RELIABILITY DESIGN OF HYDRAULIC DRIVE SYSTEM FOR THE MECHANICAL ARM OF THE LOGGER

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ABSTRACT: In order to solve the problem of single drive function and poor reliability of the existing hydraulic press, in this research, the hydraulic drive system of the mechanical arm of the logger is studied. Firstly, according to the reliability theory, the reliability model of the hydraulic drive system is established. Then, the influence and danger of the fault mode of the hydraulic system are analyzed. Finally, the reliability test is predicted, analyzed, and designed under high temperature and high pressure, and the environmental stress screening experiment and reliability development experiment are simulated. The results show that the hydraulic drive system of the mechanical arm of the logger, which can withstand high temperature and high pressure, is finally developed by taking relevant measures according to the problems exposed in the experiment. It is hoped that the results in this study can improve the measuring depth of the logger and have a good guiding significance for improving the oil exploration technology in China.

KEYWORDS: Logger, Hydraulic Drive System, Reliability Design, Mechanical Arm

1 INTRODUCTION

The logger is generally used in the field of drilling wells. It can not only perform continuous scanning of the well wall, but also perform transverse scanning at any horizontal level to provide technical data such as vertical wellbore section, horizontal section, effective wellbore section, and wellbore deflection distance [1]. The logger is often used in the process of oil exploitation. Because the risk factor is large during the oil exploitation process, it is necessary to ensure the safety of the logging work. Generally, logging tools are used in the process of oil extraction [2, 3].

The logging tool can judge and evaluate the geological problems of the oilfield, and it is an important tool and means in oilfield exploration and mining. Petroleum engineers need to use the relevant information and data provided by the logger to judge the oil and gas reservoir and geological problems in a certain place, so they need to develop a variety of loggers to determine the physical and engineering parameters related to the rock and stratum around the oil field. At present, there are various types of loggers, including induction loggers, dipmeters, and memory acoustic loggers. The purpose of developing different logging tools is to provide oil workers with more comprehensive geological data and make up for various logging shortcomings [4-6]. However, with the continuous development and exploitation of oil fields and the increase of oil demand industries, the oil resources are facing a severe test. Oil resources are going to be exhausted, and oil and natural gas in shallow oil fields have been exploited to the later stage. Although the deep oil fields have relatively high reserves, the deep oil fields are difficult to be exploited and the environment is relatively harsh. Therefore, the exploitation of deep oil fields has put forward an urgent demand for logging instruments working under the harsh development environment [7]. At present, the exploration of oil and natural gas in deep water is testing many exploration companies at home and abroad. According to relevant data, in the actual exploration process of the oil field, the temperature of deep well at 8000m can be as high as 175°C and the pressure is 140Mpa. In order to explore the oil field, the logging tool can be combined with the mechanical arm to form a “sidewall contact device”, which can measure the deep well. As the core component of the equipment is the drive system, the high temperature and high pressure resistance of the hydraulic drive system determines the test depth of the logger [8].

To sum up, it is urgent to research and develop a mechanical arm of a logging tool due to the increasingly harsh oil exploration conditions and the fact that foreign logging tools are not sold in China.
The driving device of the mechanical arm of the logging tool is its core part. At present, the reliability of the existing hydraulic drive in China is relatively poor and the function is relatively simple, which can’t meet the actual demand. Therefore, in this research, according to the reliability theory, the existing drive system is designed and improved under the condition of high temperature and high pressure, and it is predicted, analyzed, and designed to develop a drive system that can withstand high temperature and high pressure. It is hoped that the drive system of mechanical arm of logger designed in this research can improve the ability of petroleum exploration in China.

2 METHODOLOGY

2.1 The establishment of reliability model of hydraulic drive system for the mechanical arm of the logger

Reliability is defined as the ability of a product to fulfill a specified requirement in a specified time and under specified conditions. For the design of reliability, it is necessary to measure with reliability indicators. Reliability indicators include reliability, failure rate, and average life [9-11].

Reliability is a function of time, which refers to the probability that the product can achieve reliability, as shown in equation (1).

\[ P(t) = S(T > t) \]  

(1)

Among them, T represents the life of the product, and t is the working time.

Failure rate refers to the probability that the product will fail in the following work after a period of time. It can be expressed as \( \lambda(t) \), as shown in equation (2).

\[ \lambda(t) = \lim_{\Delta t \to 0} \frac{1}{\Delta t} P(t \leq T \leq t + \Delta t | T > t) \]  

(2)

The data that the general manufacturer refers to is the evaluation failure rate, which is the average of the failure rates in the specified time period.

The relationship between reliability and failure rate can be expressed by equation (3).

\[ P(t) = e^{-\int_0^t \lambda(t) dt} \]  

(3)

Life expectancy is a relatively abstract measure index of both reliability and failure rate. In the process of practical application, the average life is the most relevant measurement index for engineers, and the average life can be denoted as MTBF, as shown in equation (4).

\[ MTBF = \frac{1}{N} \sum_{i=1}^{N} t_i \]  

(4)

Where, \( N \) represents the total number of products, and \( t_i \) represents the life of the ith product.

The relationship between mean trouble-free working time and reliability can be expressed as equation (5).

\[ MTTF = \int_0^\infty R(t) dt \]  

(5)

Reliability prediction of hydraulic drive system of mechanical arm of logger refers to the analysis of its working principle based on the overall design scheme of hydraulic drive system of mechanical arm of logger, so as to establish a reliability model and to judge whether the average trouble-free time of the system is balanced. If the mean trouble-free time of the system is not reached, the design scheme needs to be improved [12].

Generally, reliability indicators need to be clarified before reliability prediction. In this research, the hydraulic drive system of the mechanical arm of the designed logging tool needs to work at a depth of 8000m. In order to ensure that the mechanical arm can work and avoid the influence of multiple booting on the system reliability, it establishes the reliability model with the one-time booting as the reliability index in this research.

Reliability model is a mathematical model representing the system with reliability block diagram, whose function is to predict reliability. In this research, according to the reliability data of the main components and the logical relationship of the reliability block diagram, the reliability block diagram of the hydraulic drive system of the logging tool is shown in figure 1, and the reliability data is shown in table 1.

![Figure 1. Reliability block diagram of hydraulic drive system of logging tool](image-url)
Table 1 Reliability data of components of hydraulic drive system of logging tool

<table>
<thead>
<tr>
<th>The name of the component</th>
<th>$\lambda/\times10^{-3}\text{h}^{-1}$</th>
<th>$\text{MTTF}/\times10^{3}\text{h}$</th>
<th>Data Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel tank</td>
<td>1.1</td>
<td>909</td>
<td>Empirical data</td>
</tr>
<tr>
<td>Filter</td>
<td>0.045</td>
<td>20000</td>
<td>Data provided by the manufacturer</td>
</tr>
<tr>
<td>Motor-driven plunger pump</td>
<td>2.9</td>
<td>344.8</td>
<td>Empirical data</td>
</tr>
<tr>
<td>Integrated package</td>
<td>0.012</td>
<td>83333</td>
<td>Empirical data</td>
</tr>
<tr>
<td>Overflow valve</td>
<td>1.25</td>
<td>800</td>
<td>Data provided by the manufacturer</td>
</tr>
<tr>
<td>Normally closed valve</td>
<td>1.25</td>
<td>800</td>
<td>Data provided by the manufacturer</td>
</tr>
<tr>
<td>Normally open valve</td>
<td>1.25</td>
<td>800</td>
<td>Data provided by the manufacturer</td>
</tr>
<tr>
<td>Check valve</td>
<td>0.625</td>
<td>1600</td>
<td>Data provided by the manufacturer</td>
</tr>
<tr>
<td>Hydraulic cylinder</td>
<td>0.005</td>
<td>20000</td>
<td>Empirical data</td>
</tr>
<tr>
<td>Balanced piston assembly</td>
<td>0.5</td>
<td>2000</td>
<td>Empirical data</td>
</tr>
</tbody>
</table>

According to figure 1, the reliability block diagram is simplified according to three assumptions. First, the components of the system and the system have only normal and fault states. Secondly, the boxes in the diagram represent the functions of subsystems or units, and each unit in the diagram works independently of the other. Thirdly, systems or units that are not in a reliable block diagram are considered safe and reliable.

The establishment of reliability mathematical model refers to the quantitative relationship between time, fault, and reliability indicators, which can be calculated to predict the reliability of the system.

The establishment of the mathematical model is divided into two steps. The first step is to determine the reliability function of components, which means that all components need to be screened for environmental stress before installation. If the component fails at an early stage, it can be ignored, eliminating the early failed component. In the later failure components, the probability of failure of components of the hydraulic system does not change with time, so it can be regarded as the exponential function distribution \[13\]. The component reliability equation can be expressed as follows.

$$ P(t) = e^{-\lambda t} \quad (6) $$

Among them, $P(t)$ represents the reliability function of a single component; $\lambda$ represents the average failure rate of a single component; $t$ represents the working time of a single component. The relationship between MTTF and failure rate of a single component can be expressed by equation (7).

$$ MTTF = \frac{1}{\lambda} \quad (7) $$

Then the reliability mathematical model is established according to the reliability block diagram.

$$ P_s(t_s) = \prod_{i=1}^{s} P_i(t_i) = e^{-\sum_{i=1}^{s} \lambda_i t_i} \quad (8) $$

Among them, $P_s(t_s)$ represents the reliability function of the entire drive system, $t_i$ represents the working time of the whole driving system, $P_i(t_i)$ represents the reliability of the ith component of the driving system, and $t_i$ indicates the working time of the ith component of the drive system.

The reliability model of the system is established, and the reliability of the system can be calculated, as shown in equation (9).

$$ \sum_{i=1}^{s} \lambda_i t_i = \bar{\lambda} \sum_{i=1}^{s} t_i, \quad \sum_{i=1}^{s} \lambda_i t_i = \bar{\lambda} \sum_{i=1}^{s} t_i, \quad \sum_{i=1}^{s} \lambda_i t_i = \bar{\lambda} \sum_{i=1}^{s} t_i \quad (9) $$

Among them, $\pi_{\bar{E}}$ indicates the environmental factor, $\pi_{\bar{D}}$ represents the derating factor, $\pi_{\bar{C}}$ indicates the correction factor, $\lambda_{s+1}$ represents the total basic failure rate of the loop under condition j,
and $t_0$ represents the working time of the whole hydraulic system.

In the process of pushing and recovering the hydraulic system, the reliable model of the hydraulic parts used is consistent, so the proportion of working time is not considered here.

### 2.2 The influence and hazard analysis of the failure mode of hydraulic system of the mechanical arm of the logger

In this research, it adopts the fault modes, effects, and criticality analysis (FMECA), which is a commonly used method for reliability analysis. And it is a method for analyzing potential faults of internal parts of hydraulic drive system.

Figure 2 is the process diagram of FMECA analysis, which consists of three links: system definition, fault modes and effects analysis (FMEA), and criticality analysis (CA). The purpose is to analyze the defects and weak links in the functional design of hydraulic drive system and to further improve the system.

Figure 3 is a diagram showing the function and structure of the drive system. It can be found that the function of the system is that the motor drives the plunger pump to inhale the hydraulic oil in the integral oil tank, and then the hydraulic components outputs the hydraulic oil to the hydraulic cylinder with a certain pressure and flow, and finally the pressure drives the mechanical arm to operate.

In FMECA analysis, it is necessary to analyze the functions of the analysis system and classify the functions of the system through the agreement between the initial agreement level and the agreement level. Figure 4 is a drawing function and structure diagram.
2.3 Reliability test of hydraulic system of the mechanical arm of the logger

Reliability test is used for the reliability analysis and evaluation of the developed products, statistical analysis, fault analysis, and improvement analysis of the results of reliability test are carried out to determine whether the reliability index requirements can be met. Combined with the characteristics of the hydraulic drive system, the experiment scheme is designed by adopting reliability development test and environmental stress screening test.

For environmental stress screening test, it is aimed at the components in the system, which can expose the weak parts and quality problems of the product. But, in contrast, reliability experiments focus more on the whole than the parts.

In this research, the key components of the system are placed in high temperature hydraulic oil to examine the time during which it can work stably. Considering that there are few components in the system, there is no environmental stress or destructive life test, but a screening experiment to ensure the time of the experimental process. The experiment is divided into two parts. The first is the experiment of oil-immersed motor and hydraulic pump. Because the oil-immersed motor can’t work for a long time in a high temperature environment, the motor is guaranteed to work for two minutes in each experiment stage, and then it is placed in a high temperature environment for a period of time. Then it is started up for two minutes, and finally installed in the hydraulic system to observe if the driver can meet the work requirements. The second is the electromagnetic reversing valve experiment. In order to make the electromagnetic reversing valve work for a long time, it is necessary to conduct the environmental stress selection experiment on the solenoid valve.

The reliability research and development experiment is to make the whole system under the environmental stress, to add the appropriate load to the product, to constantly look for loopholes of product design, so as to improve the reliability of the product. Although the construction environment encountered by the mechanical arm in field work may be more complex, only one or several reliability tests are generally performed under experimental conditions. The experiment usually needs to be divided into several stages. After each discovery of faults, judgment is made and improvement plans are proposed. The FMECA table is a method to find defects. After the formation of the designed hydraulic cylinder and the loading, the duration of the displacement of
each millimeter is recorded. Even if problems are found in the experiment, the reliability of the pressure system of the mechanical arm of the logging tool is gradually improved.

3 RESULTS AND DISCUSSION

3.1 Analysis of the results of environmental stress screening experiments

In this research, environmental stress data of different parts are recorded, and the results of environmental stress screening experiments of each key part are analyzed, as shown in table 2 and table 3.

Data results from all components show that the motor and solenoid valves are reliable at all stages.

<table>
<thead>
<tr>
<th>Experiment stage</th>
<th>Oil temperature / °C</th>
<th>Continuous working time / min</th>
<th>Cumulative continuous working time / min</th>
<th>Final operating current / mA</th>
<th>Can it work properly?</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>24</td>
<td>5</td>
<td>5</td>
<td>0.54</td>
<td>Yes</td>
</tr>
<tr>
<td>2</td>
<td>24</td>
<td>5</td>
<td>10</td>
<td>0.58</td>
<td>Yes</td>
</tr>
<tr>
<td>3</td>
<td>175</td>
<td>5</td>
<td>15</td>
<td>0.60</td>
<td>Yes</td>
</tr>
<tr>
<td>4</td>
<td>175</td>
<td>5</td>
<td>25</td>
<td>0.60</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Table 3 Environmental stress screening test of electromagnetic reversing valve

<table>
<thead>
<tr>
<th>Experiment stage</th>
<th>Oil temperature / °C</th>
<th>Continuous working time / min</th>
<th>Cumulative continuous working time / min</th>
<th>Final operating current / mA</th>
<th>Can it work properly?</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>24</td>
<td>5</td>
<td>4</td>
<td>0.082</td>
<td>Yes</td>
</tr>
<tr>
<td>2</td>
<td>24</td>
<td>5</td>
<td>8</td>
<td>0.094</td>
<td>Yes</td>
</tr>
<tr>
<td>3</td>
<td>175</td>
<td>10</td>
<td>16</td>
<td>0.092</td>
<td>Yes</td>
</tr>
<tr>
<td>4</td>
<td>175</td>
<td>10</td>
<td>24</td>
<td>0.096</td>
<td>Yes</td>
</tr>
</tbody>
</table>

3.2 Analysis of results of reliability development experiment

In this research, the standard of the measurement stage is to find faults or defects in the design, and gradually improve and enhance the reliability of the hydraulic drive system in the process of the experiment. In stage 1 of test machine, disc spring is not used, which results in obvious deep scratches on piston rod without loading stress in the initial experiments, as shown in figure 5. According to the analysis, it can be concluded that the piston rod adopted has not been hardened, and the hardness of the piston rod is relatively low. In addition, the long-term work leads to the rapid increase of leakage at the piston rod. After analyzing the reasons, the piston rod should be improved and strengthened with appropriate hardness. In this research, heat treatment is adopted to quench the surface with a quenching depth of 0.5mm, so as to improve the hardness of piston rod. The measurement result is HRC50.

In the second stage, the disc spring is also not used, at which time the hydraulic drive system can push out the normal information, but there is a significant lack of thrust, leading to serious leakage. By disassembling it, it is found that the overflow valve forms a block on the mounting hole when it is pressed out by hydraulic oil. Because of this situation, the overflow valve becomes a throttle valve, which maintains some pressure on the system, but there is no way to suppress the leakage. It is found that the overflow valve is installed incorrectly. In this research, the overflow valve is reinstalled after reading the overflow valve manual.

In the third stage, the disc spring is not used and the applied thrust is 10000N. When the working state is maintained, the pusher is slowly lowered. In the initial stage of 10mm, the system can only last 20min per millimeter, but in the next 10mm, the system can be maintained at 60min per millimeter. This phenomenon indicates that the cylinder barrel of the hydraulic cylinder appears to be working towards the “horn mouth”, which is caused by the fault in the processing process through analysis.
In this study, the time required for loading the piston rod of the hydraulic cylinder after it is fully extended is recorded, as shown in figure 6. It can be observed from figure 6 that the displacement of the push rod lasts less than 1mm per mm within the initial 5mm. With the increase of displacement, the duration of displacement per mm of the load push-back rod gradually increases, with the maximum displacement of 1mm at 75min. If the push-back rod is kept in such a condition for operation, it can be maintained for 6h with a displacement of 5mm, so that the good condition can satisfy a complete logging process. The data in figure 6 also shows that the sealing performance of the hydraulic system has been improved to a certain extent, but there are also deficiencies. In the process of processing, the
quality of the cylinder barrel of the hydraulic cylinder is poor, resulting in the working state of the “horn mouth”. Therefore, it is necessary to grind the cylinder barrel of the hydraulic cylinder to achieve the required quality and ensure the correct size of the inner hole after machining.

In the fourth stage, no disc springs are used. The loading test is carried out at 24 °C, and the duration of unit displacement under the return displacement of the push rod is recorded, as shown in figure 7. As can be observed from figure 7, in the initial 3mm, the displacement per mm lasts for a relatively short time, which makes the piston rod return faster. The main reason is that there is a certain loophole in the initial stage of the check valve and solenoid valve that needs to be inserted into the front end of the plunger pump in the initial stage. After the initial stage, it can be observed from the figure that the displacement compression time per millimeter after 5mm can reach about 60min, so the unit displacement duration can meet the requirements of one logging. In order to reduce leakage, a one-way valve is installed in the integrated block in this experiment, which can achieve the parallel effect of the reliability block diagram of the plunger one-way valve and further improve the reliability of the one-way valve.

In order to reduce the displacement in the initial stage, so that the system of the hydraulic drive device can work for a long time from the beginning, and the disc spring is used in this experiment, which is installed in the guide sleeve. Its working curve is shown in figure 8. As can be observed from figure 8, after the disc spring is added, the hydraulic drive device can reach about 30min per millimeter displacement and return time at the beginning, which greatly improves the working time of the whole system.

In the fifth stage, the working time of the system reaches 175 °C. The excessive temperature can make the discharge valve in the balance piston assembly open, further releasing the excess hydraulic oil. This situation can easily lead to safety problems in the test process, which need to be improved. The improved method is to operate the hydraulic system under normal pressure without allowing the piston assembly to release hydraulic oil.

In the sixth stage, due to the experimental conditions, there is no proper pressure simulator. Therefore, under the normal pressure and 175 °C, it is found that the viscosity of hydraulic oil of the hydraulic drive system decreases rapidly, resulting in a very large leakage, and the hydraulic drive system would not be able to work. When the applied load is 2400N, the piston can still be pushed to move. This situation proves that the solenoid valve hydraulic pump and high temperature motor can work normally under high temperature environment.

In this research, the test under high pressure and high temperature environment is not carried out. If it is necessary to verify the working performance under high pressure and high temperature environment, first of all, experimental equipment should be prepared under this condition. Secondly, it is necessary to conduct a screening experiment on each environmental stress, so as to conduct reliability development experiment under high temperature and high pressure, and the corresponding record work should be done. In this research, FMECA form is used in the development of the driving system. According to the record of this form, the fault point can be quickly found for further correction. It is found that under the good experimental environment, that is, without
pollution, the hydraulic cylinder and the relief valve of the hydraulic drive system are the main components of the system, which are basically consistent with the results of the reliability analysis. Therefore, the process of this experiment gradually improves the reliability of the hydraulic drive system, which basically meets the technical requirements.

4 CONCLUSION

In this research, the reliability design of hydraulic drive system for mechanical arm of logging tool is studied. Firstly, based on the theory of reliability, a reliability model of the hydraulic drive system for mechanical arm of logging tool is established. Then the influence and danger of the failure mode under the reliability model are analyzed. Finally, the reliability test of the hydraulic system of the mechanical arm of the logger is carried out according to the actual conditions. In this experiment, through the screening experiment of environmental stress and the reliability development experiment of simulated loading, deficiencies in the design are continuously found, and the reliability of the hydraulic drive system of the mechanical arm of logging tool is constantly improved, so that the hydraulic drive system of the mechanical arm of logging tool can reach the experimental requirements in the simulation stage.

Although the system in this research has reached the experimental requirements of the final simulation stage in the reliability design, due to the limited conditions in this research, it can’t carry out the realistic reliability experiment, so it can’t ensure the reliability of the hydraulic drive system. It is hoped that the results of this research can provide good guidance for China’s oil exploration technology.

5 REFERENCES