L·min^{-1})	3.85	3.81	3.78	3.73	3.56	3.48

Various valves.

The electro-hydraulic servo mechanism comprises several valves, including high-pressure safety valves, bypass valves, low-pressure safety valves, and overflow valves. These valves consist of a valve body, valve core, spring, locking structure, and seals. The pressure adjustment of the valve is achieved by the built-in spring, which exerts a pre-tightening force in the non-working state, ensuring the valve's switch state's stability. However, long-term storage and usage may cause a decrease in spring force and valve opening pressure. Table 3 presents the retest data of spring force values for springs of different specifications at varying storage times. The decrease in spring force is dependent on the thickness of the spring wire and the number of effective turns of the valve. Thinner and longer spring wire results in greater force decrease, and the possibility of spring failure and loops increases. In the case of spring failure, the spool's movement may lead to the disorder of the valve's opening state or not tightly closed, thus affecting the entire servo mechanism's working state.

Seals.

Electrohydraulic servomechanisms employ various sizes and types of seals. The aging degree of these seals varies with the storage period of the entire machine, owing to the diverse rubber materials and environments used. Subsequently, a decrease in sealing performance occurs, leading to issues such as oil and air leakage. In light of this, mature accelerated storage methods have been developed globally to tackle the problem of sealant aging [9]. For example, the GJB92-1986 "Guidelines for Determination of Storage Properties of Vulcanized Rubber by Hot Air Aging Method" recommends accelerating the performance of aging materials using high temperature. This method allows deducing the performance of materials at the storage temperature and determining the degradation law of material performance of the rubber compound and product during

Table 3. Elastic value of different springs at different storage times

Diameter of spring wire	Storage Time (Years)					
	0	***4***	***8***	***12***	***16***	***20***
0.3	2.00	1.98	1.94	1.85	1.78	1.68
1.2	93.1	92.0	91.1	91.5	91.5	90.7
2.5	168.8	167.5	166.2	162.8	160.8	158.6

long-term storage. The equivalent relationship between material performance and storage time under various aging stress levels can be established, and the storage life of the seal can be determined accordingly.

However, the electro-hydraulic servo mechanism's seals differ in size and working media, necessitating conducting accelerated storage tests under similar working conditions for an accurate assessment of the seals' storage life. To this end, the author tested the rubber material's performance parameters during the accelerated aging process, including compression set, tensile strength, elongation at break, permanent set at break, and hardness. The performance parameters of the seals were compared to validate the accuracy of the acceleration factors employed. The analysis revealed good consistency between the accelerated storage test and natural storage conditions, enabling the description of the seal's performance change under different storage times by combining the results of the accelerated storage test. Notably, during the servo mechanism's product storage process, the seals come into contact with nitrogen and red oil medium simultaneously. Therefore, both these media environments need simultaneous consideration during testing.

3.2 Performance Analysis of Control Circuit's Components Under Natural Storage

Servo valve.

The servo valve is the core control element of the electro-hydraulic servo mechanism. It converts the low-power electrical signal into the movement of the spool, and then the movement of the spool controls the direction and flow of high-pressure liquid flowing to the hydraulic servo actuator, so as to drive the piston rod of the servo actuator to move quickly and accurately according to the predetermined instructions. Sports.

As time goes by, on the one hand, the performance of the servo valve magnetic steel will decrease, which will lead to an increase in the overall stiffness of the armature assembly, resulting in a decrease in the dynamic performance of the servo valve, a decrease in flow gain, and a change in the zero position; on the other hand, due to the Core wear and increased static consumption will also have a direct impact on the high-speed continuous capability of the machine. The above two performance changes have varying degrees of impact on the dynamic performance of the entire servo mechanism [10]. Table 4 shows the change curves of servo valve performance parameters at different storage times. According to the statistics of retest data results, with the prolongation of the storage time, the flow gain of the servo valve decreases obviously, and the zero

Table 4. Retest data of servo valve performance at different storage times

Items	**Storage Time (Years)**					
	0	***4***	***8***	***12***	***16***	***20***
Flow gain /(L·(min·mA)$^{-1}$)	0.442	0.434	0.427	0.428	0.416	0.409
Zero bias/mA	0.05	0.09	0.12	0.16	0.18	0.20

deviation increases. Therefore, in the case of the core component of the whole machine, these changes will affect the dynamic performance and reliability of the whole machine of the servo mechanism to varying degrees. Electrical performance of the motor.

The electro-hydraulic servo mechanism is controlled by the servo valve, which is the core control element. The valve converts low-power electrical signals into spool movement, thereby controlling the flow of high-pressure liquid to the hydraulic servo actuator. Over time, the performance of the servo valve magnetic steel decreases, resulting in an increase in the overall stiffness of the armature assembly. This, in turn, leads to a decrease in the dynamic performance of the servo valve, a decrease in flow gain, and a change in the zero position. Additionally, core wear and increased static consumption also directly impact the high-speed continuous capability of the machine. These performance changes have varying degrees of impact on the dynamic performance of the entire servo mechanism. The change curves of servo valve performance parameters at different storage times are shown in Table 4. Retest data results show that with the prolongation of storage time, the flow gain of the servo valve decreases obviously, and the zero deviation increases. These changes affect the dynamic performance and reliability of the entire servo mechanism to varying degrees, especially in the case of the core component of the machine.

Feedback potentiometer.

The feedback potentiometer consists of a resistor assembly and a brush holder assembly. The resistance film of the resistance component is sprayed by mixing graphite powder, quartz powder, resin and other materials. However, long-term storage and use will lead to wear of the resistance film and changes in non-metallic materials, resulting in large changes in linearity. The brush holder assembly is under pressure for a long time, resulting in plastic deformation of the brush, reducing the free height, and reducing the amount of compression. The calculation method of the compression amount is calculated by: Δh = free height H-compressed height h, where h is a fixed value after being limited by the mechanical position. Table 5 shows the retest curves of the feedback potentiometer at different storage times. It can be seen that the compression of the brush holder assembly used in a certain type of product has been reduced by 50% under long-term pressure. A small amount of compression leads to poor vibration resistance of the product and reduces working reliability. The feedback potentiometer is one of the data acquisition elements in the closed-loop control system, and its linearity directly affects the control accuracy. From the retest data, during long-term storage and use, the wear of the resistance film of the feedback potentiometer has a great influence on its linearity, which in turn has a certain impact on the tracking accuracy of the servo machine.

The feedback potentiometer is a critical data acquisition element in the closed-loop control system, composed of a resistor assembly and a brush holder assembly. The resistance component's resistance film is created by mixing graphite powder, quartz powder, resin, and other materials, which may wear over time and lead to changes in non-metallic materials, causing significant changes in linearity. Furthermore, the brush holder assembly is subjected to prolonged pressure, resulting in plastic deformation of the brush, a decrease in free height, and reduced compression. The compression amount is calculated using the formula Δh = free height H-compressed height h, where h is a fixed value determined by the mechanical position. The retest curves of the feedback

Table 5. Retest data of feedback potentiometer performance at different storage times

Items	Storage Time (Years)					
	0	***4***	***8***	***12***	***16***	***20***
Free height of brush /(mm)	4.50	4.17	3.88	3.77	3.58	3.22
Degree of non-linearity	0.05%	0.11%	0.19%	0.21%	0.29%	0.38%

potentiometer at different storage times, presented in Table 5, indicate that the brush holder assembly's compression has decreased by 50% under long-term pressure in a specific product. A reduction in compression reduces the product's vibration resistance and working reliability. The feedback potentiometer's linearity directly affects the control accuracy, and from the retest data, it is evident that the wear of the resistance film has a significant impact on its linearity during long-term storage and use, which, in turn, affects the servo mechanism's tracking accuracy.

4 Servo Mechanism Storage Life Extension Measures

The present study identifies that the hydraulic circuit and control circuit of the electro-hydraulic servo mechanism exhibit performance degradation, out-of-tolerance, and unreliable links with increasing storage time, which are critical weak links that adversely impact the reliability and performance of the entire system.

Therefore, it is imperative to implement remedial measures to enhance the storage period of the servo mechanism in a reasonable and reliable manner. In this regard, life extension measures primarily targeting components that have a substantial impact on the overall system performance, such as servo motors, oil pumps, servo valves, and various valves, are recommended based on a dual consideration of reliability and economic benefits, listed in Table 6. Furthermore, accessories can be directly replaced for components of other weak links. Such measures would significantly mitigate the negative impact of the identified weak links, thereby enhancing the overall performance and reliability of the electro-hydraulic servo mechanism.

Following the implementation of life extension measures outlined in Table 6 on the actual servo mechanism samples, a performance test was conducted on the products. The results indicated significant improvements in the linearity, fixed-point speed, and dynamic characteristics of the entire machine post-repair. Moreover, the machine successfully passed environmental tests for high temperature, low temperature, vibration, impact, and a 40-h life test assessment, validating the efficacy of the storage life extension measures.

Table 6. Life extension measures for key components

Items	Storage Time (Years)
Servo motor	Replace worn brushes, bearings, springs, and stators. Inspect the rotor and shunt and replace if necessary.
Oil pump	Check and measure the gap between the metering rod and the seat rod, conduct fluorescent flaw detection on the rotor, and replace worn components such as seals, springs, dynamic and static rings, and the rotor's friction surface and oil separator. Conduct performance tests after reassembly.
Servo valve	The no-load flow curve and static consumption curve must be retested. The high-precision metal parts on the servo valve should be reused as much as possible after long-term storage, while ensuring quality. The slide valve edge, housing throttling window, and main hole should be observed under a magnifying glass to check for defects such as collapse.
Various valves	Once the visual inspection confirms that the valve is qualified, it can be reused by only replacing the spring and reconfiguring the valve core. Afterward, it is necessary to conduct tests to ensure that the valve has no leakage and the opening/closing pressure meets the required standards.

5 Conclusion

The electro-hydraulic servo mechanism is a sophisticated system that combines both control and hydraulic technology, offering high precision control and rapid feedback response. It has a wide range of applications, including aerospace, shipbuilding, and high-precision manufacturing. However, due to the involvement of various components from different professional fields in both the control and hydraulic circuits, it is challenging to apply traditional accelerated storage methods for life extension. This paper presents an engineering study on the performance changes of electro-hydraulic servo mechanisms under natural storage conditions. The study utilizes a divide-and-conquer approach to analyze the component performance variation over time in the control and hydraulic circuits. Based on the results, the paper proposes corresponding life extension measures, which have been tested on actual samples, leading to significant performance improvements and an extended storage life.

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