Fatigue life analysis of key equipment for high temperature reactor under variable working conditions

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Abstract. For the high temperature reactor with helium gas in the nuclear power plant, this paper has analysed the stress changes and temperature changes of the key equipment in the reactor under the changing conditions of the actual operation of the critical equipment [1-3]. Based on the threshold value that can satisfy the normal work, according to the expansion mechanism of fatigue crack in fracture mechanics, combined with the actual material parameters of the inner rod, this paper has prejudged the critical location or key products in the equipment, and the location and timing of their work tolerance limits. This paper has also calculated their residual fatigue life. It has certain guiding significance for the calculation of residual fatigue life of proprietary equipment in high temperature gas cooled reactor.

1. Introduction
The stepping motor is the power source of the high-temperature gas-cooled reactor control rod drive mechanism, and must have the ability to continuously operate in high-temperature helium gas for a long time. When the control rod is kept at the specified position, the stepping motor should have sufficient holding torque and not slip due to external force disturbance or gravity. In the case of emergency shutdown, the stepper motor should be able to quickly shut down the bar [4]. And when the power is lost, it should have a small positioning torque to ensure the falling of the control rod. In the event of an accident, it may cause radioactive contamination and threaten environmental safety. Since the equipment is subjected to a certain external pressure in normal operation and in the event of an accident, these loads have a great influence on its life [5-6]. Therefore, it is necessary to carry out detailed calculation and analysis on the fatigue life of the high-temperature gas-cooled reactor stepper motor.

Stepper motor with load operation mode, output working torque 6~8Nm in the range of 50~251r/min. Considering the additional damping of the control rod drive mechanism, the mechanical transmission efficiency is 90%, and the output torque of the motor is three times the actual load, and the output torque of the motor under normal working conditions is not less than 18Nm. In addition, the holding torque is three times the actual load of the output motor output torque, and the torque is not less than 15Nm under normal working conditions.

Finite element numerical simulation is wildly used in mechanical analysis work, and benefit from the finite element software and virtual environment, the simulation is easy to implement. As proposed in [7-9], finite element numerical simulation can apply to find the weak part under given mechanical environment.
The fatigue of material account for a significant proportion of reliability problems, and over 80% of fatigue failure is due to crack, thus, by introducing the methods of probability and statistic into fracture mechanic, probabilistic fracture mechanics is established to assist the work of fatigue life analysis as in [10-12].

Based on the finite element numerical simulation of the three working conditions of the high temperature gas cooled reactor stepper motor, this paper has identified the weak points and calculated the fatigue life, which is based on the simulation output results, including the overall simulation results and key part simulation results, and the actual material parameters.

2. Finite element numerical simulation
This paper has created a three-dimensional finite element simulation environment under steady state conditions in finite element software. Based on the 3D geometric model of the stepper motor, the boundary surfaces of the model, such as the end cover surface, the narrow surface, the sharp corner, the redundant edge and the vertex, have been optimized. The initial simulation environment is shown in Figure 1.

![Figure 1. Initial simulation environment of the main reducer.](image1)

In the numerical calculation, the box material is valued with reference to 20CrNi2Mo, and the shaft material refers to the value of ZG32MnMo, as shown in Table 1.

| Material Name   | Density (g/cm³) | Elastic Modulus (GPa) | Poisson Ratio |
|-----------------|-----------------|-----------------------|---------------|
| ZG32MnMo        | 7.8             | 232                   | 0.27          |
| 20CrNi2Mo       | 7.85            | 210                   | 0.275         |

The model is meshed by a four-node tetrahedral element, and 122130 tetrahedral elements are divided into sections, and the average unit mass is 0.6711. The unit mass distribution is shown in Figure 2. Figure 3 shows the grid distribution of the final drive and its internal structure.

![Figure 2. Element mass distribution.](image2)
Figure 3. Stepper motor and its internal structure grid distribution.

During the operation of the stepper motor, the stress concentration mainly occurs at the contact position between the motor shaft and the chassis. Figure 4 shows the Mises stress distribution cloud diagram of the final drive. Based on the Mises yield criterion, the plastic zone (weak zone) of the final drive can be clearly obtained, as shown in Figure 5. The color part is the position of the weak area. It can be seen from the figure that the weak area mainly concentrates on the contact position between the motor shaft and the chassis, which is relatively dangerous and needs to be strengthened.

Figure 4. Mises stress calculation results.

(a) Distribution of weak areas.  
(b) Left view
3. Calculation of fatigue life based on probabilistic fracture mechanics

The wear law of the equipment is related to the type of parts, the nature and size of the load, the environmental conditions, the working conditions, and the failure mechanism. In this paper, the high-efficiency central composite design has been used for multiple simulations, and the maximum stress point, maximum stress value, load spectrum and nominal stress spectrum in each simulation have been recorded, and the fatigue life calculation of the equipment has been carried out.

The material of the dangerous part of the stepping motor is ZG32MnMo. By consulting the relevant literature (due to the lack of ZG32MnMo related fatigue test literature, this paper has replaced it with the closest experimental literature data of ZG32MnMoNiCu), the value of fatigue crack propagation parameters of ZG32MnMo has been obtained by fitting calculation, as shown in Table 2.

Table 2. Related parameters of the paris formula for ZG32MnMo [1].

| Material Name (Number of Experiments) | Fatigue Crack Propagation Parameter C | Fatigue Crack Propagation Parameter m |
|--------------------------------------|--------------------------------------|--------------------------------------|
| ZG32MnMo                             | 1.69*10^-8                           | 2.22                                 |

Combined with the test results in the literature, the standard deviation of the fatigue crack propagation parameter lgC is about 0.0833. The final fatigue crack growth parameters and other basic parameters of ZG32MnMo material are shown in Table 3.

Table 3. Mechanical and fatigue crack propagation parameters of ZG32MnMo.

| Material Name | Density (g/cm3) | Elastic Modulus (GPa) | Poisson Ratio | Fatigue Crack Growth Parameter lgC and Standard Deviation | Fatigue Crack Propagation Parameter m |
|---------------|-----------------|-----------------------|---------------|-----------------------------------------------------------|--------------------------------------|
| ZG32MnMo      | 7.8             | 232                   | 0.27          | -7.7721/0.0833                                           | 2.22                                 |

The residual fatigue life assessment based on probabilistic fracture mechanics is a method to evaluate the residual fatigue life of the structure by considering the random parameters as statistics with a certain statistical distribution.

In practical engineering, the member is subjected to constant amplitude stress. In most cases, the member is subjected to variable amplitude stress. Under variable amplitude loading, there are interactions between different load cycles, so the load sequence affects the fatigue crack growth life. Usually, for the sake of simplicity, the effect of the load sequence is not considered. The Paris formula applies to constant amplitude stress. Usually, the Miner criterion is used to convert the variable amplitude stress into the corresponding equivalent normal amplitude stress, and the residual fatigue life of the member is obtained.
Fatigue crack growth life:

\[ N_e = \frac{2}{(m-2)C(\alpha \Delta \sigma_c \sqrt{\pi})^m} \left( \frac{a_0^1}{a_c^1} - \frac{a_0^{m/2}}{a_c^{m/2}} \right) \]  

(1)

There are six parameters in Equation (1). Considering these parameters as random variables, the fatigue crack growth life can be written as a function of 6 random variables.

\[ N_e = \left( C, m, \alpha, \Delta \sigma_c, a_0, a_c \right) \]  

(2)

Usually, for the sake of simplicity, it will be taken as a constant \((\alpha = 1)\) in actual engineering. Then, there are only 4 independent variables in the fatigue crack growth life evaluation formula of the member.

Calculate the logarithm of the Formula (1)

\[ \lg N_e = \lg \frac{2}{(m-2)C(\alpha \Delta \sigma_c \sqrt{\pi})^m} - \lg C - m \lg \Delta \sigma_c + \lg \left( \frac{a_0^1}{a_c^1} - \frac{a_0^{m/2}}{a_c^{m/2}} \right) \]  

(3)

The calculation parameters required for the stepping motor are shown in the table. In the fatigue crack propagation calculation, it is generally considered that the equivalent normal amplitude stress \(\Delta \sigma_c\) follows a lognormal distribution with a standard deviation of about 2% of the mean value; According to the experimental data in the literature, the average value is obtained, and then the fatigue crack propagation parameters \(C\) and \(m\) are obtained, and the lognormal distribution is obeyed; Usually due to \(a_0 = a_c\), \(\lg \left( \frac{a_0^{m/2}}{a_c^{m/2}} \right)\) is approximately equal to \(1 - \frac{m}{2}\log a_0\). The statistical results of a large number of initial cracks without damage detection are considered to be 0.05mm~0.5mm, which also obeys the lognormal distribution. Since the stepper motor is a spring component, the geometric curvature is large, so this report takes half of its maximum value. It is 0.25mm and has a coefficient of variation of 0.5. The specific parameters are shown in Table 4. By substituting each of the above variables into the Formula (3), it is known that the fatigue crack growth life of the member also obeys a lognormal distribution, and the mean \(\mu_{\lg N_e}\) and standard deviation \(\sigma_{\lg N_e}\) of \(\lg N_e\) can be obtained. Given the level of reliability \(p_r\), a table can be found to obtain \(u_{p_r}\) \((u_{p_r}\) is the "standard normal offset" associated with reliability \(p_r\)). The following is the logarithmic extended life at this level of reliability.

\[ \lg N_e = \mu_{\lg N_e} + u_{p_r} \sigma_{\lg N_e} \]  

(4)

\[ N_e = 10^{\mu_{\lg N_e} + u_{p_r} \sigma_{\lg N_e}} \]  

(5)

**Table 4.** Stepper motor fatigue calculation parameters.

| Parameter Name                                             | Obey Distribution         | Mean      | Standard Deviation |
|------------------------------------------------------------|---------------------------|-----------|--------------------|
| Equivalent Stress Extreme Value                            | Lognormal Distribution    | 0.32Mpa   | 0.0064Mpa          |
| (Input torque = 6Nm) \(\sigma_e\)                         |                           |           |                    |
| Equivalent Stress Extreme Value                            | Lognormal Distribution    | 0.80Mpa   | 0.016 Mpa          |
| (Input torque = 15Nm) \(\sigma_e\)                        |                           |           |                    |
| Equivalent Stress Extreme Value                            | Lognormal Distribution    | 0.96Mpa   | 0.0192 Mpa         |
| (Input torque = 18Nm) \(\sigma_e\)                        |                           |           |                    |
| Fatigue Crack Growth Parameter \(\lg C\)                  | Lognormal Distribution    | -7.7721   | 0.0833             |
| Fatigue Crack Growth Parameter \(m\)                      |                           | 2.22      |                    |
| Shape Parameter \(\alpha\)                                | 1                         |           |                    |
| Initial Crack \(a_0\)                                     | Lognormal Distribution    | 0.5       | 0.25               |
For $a_0$:
\[
\mu_{\lg a_0} = \lg \frac{\mu_{a_0}}{\sqrt{1 + \delta_{a_0}^2}} = \lg \frac{0.5}{\sqrt{1 + 0.5^2}} = -0.3495
\]
\[
\sigma_{\lg a_0}^2 = \frac{\lg(1 + \delta_{a_0}^2)}{2.303} = \frac{\lg(1 + 0.5^2)}{2.303} = -0.0421
\] (6)

For $\sigma_e$ (Input torque = 6Nm):
\[
\mu_{\lg \sigma_e} = \lg \frac{\mu_{\sigma_e}}{\sqrt{1 + \delta_{\sigma_e}^2}} = \lg \frac{0.32}{\sqrt{1 + 0.02^2}} = -0.4949
\]
\[
\sigma_{\lg \sigma_e}^2 = \frac{\lg(1 + \delta_{\sigma_e}^2)}{2.303} = \frac{\lg(1 + 0.02^2)}{2.303} = 7.5416e-05
\] (7)

For $\sigma_e$ (Input torque = 15Nm):
\[
\mu_{\lg \sigma_e} = \lg \frac{\mu_{\sigma_e}}{\sqrt{1 + \delta_{\sigma_e}^2}} = \lg \frac{0.80}{\sqrt{1 + 0.02^2}} = -0.097
\]
\[
\sigma_{\lg \sigma_e}^2 = \frac{\lg(1 + \delta_{\sigma_e}^2)}{2.303} = \frac{\lg(1 + 0.02^2)}{2.303} = 7.5416e-05
\] (8)

For $\sigma_e$ (Input torque = 18Nm):
\[
\mu_{\lg \sigma_e} = \lg \frac{\mu_{\sigma_e}}{\sqrt{1 + \delta_{\sigma_e}^2}} = \lg \frac{0.96}{\sqrt{1 + 0.02^2}} = -0.0178
\]
\[
\sigma_{\lg \sigma_e}^2 = \frac{\lg(1 + \delta_{\sigma_e}^2)}{2.303} = \frac{\lg(1 + 0.02^2)}{2.303} = 7.5416e-05
\] (9)

Bring the Formula (6) ~ Formula (13) into the Formula (3) respectively, and obtain the sum under the respective working conditions. Then, by using the Formula (4) or the Formula (5) and combining the standard normal distribution cumulative distribution lookup table, the reliability-life value is obtained.

4. Conclusions

16 sets of reliability were taken: 0.90, 0.91, 0.92, 0.93, 0.94, 0.95, 0.96, 0.97, 0.98, 0.99, 0.999, 0.9999, 0.99999, 0.999999, 0.9999999, 0.99999999. Calculating the corresponding life for the above reliability, the calculation results and the probability-life curve under the three operating conditions are as follows.

From the data in Table 5, the expression of the approximate fitting of the stepper motor probability-life curve is obtained:

\[
\begin{align*}
\Pr_{t_0} &= \begin{cases} 
-0.4525* X_1^4 + 1.3371* X_2^3 - 1.2904* X_1 + 1.4062 & \text{(Input torque:6Nm)} \\
-0.2022* X_1^3 + 0.7817* X_2^2 - 0.9867* X_1 + 1.4062 & \text{(Input torque:15Nm)} \\
-0.6811* X_1^3 + 1.7563* X_2^2 - 1.4789* X_1 + 1.4062 & \text{(Input torque:18Nm)}
\end{cases}
\end{align*}
\]

Among them, $X_1 = N*10^a$, $X_2 = N*10^b$. N represents the number of times, and the “motor runs” once as "1 time". The reliability-life curve is shown in Figure 6.

After calculation, the fatigue life of the equipment exceeds the expected life and meets the design requirements under conservative estimation.

This paper proposes a methodology to calculate the reliability life of the key equipment for high temperature reactor by using finite element numerical simulation and probabilistic fracture mechanics based fatigue life calculation. And take the stepper motor as an example to predict its reachability life under given operating condition and other parameters including material parameters and shape.
parameters. The result shows the correction and availability of proposed methodology. To improve the accuracy of simulation, the influence of temperature of operation condition should be considered.

Table 5. Stepper motor reliability - life calculation results (6Nm).

| Number | Reliability (Probability) Pr | Times N (6Nm) | Times N (15Nm) | Times N (18Nm) |
|--------|------------------------------|---------------|----------------|----------------|
| 1      | 0.90                         | 1618661377    | 211704066      | 141236466      |
| 2      | 0.91                         | 1600356499    | 209309977      | 139639266      |
| 3      | 0.92                         | 1580705244    | 206739799      | 137924599      |
| 4      | 0.93                         | 1559376066    | 203950166      | 136063511      |
| 5      | 0.94                         | 1535894733    | 200879044      | 134014655      |
| 6      | 0.95                         | 1509545455    | 197432833      | 131715544      |
| 7      | 0.96                         | 1479165388    | 193459433      | 129064722      |
| 8      | 0.97                         | 1442653500    | 188684066      | 125878877      |
| 9      | 0.98                         | 1395508877    | 182518033      | 121765266      |
| 10     | 0.99                         | 1324311144    | 173206111      | 115552900      |
| 11     | 0.999                        | 1143563199    | 149566166      | 99781719       |
| 12     | 0.9999                       | 1013448155    | 132548477      | 88428519       |
| 13     | 0.99999 (5)                  | 912556925     | 119352955      | 79625245       |
| 14     | 0.999999 (6)                 | 830811045     | 108661444      | 72492500       |
| 15     | 0.9999999 (7)                | 762606159     | 99740947       | 66541276       |
| 16     | 0.999999999 (8)              | 704485934     | 92139427       | 61469990       |

Figure 6. Stepper motor reliability - life curve.
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