Reliability Analysis of Reduction Transmission Device for Polar Deep Ice Drilling

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Abstract. In this paper, the reliability of the reduction transmission device used in ice drills for deep ice coring in the polar region is analyzed. The reliability of the reduction transmission device for polar deep ice drilling has a great influence on the performance, reliability and life of the drilling. The ANSYS Workbench is used to analyze the dynamics and reliability of the transmission device. The results show that the reliability of the reduction transmission device meets the design requirements.

1. Introduction
The polar deep ice cores have a high resolution, long-record time, and high fidelity and provide abundant information. The most direct scientific data can only be obtained by accessing the polar deep ice cores. Therefore, the development of deep ice coring technology plays a vital role in the scientific studies of polar regions. Cable-suspended electromechanical coring technology has the advantages of low weight, low energy consumption, low logistics requirements, simple structure, convenient maintenance, and adaptability to the bad weather and low temperature of the polar environment. These characteristics has been widely used in polar ice core drilling, and they reveal increasing advantages. Recently, such a type of coring drill has been successfully implemented in some deep boreholes in the Antarctic ice sheet, and the depth of the deepest borehole that was drilled was 3769.3 m [1, 2].

Through preliminary research and development, the rolling movable teeth transmission is selected as the reduction transmission device in cable-suspended electromechanical coring drills. Rolling movable teeth transmission is multi-teeth meshing transmission, which can reduce the torque of deceleration drive to multiple teeth, and the torque of each tooth being greatly reduced making the life of reduction transmission device greatly increased [3]. Because more than half of the movable teeth are in the meshing state, the reduction transmission device has strong impact capability and strong bearing capacity. The movable tooth is placed in the internal teeth ring, which makes the reduction transmission device a compact construction of light weight and small volume. The reduction transmission device has wide transmission ratio and high transmission efficiency. Therefore, the rolling movable teeth transmission is applied in the ice drilling of the polar drilling equipment and the application, which satisfies the preconditions of light, high efficiency, energy conserving and environment protecting, and which entails extensive prospects [4].

2. Dynamic Analysis of Reduction Transmission Device
Polar deep ice coring drilling is a very complex dynamic process. In the process of drilling, the reduction transmission device of polar ice drilling will be affected by vibration, which will affect the
efficiency, life and reliability of drilling tools. Therefore, in the design of reduction transmission device, the frequency corresponding to the basic modes of the device can be determined by modal analysis, and the trend of structural deformation under natural resonance frequency can be clearly understood. By changing structural rigidity or other methods, the weak parts of the components can be strengthened or avoided these frequencies, so as to avoid resonance phenomenon.

Prior to the finite element analysis, it is necessary to simplify the 3D solid model of the reduction transmission device using Inventor. To this end, the keyways, threaded holes, tapered edges, and round corners are omitted. The end turns of the ladder cover and shaft may be reduced. The part that has no effect on the results of the analysis is simplified [5, 6]. The material, GCr15 is selected for the center wheel and rollers. The material, 40Cr is selected for the cage and eccentric disc. The input shaft, end cover, bearing, and eccentric wheel are made from ZGD650-830. The above material properties are listed in Table 1.

![Table 1. Material and parameters of some components of the reduction transmission device [7].](image)

| Material | Density(kg/m³) | Elastic Modulus (Mpa) | Poisson Ratio |
|----------|----------------|-----------------------|--------------|
| GCr15    | 7.81×10³       | 2.08×10⁵              | 0.3          |
| 40Cr     | 7.8×10³        | 2.11×10⁵              | 0.277        |
| ZGD650-830 | 7.85×10³       | 2.06×10⁵              | 0.3          |

It is assumed that there is no friction between the bearing and shaft of the reduction transmission device, i.e., they remain bonded. A cylindrical constraint is applied to the output shaft, and a fixed constraint is imposed on the center wheel. The natural frequencies and vibration modes of the reduction transmission device are obtained by solving the modal of the reduction transmission device, as shown in Table 2. Table 2 shows that at low frequencies, the movable teeth frame and input shaft are prone to bending vibration, and the center wheel is prone to torsional vibration. At high frequencies, the movable teeth frame and the input shaft are prone to axial vibration, and the center wheel is prone to axial vibration. The mode shapes of the 4th, 6th, 8th and 10th order modes of the reduction transmission device are shown in Fig. 1.

![Table 2. Natural frequency and vibration mode of the reduction transmission device.](image)

| Order number | Natural Frequency (Hz) | Vibration Mode                                      |
|--------------|------------------------|-----------------------------------------------------|
| 1            | 1367.56                | Bending vibration of eccentric disc and bending vibration of eccentric wheel. |
| 2            | 1893.21                | Bending vibration of input shaft.                   |
| 3            | 2145.02                | Radial vibration of eccentric wheel.                |
| 4            | 3598.1                 | Radial vibration of eccentric disc and bending vibration of input shaft. |
| 5            | 3603.6                 | Torsional vibration of center wheel.                |
| 6            | 4158.2                 | Bending vibration of tooth rack and bending vibration of input shaft. |
| 7            | 4161.3                 | Bending vibration of tooth rack.                    |
| 8            | 5785.9                 | Axial vibration of input shaft and radial vibration of center wheel. |
| 9            | 6391                   | Axial vibration of input shaft and axial vibration of tooth rack. |
| 10           | 6937.3                 | Axial vibration of tooth rack and bending vibration of center wheel. |
When the load changes and the error is small, the excitation frequency of the reduction transmission device is as follows:

\[ f = \frac{n_1}{60} \]  

(1)

Where \( f \) is the excitation frequency of the reduction transmission device, Hz; \( n_1 \) is the motor speed, r/min.

According to the modal vibration pattern and the analysis of vibration frequency, it can be seen that the natural frequency of the reduction transmission device is higher than the excitation frequency of the reduction transmission device, and there will be no resonance; tooth rack has larger deformation and smaller stiffness. The main reason is that the movable gear frame is a thin-walled structure, so the wall thickness or stiffness of the tooth rack can be increased appropriately. The material with greater stiffness should be replaced; the input shaft is prone to bending vibration, and the bearing stiffness of the input shaft should be increased.

3. Reliability Analysis of Reduction Transmission Device

In the early stage, the static analysis of the structure of the reduction transmission device is carried out. As shown in Fig 2, the stress nephogram shows that the input shaft is the weak link of the reliability of the reduction transmission device. It is found that the input end of the input shaft is prone to fatigue damage. And limited to space, this paper uses the Six Sigma Analysis module in ANSYS Workbench to discuss the reliability of the input shaft of the reduction transmission device. The main dimensions of the input shaft are taken as input parameters for reliability analysis. The stress of the input shaft is taken as the output parameter of reliability analysis. The distribution range of input parameters conforms to normal distribution, and the statistical characteristics of each input parameter are listed in Table 3. According to the statistical characteristics of each parameter, the reliability analysis system sampled the parameters randomly and sampled the parallelism of the parameters, as shown in Fig 3. Parallel graph of sampling parameters clearly shows the combination of variables.
Table 3. Statistical characteristics of input parameters.

| Parameters                        | Symbol | Mean value | Standard variance |
|-----------------------------------|--------|------------|-------------------|
| Diameter of middle section (mm)   | DS_1   | 30         | 0.42              |
| Diameter of input end (mm)        | DS_2   | 15         | 0.21              |
| Length of input end (mm)          | DS_3   | 47         | 0.73              |

The response surface model is established according to the random sample points generated by the reliability analysis system. The response surfaces of the input variable's influence on the maximum stress of the input shaft are shown in Fig. 4. The response surface graphs show that when the input diameter of the input shaft is maximized, the maximum stress on the input shaft is minimal.
a. Effect of DS1 and DS2 on maximum stress.

b. Effect of DS2 and DS3 on maximum stress.

Figure 4. Response surface of the effect of input variables on the maximum stress of input shaft.

The sensitivity of each parameter to the maximum stress of the input shaft is shown in Fig. 5. As can be seen from the figure, according to the height of its histogram, the most obvious degree of sensitivity is the diameter of input end. The parameter list is a more accurate alternative to reading the probability from the cumulative distribution function curve. The maximum stress probability list of the input shaft is shown in Fig. 6. It can be seen from the figure that the maximum stress of the input shaft is 260.81MPa, which is larger than the output variables, and the reliability of the input shaft is 100%. Therefore, the reliability of the input shaft of the reduction transmission device meets the design requirements.

Figure 5. Sensitivity of input variables to the maximum stress of input shaft.
4. Conclusion

The reliability of the reduction transmission device for polar deep ice drilling designed in the earlier stage is analyzed. The dynamic analysis of the reduction transmission device is carried out by using ANSYS Workbench. The natural frequency of the deceleration transmission device is higher than the excitation frequency of the deceleration transmission device when it works, and there is no resonance. The movable gear frame has large deformation and can be increased appropriately. The wall thickness of large movable teeth rack or the material with greater stiffness should be replaced; the input shaft is prone to bending vibration, so the bearing stiffness of the input shaft should be increased. This paper uses the Six Sigma Analysis module in ANSYS Workbench to discuss the reliability of the input shaft of the reduction transmission device, and the reliability of the input shaft meets the requirements. The results show that the design of the reduction transmission device is reasonable. This paper lays a foundation for the reliability experimental study of the reduction transmission device for polar deep ice drilling.

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