Design method and research of high temperature gas floating ring seal with slightly variable gap

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Abstract. The problem of seal failure caused by rubbing between floating ring and shaft directly affects the actual production efficiency. In this paper, the mathematical model of floating ring seal was established, the expression of seal clearance under the working condition of floating ring was calculated, and the design method of "slightly variable gap" gas floating ring was proposed. The finite element model was established by using Workbench, and the correctness of the mathematical model was verified. The results show that the ideal insert ring material calculated by the "slightly variable gap" design method can keep the working clearance of floating ring seal stable. In practical application, the insert ring with the same material as the axle runway can also be selected to achieve a more stable working clearance. The design method can avoid the rubbing between the runway and the inside of the floating ring under harsh conditions.

1. Introduction
In today's era of rapid development of modern industry, sealing has become an essential technical product to ensure the efficient, long-term, safe and stable operation of modern industry. Common seals mainly include non-contact seals: floating ring seals, labyrinth seals, etc, contact seals: brush seals, packing seals, etc [1-3]. With the rapid development of science and technology, sealing conditions gradually develop to high temperature, ultra-low temperature, supercritical and other special conditions. The sealing effect also needs to meet the requirements of reducing leakage and environmental pollution [4]. These problems need people to constantly develop more superior sealing products [5,6]. Because of its simple structure, small axial width and reliable sealing performance, floating ring seal has been applied in many special conditions, so it plays an important role in modern sealing technology. According to the structure and principle of floating ring seal, the sealing effect is directly related to the clearance of
floating ring. From the point of view of reducing leakage and improving sealing efficiency, the clearance of floating ring should be reduced as much as possible. However, if the clearance is too small, the working condition of floating ring will be deteriorated, and even the floating ring will lock shaft [7,8]. If the floating ring clearance is too large, the leakage will increase [9~11]. Therefore, it is very important to choose reasonable clearance for sealing effect [12].

The initial clearance of floating ring is determined by the interference fit and initial size. The working time gap will change with the temperature, speed and other factors. The change of clearance may lead to the failure of the rubbing between the floating ring and the shaft, and eventually lead to machine failure and equipment shutdown. However, there are few studies and literatures on how to keep the floating ring clearance stable. Therefore, a design method of "slightly variable gap" is proposed in this paper. By analyzing the influence of different structural parameters and operating parameters on the clearance value, the mathematical modeling was used to quantify the clearance value, and the specific expression of floating ring seal clearance was obtained, and the method to achieve slightly variable gap by selecting materials was established. This paper also used Workbench software to verify the model, and the software data supports the conclusion.

2. Structure and working principle of gas floating ring seal with slightly variable gap
Floating ring seal, also known as clearance seal [6], its working principle is a flow resistance non-contact dynamic seal which combines radial clearance seal and axial face seal. The floating ring seal can minimize the radial clearance without friction, so as to minimize the leakage. Due to the existence of radial clearance, the mutual contact and friction between solids are avoided. It is suitable for principal axis of high speed, such as hydrogen turbine pump of liquid rocket engine, centrifugal compressor of high and medium pressure, steam turbine and centrifuge [13,14].

The structure of the floating ring is shown in Figure 1. The floating ring is located on the shaft and located in the sealing cavity, which has a small gap with the rotating shaft runway. After sealing oil or gas is injected into the sealing cavity of floating ring, it leaks along the clearance of floating ring. Due to the high-speed rotation of the rotor, the sealing oil or gas flowing into the floating ring gap forms a membrane with certain bearing capacity under the action of the rotating shaft. On the one hand, the film lifts the floating ring to realize liquid lubrication between the floating ring and the journal, so as to reduce friction and wear. On the other hand, because the oil film fills the whole floating ring gap, it can prevent the gas medium from leaking out, thus playing a role of sealing [15~17].

![Fig.1 High Speed And High Temperature Gas Floating Ring Seal Structure Diagram.](image)
3. Calculation basis and hypothesis of mathematical model

The calculation and analysis of the working clearance of floating ring seal is mainly based on the linear strain analysis of floating ring structure size under operating conditions, and the core part of calculation is to solve the contact surface stress of thick wall cylinder according to the stress of the microelement. The calculation model is that the interference structure is equivalent to the thick wall cylinder, the insert ring is equivalent to the thick wall cylinder under internal pressure, and the graphite ring is equivalent to the thick wall cylinder under external pressure. Microelement stress solving equation [18-20]:

(1) The equilibrium equation of microelement:

\[
\sigma_0 - \sigma_r = r \frac{d\sigma_r}{dr}
\]

(2) Deformation compatibility equation:

\[
\frac{1}{r} (\varepsilon_r - \varepsilon_0) = \frac{d\varepsilon_0}{dr}
\]

(3) Comprehensive equations of equilibrium, geometry and physics:

\[
\varepsilon_r - \varepsilon_0 = \frac{1 + \mu}{E} (\sigma_r - \sigma_0)
\]

According to the above three calculation equations, the three-dimensional stress on the contact surface of the insert ring and graphite ring is solved, and the deformation of the floating ring under the operating condition is calculated by combining the interference inserting condition and the operating condition, and then the working clearance of the floating ring seal under the operating condition is calculated.

The following assumptions are made in the mechanical model calculation of the insert floating ring:

(1) The internal and external pressure of the insert ring and graphite ring are both axisymmetric, The elastic deformation of cylindrical shell is also axisymmetric without axial bending, Therefore, the stress and strain on the axial section are constant;

(2) The deformation of the insert ring and graphite ring on the contact surface is linear elastic deformation, and no plastic strain occurs.

4. Derivation of design method for gas floating ring seal with slightly variable gap

4.1. Calculation Of Clearance Caused By Interference

The floating ring is mainly composed of two parts. The outer ring is metal insert ring, and the inner ring is graphite ring. The two rings are assembled together by interference fit. The method of hot charging or cold pressing is widely used in interference connection. The interference of floating ring can be adjusted by modifying the design tolerance of inner circle of metal ring and outer circle of graphite ring, and the inside and seal end face of floating ring can be machined to the required size after inserting.
The symbols used are described as follows: $\sigma_r$ - radial stress of contact surface, $\sigma_\theta$ - circumferential stress of contact surface, $\sigma_z$ - axial stress, $r$ - diameter of any point on the insert ring or graphite ring, $P_m$ - the average contact stress on the contact surface of the insert ring, $P_g$ - the average contact stress on the contact surface of graphite ring, $R$ - diameter of the runway, $E_1$ - elastic modulus of insert ring, $E_2$ - elastic modulus of graphite ring, $H_g$ - axial thickness of graphite ring, $H_m$ - axial thickness of the insert ring.

Stress at any point on the insert ring:

\[
\begin{align*}
\sigma_\theta^m &= \frac{P_m R_2^3}{R_1^3 - R_0^3} \left(1 + \frac{R_2^2}{r^2}\right) \\
\sigma_r^m &= \frac{P_m R_2^3}{R_1^3 - R_0^3} \left(1 - \frac{R_2^2}{r^2}\right) \\
\sigma_z^m &= \frac{P_m R_2^3}{R_1^3 - R_0^3}
\end{align*}
\] (4)

Stress at any point on the graphite ring:

\[
\begin{align*}
\sigma_\theta^g &= -\frac{P_g R_1^3}{R_1^3 - R_0^3} \left(1 + \frac{R_1^2}{r^2}\right) \\
\sigma_r^g &= -\frac{P_g R_1^3}{R_1^3 - R_0^3} \left(1 - \frac{R_1^2}{r^2}\right) \\
\sigma_z^g &= -\frac{P_g R_1^3}{R_1^3 - R_0^3}
\end{align*}
\] (5)

According to the formula (4), when $r=R_3$, the preload of the metal ring on the contact surface can be obtained, and the three-dimensional stress on the contact surface of the metal ring is obtained as follows:

\[
\begin{align*}
\sigma_\theta^m |_{r=R_3} &= \frac{P_m (R_2^3 + R_0^3)}{R_1^3 - R_3^3} \\
\sigma_r^m |_{r=R_3} &= -P_m \\
\sigma_z^m |_{r=R_3} &= \frac{P_m R_2^3}{R_1^3 - R_0^3}
\end{align*}
\] (6)
According to the calculation formula (5), when $r = R_3$, the preload of graphite ring on the contact surface can be obtained, and the three-dimensional stress on the contact surface of graphite ring is obtained as follows:

\[
\begin{align*}
\sigma^r_{g}\bigg|_{r=R_3} &= \frac{-P_0 (R^2_1 + R^2_3)}{R^2_1 - R^2_3} \\
\sigma^r_{t}\bigg|_{r=R_3} &= -P_t \\
\sigma^g_{t}\bigg|_{r=R_3} &= \frac{-P_t R^2_3}{R^2_1 - R^2_3}
\end{align*}
\]

(7)

According to the calculation hypothesis (2) of the mechanical model, the strain deformation of the sealing ring is linear elastic deformation. The interference between the insert ring and the graphite ring can be considered as the linear superposition of the deformation $\lambda_1$ of the inner circle of the insert ring and the deformation $\lambda_2$ of the outer circle of the graphite ring. The numerical calculation relationship is as follows:

\[
\Delta = |\lambda_1| + |\lambda_2|
\]

(8)

(1) Radial displacement $\lambda_1$ of the inner circle of the insert ring

Suppose that the radial displacement of the inner circle $R_3$ of the insert ring is $\lambda_1$ and the radial linear strain $\epsilon_3^m$ is:

\[
\epsilon_3^m = \frac{2\pi(R_3 + \lambda_1) - 2\pi R_3}{2\pi R_3} = \frac{\lambda_1}{R_3}
\]

(9)

According to the generalized Hooke's Law:

\[
\epsilon_3^m = \frac{1}{E_1}[\sigma^m - \mu(\sigma^m_\sigma^m_\sigma^m)]
\]

(10)

Substituting (6) (9) into (10) shows that:

\[
\epsilon_3^m = \frac{\lambda_1}{R_3} \approx \frac{1}{E_1}[\sigma^m_{g}\bigg|_{r=R_3} - \mu(\sigma^m_{t}\bigg|_{r=R_3} + \sigma^m_t\bigg|_{r=R_3})]
\]

(11)

After finishing, we can get the following results:

\[
\lambda_1 = \frac{-P_0 R_3}{E_1} (1 + \mu) \frac{R^2_1 + 2R^2_3}{R^2_1 - R^2_3}
\]

(12)

(2) Radial displacement $\lambda_2$ of the outer circle of the graphite ring:

Similarly, suppose the radial displacement of the outer circle $R_3$ of graphite ring is $\lambda_2$, After finishing, we can get the following results:

\[
\lambda_2 = \frac{-P_0 R_3}{E_2} (1 - \mu) \frac{2R^2_1 + R^2_3}{R^2_1 - R^2_3}
\]

(13)

The diameter interference of the insert ring and graphite ring is $\Delta$ and the radial force of the insert ring and graphite ring is acting force and reaction force, and the force is assumed to be $F_0$. For the convenience of calculation, the following assumption is made on the contact surface of floating ring: the force of insert ring and graphite ring on the contact surface is evenly distributed on their respective contact surfaces. According to the balance of forces:

\[
P_m A_m = P_g A_g
\]

(14)
It can be obtained:

\[ P_m = P_e \frac{H_m}{H_e} = P_e \gamma \]  \hspace{1cm} (15)

Let \( H_m/H_e = \gamma \), where \( \gamma \) is defined as the axial width ratio of graphite ring to metal ring, and \( \gamma \) is generally greater than 1. The radial displacement of the insert ring and graphite ring on the contact surface presents a linear distribution in the radial direction. According to the calculation hypothesis:

\[ \frac{\Delta}{2} = |\lambda_1| + |\lambda_2| \]  \hspace{1cm} (16)

Substituting the formula (12) and (13) into formula (16), we can get:

\[ \frac{\Delta}{2} = \left| -\frac{P_g R_{12}}{E_1} \left( 1 - \mu_2 \frac{2R_g^2 + R_{12}^2}{R_g^2 - R_{12}^2} \right) \right| + \left| \frac{P_g R_3}{E_2} \left( 1 - \mu_2 \frac{2R_{12}^2}{R_{12}^2 - R_3^2} \right) \right| \]  \hspace{1cm} (17)

The inserting stress \( P_e \) on the contact surface of graphite ring is obtained as:

\[ P_e = \frac{\Delta}{2} \]  \hspace{1cm} (18)

Substituting (18) into (21), the radial displacement of the inner hole of floating ring under interference condition can be obtained as:

\[ C_0 = \frac{R_1 \mu_2 \frac{3P_e R_{12}^2}{E_2 (R_{12}^2 - R_g^2)}}{E_2 \frac{R_{12}^2}{R_{12}^2 - R_g^2} |\lambda_0|} \]  \hspace{1cm} (21)

By substituting (19) into (21), the radial displacement of the inner hole of floating ring under interference condition can be obtained as:

\[ C_0 = \frac{R_1 \mu_2 \frac{3P_e R_{12}^2}{E_2 (R_{12}^2 - R_g^2)}}{E_2 \frac{R_{12}^2}{R_{12}^2 - R_g^2} |\lambda_0|} \]  \hspace{1cm} (22)
where $k$ is the conversion factor:

$$k = \frac{R_1\mu_1}{E_1} \frac{3R_3^2}{R_3^2 - R_1^2} \left( \frac{1}{E_0} \frac{2R_1^2 + R_2^2}{R_1^2 - R_0^2} + \frac{R_0}{E_0} \frac{1}{1 - \mu_2} \frac{2R_2^2 + R_3^2}{R_2^2 - R_0^2} \right).$$ \hspace{1cm} (24)

### 4.2 Calculation Of Clearance Caused By Temperature Load

When the temperature is set at $T_0$, the diameter interference is $\Delta$; while at $T_1$ is $\Delta_1$, and $\Delta_1 > 0$. The radial displacement of the insert ring on the contact surface $R_3$ is $\Delta B$, and that of the graphite ring on the contact surface $R_3$ is $\Delta C$.

According to hypothesis (2) and contact surface deformation analysis, $\Delta B$ is approximately equal to the change of interference $\Delta - \Delta_1$ and thermal deformation $\Delta C$ of graphite ring outer circle, namely:

$$\Delta B = \Delta - \Delta_1 + \Delta C$$ \hspace{1cm} (25)

Where:

$$\Delta C = R_3\beta_3(T_1 - T_0)$$ \hspace{1cm} (26)

$$\Delta B = R_3\beta_3(T_1 - T_0)$$ \hspace{1cm} (27)

It can be obtained by substituting the above formula into (25):

$$\Delta_1 = \Delta - R_3(\beta_2 - \beta_3)(T_1 - T_0)$$ \hspace{1cm} (28)

Where $\beta_1$ and $\beta_2$ are the linear expansion coefficients of the insert ring and the graphite ring respectively. When there is contact stress and the operating temperature is $T_1$, the inner diameter displacement $C_1$ under interference condition is obtained:

$$\frac{C_1}{C_0} = \frac{\Delta_1}{\Delta} = 1 - \frac{R_3(\beta_2 - \beta_3)(T_1 - T_0)}{\Delta}$$ \hspace{1cm} (29)

When the conversion factor $k$ is brought in, the following results are obtained:

$$C_1 = C_0 - kR_3(\beta_2 - \beta_3)(T_1 - T_0)$$ \hspace{1cm} (30)

The total deformation $U_1$ of floating ring inner circle at temperature $T_1$ consists of three parts: (1) At normal temperature, the radial displacement of floating ring inner circle caused by interference is $C_0$; (2) When the operating temperature is $T_1$, the radial displacement of floating ring inner circle is $C_1$ under interference condition; (3) When the operating temperature is from $T_0$ to $T_1$, the change of inner circle caused by the expansion of graphite ring is $R_3\beta_3(T_1 - T_0)$.

The numerical relationship is as follows:

$$U_1 = C_0 - C_1 + R_3\beta_3(T_1 - T_0)$$ \hspace{1cm} (31)

$$U_1 = kR_3(\beta_2 - \beta_3)(T_1 - T_0) + R_3\beta_3(T_1 - T_0)$$ \hspace{1cm} (32)

If the expansion coefficient of floating ring is defined as $\beta_k$, then:

$$U_1 = R_3\beta_k(T_1 - T_0)$$ \hspace{1cm} (33)

By combining formula (32) and (33), we can get the following results:
4.3 Design method of gas floating ring seal with slightly variable gap

Assuming that the initial radial seal clearance of floating ring is \( \delta_0 \), the radial displacement of \( \delta_{R2} \), \( \delta_{K2} \) includes radial displacement \( \delta^p_{R2} \) caused by rotation speed and radial displacement \( \delta^T \) by temperature load. The actual radial seal clearance can be calculated by formula:

\[
\delta = \delta_0 + R_i \beta_k \frac{\Delta T}{2} - \delta^p_{R2} - \delta^T
\]  
\[
(37)
\]

To sum up, the actual radial working clearance of floating ring is as follows:

\[
\delta = \delta_0 + R_i \beta_k \frac{\Delta T}{2} - R_i \beta_k \frac{\Delta T}{2} - \delta^p_{R2}
\]  
\[
(38)
\]

According to the result of formula (38), under the condition of not considering the influence of rotating speed on the working clearance of floating ring temporarily, that is, \( \delta^p_{R2} = 0 \), \( \beta_k \) is the expansion coefficient of floating ring after inserted, see equation (34). The calculation formula of the actual working clearance of floating ring can be obtained as follows:

\[
\delta = \delta_0 + \left( kR_i (\beta_2 - \beta_1) - R_i (\beta_3 - \beta_1) \right) \frac{\Delta T}{2}
\]  
\[
(39)
\]

The design concept of "slightly variable gap" is that the working clearance \( \delta \) of floating ring will not change with the change of operating temperature. Therefore, the above formula can be written as \( \delta = \delta_0 \), after calculation, the condition to be satisfied by the linear expansion coefficient of floating ring is:

\[
\beta_2 = \frac{R_i}{kR_i} (\beta_3 - \beta_1) + \beta_1
\]  
\[
(40)
\]

Among them, the conversion factor is:

\[
k = \frac{R_i \mu_1}{R_1} \frac{3R_i^2}{E_1 (R_1^2 - R_i^2)} + \frac{R_2 (1 - \mu_2) (2R_2^2 + R_2^2)}{E_2 (R_i^2 - R_2^2)}
\]  
\[
(41)
\]

5. Finite element analysis and verification

In this section, the Workbench software is used to model and calculate the working clearance floating ring, and the correctness is verified by comparing the calculated value of the mathematical formula model with that of the model. The floating ring model established by the software is divided into two parts: insert ring and graphite ring. The grid division cell size is 0.5 mm, the
of nodes is 361238, and the number of elements is 78013. After checking, the calculation results do not change with the grid density. Therefore, through the verification of grid independence, the meshing method meets the requirements of calculation accuracy. The floating ring structure diagram and grid division are shown in Figure 3.

![Floating Ring Structure](image1)

(a) Floating Ring Structure

![Floating Ring Meshing](image2)

(b) Floating Ring Meshing

Fig.3 Numerical Calculation Model Of Insert Floating Ring

By changing the operating temperature and material of the insert ring, the calculation results of the working clearance between the mathematical model and the finite element floating ring were compared. Choose EY308 graphite ring and insert ring of different material, while material of runway is GH4169. The calculation results are arranged as shown in Figure 4. Through the comparison between the experimental results and the simulation value, it is known that the deviation between the measured working clearance and the simulation calculation is not large, and they are all within the allowable range of error. Therefore, it is feasible to use numerical simulation to calculate the inner diameter variation of insert floating ring.

According to Fig. 4, the calculation results show that the change trend of the two methods in the calculation of floating ring working clearance is almost the same. The mathematical model and finite element numerical calculation values of different material insert ring structures and different temperatures have good fitting, and the correctness of the mathematical model has been verified.

Furthermore, it can be deduced from the mathematical model that the conversion factor is only related to the floating ring structure. When the structural parameters are fixed, the ideal material parameters of the insert floating ring satisfying the design condition of "slightly variable gap" are
calculated as follows. Assuming that the elastic modulus of the insert ring is a constant value, the conversion factor $k$ can be obtained by calculation. The linear expansion coefficient $\beta_2$ of the ideal material of insert ring is obtained by substituting the formula (40). The ideal material is compared with the other two materials, and the working clearance of the floating ring at fixed speed and different operating temperature are calculated respectively. The calculation results are shown in Fig. 5.

(a) The Results Of Working Clearance Are Calculated By Mathematical Formulas Under Different Temperatures And Materials

(b) Finite Element Numerical Calculation Of Working Gap Under The Corresponding Conditions
Note: the inflection point indicated by "★" is the calculated value of the working gap at the operating temperature after floating ring detangling, which is not considered in this paper

Fig.4 Comparison Between Mathematical Model And Finite Element Numerical Calculation Results

Fig.5 Working Clearance Comparison Under The Design Method Of “Slightly Variable Gap”
According to the calculation results, when the operating temperature rises to 300 °C, the clearance of floating ring of ideal material changes from 0.04196mm to 0.03336 mm. From the overall change trend, the working clearance of floating ring has little change, which indicates that it is feasible to calculate the linear expansion coefficient of ideal insert ring material by formula (40) in the structural design of "slightly variable gap" of insert floating ring. Therefore, in the design, the selection of insert ring material should be as close as possible to the linear expansion coefficient of the ideal material in the calculation of "slightly variable gap". According to the analysis, it can also be found that when the material of the insert ring is the same as that of the shaft runway like the GH4169 curve in Fig. 5 can also maintain a relatively stable slightly, which can be used in the actual production process.

Conclusions

1) The calculation method of working clearance of gas floating ring seal is established, which provides reference for the research of floating ring seal clearance.
2) The sealing clearance of floating ring can be kept stable by selecting suitable material of insert ring. The ideal floating ring material calculated by the design method of "slightly variable gap" in this paper can achieve better effect.
3) In practical application, choosing the same material as the axis runway can have a small clearance change and keep the sealing performance stable.

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