Study on Wear Mechanism and Pollution Life of Servo Valve Based on Oil Particles

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***Abstract*—In this paper, the servo valve is taken as the research object, and the influence mechanism of the contaminated particles in the contaminated oil on the servo valve is analyzed in detail. The contaminated particles in the servo valve cause friction on the one hand to prevent the relative movement of the valve core relative to the valve body, and on the other hand change the surface topography of the valve body. The contamination of the servo valve by contaminated particles affects the service life of the servo valve. Through theoretical derivation, the theoretical formula of the pollution life of the servo valve is obtained, which affects the pollution life of the servo valve. This formula has guiding significance for the life test of servo valves.**

Keywords-servo valve; contaminated particles; life test; life model

I. INTRODUCTION

Since the 1930s, hydraulic transmission has been reliably used on aircraft, and it is one of the most important modern aircraft systems, aircraft control surfaces used to manipulate performed brakes, retractable landing gear. As the flight speed, maneuverability and load capacity of the aircraft continue to increase, the force and power required to operate the aircraft's rudder surface and components are greatly increased, and higher requirements are imposed on the hydraulic transmission system. The safe and reliable work of the hydraulic system is to ensure the normal flight of the aircraft. The normal operation of the hydraulic system is inseparable from the smooth operation of the hydraulic components. The electro-hydraulic servo valve is the core component of the hydraulic servo system. It is used to connect the electrical and hydraulic parts of the system, transforming the input low-power electrical signal into the movement of the valve, and the movement of the valve controls the flow of hydraulic energy to the hydraulic actuator. With pressure, the conversion and amplification of electrical and hydraulic signals, as well as the control of hydraulic actuators. The servo valve is an oil circuit connected to the transmission and pressure supply part, which turns on the liquid flow, turns off or changes the flow direction to control the operation of the transmission part, and is a control component of the hydraulic system. Keeping the servo valve in good working condition is a necessary condition for the normal flight of the aircraft. At the same time, the electro-hydraulic servo valve is the component with the highest failure rate in the hydraulic servo system, and its performance affects the running quality of the whole system.

Servo valve life test is the main method of servo valve PHM research. By obtaining the physical characteristics of servo valves such as speed, flow, pressure and driving energy through experiments, the servo valve can be diagnosed and predicted healthily. In the PHM research process, it is necessary to clarify the experimental research object and the research content, so as to conduct targeted experiments. Firstly, through the theoretical derivation, the life-influencing factor of the servo valve is obtained, and then the impact factor is tested in a targeted manner to verify the correctness of the theoretical formula of the servo valve life. With the guidance of the servo valve life formula, the life test can avoid blindness and greatly save the research cycle.

Common fault modes such as erosion failure, siltation failure, and jamming failure of servo valves are closely related

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to the contamination of contaminated particles in hydraulic fluid. The service life of servo valves is mainly affected by contaminated particles in hydraulic fluid. In actual hydraulic systems, there are often many contaminants that have a large impact on the performance of the hydraulic system. Contaminants in the oil (mainly solid particulate contaminants) follow the movement of the oil into the valve core and the valve body, which adversely affects the performance of the servo valve. The concrete performance is two points: First, the solid particles cause wear on the surface of the moving pair, damage the surface of the moving pair, increase the surface roughness of the moving pair and the gap of the moving pair, causing the leakage in the servo valve to increase, shortening the sliding valve. Service life. After the Second, the solid particles into the secondary gap motion, increasing the friction between the valve body and the valve body, the frictional force referred to contaminant particles entraining frictional force PIF (Particle I conduced Force). The friction caused by the contaminated particles works to generate heat, which causes the oil to heat up. When the temperature of the oil rises, the viscosity of the oil will decrease, the internal leakage will increase, and the thickness of the hydraulic film will be affected. When this kind of damage develops to a certain extent, it will cause the servo valve to jam, causing the servo valve to malfunction, causing considerable damage to the entire hydraulic system.

In this paper, through the analysis of the movement process of the contaminated particles in the hydraulic fluid in the servo valve, the pollution mechanism of the contaminated particles in the contaminated oil on the servo valve is discussed in detail. At the same time, the service life of the servo valve is deduced and the life impact factor is analyzed. The formula derivation results can guide the formulation of the servo valve life test plan, and the targeted design test study acceleration factor, paving the way for subsequent fault diagnosis, life prediction and realization of the servo valve PHM system.

II. OVERVIEW

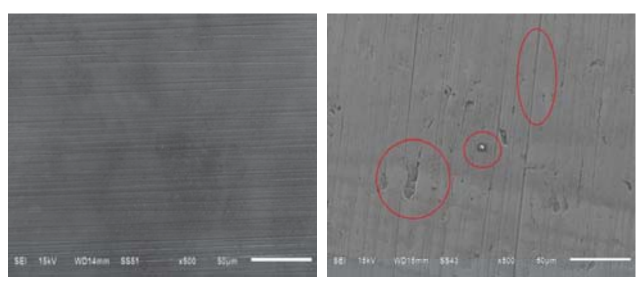
Hydraulic servo system fault is more than 85% of oil pollution, oil in a large amount when the fine solid particles with high-speed flow of oil through the valve opening, the throttle erosion on the edge side of the spool and the valve sleeve, so that the section flow down blunt edge, leading to changes in the servo valve Laid zero area, reducing pressure gain, zero leakage is increased, so that the decline in the overall performance of the valve, fails even unusable.

A. Overview of the effects of contaminated particles on surface topography

For the influence of pollutant particles on the surface morphology of the moving pair, people mainly rely on experimental research. Surjaatmadja and Fitch[1-4] through experiments, found out the size distribution of the contaminated particles, the relative hardness of the particles and the moving auxiliary surface, the eccentricity of the valve core, the roughness of the moving pair surface on the pollution clamping force, and According to the different sizes of contaminated particles, three kinds of clamping mechanisms are proposed, namely the mechanism of friction clamping, the mechanism of furrow and cutting, and the mechanism of clogging and wedging. It is pointed out that these three effects are not unique. In most cases, one or several simultaneous occurrences, the size and concentration distribution of the contaminated particles have a major influence on which clamping mechanism plays a major role. For convenience of presentation, it is assumed that the contaminating particles in the contaminated oil are spheres. When the diameter of the contaminated particles is larger than the minimum gap of the moving pair, the contaminated particles and the moving pair are deformed to pass. At this time, the motion pair is elastically or plastically deformed, so that the contaminated particles pass through the motion pair gap. When the motion pair is plastically deformed, its surface topography changes. Since the contaminated particles are in a rolling state during contact with the moving pair surface, the main wear mechanism of the pollution on the moving pair surface is plastic deformation. In fact, Wang Yilin , son Wang Xiang[5] also pointed out that three-body abrasion wear mechanisms are mainly plastic deformation. Through experiments, it was found that the effects of contaminated particles in the contaminated oil on the surface morphology of the moving pair mainly have three failure modes: cutting wear, fatigue wear and particle embedding.

In order to study the influence of the polluted oil on the surface morphology of the moving pair, the specially built test rig consists of a test control module, a fault injection module, a test pedestal body, etc., which can inject oil of different pollution levels, and test the needle bearing in this environment. The needle bearing was tested on a special test bench. When the needle bearing is in operation, the needle roller rolls or slides relative to the outer ring and the inner ring of the bearing to form a motion pair. The needle bearings are numbered 1, 2, and 3, and each bearing operates at the same speed and carries the same torque. Their working fluid pollution degree is different. The No. 1 needle roller bearing works for 10 hours under the NAS-1638 class 9 working condition, the No. 2 needle roller bearing works under the 10 -level pollution degree oil for 10 hours, the No. 3 needle roller bearing is in Working at 11 levels of pollution for 10 hours under oil. In the No. 2 needle bearing test, due to equipment failure, the needle roller bearing is subjected to a large torque, the time is about 2 hours, which will have a great impact on the test results, so it is not a qualified test.

The shape of the needle roller bearing before the test and the needle bearing after the test were observed by a scanning electron microscope and photographed. The comparison of the morphology before and after the test is shown in Fig.1:



before rolling bearing test after rolling bearing test

Figure 1. Effect of contaminated oil on the surface morphology of the moving pair

The left side of Fig.1 shows the surface topography of the needle roller bearing before the test. It can be seen that the surface of the needle bearing has no obvious pits before the test, and the groove is relatively small and uniform, and the surface has no impurities. The surface morphology after the test is as shown in the picture on the right. It can be seen that the movement pair has a relatively large groove, and the distribution is uneven. There is also fatigue spalling due to material fatigue, and the contaminated particles will Embedding the motion side surface.

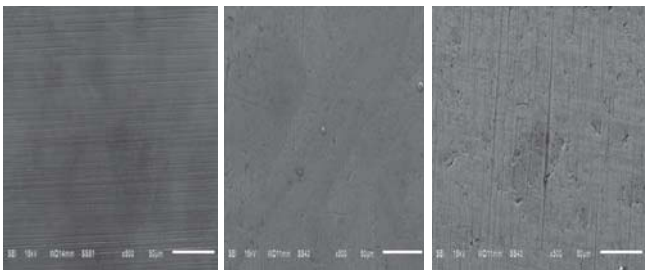


Figure 2. Comparison of the surface topography of the sports pair

Fig.2 shows the comparison of the surface topography of the exercise pair before the test, No. 1 and No. 3 exercise. It can be seen from the comparison that the above three kinds of wear phenomena will occur, and the wear phenomenon of the working pair working in the polluted oil with higher pollution degree is more obvious.

B. Overview of friction caused by contaminated particles

When the contaminating particles pass through a moving pair smaller than the gap of the particle diameter, deformation of the moving pair is caused.Due to the deformation of the motion pair, a force is generated to prevent its relative motion. This force is called particle introduced force.

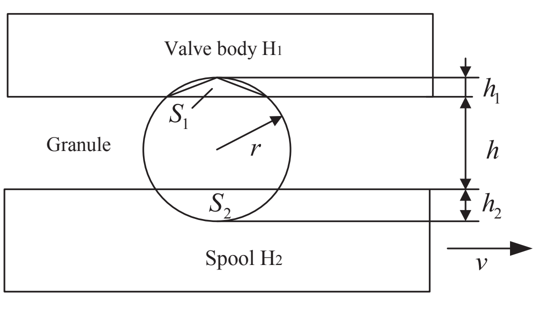


Figure 3. Schematic diagram of hydraulic valve pollution wear

As shown in Fig.3, in fact, the particle radius is much larger than the particle indentation depth, as $r \quad h_1 \quad r \quad h_2$. In this state, there is a definition of hardness and a balance of stress:

$$\pi \cdot 2r \cdot h_1 \cdot H_1 = \pi \cdot 2r \cdot h_2 \cdot H_2 \tag{1}$$

In the formula, the depth at which the contaminating particles are embedded in the motion pair, here h_1, h_2 are the depth of the valve body and the spool. r the particle radius. h is the motion pair clearance, here is the gap between the valve plug and the valve body, H_1, H_2 the hardness of the sports pair, here is the hardness of the valve body and the valve core.

From the geometric relationship:

$$h_1 + h_2 + h = 2r \tag{2}$$

From formula (1) and formula (2):

$$h_1 = \frac{H_2}{H_1 + H_2}(2r - h), h_2 = \frac{H_1}{H_1 + H_2}(2r - h) \tag{3}$$

The squeezing force of a single contaminated particle can be obtained:

$$F_N = 2\pi r(2r - h)\frac{H_1 H_2}{H_1 + H_2} \tag{4}$$

The friction caused by a single contaminated particle:

$$Fp = \mu F_N = 2\mu\pi r(2r - h)\frac{H_1 H_2}{H_1 + H_2} \tag{5}$$

Since the contaminated particles can directly or indirectly reflect the degree of equipment wear, Ge PengFei of Beijing Institute of Technology analyzed the size distribution of the contaminated particles, analyzed the friction caused by the contaminated particles to determine the influencing factors of the friction caused by the contaminated particles. By statistical analysis of the contaminated particles in the actual contaminated oil, the corrected logarithmic normal distribution is used to better describe the size distribution of the contaminated particles. The expression of the particle concentration distribution $\rho(r)$ is:

$$\rho(r) = \frac{2Bn_1 \ln(2r) e^{-B\ln 2(2r)}}{r} \tag{6}$$

In the middle, n_1 is total number of particles which greater than $1um$ (piece/ml); B is $\lg - \lg^2$ the slope of the line of the particle size distribution on the coordinates.

Then the friction caused by contaminated particles in the oil:

$$F_f = \int_{r_{min}}^{r_{max}} Q p(r) Fp dr = 4\mu\pi Q B n_1 \frac{H_1 H_2}{H_1 + H_2} \int_{r_{min}}^{r_{max}} \ln(2r) e^{-B\ln 2(2r)}(2r - h) dr \tag{7}$$

In the middle, Q is lubricant flow, $r_{\min}$ is the radius of the least contaminated particles, $r_{\max}$ is the radius of the largest contaminating particles.

It can be known from the formula (7) that the friction caused by the contaminated particles in the contaminated oil is affected by the radius of the contaminated particles, the gap of the moving pair, the hardness of the moving pair, the flow rate of the lubricating oil, $\lg-\lg^2$ the slope of the particle size distribution line on the coordinates etc.

III. Servo Valve Pollution Life

Contamination wear leads to an increase in the clearance of the movement of the hydraulic valve, which further leads to an increase in leakage and eventually a leakage failure. In this chapter, the mathematical model of pollution failure is established by analyzing the failure mechanism of servo valve pollution. This model has a good guiding effect on servo valve life test.

A. Servo valve failure determination

In engineering, the loss of the function specified by the original design is called failure. Failures include complete loss of intended function, reduced functionality, and serious injury or hazard, which can result in loss of reliability and safety. There are many types of servo valve failures, and here the leakage failure is the criterion.

In hydraulically driven components, the proper gap is necessary for normal relative motion between the components. The gap has a great influence on the performance of the hydraulic components. Therefore, it is of practical significance to discuss the flow characteristics of the liquid flow in the gap for the analysis of the design, manufacture and use performance of the hydraulic component, and calculation of leakage.

The service life of the servo valve is the maximum allowable leakage $q_{\max}$ decided. Assuming that the eccentricity of the spool is zero, the maximum allowable clearance of the hydraulic valve is $h_{\max}$ The girth leakage formula has:

$$q_{\max} = \frac{\pi d {h_{\max}}^3}{12\mu_o L}\Delta p \tag{8}$$

Among them, μ_0 is oil viscosity, Δp is the pressure difference between the two ends of the ring , L is the length of the valve body movement pair, d is the spool diameter.

Therefore, the maximum allowable gap $h_{\max}$ is:

$$h_{\max} = \sqrt[3]{\frac{12\mu_o L q_{\max}}{\pi d \Delta p}} \tag{9}$$

When the gap between the valve core and the valve body is reached $h_{\max}$, the servo valve fails.

B. Wear of spool in a single action Δh

When the sports pair works in the contaminated oil, abrasive wear will inevitably occur. Abrasive wear can be divided into monomer, two-body and three-body abrasion. It can cause components to wear out due to rapid cutting of surface materials or damage due to accelerated fatigue rates. The process of the latter phenomenon is usually slower than the material being cut. Monomer abrasion includes the impact of high-speed particles on the surface of the component in the oil, which is the damage of the surface of the component; the two-body abrasion refers to the contact of the friction particles embedded on the surface with another solid surface, or a hard convex on one surface. The wear of a portion to another softer surface; three-body abrasion refers to a free hard particle that simultaneously contacts two relatively moving surfaces.

There are two important mechanisms described hard particle surface friction element being directly damaged, and the surface properties of the element thus decline down situation. The first is a slight wear, a subtle and slow form of wear. In this form of wear, the particles are pressed out of the surface of the element and the grooves are drawn (in the case of rolling and sliding conditions). As a result, the material is misaligned or slipped, and although the material is not detached, it substantially reduces the bonding strength of the material. This action creates areas of high stress at the edges or depressions of the depressions that accelerate the rate of defect formation and expansion, lead to accelerated acceleration, and may be convex on uneven edges or stress states. Adhesion occurred at the beginning. It is important in the theory of pollution control that, in the absence of any cutting wear associated with abrasion, it is also possible to produce accelerated surface fatigue of the material caused by contaminating particles.

The second is severe hard particle wear. In this case, the particles embedded in the surface of the element and in the free state are cut such as the surface of the element to peel off the material. The peeling of the surface material causes particle contamination again, and each time the friction particles pass through the hydraulic component, a cutting peeling action can be generated, thereby causing a fouling chain reaction. The rate at which the surface of the component is severely abraded is proportional to the amount of hard particles it is in contact with. Particles produced by this abrasive mechanism, much like tiny machined chips, will increase system contamination and create additional wear in succession.

Whether it is a slight abrasive wear or severe abrasive wear can occur alone or simultaneously. Matrix plastic deformation. The cross-sectional area of the motion pair can be pressed by the particles Determine the relative sliding distance from the abrasive matrix, as shown in equation (10):

$$V = S \bullet l \tag{10}$$

In the formula, l is the relative sliding distance of the abrasive matrix.

According to mechanical analysis, definition of geometry and hardness, the particles can be obtained as shown in Fig.3 is pressed into the sub-sectional area of the motion expression, namely:

$$S = S_1 + S_2 = 4r^2\left(1-\frac{h}{2r}\right)^{\frac{3}{2}} \frac{1+\left(\frac{H_1}{H_2}\right)^{\frac{3}{2}}}{\left(1+\frac{H_1}{H_2}\right)^{\frac{3}{2}}} \tag{11}$$

In the middle, r is the radius of the particles. $\alpha = h/2r$ is define interstitial particle ratio, $\beta = H_1 / H_2$ is valve body spool hardness ratio, then Equation 2-4 can be simplified as:

$$S = 4r^2(1-\alpha)^{\frac{3}{2}} \frac{1+\beta^{\frac{3}{2}}}{(1+\beta)^{\frac{3}{2}}} \tag{12}$$

For two-body wear, the value of the base l is equal to l' the relative motion distance of the base , but for three-body wear, due to the rolling of the abrasive particles, l obviously less than l' . Rabinowitz[6] believes that under the same conditions, l with l' usually differ by an order of magnitude. Assume L is the contact length of the valve body movement pair, l' the relative movement distance between the single movement of the spool and the valve body is not equal, the relationship between the two can be calculated through the structural parameters of the valve. Here, we define the sliding distance conversion factor u , which is:

$$l = u \bullet L \tag{13}$$

The amount of wear caused by a single particle in a single wear W is:

$$W = 4ucLr^2(1-\alpha)^{\frac{3}{2}} \frac{1+\beta^{\frac{3}{2}}}{(1+\beta)^{\frac{3}{2}}} \tag{14}$$

Number of particles causing wear in a single action n can be expressed as:

$$n = \rho \cdot V_{\mathrm{c}} \tag{15}$$

Among them, ρ is the number of particles in the unit oil volume contained in the movement gap of the hydraulic valve that can cause wear. V_c is the motion of the secondary annular gap volume, regardless of the spool eccentricity, there are:

$$V_{\mathrm{c}} = \pi dhL \tag{16}$$

The wear volume caused by all particles in a single action W_n is:

$$W_n = 4\pi dhuc\rho L^2 r^2(1-\alpha)^{\frac{3}{2}} \frac{1+\beta^{\frac{3}{2}}}{(1+\beta)^{\frac{3}{2}}} \tag{17}$$

The amount of wear of the servo valve after a single action can be obtained by the amount of wear Δh :

$$\Delta h = \frac{W_n}{\pi dL} = 8uc\rho Lr^3\alpha(1-\alpha)^{\frac{3}{2}} \frac{1+\beta^{\frac{3}{2}}}{(1+\beta)^{\frac{3}{2}}} \tag{18}$$

For the convenience of calculation, in formula (18) Δh ρ r s unit is um , piece/ml, um ,the formula (18) can be converted into the formula (19).

$$\Delta h = 8uc\rho Lr^3\alpha(1-\alpha)^{\frac{3}{2}} \frac{1+\beta^{\frac{3}{2}}}{(1+\beta)^{\frac{3}{2}}} \times 10^{-6} \tag{19}$$

Step-by-step statistics on contaminated particles in oil to obtain particle concentration distribution $\rho(r)$:

$$\rho(r) = \frac{2Bn_1 \ln(2r) e^{-B\ln^2(2r)}}{r} \tag{20}$$

C. Relationship between clearance h and single wear

When the motion pair clearance is h , the particles of a certain size interval will cause the wear of the motion pair, record the size interval $[r_{\min}, r_{\max}]$, likeness, gap particle ratio α also located in a certain interval $[\alpha_{\min}, \alpha_{\max}]$ and both have a relationship as shown in the formula (21).

$$[r_{\min}, r_{\max}] = [\frac{h}{2\alpha_{\max}}, \frac{h}{2\alpha_{\min}}] \tag{21}$$

When the gap is h , a single wear depth ΔH according to formula (22).

$$\Delta H = f(h) = \int_{r=r_{\min}}^{r=r_{\max}} 8uc(r)\rho(r)Lr^3\alpha(1-\alpha)^{\frac{3}{2}} \frac{1+\beta^{\frac{3}{2}}}{(1+\beta)^{\frac{3}{2}}} \times 10^{-6} dr \tag{22}$$

Among them, $C(r)$ is the wear scale factor, the coefficient is also the Function of r .

D. Servo Valve Pollution Wear Life

As the wear progresses, the size of the particles that cause wear to the motion pair gradually increases. When the servo valve is in the initial state, the motion pair clearance h_0 is the smallest, When the hydraulic valve fails, the gap $h_{\max}$ is the largest.

Spool action times N :

$$dN = \frac{dh}{f(h)} \tag{23}$$

Simultaneous integration of both sides of equation (24), obtaining the pollution wear life of the hydraulic valve N_t.

$$N_{\mathrm{t}}=\int_{h_0}^{h_{\max}}\frac{dh}{f(h)}$$
$$=\int_{h_0}^{h_{\max}}\frac{1}{8uLBn_1h\frac{1+\beta^{\frac{3}{2}}}{(1+\beta)^{\frac{3}{2}}}\times10^{-6}\int_{r_{\min}}^{r_{\max}}r\ln(2r)\left(1-\frac{h}{2r}\right)^{\frac{3}{2}}e^{-B\ln^2(2r)}c(r)dr}dh \tag{24}$$

IV. Conclusion

In this paper, the influence of pollutant particles in the polluted oil on the motion pair is analyzed in detail. First, the polluted particles in the contaminated oil affect the surface morphology of the moving pair. Second, the polluting particles cause the friction of the relative motion of the moving pair. Through the observation of the morphology, it is found that the main failure modes caused by the contaminated particles are micro-cutting wear, fatigue spalling wear and contaminated particle embedded wear. The work of friction caused by contaminated particles will increase the temperature of the oil. The temperature rise of the lubricating oil liquid will lower the viscosity of the oil, affect the thickness of the sports sub-oil film, etc. The factors such as the thickness of the sports sub-oil film will in turn affect the friction caused by the contaminated particles, resulting in a vicious circle.

The spool and valve body in the servo valve are a pair of motion pairs, and their service life will be affected by contaminated particles in the contaminated oil. In this paper, the mathematical model of the pollution wear life of the servo valve is derived by analyzing the movement process of the contaminated particles in the polluted oil. The model involves factors affecting the servo valve pollution life test, and the influence of factors can be obtained by mathematical analysis. The derivation of the mathematical model of the servo valve pollution life has a good guiding effect on the servo valve pollution life test.

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