Research on the method of detecting the failure of dynamic seal of direct-drive pump

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Abstract. Based on the analysis of dynamic seal failure mechanism, this paper found that the dynamic seal would experience three phases before it failed completely. These three phases includes early extrusion phase, mid-term extrusion phase and final leakage phase. In final leakage phase, the failure of the dynamic seal could be detected by measuring the pressure disturbance on low-pressure side. The paper further studied the dynamic response of the crankshaft caused by the failure of dynamic seal in its early extrusion and mid-term extrusion phase, and found that the failure of the dynamic seal in extrusion phases could be detected by measuring the transient response of the crankshaft bearing. With these two methods, developing intelligent machine which can predict the failure of dynamic seal becomes possible.

1. Introduction

Usually, ultra-high pressure pump is the type of pump whose working pressure is more than 300MPa. With the development of our society, ultra-high pressure pump has been used extensively in mining, cleaning, cutting, surface treatment, etc. To water-jet cutting machine, cleaning machine, etc., high pressure pump is a key part. Therefore, the performance of high pressure pump is very important. In the last ten years, researchers around the world put a lot of effort to improve the performance of high pressure pump.

In order to improve the performance of high pressure pump, a lot of researches have been done in last ten years. In general, those researches could be divided into two categories. The first one is mainly about improving the performance of pump by improving the performance of raw material, manufacturing process, and surface treatment process, etc.. For example, in 2015, Ning Li studied how autofrettage residual stress affected the fatigue life of high pressure parts[1]. In 2016, Qi Ju[2]studied systematically the autofrettage virtual manufacturing technology of ultrahigh pressure reactors. In 2014, Chen Zhang[3]developed a simulation platform of high pressure pump. The second category concentrates on how to improve the performance of pump by optimizing the structural design through researching the static and dynamic characteristics of pump. For example, in 2000, Qingyuan Zhang, Ruheng Chen[4], et al. carried out a finite element analysis on the strength, stiffness and natural
vibration characteristics of the F-1300 reciprocating pump. Based on their research, the structural stress and deformation of the pump body were inhomogeneous, and the strength and stiffness of the pump were abundant. Their analyses provided the necessary basis for reconstruction of the F-1300 drilling pump. In 2005, Yongyou Zhu, Yongbiu Ye, etc.[5], did some research on structural characteristics of NB8-600 pump. In 2014, Yugang Zhao, Tianci Cai, etc.[6], studied BRK500/37.5 high pressure emulsion pump by using ANSYS WORKBENCH software. Through FEA analysis, the sensitive parts of the emulsion pump shell vibration were found, which provided a theoretical basis for the improvement and optimization of the shell structure. Thanks to the efforts of the above researchers, the performance of high pressure pumps has been improved greatly.

Direct-drive high pressure pump, as the name implies, is the high pressure pump which is driven by the motor directly. Comparing with intensifier pump, direct-drive pump does not need the intermediate hydraulic transmission link. Therefore, it has some extra advantages such as high efficiency, easy maintenance, etc..

As shown in Figure 1, direct-drive high pressure pump is mainly composed of four parts, which include motor, crankcase, hydraulic system and electric control system. In working process, motor drives crankshaft, connecting rod and plunger move back and forth. As plunger moves back, a confined space encircled by plunger, cylinder, dynamic seal, static seal, check valve, etc., increases gradually, and a partial vacuum is formed in the confined space. Because of the pressure difference, the inlet check valve opens, and water comes into the confined space through inlet check valve. As plunger moves forward, the confined space decreases. The pressure of fluid inside of the confined space increases dramatically. The outlet check valve opens and the high pressure fluid is squeezed out. Due to the continuously reciprocating movement of plungers, the fluid is transported from low pressure side to high pressure side.

Though direct-drive pump has many advantages, and it represents a new technology, under the same pressure conditions, most high pressure components of direct-drive pump fail in a relatively short period of time. Especially for dynamic seal, less than 500 hours are expected before it completely fail. Short life of dynamic seal leads to two problems. The first one is that user needs to replace the failed dynamic seal very often. The second one is that failed dynamic seal would lead to a series of problems if the failure of dynamic seal does not be detected in time. This paper concentrates on researching method to detect the failure of dynamic seal as early as possible.

In order to find out dynamic seal failure in time so as to avoid the subsequent loss caused by the failure of dynamic seal, this paper explores the detection method of dynamic seal failure.
2. Failure mechanism analysis on dynamic seal of direct-drive high pressure pump

As mentioned above, being a part which works under the worst situation in the whole pump, dynamic seal has the shortest service life comparing with other parts of the whole pump. One reason for dynamic seal fail so quickly is because it works continuously under an alternating pressure which is changing quickly from 0 to 400 MPa. Another reason is that there is a friction force acting on the internal surface of dynamic seal all the time. The increment of temperature caused by the friction force makes the working situation worse. As a result, the service life is very short for dynamic seal, especially for direct-drive pump. Because the plunger moves much faster in direct-drive pump.

In general, three plungers work simultaneously for direct-drive pump. Figure 2 and Figure 3 shows the cross-section of a single cylinder. As shown in Figure 2, when plunger moves to right, the confined space encircled by plunger, cylinder, dynamic seal, static seal, inlet check valve, outlet check valve, etc., increases. As a result, a vacuum is formed in the confined space. Because of the pressure difference, water comes into the confined space through inlet check valve. As plunger moves to the left, water in the confined space is squeezed out through the outlet check valve. During this whole process, pressurized water is trying to escape from each gap formed between two contacting surface. And dynamic seal is one of the parts which are trying to prevent water escape from the small gap between external surface of plunger and the internal surface of cooling valve body.

During pump working process, plunger moves back and forth quickly. In order to protect the external surface of plunger, all the parts made of metal material in the way of plunger moving are forbidden to contact with plunger directly. Because of this, a small gap between the internal surface of cooling valve body and the external surface of plunger is necessary. When pump is working, the pressure in the confined space might goes up to 400 MPa. The pressure is so high that dynamic seal which seats on cooling valve body would be squeezed into the gap. In real life, due to the manufacturing error, the gap between the internal surface of cooling valve body and the external surface of plunger cannot be evenly distributed around the plunger. As a result, the extrusion of dynamic seal could be different at different spots around plunger. The dynamic seal would experience three phases before it fail completely. Phase I, an early extrusion phase. In this phase, a small amount of dynamic seal material is squeezed into some spots which have bigger gap comparing with other spots. Phase II, a mid-term extrusion phase. In this phase, much more dynamic seal material has been squeezed into the gap unevenly. The friction force might increase dramatically in this phase. In worst case, the plunger might get stuck. Phase III, a final leakage phase. In this phase, the squeezed dynamic seal material is cut off and then leakage occurs.
3. The method to detect dynamic seal failure in final leakage phase

As mentioned above, the failure process of dynamic seal could be divided into three phases which include early extrusion phase, mid-term extrusion phase and final leakage phase. In these three phases, it is easy to detect dynamic seal failure in phase III, but not in phase I and II. Theoretically, if leakage occurs, fluid must flow from high pressure side to low pressure side. Therefore, logically, by measuring the flow-rate of the fluid, it is possible to find out whether leakage occurs or not. However, this method is almost infeasible in practical applications. Firstly, when leakage just occurs, the amount of fluid leaking is not enough to be measured easily. Secondly, in high pressure pump, the flow-rate of water is changing dynamically. So, it is not easy to recognize whether the leakage occurs or not. In a word, by measuring the flow-rate to detect dynamic seal leakage is not a feasible method.

Is there another way to detect dynamic seal leakage? Based on analysis, when high pressure pump is working, the pressure in each cylinder periodically fluctuates from 0 to 400MPa. As pressure goes up, if the leakage channel has been formed, the high pressure water must be pushed into the low pressure side. Therefore, a pressure disturbance in low pressure side should be expected. Logically, the higher the pressure difference is, the larger the disturbance is. Since the pressure on high-pressure side fluctuates periodically, the disturbance should also fluctuate periodically. Is it possible to detect dynamic seal leakage by measuring the pressure disturbance? In order to verify the above reasoning, two cylinders have been selected randomly for pressure disturbance measurement on the low-pressure side. As shown in Figure 4, the direct-drive pump used in this experiment is manufactured by OMAXCor., Ltd. of America. The pump power is 30KW and the working pressure is 380MPa. In principle, the pressure sensor should be installed as close as possible to the leakage spot in order to get leakage number accurately. However, due to the limited installation space, in this experiment, the pressure sensor is installed at a spot which is around 30mm away from dynamic seal.

Under normal working conditions, the dynamic seal of direct-drive pump can last about 500 hours before it fails. Theoretically, no leakage, no pressure disturbance. In order to detect the pressure disturbance, the measurement has been carried out for a long time in this experiment. As shown in Figure 5, before dynamic seal leakage occurs, though pressure fluctuates in both cylinders, the average pressure is almost the same, around 70KPa. And the fluctuation of pressure should be caused by cooling water flowing.
With time going, dynamic seal gradually begins to fail. As shown in Figure 6, when leakage occurs, water pressure on low pressure side starts to increase. Around 20% increment has been detected in this experiment. In order to get further information of leakage, high pressure pump has been kept running. In less than half hour, the pressure fluctuations on low-pressure side changed significantly. As shown in Figure 6, it seems that a leakage channel has been formed in half hour. And water can flow freely through the leakage channel. In water sucking stroke, water enters the confined space of cylinder from cooling water side. As a result, the pressure in cooling side becomes lower. In water draining stroke, water comes out from the confined space of cylinder and enter low pressure side. As a result, the pressure in cooling side becomes higher. The above test results show that water pressure on
low-pressure side has a significant change in final leakage phase. Therefore, by measuring the pressure disturbance on low-pressure side, dynamic seal leakage can be detected.

4. The method to detect dynamic seal failure in early extrusion phase & mid-term extrusion phase

Based on the above discussion, it is feasible to obtain dynamic seal leakage information by detecting pressure disturbance on low pressure side. The advantage of this detection method is that the method is easy to use and easy to understand. The disadvantage is that the failure of dynamic seal cannot be detected until leakage occurs. This might cause a big trouble. Generally, in ultra-high pressure application, as long as leakage occurs, high speed jet would be formed. And since the jet is so powerful, it would damage some expensive parts which are in the way of jet passing through. For water jet cutting, as long as leakage occurs, working pressure would drop down dramatically in a short period of time. As a result, the workpiece cut by waterjet might be damaged because of the pressure drop. Therefore, although detecting dynamic seal leakage by measuring pressure disturbance on low pressure side is a feasible method, it is not an ideal method. An ideal method is the one by which dynamic seal failure can be detected in its early failure phase. In order to find a better measurement method, this paper explores the method of detecting dynamic characteristics of crankshaft caused by lateral torque.

4.1. Establishment of dynamic analysis model

As mentioned above, the original reason for dynamic seal failure is the extrusion of dynamic seal material. Because of manufacturing error, the gap between the external surface of plunger and the internal surface of cooling valve body is not distributed evenly around plunger. Therefore, the extrusion on different spots is not distributed evenly. This unevenness of extrusion made reciprocating plunger suffer a lateral force. Theoretically, reciprocating plunger will be affected by this lateral force. Therefore, by measuring the lateral force, it should be possible to know whether the extrusion occurs or not. Practically, measuring the lateral force directly is not feasible. So, finding another way is necessary. Since the lateral force would cause crankshaft vibrate, it should be possible to detect the lateral force by measuring the dynamic response of the crankshaft. Logically, if there is a lateral force working on plunger, it means there is a torque working on the crankshaft. Though the value of the lateral force caused by dynamic seal extrusion would be a relatively fixed number, the location of acting spot is changing quickly and continuously since the plunger moves back and forth quickly and continuously. So, the torque is changing all the time. For analysis purpose, another lateral force which acts on the end face of plunger has been used to replace the actual lateral force. This replacement would not change anything, because both of them would lead to the same torque. In theory, the lateral torque received by plunger will be transmitted to crankshaft via connecting rod and will cause crankshaft vibrate. Therefore, it should be possible to detect the lateral force generated by dynamic seal extrusion by measuring transient dynamic response of crankshaft. To verify the above reasoning, this paper carried out dynamic analysis on plunger, connecting rod and crankshaft.

To simplify the analysis, in this paper, some irrelative components have been removed. This would not change the analysis results since those components removed are not necessary for analyzing the dynamic characteristics of the crankshaft. After simplification, the analysis model established in this paper is shown in Figure7. As can be seen from Figure7, all the components related to the analysis object are modelled according to actual conditions.

In actual working situation, two types of loads might act on plungers. The first one is a positive force, which is perpendicular to the end face of plunger and loading on the whole end face. The second one is a lateral force, which is loading in the end face of plunger and with a randomly selected direction. The resultant force of positive force and lateral force is named deviation force. Since any force loads on plunger would transmit to crankshaft, therefore, a point randomly selected on crankshaft bearing has been analyzed (as shown in Figure8).
4.2. Dynamic analysis of crankshaft bearing with loading on a single plunger

| Loading Groups | Plunger1 | Plunger2 | Plunger3 |
|----------------|---------|---------|---------|
| 1              | 0       | Positive fluctuation load or Deviation fluctuation load | 0 |
| 2              | 0       | 0       | Positive fluctuation load or Deviation fluctuation load |
| 3              | Positive fluctuation load or Deviation fluctuation load | 0 | 0 |

Generally, there are three-plungers working simultaneously for direct-drive high pressure pumps. In order to verify that lateral torque caused by dynamic seal extrusion would lead to dynamic response on crankshaft bearing, a positive force and a deviation force have been added on the end face of plunger respectively. In this experiment, only one plunger is loaded. The reason for that is to simplify the
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analysis process and to get away some other disturbances. Normally, the value of positive force and lateral force are not fixed, and they are changing along the positive half cycle of the sine curve, as shown in Figure 9. For research purpose, a load which is in the YZ plane and has the direction of 45° from Y axis has been selected as the lateral force (not shown in the figure) to simulate dynamic seal material extrusion. In this experiment, amplitude of 1 has been selected for both loads (as shown in Figure 10). And each one lasts0.05S. This is based on the calculation of load cycle. 0.05S is long enough for each load to work on plunger for more than one cycle. A series of dynamic analysis have been carried out. The loading combination for the analysis has been listed in table 1.

![Figure 11](image1.png)

**Figure 11.** The transient dynamic response of the crankshaft bearing on Y direction caused by positive loading and deviation loading (The left figure represents the bearing 1 shown in Figure 8, the right one represents the bearing 2 shown in Figure 8, and the load is the combined load 1 of Table 1.)

![Figure 12](image2.png)

**Figure 12.** The transient dynamic response of the crankshaft bearing caused by positive loading and deviation loading (The left figure represents the bearing 1 shown in Figure 8, the right one represents the bearing 2 shown in Figure 8, and the load is the combined load 2 of Table 1.)

As shown in Figure 11, Figure 12, and Figure 13, a positive force and a deviation force lead to different transient response on the crankshaft bearings. Obviously, when a positive force is replaced by
a deviation force, different dynamic responses occurs on both crankshaft bearings 1 and 2. Therefore, by detecting the transient response characteristics on bearings 1 and 2, it is fully possible to obtain the information of dynamic seal failure in its early extrusion phase.

Figure 13. The transient dynamic response of the crankshaft bearing caused by positive loading and deviation loading (The left figure represents the bearing 1 shown in Figure 8, the right one represents the bearing 2 shown in Figure 8, and the load is the combined load 3 of Table 1.)

4.3. Dynamic analysis of crankshaft bearing with loading on three plungers simultaneously
Loading on a single plunger showed the feasibility of detecting dynamic seal failure in its early extrusion phase by detecting dynamic response of crankshaft bearing. To further confirm the conclusion, simulating the actual working conditions is necessary. To do that, the loading has been added on all three plungers simultaneously instead. The same as above, there are two types of loading acting on plungers. The first one is a positive force, which is perpendicular to the end face of plunger and loading on the whole end face. The second one is a lateral force, which is loading in the end face of plunger and with a randomly selected direction. The resultant force of positive force and lateral force is named as the deviation force. For each type of loading, though the value of loading is the same for each plunger, the phases of loading on each plunger are different. The phase difference is 120 degree for each pair of plungers. Each loading is changing along a positive half cycle of sine curve, as shown in Figure 14 and Figure 15. In order to verify the conclusion drawn from loading on a single plunger, two representative load combinations have been selected randomly, as listed in Table 2.

| Loading Groups | Plunger1                  | Plunger2                  | Plunger3                  |
|----------------|---------------------------|---------------------------|---------------------------|
| 1              | Positive fluctuation load  | Deviation fluctuation load| Positive fluctuation load  |
| 2              | Positive fluctuation load  | Positive fluctuation load  | Deviation fluctuation load |
Figure 14. Loading on three plungers.

Figure 15. Loading on three plungers simultaneously.

Figure 16. The transient dynamic response of the crankshaft bearing caused by positive loading and deviation loading (The left figure represents the bearing 1 shown in Figure 8, the right one represents the bearing 2 shown in Figure 8, and the load is the combined load 1 of Table 3.)
As shown in Figure 16, Figure 17, a positive force and a deviation force lead to different transient responses on the crankshaft bearings. Obviously, when a positive force is replaced by a deviation force, different dynamic responses occur on both crankshaft bearings 1 and 2. This analysis further verified that, by detecting the transient response characteristics on bearings 1 and 2, it is fully possible to obtain the information of dynamic seal early extrusion phase.

In fact, when a positive force is replaced by a deviation force, extra high-frequency vibration would be expected, as shown in Figure 18 and Figure 19. Therefore, by measuring extra high-frequency components, whether dynamic seal extrusion occurs or not should be detected.

**Figure 17.** The transient dynamic response of the crankshaft bearing caused by positive loading and deviation loading. (The left figure represents the bearing 1 shown in Figure 8, the right one represents the bearing 2 shown in Figure 8, and the load is the combined load 2 of Table 2.)

**Figure 18.** The frequency response of the crankshaft bearing caused by positive loading and deviation loading. (The left figure represents the bearing 1 shown in Figure 8, the right one represents the bearing 2 shown in Figure 8, and the load is the combined load 1 of Table 3.)
Figure 19. The frequency response of the crankshaft bearing caused by positive loading and deviation loading (The left figure represents the bearing 1 shown in Figure 8, the right one represents the bearing 2 shown in Figure 8, and the load is the combined load 2 of Table 2.)

5. Conclusions
Based on the analysis of the dynamic seal failure mechanism, this paper found that the dynamic seal would come through three phases before it failed completely. These three phases includes early extrusion phase, mid-term extrusion phase and final leakage phase. In final leakage phase, the failure of the dynamic seal could be detected by measuring the pressure disturbance on low-pressure side. The paper further studied the dynamic response of the crankshaft caused by the failure of the dynamic seal in its early extrusion phase and mid-term extrusion, and found that the failure of the dynamic seal in extrusion phases could be detected by measuring the transient response of the crankshaft bearing. These two ways of detecting the failure of dynamic seal would be very useful in developing intelligent machine.

References
[1] Li N 2015 The Study on residual stress and fatigue life of autofrettage Super-high pressure pump head [D]. Wuhan: Wuhan University of Science and Technology72-101
[2] Ju Q 2016 Research on virtual manufacturing of ultra-high pressure tubular reactor with autofrettage [D]. Daqing: Northeast Petroleum University14-47
[3] Zhang C 2014 Research of ultrahigh pressure pump head material simulation platform [D]. Wuhan: Huazhong University of Science and Technology6-44
[4] Zhang Q Y, Chen R H, Pu R C et al. 2000 Static dynamic finite element analysis of drilling pump body J. Beijing: Journal of petroleum 08:227-229
[5] Leng R B 2003 Dynamic simulation and optimization design of high pressure water injection pump[D]. Chengdu: Southwest Petroleum Institute ,6-69
[6] Zhu Y Y, Ye Y B, Zhou R, Zhang W 2005 Finite element modal analysis of high pressure emulsion pump boxJ. Beijing: General Machinery(05):65-67