Creative Design of Streamline Groove Mechanical Seal Based on TRIZ Theory

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Abstract. In view of the problems of poor stability and large leakage of dynamic pressure non-contact mechanical seals in a specific working environment, through the analysis of the mechanical seal principles and end structure, based on the TRIZ theory, choose the "structure stability", "adaptability and versatility" as the improve elements, the "harmful emission" and "foreign harmful factors" as the deteriorate elements. The principle numbers of the invention are obtained from the contradiction matrix. According to the principles of the invention, a new type of streamline groove mechanical seal is designed. Through the technology of making groove on the end face, a fluid film with a certain stiffness is obtained, and the end face is sealed. Through improving the stability and adaptability of the mechanical seal operation, it can operate safely and stably in a specific working environment and meet the requirements of the seal.

Keywords: seals; mechanical seals; TRIZ theory; streamline groove

1. Introduction

Mechanical seal is a kind of sealing device that at least has a pair of end surfaces perpendicular to the rotational axis, under the action of the compensation element and the dielectric pressure to prevent leakage of fluid, also known as end face seal. It is an indispensable part in fluid machinery and power machinery [1]. From the patent of the first face seal in the UK in 1885 to the present one hundred years, the mechanical seal technology has developed greatly. The mechanical end face seal has the characteristics of reliable operation, small leakage, long service life and low power consumption, so it is suitable for petrochemical industry and water pump repair industry[2]. According to the size of the seal face clearance, mechanical seals are divided into contact seals and non-contact seals, and non-contact seals are divided into hydrostatic and hydrodynamic pressure types. From the perspective of the development of sealing technology at home and abroad, fluid dynamic pressure mechanical seals with macro grooves on the surface can better meet the conditions of high PV values, and have received greater attention[3]. This article focuses on the research and design of non-contact mechanical seals. The grooved mechanical seal on the sealing surface has become an advanced sealing technology in the field of non-contact mechanical seals. With its unique dynamic pressure effect and good sealing performance, it has been widely used [4]. Among them, the most widely used grooves are: spiral grooves, "T" grooves, arc grooves, straight grooves, etc. With the rapid development of petrochemical,
energy, aerospace and other fields, higher requirements are placed on the performance, service life and reliability of mechanical seals under extreme conditions (high temperature, high pressure, high speed or ultra-low temperature, vacuum, etc.))[5]. Based on the analysis of mechanical seals, this paper uses TRIZ theory to improve the sealing performance and applicability of mechanical seals, and carries out an innovative design.

2. TRIZ theory
TRIZ theory is an innovative method theory proposed by G. S. Altshuller and his research team on the basis of analyzing and studying more than 2.5 million patents in various countries and integrating multiple disciplines and field principles, which means the theory of solving invention problems. Generally speaking, the process of solving problems in TRIZ theory is as follows: first, the actual problem to be solved is transformed into a problem model; then, the solution model is obtained by using TRIZ tools; finally, the solution model is applied to the specific problem to obtain the solution[6]. There are four basic models of TRIZ problem: technical contradiction model, physical contradiction model, functional model and physical field model[7]. Technical contradiction model is widely used in engineering and technical problems, and contradiction matrix is an important tool for analyzing technical contradictions. The contradiction matrix is composed of 39 general engineering parameters and 40 invention principles refined by G. S. Altshuller and his research team. The 39 general engineering parameters are arranged horizontally and vertically. Horizontal represents the deteriorating parameters, vertical represents the improving parameters. There is a contradiction between the improved parameters and the deteriorated parameters. The number in the grid where the engineering parameters cross is the number of the recommended principle of invention[8]. With the development of technology and economy, the number of general engineering parameters has increased from 39 to 48, the number of invention principles has also increased to 77, the contradiction matrix table has changed from 39×39 to 48×48, and the diagonal positions have been filled[9]. In the mechanical design industry, there is also a basic process of convenient invention principle solution method[10].

3. Innovative design

3.1. Problem description
In the traditional seal face groove design and research process, a groove shape is generally designed first, and then some sealing performance indexes are selected to optimize the groove structure and parameters in order to obtain the best end face fluid film characteristics. The idea is to give the groove type first and then correlate the groove type parameter with the seal. This makes the groove configuration unable to actively and well match the characteristics of the end face fluid film, so it is difficult to obtain the best dynamic pressure effect of the end face fluid, and thus cannot obtain greater fluid film stiffness and opening force.

3.2. Extracting contradictions and parameters determining
In the design process of mechanical seal, the leakage rate is an important parameter to determine the seal performance. For a given slotted mechanical seal, there is a corresponding minimum leakage. In certain workplaces (such as nuclear power plants), the leakage requirements are so strict that some grooves cannot meet the requirements, so new grooves need to be designed. However, the new groove design takes a long time and may not be suitable for emergency situations. At the same time, consideration should be given to increasing the stability of the mechanical seal in the face of overload in order to better adapt to the workplace. According to the above analysis, the engineering parameters determined are "adaptability", "structural stability", "harmful emission" and "external harmful factors".

3.3. Check the contradiction matrix
According to the analysis, the improvement parameters are "adaptability" and "structural stability", and the deterioration parameters are "harmful emission" and "external harmful factors". Find the contradiction matrix table to get the serial number of the invention principle, as shown in Table 1.

| improvement parameters | … | 30 | … | 40 |
|------------------------|---|----|----|----|
| deterioration parameters | harmful emission | 1,15,24,21,12,35 | 40,35,31,17,11,24,18,30 |
| … | structural stability | 31,9,30,14,18,29,3 | 35,24,31,3,40,11,19,14,17 |
| … | adaptability | 31,9,30,14,18,29,3 | 35,24,31,3,40,11,19,14,17 |

### 3.4. Invention principle

From "structural stability" and "harmful emission", the invention principle number can be obtained: 1, 15, 24, 21, 12, 35. No.1 is segmentation, and the description is: a. Divide the object into separate parts; b. Make the object detachable; c. Increase the division of the object. This principle does not contribute to the solution of the problem. No.15 is dynamicity, described as: a. The change of the characteristics of the object (or external medium) should be optimal at each working stage; b. Divide the object into several parts that move relative to each other; c. Make the immobile object moving. According to this principle, the mechanical seal can be designed as a rotating form. The dynamic pressure type non-contact mechanical seal relies on the dynamic pressure effect of the fluid to achieve the sealing effect. No.24 is intermediary which is described as: A. The use of intermediate objects that can be migrated or transported; B. To temporarily attach another (easily separable) object to an object. According to the principle, the sealing medium can be used to solve the problem. The sealing device relies on the sealing medium to form a fluid film between the sealing rings to achieve the sealing. No.21 is reducing the harmful effect time, No.12 is equipotential, No.35 is physical or chemical parameter changes, none of these principles contribute to the solution of the problem.

From "structural stability" and "external harmful factors", the invention principle number can be obtained: 40, 35, 31, 17, 11, 24, 18, 30. No.40 is composite material. According to this principle, composite material can be selected for the seal ring to improve the adaptability and stability of the seal. No.31 is porous materials, No.17 is one-dimensional variable multidimensional, No.11 is pre-protection, No.18 is mechanical vibration, none of these principles contribute to the solution of the problem. No.17 is flexible shell or film, according to this principle, a film can be placed between the seals to prevent leakage.

From "adaptive" and "harmful emission", the invention principle number can be obtained: 31, 9, 30, 14, 18, 29, 3. No.9 is in advance reaction, according to this principle, a compensating device can be installed on the sealing device to cope with small axial movement. No.14 is the curvature increasing, This principle does not contribute to the solution of the problem. No.29 is pneumatic or hydraulic structure, according to this principle, sealing structure can be achieved according to hydraulic or pneumatic principle. No.3 is local changes, according to this principle, the sealing ring torus can be grooved to produce hydrodynamic pressure effect.

From "adaptation" and "external harmful factors" the invention principle number can be obtained: 35, 24, 31, 3, 40, 11, 19, 14, 17. No.19 is periodic action, according to this principle, the sealing grooves can be evenly distributed on the sealing ring.

Based on the above principles, the groove shape on the seal end face is designed according to the flow linear motion track of the seal fluid on the seal end face. He sealing principle is to make the seal-
ing fluid squeeze and shrink gradually from the opening of the groove to the root of the groove, and finally form a strong shearing and squeezing effect at the root of the groove, thus forming a significant dynamic pressure effect of the fluid. The basic shape of the boundary line of the streamline groove is determined by the fluid track of the end seal fluid film. The particles of the sealing fluid move in an approximately uniform speed along the circumferential direction, the sealing fluid particles move with approximately uniform velocity in circumferential direction and in radial direction with the regularity that the velocity is inversely proportional to the radius. The synthesis of circumferential and radial motion is the basic streamline shape of sealed fluid particles. As shown in figure 1, the relationship between the polar Angle and the polar diameter of the streamline groove marginal line (12,13) is as follows:

$$\theta = \theta_0 + \frac{\pi h \omega (r_0^2 - r^2)}{Q} \quad (1)$$

where:
- $\theta_0$ is the initial polar Angle of type line edge starting at the opening of the groove;
- $r_0$ is the radius of the starting point of the groove (11) at the opening of the groove (11);
- $h$ is the average clearance between two opposite axial sealing faces;
- $Q$ is the leakage of medium volume in sealing clearance;
- $\omega$ is the angular velocity of relative rotation of the two sealing end faces.

4. Streamline groove seal

As shown in Figure 1–2, shows the structure of mechanical seal device with a streamline groove end face seal ring, and the streamline groove is located on the outer diameter side of the rotary ring seal end face. The mechanical seal device is composed of a static ring 1, a rotating ring 2, a static ring seat 3, a shaft sleeve 4, a transmission pin 5, a tolerance ring 6, a compression sleeve 7, a push ring 8, a spring 9, an anti-rotation pin 10, etc. The coaxial lines of the static ring 1 and the rotating ring 2 are arranged face to face, and the opposite end faces form a sealing surface. The static ring 1 is axially supported by the push ring 8 and spring 9 and positioned by the anti-rotation pin 10. Therefore, the static ring 1 can only float freely along the axial direction. The moving ring 2 is expanded on the cylindrical surface of the shaft sleeve 4 radially by the tolerance ring 6, contacts with the step surface of the shaft sleeve 4 axially and is compressed axially by the compression sleeve 7, and is fixed together with the shaft sleeve 4 by the driving pin 5 in the circumferential direction, so the moving ring 2 can rotate synchronously with the shaft sleeve 4 and the rotating shaft.

On the seal face of the moving ring shown in Figure 1 and Figure 2 (it can also be a static ring, or the seal face of the rotating ring and the static ring at the same time), a streamline groove 11 is provided, which is divided into 8-18 numbers and generally no more than 25 evenly arranged streamline grooves by the same form isolation part 14 (weir area) with the end plane height.
As shown in Figure 2, the ratio of the radial length of the ring area with groove part on the sealing end face to the radial length of the ring area without groove part is 0.3~5, preferably 0.6~1.5. The ratio range of the arc length of the opening along the circumference of the sealing ring and that of the adjacent isolation part along the circumference of the sealing ring is 0.2~5, and the preferred ratio range is 0.8~1.2. The depth of the type groove can generally be 0.002~10 mm, preferably 0.002~0.030 mm. The number of grooves on the seal end face may be determined according to different working conditions and requirements. Under normal circumstances, along the circumference of the sealing end face, there are less than or equal to 25 grooves. In terms of the driven pressure effect and the processing technology, the number of grooves on the seal end face can be optimized as 8~18. The shape of the seal ring is shown in Figure 2.

The clearance of the groove-free area of the two sealing end faces is 3μm, the groove depth is 6μm, the inner diameter is 120 mm, the radial groove length is 12 mm, the blocking structure radial length is 10 mm. The above data were taken to calculate and analyze the bearing capacity of the fluid film in logarithmic spiral groove and "T" shaped groove respectively. Firstly, the optimized structure parameters of logarithmic spiral groove and "T" groove are obtained. Then, the designed groove should be consistent with the first two types in terms of the number, depth and ratio of the dam (block structure 15) except for the borderline, to enhance the comparability of the results. The results show that the bearing capacity of the fluid film in logarithmic spiral groove is 620N, that in "T" groove is 560N, and that in streamline groove is 667N. By contrast, the new type of streamline groove mechanical seal fluid film has a greater bearing capacity.

5. Conclusion
In this paper, TRIZ theory is applied to carry out innovative design of dynamic pressure non-contact mechanical seal. Problems encountered in practical application are analyzed, technical contradictions are found, engineering parameters are determined, and the serial number of invention principle is obtained through contradiction matrix table. By analyzing the principle of invention, a new type of streamlined groove mechanical seal is designed innovatively. Compared with the current sealing ring in the form of logarithmic spiral groove or "T" shape groove, the sealing device with the above design structure seal ring can have more superior fluid dynamic pressure effect. Under the same conditions, the bearing capacity of the fluid film on the end face of the designed streamline groove is increased by 7.6% compared with that of the logarithmic spiral groove, and increased by 19.1% compared with that of the "T" groove, which obviously has better opening force, stiffness and bearing capacity, and also has better dynamic pressure effect of end face fluid.

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