

# Optical Fiber Grating Vibration Sensor for Vibration Monitoring of Hydraulic Pump

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**Abstract:** In view of the existing electrical vibration monitoring traditional hydraulic pump vibration sensor, the high false alarm rate is susceptible to electromagnetic interference and is not easy to achieve long-term reliable monitoring, based on the design of a beam of the uniform strength structure of the fiber Bragg grating (FBG) vibration sensor. In this paper, based on the analysis of the vibration theory of the equal strength beam, the principle of FBG vibration tuning based on the equal intensity beam is derived. According to the practical application of the project, the structural dimensions of the equal strength beam are determined, and the optimization design of the vibrator is carried out. The finite element analysis of the sensor is carried out by ANSYS, and the first order resonant frequency is 94.739 Hz. The vibration test of the sensor is carried out by using the vibration frequency of 35 Hz and the vibration source of 50 Hz. The time domain and frequency domain analysis results of test data show that the sensor has good dynamic response characteristics, which can realize the accurate monitoring of the vibration frequency and meet the special requirements of vibration monitoring of hydraulic pump under specific environment.

**Keywords:** Fiber Bragg grating; uniform strength beam; vibrating monitoring; vibration sensor

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## 1. Introduction

The mechanical vibration of the hydraulic system is one of the key factors that affect the reliability of the hydraulic system. Analyzing and monitoring the mechanical vibration of hydraulic pump has a positive theoretical and practical significance in the vibration and fault diagnosis of the hydraulic system [1, 2]. At present, the traditional hydraulic pump vibration monitoring technology mainly uses electrical sensors as the signal acquisition unit to turn the vibration signal into electrical signal, by monitoring the electrical signal to indirectly reflect the size of the vibration,

which is now the most widely used vibration monitoring method [3, 4]. The advantages of this method are that the technology is mature, and the sensitivity is higher than the mechanical measurement. But it is difficult to achieve insulation measurement and very vulnerable to electromagnetic interference, which runs a high risk of causing accidents.

Based on the optical fiber sensing technology, the vibration monitoring system of the hydraulic pump is based on the optical fiber, and the light wave is the information carrier. The structure of the monitoring system is greatly simplified [5]. The optical fiber itself has the advantages of electrical

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insulation, anti electromagnetic interference, and good environmental adaptability, and can be highly integrated with the modern communication equipments, which provides a new technical approach for the vibration monitoring of the hydraulic system [6, 7]. The vibration signal sensing and detection technology of the hydraulic pump is the core of the whole monitoring system, and its performance directly affects the stability, sensitivity, and reliability of the whole monitoring system [8–10]. However, the vibration sensor which is widely used at present is mostly based on the switch quantity detection sensor unit integration, and the sensor network has not been formed, thus the price is high.

The fiber Bragg grating (FBG) is a kind of optical passive devices using spatially periodic refractive formation in the fiber core distribution to change the wave propagation behavior in the fiber. In addition to the advantages of the general optical fiber sensor, one can also use its unique advantages of wavelength encoding, through the vibration sensor with a specially designed structure [11, 12]. The FBG vibration sensor has a higher accuracy and lower price than the long period grating (LPG) vibration sensor and interferometric vibration sensor. In view of the above background, a kind of the FBG vibration sensor based on the equal intensity beam is studied and designed in this paper, which has an important application value in the vibration monitoring and fault diagnosis of the hydraulic pump.

## 2. FBG vibration sensing principle and analysis

### 2.1 Basic principle of FBG strain sensing

According to the coupled mode theory, the refractive index perturbation of the FBG cycle is only affected by a narrow range of wavelengths, i.e., the Bragg condition is only [13]

$$\lambda_B = 2n_{\text{eff}}A. \quad (1)$$

The light wave can be reflected by the grating, the rest of the transmission spectrum is not affected, and the FBG acts as a mirror or a filter. Equation (1) shows that the central wavelength  $\lambda_B$  changes with the grating period  $A$  and the effective index of refraction of the core  $n_{\text{eff}}$ . Strain is one of the physical parameters which is directly sensitive to the FBG, which affects the central reflection wavelength  $\lambda_B$  by the changes of the photoelastic effect and the grating period:

$$\Delta\lambda_B = (1 - P_e)\varepsilon\lambda_B \quad (2)$$

where  $P_e$  is the effective elastic optic coefficient of the fiber, and  $\varepsilon$  is the axial strain. When the FBG is affected by the external stress field, by means of the variation of the wavelength demodulation device to measure the central wavelength, we can accurately obtain the corresponding parameters of the external role information [14], which is the basic principle of the FBG strain sensor. By using the special structure design, we can use the FBG to realize the sensing and measurement of vibration and other physical parameters [15].

### 2.2 FBG vibration sensing principle of cantilever beam structure

Equation (2) shows that if the strain of the FBG  $\varepsilon$  changes periodically with time, the model can be used to measure the vibration periodically. The vibration element based on the cantilever beam structure has the advantages of simple structure, easy manufacture, and good bending property, so it is often used as the basic structure of the FBG vibration sensor [16, 17]. Because the gate area of the FBG with a certain length (8 mm – 10 mm) and the surface strain of the equal strength beam for pure bending can ensure that the tensile stress and compressive stress of each part of grating are the same, the chirp effect will not happen because of the local stress of FBG.

Based on the above analysis, this paper uses the equal intensity beam as the elastic element of the FBG vibration sensor. In order to analyze the

mechanical properties of the strength beam and further deduce the sensitivity and natural frequency of the vibration sensor, let  $L$ ,  $b$ , and  $h$  be the length, width, and thickness of the equal strength beam, respectively,  $E$  be the elastic modulus of the beam, and  $F$  be the end force of the beam. The structure and principle of the FBG vibration sensor are shown in Fig. 1.

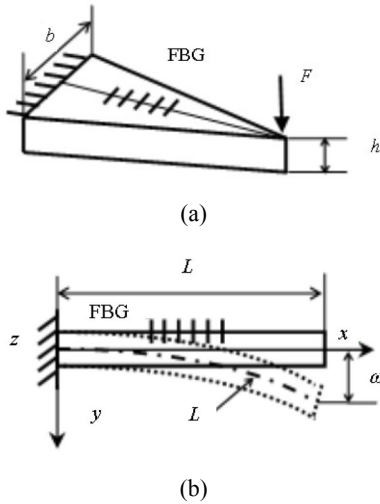


Fig. 1 Schematic of the FBG vibration sensor structure and beam bending with force: (a) sensor structure and (b) schematic of beam bending with force.

According to the structure shown in Fig. 1, the FBG is attached to the central axis of the equal strength beam along the axis, and the vibrator (mass) is fixed at the free end of the beam. When the external vibration causes the acceleration  $a$  of the vibrator to change, the oscillator will produce a periodic force  $F$ , which will be transformed into a periodic dynamic strain. The vibration information can be obtained by detecting the variation of the FBG central wavelength on the surface of the beam. Since the vibrational strain at the maximum amplitude of the grating reaches the maximum, and the central wavelength of the grating returns to the initial value when the vibrator returns to the equilibrium position, the frequency reflected by the change in the FBG wavelength is the vibration frequency to be measured.

According to the mechanical principle of the

equal strength beam, the strain [18] of each point on the beam can be obtained by

$$\varepsilon = \frac{6L}{Ebh^2} F = KF \quad (3)$$

where  $K$  is the strain stress sensitivity of the equal strength beam. The quality of the cantilever beam is  $m$ , the vibration acceleration is  $a$ , and the force of the free end of the beam is  $F=ma$ . By means of (2) and (3), the sensitivity of the FBG vibration sensor  $S$  is

$$S = \frac{\Delta\lambda_B}{a} = \frac{6(1-P_\varepsilon)mL}{Ebh^2} \lambda_B \quad (4)$$

Sensitivity  $S$  is used to describe the relationship between the change in the FBG wavelength and the measured vibration acceleration  $a$ . The length of the mass block is  $L_m$ , and the length of the beam is about  $L$ . According to the knowledge of mechanics, the natural frequency of the FBG vibration sensor  $\omega_0$  is

$$\omega_0 = \sqrt{\frac{Ebh^3}{L(2L^2 + 6LL_m + 3L_m^2)m}} \quad (5)$$

The sensitivity and natural frequency in (4) and (5) are two important parameters in determining the performance of the FBG vibration sensor, and the correct choice of the two parameters is essential for the design and test of the effect of the vibration sensor.

### 3. Structure design and finite element analysis of FBG vibration sensor

#### 3.1 Structure design

According to (4) and (5), the sensitivity of the sensor  $S$  and the natural frequency  $\omega_0$  are related to the size, material, and the quality of the cantilever beam. Because the natural frequency of the sensor should be higher than the upper limit of the sensor system, in order to improve the upper limit of the frequency of the vibration sensor, the natural frequency of the sensor should be increased as much as  $\omega_0$ . However, increasing the natural frequency means reducing the sensitivity of the sensor.

Therefore, the design requirements of the FBG vibration sensor is to meet the needs of the frequency measurement range, and the sensitivity should be as high as possible, so it is necessary to combine the actual needs of the above parameters for the rational design and selection.

In the hydraulic system, the hydraulic pump vibration frequency is generally located in the range of 20 Hz – 80 Hz. The vibration sensor is a typical two-order system, and the upper limit of the measured vibration frequency is about 80% of the natural frequency of the sensor. Therefore, the design of the natural frequency of the vibration sensor at 100 Hz or so is to meet the use requirements. In the concrete design, the material of the cantilever beam is chosen as 304 stainless steel, and its young's modulus  $E$  is about 193 GPa. Taking into account the length of the beam to reduce  $L$  can improve the natural frequency of the sensor and the impact on the sensitivity of small and convenient processing, to meet the premise of FBG paste and determine the length of the beam  $L$  being 50 mm and the width of  $b$  being 10 mm. The beam thickness  $h$  and the oscillator mass  $m$  are two important parameters in the design. In order to facilitate the processing, the cantilever beam can be directly used with the thickness of 0.5 mm of the plate, so the design is focused on the quality of the oscillator  $m$  optimization and selection. Figure 2 shows the change trend of the vibrator mass  $m$  with the natural frequency  $\omega_0$  of the cantilever beam when the above design parameters are used for the equal strength beam.

According to the relationship between the vibrator mass and the natural frequency in Fig. 2, we can see when the other parameters are determined, with an increase in the quality  $m$  of the oscillator, the natural frequency of the sensor negatively exponentially decreases. According to the calculation, when the natural frequency of the sensor is 100 Hz, the corresponding oscillator mass  $m$  is about 7.2 g. At this point, the sensitivity of the FBG

vibration sensor is about  $0.05 \text{ nm}/(\text{m}\cdot\text{s}^{-2})$  when the central wavelength  $\lambda_B$  is 1550 nm.

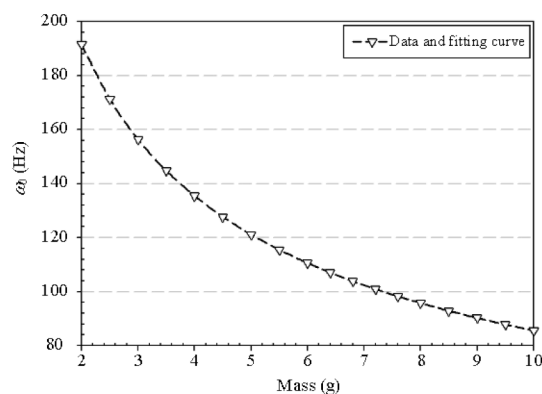


Fig. 2 Relation curve of the sensor natural frequency with the changes in vibrator mass.

### 3.2 Finite element analysis

In order to further analyze the theoretical model of the vibration sensor, based on the above theoretical design, the finite element and modal analysis of the FBG vibration sensor are carried out by using ANSYS software. According to the design parameters of the equal strength beam and the fixed requirements of the experimental platform, the structural model of the sensor is established. The vibration quality of the sensor is chosen to be a cylindrical stainless steel profile with a diameter of 10 mm, and the material is the same as that of the equal strength beam with a density of  $7.93 \text{ g}/\text{cm}^3$ . In order to facilitate the processing, the design height of the vibrator is 12 mm, and the corresponding mass is about 7.4 g. According to the design parameters, a three-dimensional model of the vibration sensor by using Pro/E software is imported into the ANASYS software to mesh for the finite element analysis, and the results are shown in Figs. 3(a) and 3(b).

According to the results of the finite element analysis, the natural frequency of the vibration sensor is 94.739 Hz, and the maximum deflection deformation of the first order resonance is 4.16 mm. The finite element analysis results agree well with the theoretical analysis, which can meet the actual needs.

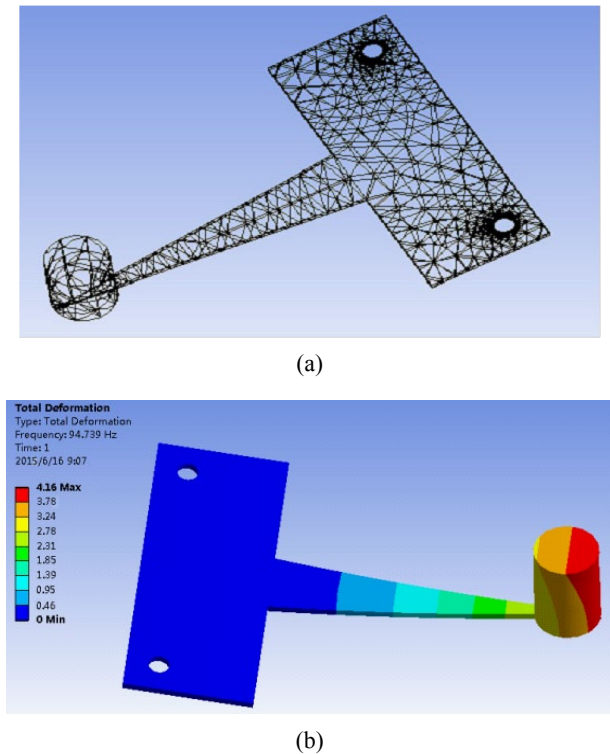


Fig. 3 Meshing the vibration sensor and finite element analysis: (a) mesh generation and (b) strain distribution of the first-order resonance.

#### 4. Experimental measurement and analysis of the FBG vibration sensor

According to the above theory and the results of the finite element analysis, the structural dimension of the equal intensity beam used in the FBG vibration sensor is determined as: the length of  $L$  is 50 mm, the width of  $b$  is 10 mm, and the thickness of  $h$  is 0.5 mm. The vibrator is made up of 10 mm in diameter, with a height of about 12 mm, which is the same as that of the cantilever beam. The corresponding mass is about 7.4 g. The FBG central wavelength is 1550 nm, the gate length is 10 mm, the reflectivity is higher than 85%, and the fiber type is SMF-28, using epoxy glue FBG along the central axis of the cantilever beam, which is pasted on the surface. In the experiment, first, the FBG vibration sensor is fixed on the test bench, and the vibration frequency is 35 Hz and 50 Hz, respectively. The wavelength range of the FBG demodulator using wave capture series of high-speed demodulation module is 1520 nm – 1570 nm with a resolution of

1 pm and wavelength measurement repeatability of 5 pm. The schematic diagram of the FBG vibration sensing experiment is given in Fig. 4.

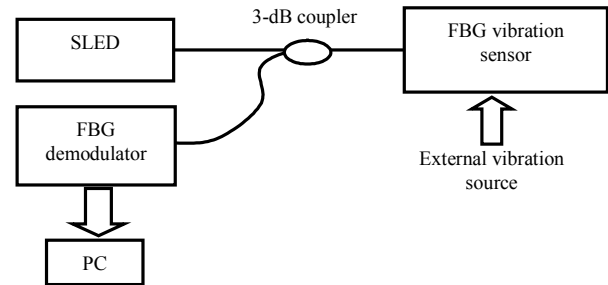


Fig. 4 Principle schematic of the FBG vibration test.

In Fig. 5, the actual measured FBG wavelength variation data are given when the excitation source is excited by 35 Hz, and the spectral curve of the experimental data are processed by fast Fourier transform algorithm (FFT). The sampling frequency of the FBG demodulator is 100 Hz.

According to the experimental data and analysis results, it can be seen that under the excitation frequency of 35 Hz, the change in FBG central wavelength is in the range of 1.2 nm – 1.6 nm. And the central wavelength of the FBG shows significant periodicity. The FFT spectrum analysis shows that it has an obvious peak value near 33 Hz, which is close to the frequency of the vibration source, and the FBG vibration sensor can measure the vibration frequency of the vibration source.

Similarly, in Fig. 6, the actual measured FBG wavelength variation data and the spectral curve after FFT treatment are given by using the 50-Hz excitation source.

According to the experimental data and analysis results, it can be seen that the central wavelength of the FBG also shows a periodic variation rule under the excitation frequency, and the peak frequency obtained by the FFT spectrum analysis is about 48 Hz. Compared with the experiment in Fig. 5, the variation range of the FBG central wavelength in Fig. 6 is only about 0.1 nm, which is mainly due to the different powers of the vibration motor in the experiment. In the above two experiments, the

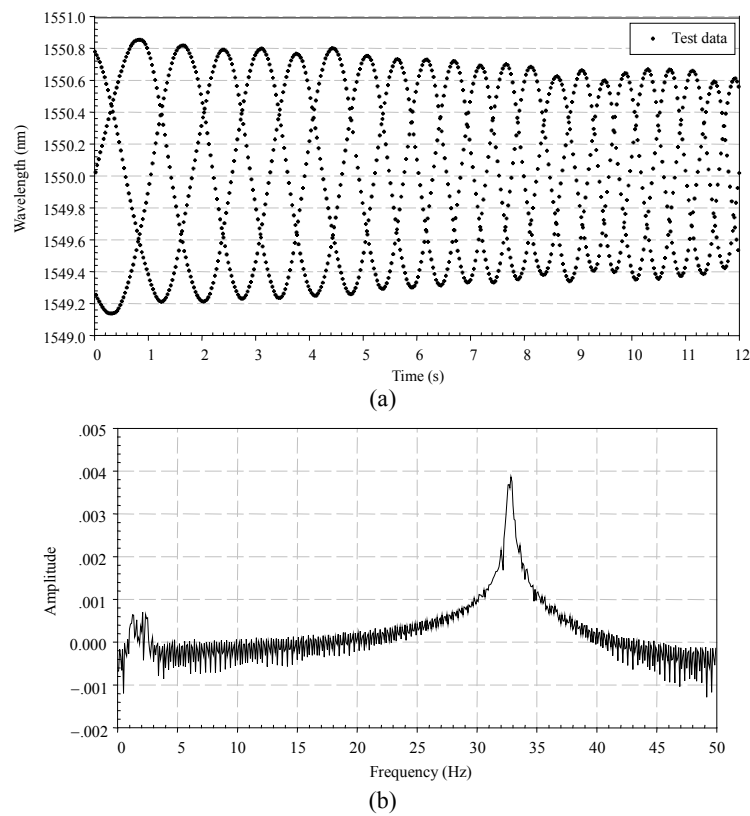


Fig. 5 Test data and FFT analysis with the vibration source at 35 Hz: (a) test data and (b) FFT spectral curve after treatment.

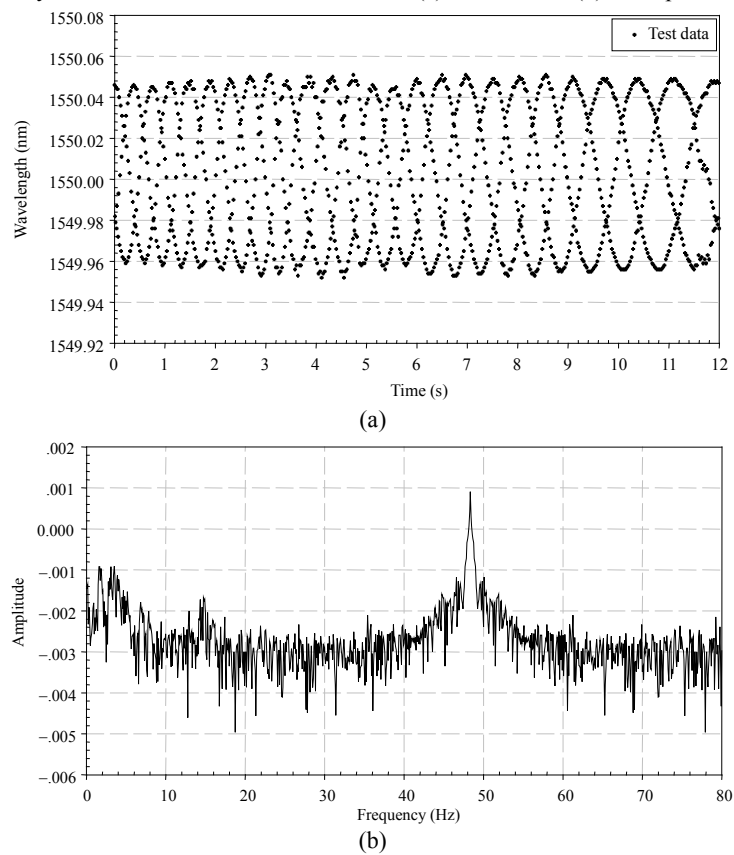


Fig. 6 Test data and FFT analysis with the vibration source at 50 Hz: (a) test data and (b) FFT spectral curve after treatment.

vibration frequency measured by the FBG vibration sensor is slightly smaller than the actual frequency of the vibrating motor, which may be due to the fact that there is no connection between the motor and the test bench. However, the measurement error is small, which does not affect its engineering application.

## 5. Conclusions

A fiber grating vibration sensor based on the intensity of the beam structure is designed in this paper, so as to solve the problem of hydraulic pump vibration electrical measurement of the vibration sensor, such as the high false alarm rate, vulnerability to electromagnetic interference, and not easiness to achieve long-term and reliable monitoring and other issues. In this paper, based on the analysis of the vibration theory of the equal strength beam, the principle of FBG vibration tuning based on the equal intensity beam is derived. Combined with the practical application of the project, the structural dimensions and the oscillator mass of the equivalent strength beam are optimized, and the finite element analysis is carried out by using ANSYS software. Through the establishment of the test platform, two different frequencies of the vibration source are used to test the FBG vibration sensor design. Test data analysis results show that the sensor has good response characteristics and can realize the accurate test of vibration frequency. The advantages of the optical fiber sensing technology and the unique advantages of FBG wavelength coding, especially for the vibration measurement and fault diagnosis of the hydraulic pump, have important application prospects.

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