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# Design and Seal Performance Analysis of Bionic Sealing Ring for Dynamic Seal

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## 1. Introduction

Rubber O-ring has been widely used in national defence industry, petrochemical industry, transportation, machinery manufacturing and other fields. Seal performance and frictional resistance of sealing ring are important factors restricting hydraulic system, rotating machinery and reciprocating machinery. The existing rubber sealing rings such as O-ring, rectangular ring and so on can play a good seal performance in engineering practice. But, they are prone to twist, wear and bite in the process of working. And the frictional resistance of the ring is large, which increases the energy consumption of the system. And the non-smooth surface technique in the bionic principle can reduce the frictional resistance. Therefore, it is an innovative method to apply non-smooth surface technology to rubber sealing ring. It is significant to be used in design, installation, and operation of rubber sealing rings in static and dynamic seals.

Zhang et al. [1] used the finite element software to analyse the heat extraction for EGS with tree-shaped wells to find that the finite element software can accurately simulate the actual working conditions. Wang [2] established the model of O-ring, and obtained the change trend of equivalent stress under fluid pressure and seal clearance. Shang [3] obtained the factors that affect the failure of O-ring under ultra-high pressure. Chen [4] explored the failure factors of O-ring in dynamic seal. Walsh et al. [5] studied the drag reduction of various bionic surface structures. The results showed that triangular grooves have the best drag reduction performance. Viswanath et al. [6] found that bionic grooves reduced resistance of wing by 2-3% compared with no bionic groove. Lee et al. [7] took NACA0012 wing as the experimental object, calculated and analysed the model with V-shaped surface structure, and found that the drag reduction efficiency decreased by 6.6%. Zhang [8] observed the shape characteristics of pigeons, found that bionic shape features can reduce the resistance of pigeons. Ren and Deng [9-10] established two models of bionic surface and non-bionic surface that based on piston and cylinder liner. The experimental results showed that bionic surface can reduce resistance and wear. Liu et al. [11] established several bionic models with different cavity radii, and found that the seal performance became more obvious with the decrease of cavity radius.

In this paper, the non-smooth surface technology is applied to the surface structure of rectangular sealing ring to design a bionic sealing ring. The effects of precompression amount, fluid pressure, friction coefficient and reciprocating velocity on the static and dynamic seal performance of rectangular and bionic sealing rings are studied by finite element simulation.

## 2. Design of bionic rubber sealing ring

### 2.1. Non-smooth surface technology theory

The essence of bionics is to take biology as the carrier, and to understand their morphological characteristics, way of life and living environment. This kind of self- shape structure which can adapt to the bad environment is introduced into the engineering actual equipment. The appearance characteristics of parts are changed by artificial design, to enhance the working efficiency and service life of equipment.

In the process of biological evolution, organisms have formed a non-smooth form that is favorable to their survival. Therefore, a lot of material basis are provided for engineering research. In this paper, the morphological characteristics and survival patterns of shells and earthworms were studied to find the surface had non-smooth morphological features. At the same time, according to the analysis of the drag reduction experiment, it was found that the introduction of the concave non-smooth surface structure to the rectangular sealing ring can be realized, and the research value is higher.

### 2.2. Constitutive model of rubber material

A variety constitutive models are used to describe rubber material, such as Heo-Hooken strain energy function, Exponential-Hyperbolic law, and Mooney-Rivlin model, Klosenr-Segal model, and Ogden-Tschoegl model [12]. In this paper, the Mooney–Rivlin model was selected to describe the mechanical characteristics of the rubber O-ring. The function can be expressed as follows [13]:

$$W = C_1\left(I_1 - 3\right) + C_2\left(I_2 - 3\right), \quad (1)$$

where: $W$ is the strain energy density, $C_1$ and $C_2$ are Mooney-Rivlin coefficients, and $I_1$ and $I_2$ are the first and second strain tensor invariant.

The relationship of stress and strain can be expressed as follows:

$$\sigma = \partial W / \partial \varepsilon. \quad (2)$$

### 2.3. Design scheme of bionic rubber sealing ring

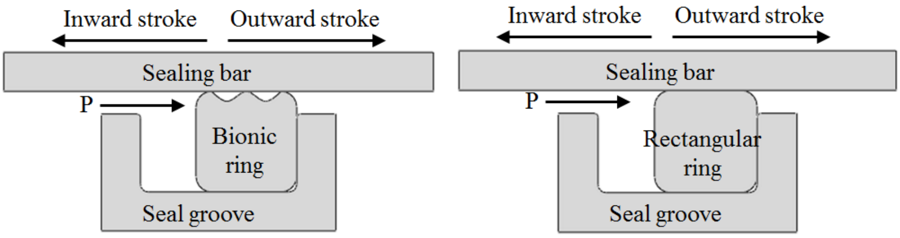
It is found that the four corners of cross section of the rectangular sealing ring, grooves, and the sealing rod are touching in the dynamic seal. This has a great effect on the stress of the sealing ring, and accelerates the rubber wear at the edge corner. A bionic sealing ring with bionic slot is obtained by chamfering edges. The schematic diagram of bionic rubber sealing ring is shown in Fig. 1, a. The main sealing surface is the contact surface between the upper surface of the ring and seal bar. The bionic sealing ring adopts two concave structures, and forms two small cavities with the main contact surface, and a circular protruding structure is presented in the middle of the ring. Therefore, it is not easy to roll and twist in reciprocating motion.

## 3. Calculation model

### 3.1. Parameters of the model

The finite element models of the rectangular and bionic sealing rings are established to study the seal performance, as shown in Fig. 1. Only the size of the bionic groove surface structure is different. The materials of sealing ring are nitrile rubber (NBR), the hardness is IRHD65, and the density is 1.2 mg•m$^{-3}$. According to the rubber compression test, in this paper the parameters of NBR select $C_1$=1.87 MPa, $C_2$ =0.47 MPa. The inner diameter of sealing ring is 45mm, and the section width is 5.16 mm. The materials of sealing rods and grooves are both steel. The density is 7.8 mg•m$^{-3}$, Poisson's ratio is 0.3 and modulus of elasticity is 2.1×10$^5$ MPa. There are two movement directions in the reciprocating motion. One is inward stroke; it is defined as the sealing groove moves against the direction of fluid pressure action. On the opposite, when sealing groove moves toward the same direction of the fluid pressure, it is called outward stroke [14].

A contact penalty algorithm with a friction coefficient was employed to simulate the interactions between the ring and steel material. The friction coefficient is 0.05, 0.1, 0.15, 0.2, 0.25. Mesh division of the model by using four-node CAX4R. The pressure applied on one side of the sealing ring is used to simulate the fluid pressure in the model. Set up the reciprocating motion of the sealing bar to simulate the dynamic seal. The influence of bionic groove on sealing ring is studied by changing the depth of bionic groove. The depth of bionic groove is 0.25 mm, 0.5 mm, 0.75 mm, 1.0 mm.




a) Rectangular sealing ring b) Bionic sealing ring

Fig. 1 Schematic diagram of two sealing structures

### 3.2. The hypothesis of finite element analysis

Rubber has the material nonlinearity, geometrical nonlinearity, and contact nonlinearity, and it is necessary to make the following assumptions for mechanical and seal performance research [14].

1. The material has definite modulus of elasticity and Poisson's ratio;

2. The tensile and compression creep properties of materials are the same;

3. The longitudinal compression of the sealing ring is caused by normal restraint;

4. Creep does not affect the volume of the sealing ring.

The maximum Mises stress and the maximum contact pressure of the two sealing rings are compared to study the seal performance [15]. With the increase of stress, the stiffness of the material decreases, which results in the failure of rubber. When the maximum contact pressure is greater than the fluid pressure, the sealing ring can be sealed. The greater the maximum contact stress, the better seal performance.

## 4. Static seal performance

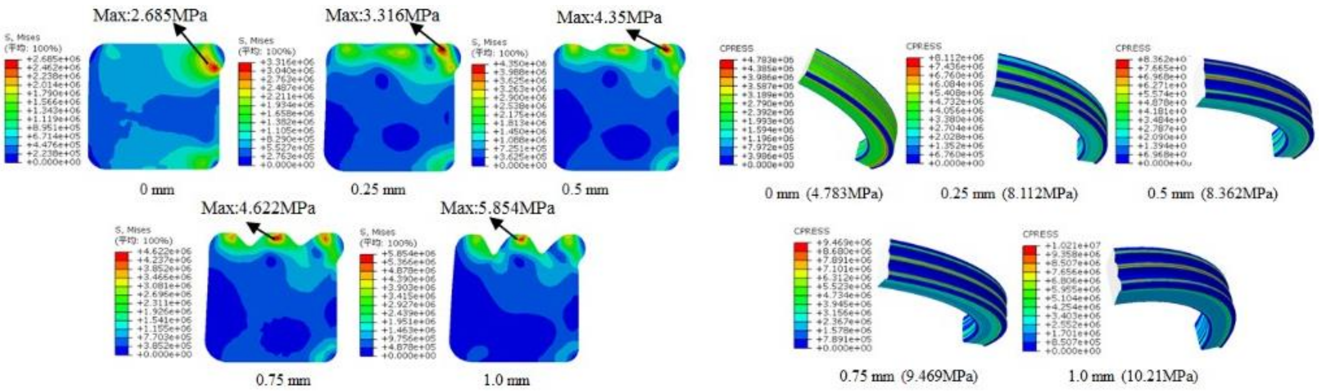
### 4.1. Groove depths

In static seal, when the initial compression is 0.2 mm, the medium pressure is 2 MPa, and the friction coefficient is 0.2, the stress distribution of sealing ring under different groove depths is shown in Fig. 2 a. The high stress area of bionic sealing ring is close to the gap between the seal bar and the groove. With the depth of the groove increases, the high-stress area moves to the protruding point of the contact surface. Materials in high stress areas are most likely to produce cracks to affect the seal failure.

As shown in Fig. 2, b, with the bionic groove depth increases, the maximum contact pressure of the main sealing surface increases. The difference between the maximum contact pressure and the fluid pressure of the bionic sealing ring is larger than that rectangular sealing ring. Therefore, the static seal performance of bionic sealing ring is good.

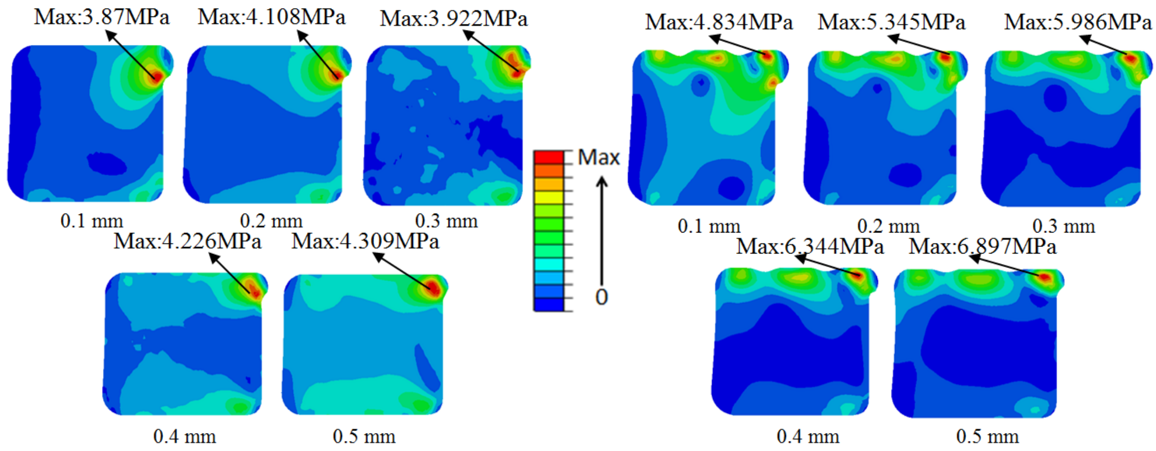
### 4.2. Compression amount

When the fluid pressure is 3 MPa, the stress distribution of the sealing ring under different compression amounts is shown in Fig. 3. The maximum Mises stress of the rectangular and bionic sealing rings increases with increasing compression amount. The maximum Mises stress of bionic sealing ring is larger than rectangular ring under the corresponding conditions. The high stress area of rectangular is concentrated on the gap between the seal rod and the groove. And the bionic sealing ring is mainly concentrated on the protrusion of the bionic groove surface. But there is more than one bionic groove on the contact surface, so the fluid medium doesn't pass through the sealing ring, to ensure seal performance and increase service time.




a) Stress distribution b) Contact pressure distribution

Fig. 2 Stress and contact pressure distribution of sealing ring under different groove depths




a) Rectangular sealing ring b) Bionic sealing ring

Fig. 3 Stress distribution of sealing ring under different compression amounts

As is shown in Fig. 4, the contact pressure increases with the increase of compression amount. The maximum contact pressure of rectangular ring is smaller than that of bionic ring under the same compression amount. The difference between the maximum contact pressure of bionic ring and the fluid pressure is greater, so the static seal performance effect is better than rectangular ring that is more suitable for the practical engineering needs.

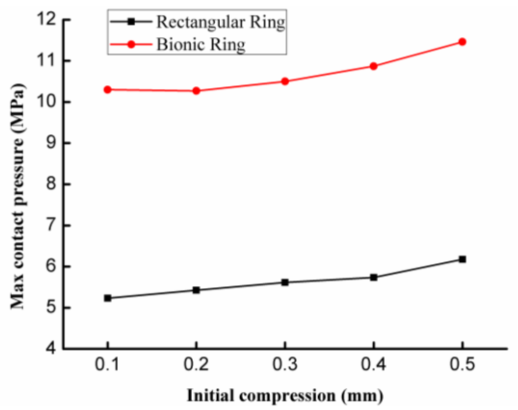



Fig. 4 Contact pressure of sealing rings

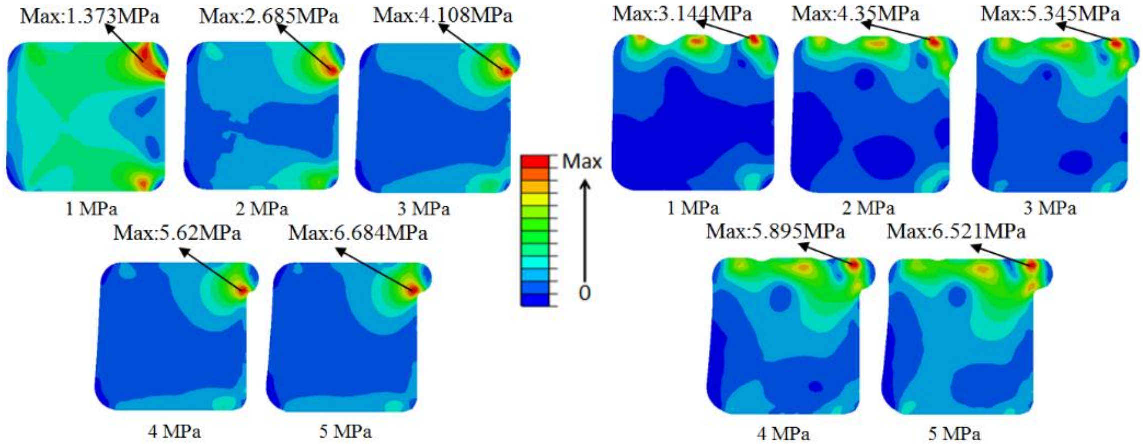
### 4.3. Fluid pressure

As shown in Fig. 5, a, the maximum Mises stress of rectangular sealing ring increases with the increasing of fluid pressure. the high stress areas change from 2 to 1 with the increasing of fluid pressure and concentrate on the gap between the seal bar and the groove. As shown in Fig. 5, b, the stress is close to the protuberance of the bionic groove surface. The maximum Mises stress of bionic sealing ring is smaller than that of rectangular sealing ring. Therefore, it is suggested that the bionic groove slow down the material failure and prolong service time of sealing ring.

The maximum contact pressure of sealing ring under different fluid pressure is shown in Fig. 6. With the increasing of fluid pressure, the maximum contact pressure increases. The maximum contact pressure of rectangular is smaller. The difference between the rectangular ring and bionic ring is great. It is suggested that the bionic sealing ring is more suitable for engineering practice.

### 4.4. Friction coefficient

As shown in Fig. 7, a, friction coefficient has little effect on the maximum Mises stress of rectangular sealing ring. And the range of high stress area expands with the increase of friction coefficient. Mises stress distribution of bionic sealing ring under different friction coefficient is shown in Fig. 7, b. With the increasing of friction coefficient, the maximum Mises stress of bionic sealing ring will fluctuate in the range of 4.3-4.7 MPa. The high stress area appears at the third bulge of the contact surface. It shows that the sealing failure is most likely to occur in third protrusion.




a) Rectangular sealing ring b) Bionic sealing ring

Fig. 5 Mises stress distribution of sealing ring under different fluid pressure

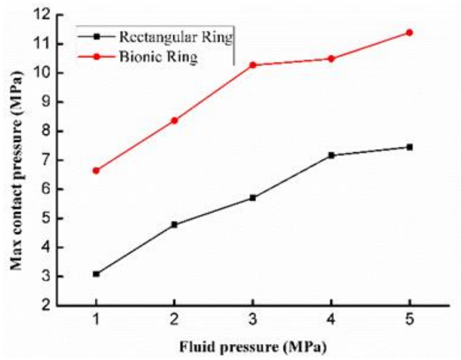
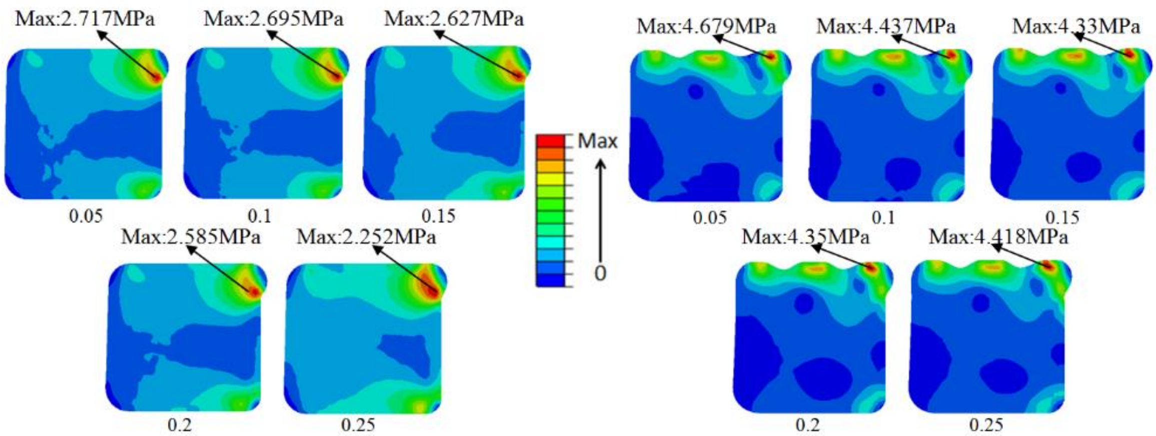



Fig. 6 Contact pressure of sealing ring

As shown in Fig. 8, with the increasing of friction coefficient, the maximum contact pressure of rectangular ring decreases and the contact pressure of bionic ring increases. Therefore, the seal performance of bionic ring can be enhanced by increasing friction coefficient properly.

The bionic sealing ring has a unique bionic groove surface structure. Two bionic grooves and three protrusions are on the main sealing surface of the bionic sealing ring. If one of the protuberance structures fails, the other protrusions can still ensure the seal performance. Therefore, it can be found that the static seal performance of the bionic sealing ring is better than that of the rectangular sealing ring.




a) Rectangular sealing ring b) Bionic sealing ring

Fig. 7 Stress distribution of sealing ring under different friction coefficients

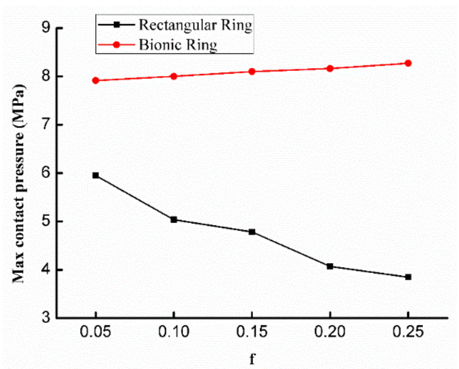
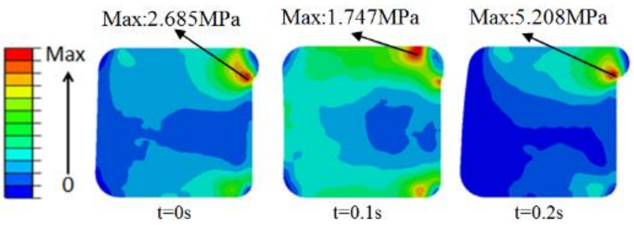



Fig. 8 Contact pressure of sealing ring

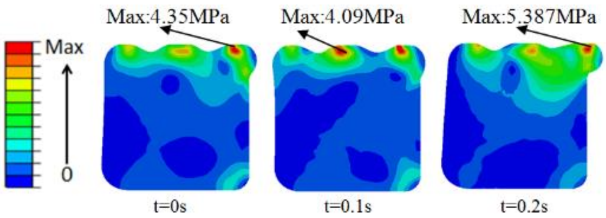
## 5. Dynamic seal performance

### 5.1. Groove depths

The maximum Mises stress of the rectangular sealing ring decrease in the inward stroke and then become increase in the outward stroke as shown in Fig. 9. The high stress area moves from the gap between the seal bar and the groove to the contact surface between sealing ring and seal bar in the inward stroke. And then the high stress area moves from the contact surface between sealing ring and seal bar to the gap between the seal rod and the groove in the outward stroke. The maximum Mises stress and variation of high stress area in bionic sealing ring are similar to those of the rectangular sealing ring.




a) Rectangular sealing ring




b) Bionic sealing ring

Fig. 9 Stress distribution of sealing ring

The stress curves of the four depths are shown in Fig. 10. Stress fluctuations are different when they are in inward stroke and outward stroke. When the groove depth is 0 mm, the maximum amplitude of stress fluctuation of sealing ring is obtained. The stress of rectangular sealing ring with bionic groove depth of 0.25 mm is minimum. Sharp fluctuations in stress will lead to material fatigue failure. Therefore, the structure design of bionic sealing ring is meaningful.

The maximum contact pressures of the four sealing rings in 2 MPa fluid pressure are shown in Fig. 11. The maximum contact pressure of 0 mm is the smallest, and it is still greater than the fluid pressure in any conditions. The bionic sealing ring with groove depth of 0.25 mm fluctuates about 6 MPa, and the bionic sealing ring with groove depth of 0.5 mm and 0.75 mm fluctuates about 8 MPa. It can be found that the bionic groove depth is not as deep as possible, there is an upper limit.

## 5.2 Compression amount

Mises stress curves of sealing ring under different compression amount as shown in Fig. 12, a. Mises stress fluctuations are different when they are in inward stroke and outward stroke. In the inward stroke, the fluctuation of bionic sealing ring is small. In the outward stroke, the Mises stress has a significant increase. When the compression amount is 0.5mm, the difference of average contact pressures in outward stroke and inward stroke is biggest. Average value in outward stroke is greater than it in inward stroke. As shown in Fig. 12, b, the contact pressure fluctuation in 0.5 mm is serious. Amplitude changes of the contact pressure curves in 0.1 mm and 0.2 mm are smaller. Average contact pressure in outward stroke is greater than that in inward stroke.

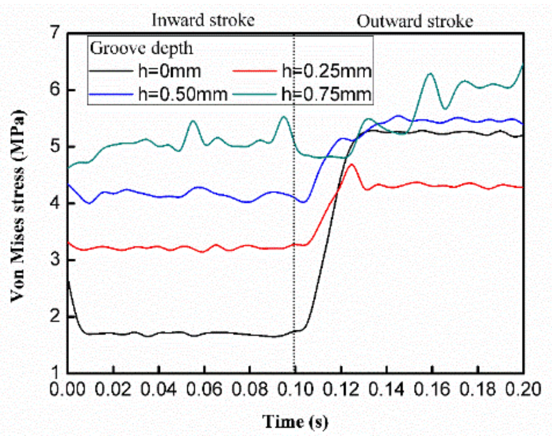



Fig. 10 Mises stress curves of sealing ring

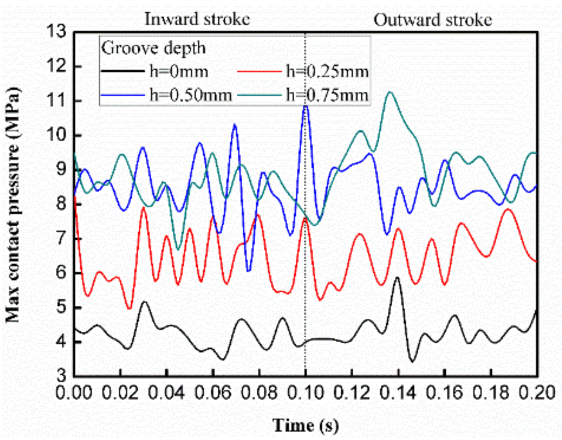
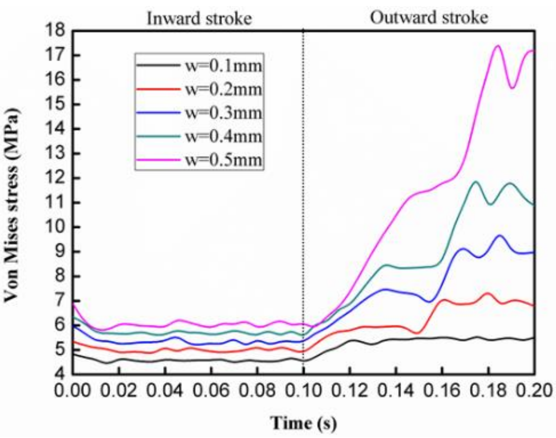
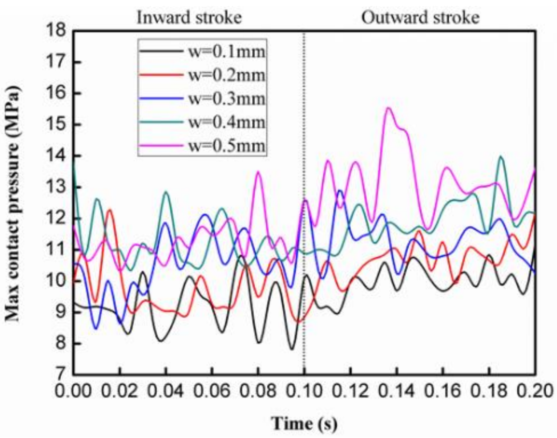



Fig. 11 Contact pressure curves of sealing ring




a) Von Mises stress

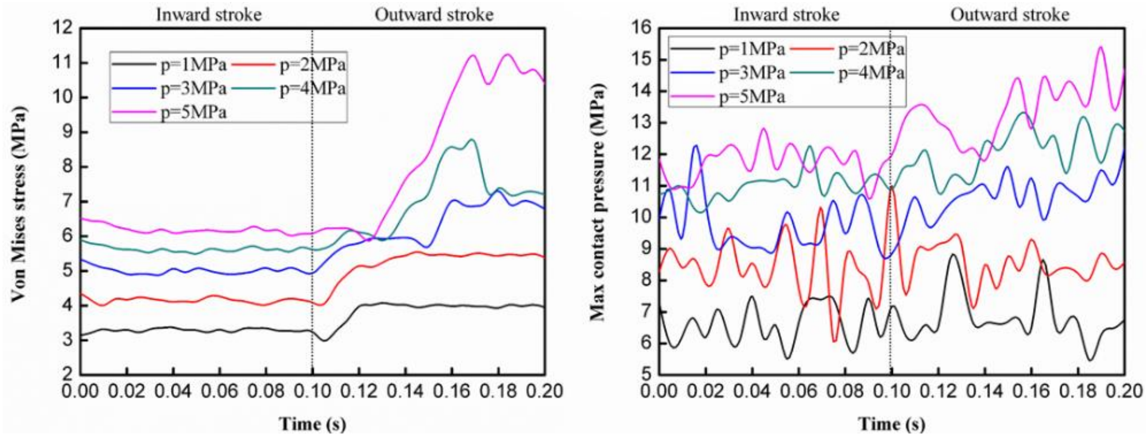



b) Max contact pressure

Fig. 12 Stress and contact pressure curves of sealing ring under different compression amount

5.3. Fluid pressure

Mises stress curves of sealing ring under different fluid pressure is shown in Fig. 13, a. With the increasing of fluid pressure, the Mises stress curves of bionic sealing ring increase. In the inward stroke, the stress decrease first and then didn't change significantly. In the outward stroke, the stress of bionic sealing ring increase first and then are in a fluctuation. Average Mises stress in outward stroke is greater than in inward stroke. Therefore, the seal performance of bionic sealing ring is better in outward stroke. Fig. 13, b shows the contact pressure curves of bionic sealing ring under different fluid pressure. The contact pressure increases with the fluid pressure increases. Average value of the contact pressure in outward stroke is greater than it in inward stroke. The difference also increases with the fluid pressure increases. Therefore, the dynamic seal performance can be enhanced by increasing the fluid pressure.

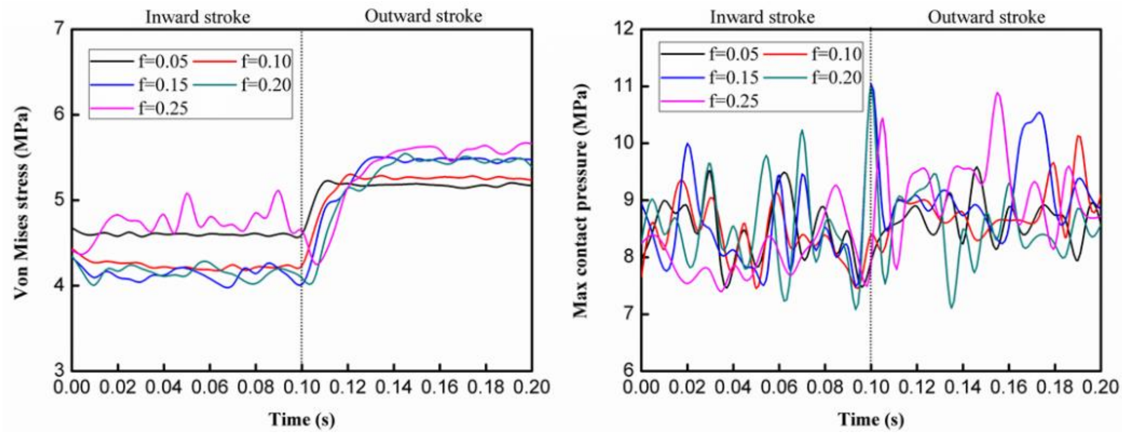



a) Von Mises stress b) Max contact pressure

Fig. 13 Stress and contact pressure curves of sealing ring under different fluid pressure

5.4. Friction coefficient

As shown in Fig. 14, a, stress difference of bionic sealing ring between inward stroke and outward stroke is smaller. Average value of the contact pressure in outward stroke is greater than it in inward stroke. Therefore, the effect of friction coefficient on seal performance can be alleviated by bionic sealing ring. Fig. 14, b shows the contact curves of bionic sealing ring under different friction coefficients. With the increasing of friction coefficient, the contact pressure curves are in a fluctuation. The contact pressure fluctuation in 0.2 is serious. The average contact pressure is greater than the fluid pressure 2 MPa. Therefore, the dynamic seal performance is reliable.

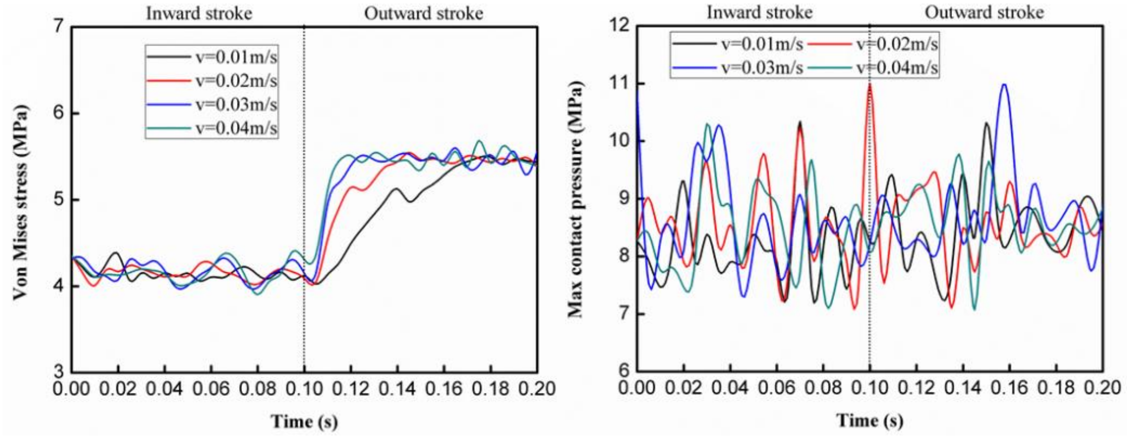



a) Von Mises stress b) Max contact pressure

Fig. 14 Stress and contact pressure curves of sealing ring under different friction coefficients

5.5. Reciprocating velocity

As shown in Fig. 15, a, stress difference of bionic sealing ring between inward stroke and outward stroke is smaller. With the reciprocating velocity increases, the average stress has a small change and the change trend of maximum Mises stress with time is the same. Therefore, reciprocating velocity has a small effect on the average Mises stress in the dynamic seal. Fig. 15, b shows the maximum contact pressure curves of bionic sealing ring under different reciprocating velocity. The contact pressure curves are in a fluctuation with the time of step increases. The average contact pressure of bionic sealing ring is greater than the fluid pressure in any conditions and varies little with the increase of velocity. Therefore, the dynamic seal performance of bionic sealing ring is better.




a) Von Mises stress b) Max contact pressure

Fig. 15 Stress and contact pressure curves of sealing ring under different reciprocating velocity

## 6. Conclusions

The seal performance of bionic sealing ring is greater than that of rectangular sealing ring. Therefore, the structure of bionic sealing ring is meaningful to engineering fields. In the static seal of bionic sealing ring, the maximum stress appears on the bulge of bionic groove. This structure prolongs the service life of the bionic sealing ring. Compression amount and fluid pressure have a great effect on the contact pressure. The seal performance increases with the compression amount and fluid pressure increases. Friction coefficient has a smaller effect on the bionic sealing ring's static seal performance than rectangular sealing ring.

Reciprocating dynamic seal performance of bionic sealing ring is different with its static seal performance. Seal performance in outward stroke is better than it in inward stroke. The average contact pressure of bionic sealing ring is greater than that of rectangular sealing ring, so the dynamic seal performance is better. The surface of bionic groove reduces the fluctuation of maximum Mises stress in inward and outward strokes, to reduce the fatigue failure and prolong the service time. The contact pressure increases with the increasing the compression amount and fluid pressure. The effect of friction coefficient on dynamic seal performance can be alleviated by bionic sealing ring. And reciprocating velocity has a small effect on the Mises stress in the dynamic seal.

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Yang Hu, Jie Zhang, Liming Chen

DESIGN AND SEAL PERFORMANCE ANALYSIS OF BIONIC SEALING RING FOR DYNAMIC SEAL

S u m m a r y

In this paper, the non-smooth surface technology is applied to the surface structure of the rectangular sealing ring for designing a bionic sealing ring. Two-dimensional axisymmetric models of rectangular and bionic sealing rings were established. Effects of pre-compression amount, fluid pressure, friction coefficient and reciprocating velocity on the static and dynamic seal performance of two sealing rings were studied. The results show that the seal performance of the bionic sealing ring is greater than that of rectangular. The static seal performance increases with the increasing of fluid pressure and compression amount. Dynamic seal performance in outward stroke is better than it in the inward stroke. Friction coefficient has a smaller effect on the bionic sealing ring's seal performance than rectangular sealing ring. Therefore, using the bionic sealing ring can improve the static and dynamic seal performances and prolong its service life in hydraulic systems, rotating machinery and reciprocating machinery.

**Keywords:** bionic sealing ring, non-smooth surface technology, rubber seal, finite element analysis, seal performance.

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