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# Research on the gear operating state detection based on the fiber Bragg grating sensing technology

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**Abstract.** With the development of people's production and the accelerated growth of industrial demand, industrial manufacturers continue to improve the level of real-time detection of gear requirements. In order to improve the safety of mechanical equipment and to reduce the gear failure of the economic losses, the real-time monitoring of gear running technology is of a positive meaning. Based on the existing research results of gear dynamic detection, this paper proposes a fiber-optic grating sense of the gear operating state detection system. Stress tests were performed by varying the different load torques. The experimental results show that at the load of 10Nm and the rotating speed of 70r/min, the dedendum stress reached 130.4MPa. Compared with the theoretical value, the test error was 6.66%.

## 1 Introduction

Gear is a kind of mechanical parts that transmit movement and power. It is an indispensable core part of many mechanical equipment, and it is widely used in rotating machinery. However, in operation, the internal components of the gear transmission system will be subject to mechanical stress, thermal stress and other multi-physical field role. When the gear is working, the bending stress of the dedendum exceeds its permissible bending stress, which is likely to cause the breakage at the dedendum. That is the main reason of gear damage. In order to timely detect gear parts in the process of running fatigue failure, the implementation of real-time online detection is particularly important. However, the current detection method is mainly to install the sensor for vibration measurement in the gear box and we still lack effective methods in on-line detection on the dedendum stress, so the dedendum bending stress real-time on-line detection technology is of great significance.

Gear bending strength is one of the most important parameters in gear design and calculation, which is directly related to the service life and production cost. With regard to the calculation of the bending strength of gears, many scholars at home and abroad have carried out relevant research. There are three main categories of methods: theoretical calculation method, finite element simulation method and experimental measurement method. In 1982, the American Association of Gear Manufacturers (AGMA) made a comprehensive consideration of the popular formulas for calculating the bending stress of the dedendum, which proposed the AGMA American Gear Standard and was continually updated to form one of the authoritative gear standards. From 1990 to 1995, von Eiff, Bibel, Filiz and Eyerciogiu studied the factors that affect the bending strength of the dedendum by establishing a two-dimensional single-tooth and two-dimensional multi-tooth model, and proposed a new dedendum stress calculation formula. In 2016, Li Yangyang, in Wuhan University of Technology, conducted an on-line test and fault simulation experiment on the experimental platform, and made a preliminary analysis and experimental study on the common faults of gear transmission. Based on those above, this paper presents a fiber grating sensing technology with the gear running state detection method. The fiber grating is attached to the dedendum in the tooth width direction, and the on-line detection of the dedendum bending stress is realized by detecting the instantaneous strain at the transmission torque of the gear. Then the stress of the dedendum is tested and analyzed under different load and different speed in order to play the advanced nature of the optical fiber sensing technology, so that its application in the field of mechanical on-line detection is becoming more and more mature.

## 2 Getting started The principle of dedendum stress detection based on fiber grating sensing technology

### 2.1 *The principle of fiber grating sensing*

The relationship between the central wavelength of the reflected wave of the fiber grating and the effective refractive index and period of the core is the most basic principle for studying the fiber optic sensor. Specifically, when a bundle of broadband light enters the grating through the fiber, most of the wavelength of light will penetrate the grating, and only a small part of the specific wavelength of light in the face of the raster will be reflected back, which is called the Bragg wavelength. According to Maxwell's classical equation, combined with the theory of fiber coupling mode, the mathematical expression of this central wavelength is obtained as follows:

$$\lambda_B = 2n_{eff}\Lambda \tag{1}$$

where: $\lambda_B$ = the center wavelength of the reflected light wave; $\Lambda$ = the raster period of the grating; $n_{eff}$ = the effective refractive index of the fiber core.

It can be seen from the above equation that the center wavelength of the corresponding reflected light wave drifts if the effective refractive index of the fiber grating or the grid period changes due to the external parameter. Numerous practice has shown that the most common cause of wavelength drift is the stress and temperature acting on the grating. When the grating is subjected to external stress, the grating's raster period and the effective refractive index neff will change $\Delta\Lambda$ and $\Delta n_{eff}$ respectively, due to the elastic effect of the grating. Therefore, whenever the external temperature or pressure changes, the light wave that meet the Bragg conditioned will drift its center wavelength. Differentiate and ignore the high-order infinitesimal after the formula (1), we have:

$$\Delta\lambda_B = 2\Delta n_{eff}\Lambda + 2n_{eff}\Delta\Lambda \tag{2}$$

From the above analysis we can see that by detecting the drift $\Delta\lambda_B$ of the center wavelength of the reflected light wave, we can obtain the change of the external parameters such as the stress or the temperature on the grating. This is the basic principle of the fiber grating based on the wavelength.

### 2.2 *Basic principle of gear running status detection*

The purpose of the gear running condition detection is to detect and report the possible damage and fault of the gear by detecting the stress, vibration and temperature in the gear operation in real time. The maximum bending stress of the gear occurs at the dangerous cross section of the dedendum. As long as the bending stress at the dangerous cross-section does not exceed the allowable value, the gear will not bend. Therefore, when calculating the bending strength of the gear, only the maximum value of the bending stress is considered. The calculation of the maximum bending stress of the dedendum is carried out according to the condition of the single pair of teeth engaged at the highest point. In the calculation of bending stress, the wheel can be regarded as cantilever beam, and then use of Hofer 30 ° tangent method to determine the location of dangerous parts of the root (as shown in Figure 1). The two straight lines at an angle of 30 ° to the axis of symmetry of the teeth are tangent to the transition curve of the crown of the dedendum. The cross section of the two points and parallel to the axis of the gear teeth is the dangerous cross section of the dedendum.

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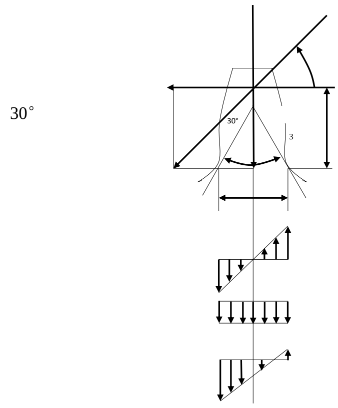


**Figure 1** Method for determining the dangerous cross section of the dedendum

The $F_n$ is moved to the symmetrical line of the teeth and is decomposed into the component force FncosαF of the dedendum subjected to the bending stress $\sigma_b$ and the component force Fnsin$\alpha_F$ of the dedendum by the compressive stress $\sigma_c$. It can be seen from the figure that the synthetic stress on the tension side is less than the synthetic stress on the compression side. However, since the tensile strength of the material is much lower than the compressive fatigue strength, the gear teeth are actually cracked at the rounded corners of the receiving side. To simplify the calculation, we only consider the bending stress. When the tooth thickness at the dangerous cross section is $s_F$ and the bending force arm is $h_F$, the bending stress of the dedendum at the dangerous cross section of the load is

$$\sigma_F = \frac{M}{W} = \frac{F_n \cos\alpha_F h_F}{b s_F^2/6} \quad (3)$$

Then let

$$Y_{Fa} = \frac{6(h_F/m)\cos\alpha_F}{(s_F/m)^2\cos\alpha} \quad (4)$$

Put $F_t = 2000T_1 / d_1$ and $d_1 = mz$ into the formula available

$$\sigma_F = \frac{2000KT_1}{bm^2z_1} Y_{Fa} Y_{Sa} \quad (5)$$

where: K is the load factor, $Z_1$ is the number of teeth, $T_1$ is the nominal torque, $Y_{Fa}$ is the tooth profile of the load applied to the tooth top, B is the gear width, $Y_{Sa}$ is the stress correction coefficient, m is the modulus.

## 3 Experimental protocols and data analysis

### 3.1 *Fiber Optic Grating Arrangement*

The vibration caused by the dedendum rupture can not be ignored, it will produce noise and have a huge impact on the transmission. Based on these factors, we take the wheel meshing tooth surface as a test point and fit the fiber, as shown in Figure 2:

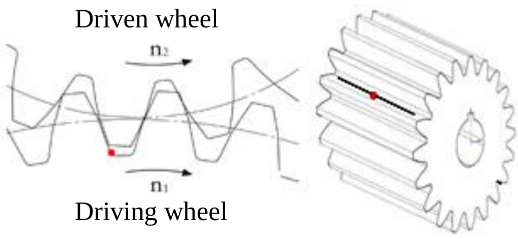


**Figure 2** Schematic diagram of fiber fit

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As shown in Figure 2, the red dot near the tooth tip of the dedendum shown in the left figure is the position where the fiber is pasted. As shown on the right, the grating is pasted in the middle of the tooth width direction. One end of the optical fiber is attached to the tooth surface of the gear, and another end is connected with the light rotary connector.

In the actual process of monitoring, when the gear in the high-speed operation, the root will inevitably have a bending stress changes, then the fiber on the tooth surface of the signal must be caused by fluctuations. The host computer then shows the ups and downs of the waveform. Since the wavelength and stress changes to a linear change, the processed data shows that the change in the host computer is only the wavelength of the reflection grating. The response is only the change of strain, so it needs to be substituted into the formula to strain to stress conversion in order to obtain the tooth bending stress value. And then through a certain image processing, it shows in the state display unit a three-dimensional dynamic stress distribution. Compared with the limit value, we can analyze whether there will be abnormal operations of the state, which plays a role in real-time detection of gear operation and the protection of gear and mechanical equipment.

Then set up the gear condition simulation platform. The gear simulation platform includes two intermeshing gears, one (with 48 teeth)is driven by the motor and the other (with 24 teeth) through the magnetic powder brake. The picture is as follows:


**Figure 3** the experimental platform of gear running state detection system

3.2 *Experimental program*

In order to understand the influence of the torque and speed on the deformation and vibration of the gear during the rotation process, a series of monitoring experiments have been down. First, change the size of the load torque in the range of 10Nm at the speed of 70r / min, then get a total of seven groups of tests. Figure 4 and 5 shows the time-domain diagram of the fiber grating wavelength variation at 0.18 Nm and 1.26 Nm. Figure 6 summarizes the changes in fiber grating wavelengths for the seven sets of test results. The corresponding data can be obtained by substituting the obtained data into the formula (6). In the host computer, set the warning and alarm value according to the theoretical formula and experience. When the load in the experiment makes the stress greater than the corresponding value, it will issue an alarm signal.

$$\sigma_x = -\frac{E}{\mu\delta^b}\cdot\frac{\Delta\lambda_B}{\alpha_\varepsilon} \tag{6}$$

Where E is the elastic modulus of the gear material, 70Gpa; μ is the Poisson's ratio, 0.3; δ is the tooth side clearance, 0.6mm; b is the tooth width, 30mm; $\alpha\varepsilon$ is the sensitivity coefficient, 1.2pm/με; $\triangle\lambda_B$ is the measured beam offset.

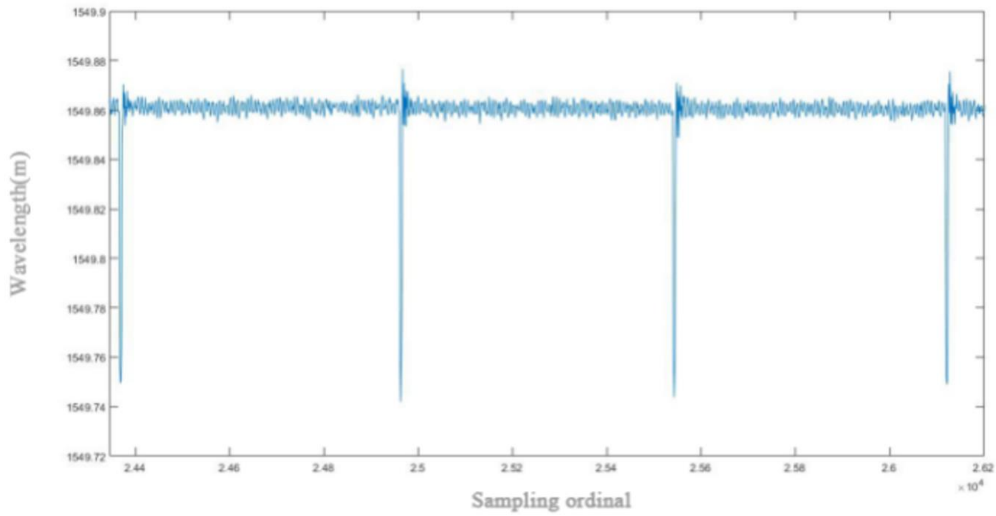


**Figure 4** Grating strain at 0.18 Nm load

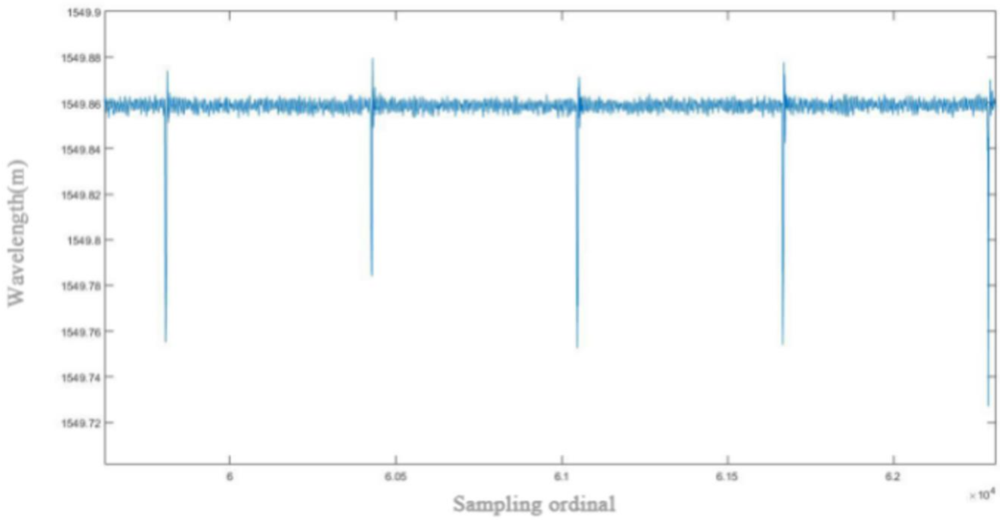


**Figure 5** Grating strain at 1.26 Nm load

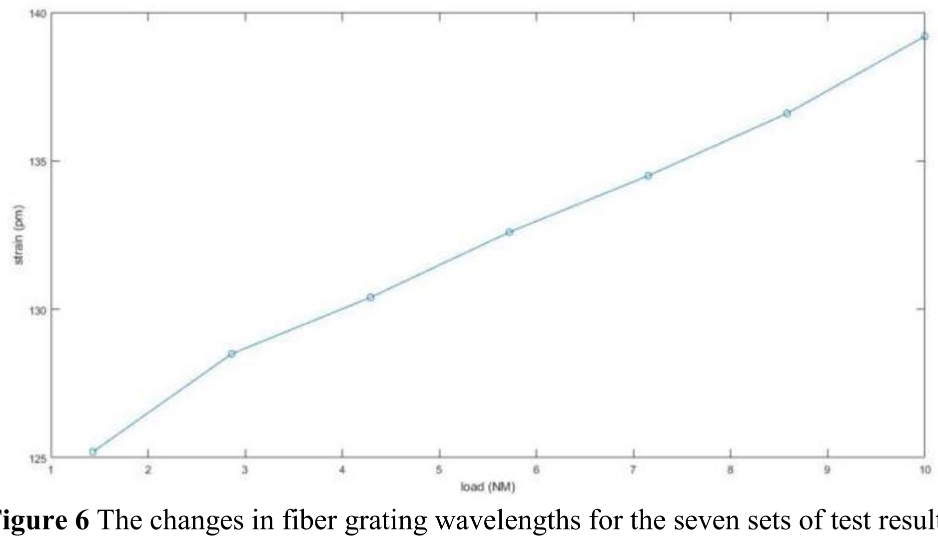


**Figure 6** The changes in fiber grating wavelengths for the seven sets of test results.

### 3.3 *Experiment analysis*

A signal similar to noise before the change is the fundamental center wavelength of the grating, and it fluctuates due to the influence of the environment and the experimental conditions. The sharp change indicates that the two gears are just engaged, at which point the bending stress will be generated and there will be strain in the axial direction. The grating paste in the tooth tip gap will detect the strain of the gear, resulting in wavelength shift.

It can be seen from Figure 6, with the increase in load torque, fiber grating measured dedendum bending stress also increases. And compared with the theoretical value, the measurement error also showed a gradual increase trend, and in the last two groups reached 5%. In general, the measurement error belongs to the normal range, because the formula method is generally used to design the gear and its calculation is relatively conservative. When designing gear parameters, we should leave some margin.

**Table 1** Calculation of gear bending stress error

| Load | Theoretical value of gear bending Stress | Measurement of dedendum bending stress | Error rate |
|---|---|---|---|
| NM | Mpa | Mpa | |
| 1.43 | 112.1 | 109.943 | 1.96% |
| 2.86 | 115.2 | 112.582 | 2.32% |
| 4.29 | 117.3 | 114.341 | 2.59% |
| 5.72 | 120.4 | 116.099 | 3.70% |
| 7.15 | 123.2 | 117.859 | 4.53% |
| 8.58 | 125.9 | 119.618 | 5.25% |
| 10.00 | 130.4 | 122.257 | 6.66% |

## 4 Conclusion

This paper presents a method of detecting the operating state of gear based on fiber grating sensing technology, and deduces and validates the detection technology. Confirming by the theory, The maximum stress occurs at the root of the tooth. Thus the fiber grating is attached to the dedendum in the tooth width direction. The stress measurement was performed by varying the load torque at 70 r / min. At 10Nm, the dedendum stress reached 130.4MPa. Compared with the theoretical value, the test error was 6.66%.

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