Reliability Analysis of Sealing Structure of Electromechanical System Based on Kriging Model

F Zhang¹*, Y M Wang¹, R W Chen², W W Deng¹, Y Gao¹

¹.School of Mechanics, Civil Engineering and Architecture, Northwestern Polytechnical University, Xi'an 710129, China
². Broad Homes Industrial International Co., Ltd, Changsha, China

Abstract. The sealing performance of aircraft electromechanical system has a great influence on flight safety, and the reliability of its typical seal structure is analyzed by researcher. In this paper, we regard reciprocating seal structure as a research object to study structural reliability. Having been based on the finite element numerical simulation method, the contact stress between the rubber sealing ring and the cylinder wall is calculated, and the relationship between the contact stress and the pressure of the hydraulic medium is built, and the friction force on different working conditions are compared. Through the co-simulation, the adaptive Kriging model obtained by EFF learning mechanism is used to describe the failure probability of the seal ring, so as to evaluate the reliability of the sealing structure. This article proposes a new idea of numerical evaluation for the reliability analysis of sealing structure, and also provides a theoretical basis for the optimal design of sealing structure.

Keywords: Y-type seal ring, Kriging model, reliability analysis, failure probability

1. Introduction

With the rapid development of the aerospace industry, the reliability requirements of the aircraft are getting higher and higher than any time. Sealing structure, a more critical part of the aircraft, its failure would cause the incredible malfunction for aircraft, affecting the completion of the task, and even crash. In June 10, 1996, when the flight 8105 was flying at an altitude of 8000 meters from Xiamen to Beijing in China, Cockpit seal failure suddenly occurred due to mechanical failure, which result the extremely dangerous situation in acute high-altitude anoxia and high-altitude decompression. Statistics has shown that in the typical incidents regarding to the failure of typical components of aircraft hydraulic system, over 45% of them are mainly caused by non-sealing. Therefore, more researchers has paid their attention to the problem of failure of the sealing structure. In order to improve flight safety in large, there is a necessary to evaluate the reliability of the sealing structure for the aircraft electromechanical system in the field[1-3].

Lots of literatures on the seal structure has been delivered, and the main research view focus on the study of constitutive model and structural parameters, and the discussion of failure criteria and so on[4-6]. And also, some research have explored numerical simulation using the relatively complete reciprocating seal theory, predicted the life value of the sealing structure, and got some referenced results[7-9]. Wang[10] has studied the status of rubber seal, mechanical seal and packing seal technology and then realized the numerical solution of the model through finite element and numerical iteration technology. The thermal deformation rules of the sealing face under the thermo-mechanical coupling effects were studied, and the structure of the sealing gasket and the loading analysis were analyzed as
well. Liu [11] has explored the sealing performance of the rectangular rubber seal ring based on the finite element analysis software Abaqus, from which the researcher found both material characteristics and the friction factor are the important factors that could affect the sealing performance. In addition, Xing [12] analyzed the deformation and force condition of Y-type hydraulic seal ring under different working pressures, and obtained the relationship between the maximum contact pressure and oil pressure from the research of sealing performance of Y-ring using finite element analysis software. Thus, the pressure distribution and deformation between seal coupling under different working pressures has already been analyzed by research. According to the sealing principle of Y-ring, the relationship between structural design and working environment was been studied by former researchers.

Based on the discussion above, it not difficulty to see the sealing technology has conducted many research conclusions in this field [13]. There are, however, not too much research literatures about the failure probability of the seal ring, especially for the Y-ring which is an important aspect of reciprocating seal structure [14,15]. The Y-ring has good performance in long service life, and dynamic pressure seal in it is 5-10 times, which is higher than the traditional rubber sealing products. Under certain conditions, it has the same life with sealing matrix. And the dynamic and static friction are equal, which are smaller than the frictional resistance of O-ring. Thus, the research on the sealing performance of Y-ring has a great significance meaning in the field.

In this paper, the contact stress between the rubber sealing ring and the hydraulic cylinder wall is calculated by the finite element method, and the relationship between the contact stress and the pressure of the hydraulic medium is obtained, and then compare the friction force under different working conditions. What’s more, the adaptive Kriging model has obtained by EFF learning mechanism through the co-simulation, which is used to calculate the failure probability of the seal ring. And finally, it can be seen that it is feasible and effective to analyze the reliability of the seal ring using this kind of method.

2. Finite element model analysis of seal ring

2.1. The establishment of geometric model

The sealing structure described below is composed of a Y-shaped sealing ring, a shaft and a sealing groove, and the three-dimensional model is shown in Fig. 1. In the process of sealing, the model needs to consider the squeezing action between the seal ring and the piston rod and the seal groove, which involves the nonlinear deformation simulation of the rubber material and the contact analysis between the seal ring and the rigid body. In this research, the material in this model is NBR, and the parameters Mooney-Rivlin function are used as the strain energy function of the rubber structure (C1 and C2 are 1.87 and 0.47, respectively), and finally shafts and seal grooves can be regarded as rigid bodies.

![Fig. 1 Three-dimensional model of the sealing structure](image)

2.2. The definition of material and boundary condition

This study intends to analyze the sealing performance of the sealing structure using the finite element analysis software which is called ANSYS. Based on the facts of geometry, material and boundary conditions of the seal structure, the three-dimensional model can be simplify analyzed into the axisymmetric model. For one thing, the elastic modulus of the sealing ring is 13.8 MPa and the Poisson’s ratio is 0.498. For another, the modulus of elasticity E1 of the shaft and the sealing groove are 210 GPA, and the Poisson’s ratio of the shaft and the sealing groove is taken as 0.33, and the
sealing groove chamfer R is 1.5 mm. Therefore, the elastic modulus of them is much larger than the sealing rubber ring, and then its deformation can be neglected. The two-dimensional meshing model is shown in Fig. 2.

![Fig. 2: Two-dimensional finite element model of sealing structure](image)

2.3. The deterministic results analysis of finite element method

In the deterministic analysis, the X-direction displacement is 2mm and the applied medium pressure is 2MPa. It can be seen from the contact stress cloud chart that the easily area adapting to gap bites is located in the upper left and upper right of the sealing ring, exactly lip.

![Fig. 3: Von Mises stress cloud chart in the installed state](image)

![Fig. 4: Contact stress cloud diagram in static pressure working state](image)

![Fig. 5: XY shear diagram under 2 MPa medium pressure](image)

![Fig. 6: Friction force diagram under 2 MPa pressure](image)

From Fig. 3 and Fig. 4, we could see that there is a larger contact area between the upper and lower lips of the sealing ring and the shaft and the sealing groove and more frictional damage will be appeared in the upper lip than the lower lip of the sealing ring than the lower lip. The maximum shear force shown in Fig. 5 usually occurs in the tiny middle are of the seal ring. In addition, the largest shear force is appeared in the two areas where the lower lip of the sealing rings with piston.

If the amount of compression is 1.5mm, uniform load is applied to the sealing ring, and 0.5, 1, 1.5, 2, 2.5 and 3 MPa are selected as the working oil pressure for studying the contact stress respectively, the maximum friction value under different media pressure can been seen in following Fig. 7 based on the
above working conditions.

![Maximum friction graph]

**Fig. 7** The maximum friction force of the sealing ring under different oil pressure

Compared the maximum friction force value of the sealing ring under different working pressures, it can be seen from Fig. 7 that the maximum friction force decreases first and then increases, and finally tends to be stable in the pre-compression amount of 1.5mm case with the suffered hydraulic medium pressure of Y-ring lip is getting bigger and bigger. In the processing, the numerical value is defined in a normal range, which indicates that the wear of sealing ring is getting small. So, under this situation, it could not be taken into account when considering the failure mode.

If the pre-compression volume are 1.5mm and 2mm, applying uniform load to the sealing ring, still under the above working conditions, 0.5, 1, 1.5, 2, 2.5, 3MPa are selected as the working oil pressure for studying contact stress respectively, the value of contact stress are different under different media pressure (see Fig. 8).

![Relationship between maximum contact stress and oil pressure graph]

**Fig. 8** Relationship between maximum contact stress and oil pressure when pre-compression amount is 15%

In a deterministic calculation, analyzing of Fig. 8, it shows that when the medium pressure increases, the contact stress decreases first and then increases. As the amount of pre-compression increases, the difference between the contact stress and the applied medium pressure is increasing as well. According to the sealing criterion, if the maximum contact stress is greater than the medium stress, the structure can be safe and reliable.

### 3. Reliability analysis

#### 3.1. Reliability analysis of sealing ring structure based on Kriging agent model

In the reliability calculation of Y-ring process, if we directly calculate using the traditional Monte Carlo method, it will take a lot of time to co-simulation Ansys and MATLAB. Therefore, in order to improve the computational efficiency, this paper adapts the Kriging model to calculate the failure
probability of the sealing ring. Also, we extract a small number of design point samples in the known
distribution variables applying Latin hypercube sampling (LHS) to, so as to the initial fitted Kriging
model can get better fitted results. Generally, the Kriging model consists of two parts. The first part is
the parameter part, which is in the form of linear regression. The second part is the non-parametric part,
which is achieved through a random process. Assuming that \( x=[x_1, x_2, \cdots, x_7]^T \) is the input variable of
the model and \( y(x) \) is the output response of the model, then the Kriging model can be expressed in
the following equation:
\[
y(x)=F(\beta, x)+z(x)=f^T(x)\beta+z(x)
\] (1)
The Eq.(1) represents the two parts of Kriging model, the polynomial parameter part and the random
distribution non-parametric part. Where \( \beta \) is the regression coefficient, \( f^T(x) \) is the basis function
vector of polynomial regression. \( z(x) \) is a stochastic process function, which obeys the normal
distribution.

In conclusion, \( f(x) \) represents the fitting of the whole global model, which can make an
approximate estimation for the entire undetermined model and then determine and obtain the overall
trend of response. Based on the Eq. (1), unknown samples \( x_{new} \) can be used to predict its response
value \( y(x_{new}) \). The optimal estimation of the Kriging model is shown as follows:
\[
\hat{y}(x_{new})=f^T(x_{new})\hat{\beta}+r^T(x_{new})R^{-1}(Y-F\hat{\beta})
\] (2)
where \( f^T(x_{new}) \) is the base function value of all unknown sample points \( x_{new} \). \( r^T(x_{new}) \) is a
7-dimensional column vector, representing the relationship between design samples \( x=[x_1, x_2, \cdots, x_7]^T \)
and unknown samples \( x_{new} \), which can be expressed as:
\[
r^T(x_{new})=[R(x_{new}, x_1), R(x_{new}, x_2), \cdots, R(x_{new}, x_7)]^T
\] (3)

At the same time, to solve the variance \( \sigma_i^2(x_{new}) \) obtained by Kriging fitting to the unknown sample
\( x_{new} \).
\[
\sigma_i^2(x_{new})=\sigma^2(1+u^T(F^TR^{-1}F)^{-1}u-r^T(x_{new})R^{-1}r(x_{new}))
\] (4)
where \( u=F^TR^{-1}r(x_{new})-f(x_{new}) \).
The Kriging variance \( \sigma_i^2(x_{new}) \) describes the least square difference of the estimated value \( \hat{y}(x_{new}) \)
obtained by the Kriging model and the value \( y(x_{new}) \) obtained from the real function at the unknown
sample.

The EFF learning mechanism is evaluating the degree that the true function value meet equality
constraint \( y(x)=a \) in the \( a \pm \varepsilon \) range though the reliability of nonlinear implicit state equation,
adopting the EFF function index. The function \( y(x) \) of the seal structure indicates whether the
sealing structure is failure or not. If \( y(x)>0 \), the seal structure is safe; if \( y(x)<0 \), the seal structure
is failure; if \( y(x)=0 \), it shows that the sealing structure is in a critical state.

In this study, we could conduct the biggest sample point that could result in the most influence on the
last fitted Kriging model based on the EFF learning mechanism. For any unknown sample points \( x_{new} \),
the predicted value of Kriging model obeys the normal distribution of \( N(\hat{y}(x_{new}), \sigma_i^2(x_{new})) \). Meanwhile,
the mean value \( \hat{y}(x_{new}) \) and the variance \( \sigma_i^2(x_{new}) \) can be obtained by Eq. (2) and Eq. (4). According to
study these theories, we can get the EFF learning function as follows:
\[
EFF(x) = \left(\hat{y}(x) - a\right) \left[2\Phi\left(\frac{a - \hat{y}(x)}{\sigma_y(x)}\right) - \Phi\left(\frac{(a + \epsilon) - \hat{y}(x)}{\sigma_y(x)}\right) - \Phi\left(\frac{(a - \epsilon) - \hat{y}(x)}{\sigma_y(x)}\right)\right]
\]

\[
-\sigma_y(x) \left[2\phi\left(\frac{a - \hat{y}(x)}{\sigma_y(x)}\right) - \phi\left(\frac{(a + \epsilon) - \hat{y}(x)}{\sigma_y(x)}\right) - \phi\left(\frac{(a - \epsilon) - \hat{y}(x)}{\sigma_y(x)}\right)\right] + \epsilon \left[\Phi\left(\frac{(a + \epsilon) - \hat{y}(x)}{\sigma_y(x)}\right) - \Phi\left(\frac{(a - \epsilon) - \hat{y}(x)}{\sigma_y(x)}\right)\right]
\]

\(\Phi(*)\) represents the standard normal distribution cumulative density function, 
\(\phi(*)\) represents the standard normal distribution probability density function, 
a represents the realized value of \(y\) specific fitting ability.

When calculating the reliability of Y-type sealing structure, it is necessary to focus on the critical state of function \(y(x) = 0\). So in this structure, \(a = 0; \epsilon = 2\sigma_y(x)\). We define the point that the maximum \(EFF(x)\) corresponding as the optimal sample point, which is \(x^* = \arg\max(EFF(x)))\).

When the maximum learning function value satisfies the learning stop condition \(\max(EFF(x)) \leq \delta\), (\(\delta\) is threshold. For the reliability calculation, let \(\delta = 0.001\)), which means the active learning process stop. It is considered that the Kriging model has reached the requirement of the optimal model at present.

In this paper, when we analyze the reliability of Y-type sealing structure, we select a series of alternative points through LHS (Latin hypercube sampling) first. And then, we calculate \(EFF(x)\) and find the maximum value. If \(\max(EFF(x)) \leq \delta\), the algorithm is finished and the reliability is solved. If it cannot satisfy the values, we need to select another sample point as the new one, adding to the original alternative point, and then recalculate the value of \(EFF(x)\) until it meet the condition \(\max(EFF(x)) \leq \delta\). At that time, learning stop, from which the Kriging model with the best fitting effect and high accuracy can be obtained. So, we calculate the reliability through the adaptive Kriging model obtained from this EFF learning mechanism, which not only guarantee the accuracy of the calculation, also improve the computational efficiency.

3.2. Result analysis

In the model, the relevant parameters of the sealing structure are shown in Table 1.

| Parameter                   | Identifier | Distribution type | Mean   | Standard deviation |
|-----------------------------|------------|-------------------|--------|--------------------|
| The length of the lip       | x_1        | Normal            | 4      | 0.04               |
| Pre compression quantity    | x_2        | Normal            | 1      | 0.01               |
| The coefficient of friction | x_3        | Normal            | 0.3    | 0.003              |
| Oil pressure (MPa)          | x_4        | Normal            | 2      | 0.02               |
| Parameter C_1               | x_5        | Normal            | 1.47   | 0.0147             |
| Parameter C_2               | x_6        | Normal            | 0.47   | 0.0047             |
| Poisson's ratio             | x_7        | Normal            | 0.498  | 0.00498            |

The research plans to delivery active learning through EFF learning mechanism. Firstly, 100 sample points are selected by LHS sampling. Then, the relationship between the number of new points and the value of learning function is shown in Fig. 9. As can be seen that with the increase of new sample points, the learning function value calculated by Kriging model satisfies the specified stopping criterion when the new samples points reached 163. As shown in Table 2, the failure probability of the sealing ring is calculated, 0.00035, by the Kriging model of the EFF learning mechanism.
The calculation results show that the Kriging model using EFF active learning is effective. If the Monte Carlo method is directly used to analyze the reliability of the Y-type sealing structure of electromechanical system, the finite element model of Y-type sealing structure needs to be invoked about $100/P_f$ times, which can maintain the convergence result of estimated failure probability in the sealing structure. So, the huge amount of calculation limits the direct application of Monte Carlo method in the reliability analysis of sealing structure. However, the finite element is invoke only 263 times if the Kriging model with EFF active learning, which could greatly saves the calculation time and meets the actual engineering calculation requirements.

4. Conclusion

The Kriging agent model is considered as a semi-parametric interpolation that need not a specific established mathematical model. In the paper, we apply it in the reliability calculation and analysis and conduct an effectively numerical evaluation. It can be a fundamental way for the effectively numerical evaluation reliability of the sealing structure as well as a theoretical basis for the optimal design for the sealing structure design. Compared with the Monte Carlo method in reliability analysis, the Kriging agent model obtained by EFF active learning can effectively select the optimum sample points according to the EFF learning function sequence and eventually improve the accuracy of the model and operational efficiency. Therefore, it can be effectively apply for the reliability analysis and the evaluation in practical engineering.

Acknowledgements

Authors gratefully acknowledge the support of China Scholarship Council, the fundamental research funds for the central universities (NPU-FFR-3102015BJ(Ⅱ) JLO4), natural science foundation of Shaanxi province (2016JQ5109), and the seed foundation of innovation and creation for graduate students in Northwestern Polytechnical University (Z2017116).

Reference:

[1] Grenier A, Gutierrez AGP, Grout H, et al. Modified coin cells to evaluate the electrochemical properties of solid-state fluoride-ion batteries at 150°C[J], Journal of Fluorine Chemistry, 2016,191:23-28.
[2] Hao XH, Ju YL, Lu YJ. Experimental study on the sealing clearance between the labyrinth sealing displacer and cylinder in the 10 K G-M refrigerator[J], Cryogenics,2017, 57:203-208.

[3] Wang ZB, Fan JJ, Xiao SH, et al. Discussion on failure analysis methods for rubber seal rings[J], Failure Analysis and Prevention, 2015, 10(5): 314-319.

[4] Sun D, Wang S, Ai TT, et al. Numerical analysis and experimental research on the influence of swirls on sealed static and dynamic characteristics[J]. Chinese Journal of Aeronautics. 2015, 36(9), 3002-3011.

[5] Liao CJ, Man M, Wang HR, et al. Study of mechanical characteristics of flange joint with metallic gasket under radial Loads[J]. Pressure Vessel Technology, 2014, 31(3):40-44.

[6] Gao BC, Meng XK, Li JY, et al. Thermal-mechanical coupled finite element model and seal performance analysis of mechanical seals[J]. Tribology, 2015, 35(5): 550-556.

[7] Zhou SM, Chen P, Shi Y. Analysis on sealing performance for a new type of rubber saddle-shaped sealing ring based on AQAQUUS[J]. Procedia Engineering.2015,130:1000-1009.

[8] Zhang K, Huang H, Duan ML, et al. Theoretical investigation of the compression limits of sealing structures in complex load transferring between subsea connector components[J], Journal of Natural Gas Science and Engineering, 2017,44:202-213.

[9] Shabani M, Carrapichano JM, Oliveira FJ, et al. Multilayered diamond mechanical seal rings under biodiesel lubrication and the full sealing conditions of pressurized water[J], Wear,2017,(384-385):178-184..

[10] Wang D Research on high-speed train service life of rubber seals evaluation techniques[D]. Qingdao University of Science & Technology, 2014.

[11] Liu M, Lu J, Duan D. Study on the sealing principle and structural optimization design of Y-type seal[J]. Special Purpose Rubber Products, 2012, 33(2): 57-59.

[12] Xing MJ. Study on sealing performance and leakage of metal W-ring in the aircraft engine[D]. Beijing Institute of Technology, 2015.

[13] Wang B, Jiao GQ, Lai DF, et al. Applying Roth Theory to Calculating Leak Rate of Rubber Gasket of Structure in Vacuum[J]. Journal of Northwestern Polytechnical University, 2010, 28(1): 129-133.

[14] Xue ZQ. Analysis on the reciprocating seal mechanism of the aircraft hydraulic cylinder[D], Zhe Jiang university, 2016.

[15] Cao YK, Wang HX, Wang X, et al. Application of domestic large pneumatic y-rings in mechanical press[J], Lubrication Engineering, 2016, 41(5): 139-145.