Turbine rotor dynamic balance vibration measurement based on the non-contact optical fiber grating sensing

Tianliang Li\textsuperscript{a)}, Yuegang Tan, Zude Zhou, Li Cai, and Lai Wei

School of Mechanical and Electrical Engineering, Wuhan University of Technology, 122 Luoshi Road, Wuhan, Hubei, P.R.China

\textsuperscript{a)} tianliangliwhut@sina.com

Abstract: This paper has presented a non-contact vibration sensor based on fiber Bragg grating (FBG) sensing, and applied to measure vibration of turbine rotor dynamic balance platform. The principle of the sensor has been introduced; it’s based on magnetic coupling principle and the FBG sensing to obtain the vibration. The sensors calibration experiments show that: sensitivity of 1\textsuperscript{st} sensor in range of 3.00–3.80 mm is −449.83 pm/mm, linearity is 5.19%; sensitivity of 2\textsuperscript{nd} sensor in range of 4.00–5.00 mm is −430.95 pm/mm, linearity is 3.31%. In addition, turbine rotor dynamic vibration detection system based on eddy current displacement sensor and non-contact FBG vibration sensor have set; and contrast analysis of experiments data shows that: the vibration signal analysis of non-contact FBG vibration sensor is basically the same as the result of eddy current displacement sensor. It verified that the sensor can be used for non-contact measurement of turbine rotor dynamic balance vibration.

Keywords: turbine rotor, FBG, non-contact, vibration sensor

Classification: Fiber optics, Microwave photonics, Optical interconnection, Photonic signal processing, Photonic integration and systems

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1 Introduction

Turbine rotor is one of the basic components of engineering systems and is widely used in the industry now. So it’s very important for the economy and national security. Balancing a turbine rotor is a vital step to ensure that the machine will operate reliably and safely [1]. If turbine rotor occurs imbalance, it will cause the vibration of rotor. Once the vibration lever exceeds the standard value, it maybe causes the rotor damage and some serious accidents. So turbine rotor could be done balancing calibration before using, the vibration accurate detection is the vital technology in the turbine rotor dynamic balance experiment.

Compared with traditional sensors, fiber Bragg grating (FBG) sensors are resistant to electromagnetic interference, corrosion, and high temperature, small in size, light in weight and easy to conduct distributed dynamic measurement [2]. So more and more scholars design displacement sensors based on FBG sensing technology. Yong Zhao et al. symmetrically pasted FBGs on the upper and lower surfaces of the beam, and used differential principle to eliminate temperature interference, its sensitivity is about 1.75 pm/um [3]. Reference [4] proposed a wide range displacement sensor, through using the spring to convert the displacement into the force applied to the beam with FBGs. Youlong Yu et al. proposed a new approach to measuring displacement and temperature simultaneously by use of a specially designed isosceles triangular cantilevered beam as a strain agent, FBG was pasted on cantilever where thickness was changing along the axis, the displacement sensor’s sensitivity is $9.24 \times 10^{-2}$ nm/mm [5]. Literature [6] used the similar principle as literature [5], the FBG was bonded crosswise on the joint section of a specially constructed cantilever that was composed by sticking the fixed end of a polymer beam on aluminum baseplate, so that the vertical displacement of cantilever’s free end can be obtained by measuring the wavelength shift of FBG. A FBG was glued at a slant orientation onto the lateral side of a specially designed cantilever beam, displacement measurement was achieved by measuring the reflected optical power of the signal from the FBG using a photodetector, linear response of 37.9 mV/mm was obtained within a displacement range of 9.0 mm [7]. All of the literatures [3, 4, 5, 6, 7] use cantilever beam as elastomer to realize displacement measurement, this kind of sensor owns a large dimension. Hideaki Iwaki et al. presented a displacement sensor based on a coil spring, and the FBG element was bonded to a metal bar, the metal bar was connected in a series with a coil spring to allow large strokes for the sensor [8, 9]. Literature [10] introduced a
exactitude displacement FBG sensor, one end of the FBG was fixed, and the other end was connected with a movable slider, through the slider move around to tense and compress FBG to measure the displacement of structure. All the above FBG sensors are belong to contact measurement, MI Haokun et al. proposed a non-contact magnetic coupling displacement sensor, a closed magnetic circuit was formed from this U-type probe and the measured moving object, by which the transferring relation between the gap and magnetic field force can be established, and then by means of a mechanical transducer based on planar circular sheet, the magnetic coupling force can be converted into the sensing FBG axial strain [11]. Although the above FBG displacement sensors can realize the different demands of displacement detection, they didn’t study on the dynamic characteristics of sensor and only apply to quasi-static displacement measurement, so they can’t use to vibration detection of rotating shaft.

This paper has proposed a non-contact vibration sensor based on fiber grating sensing, and applied to detect vibration of turbine rotor dynamic balance experimental platform. The principle of the sensor has been introduced, as well as the experimental analysis; properties of non-contact FBG vibration sensor have been analyzed in the experiment. This paper mainly falls into the following parts: principle of sensors, vibration measurement system of turbine dynamic balance, sensing properties of sensors and turbine dynamic balance vibration detection experiment and analysis.

2 Principle of sensor and turbine rotor dynamic balance vibration measurement system

2.1 Principle of the non-contact FBG vibration sensor

The principle of non-contact FBG vibration sensor is shown in Fig. 1. The non-contact FBG vibration sensor mainly consists of permanent magnet, diaphragm, FBG and screw. The two end of the FBG are fixed on the screw and base of sensor by the glue; the permanent magnet and the diaphragm is connected by the screw, also it has formed a hard core of the diaphragm which contacts with the screw. According to magnetic coupling principle between magnet and ferromagnetic axis, when the distance between permanent magnets and ferromagnetic axis changes, variational magnetic force acted on the hard core of diaphragm make diaphragm deformation state change; so the FBG connected with the diaphragm is under

Fig. 1. Principle map of non-contact FBG vibration sensor
tension and compression. And finally the shaft vibration can be obtained by the FBG center wavelength shift.

According to the theory of magnetism, the magnetic force of permanent magnet can be written as [11, 12]:

\[
F = \frac{B_r^2 A_g}{2\mu_0} \left(1 + \frac{B_r A_m L_a}{\mu_0 H_c A_g L_m}\right)^2
\]

where \(B_r\) and \(H_c\) are the permanent magnet remanence and coercivity, respectively, \(\mu_0\) is permeability of vacuum, \(A_g\) is cross-sectional area of air gap spacing, \(L_a\) is air gap spacing, \(L_m\) is the length of permanent magnet in magnetization direction.

The Force is simplified as the distribution load which exerts on the hard core of diaphragm, so according to the theory of elastic theory, the deflection of diaphragm can be expressed as [12]:

\[
\Delta w = \frac{FD}{\pi r^2 \left(1 + \frac{E_f A_f D}{\pi r^2 L}\right)}
\]

\[
D = \frac{3(1-\mu^2)}{16} R^4 E h^3 \left(1 - \frac{r^4}{R^4} + 4 \frac{r^2}{R^2} \ln \frac{r}{R}\right)
\]

is a constant, only related to the size and physical parameters of the diaphragm. Where \(E_f\) is Young’s modulus of optic fiber, \(A_f\) means cross-sectional area of the optic fiber, \(L\) represents effective length of FBG, \(\mu\) represents diaphragm Poisson ratio, \(E\) is Young’s modulus, \(\Delta w\) is the bending deflection of diaphragm hardcore, \(h, R,\) and \(r\) are the diaphragm thickness, diaphragm radius, and diaphragm hardcore radius, respectively.

According to the coupled-mode theory, the center wavelength \(\lambda\) of the FBG can be expressed as:

\[
\lambda = 2n\Lambda
\]

Where \(\lambda\) is the Fiber Bragg grating wavelength; \(n\) is the effective refractive index of the fiber core; \(\Lambda\) is the grating period.

As temperature fluctuation is ignored, and combining equation (1), the center wavelength shift \(\Delta \lambda\) is expressed as:

\[
\frac{\Delta \lambda}{\lambda} = (1 - \rho_e) \Delta \varepsilon
\]

Where \(\Delta \lambda\) is central wavelength shift; \(\varepsilon\) is strain; and \(P_e\) is the strain-optic coefficient of optical fiber. Because the FBG is connected with the diaphragm, so FBG’s deformation is equal with the deflection of diaphragm hardcore \(\Delta w\). So the strain of FBG \(\varepsilon\) can be written:

\[
\varepsilon = \frac{B_r^2 A_g D}{2\mu_0 \pi r^2 L \left(1 + \frac{E_f A_f D}{\pi r^2 L}\right) \left(1 + \frac{B_r L_a}{\mu_0 L_m H_c}\right)^2}
\]

where \(L\) represents the effective work length of FBG. Combining the above equations, the relationship between FBG wavelength shift \(\Delta \lambda\) and is air gap spacing \(L_a\) can be expressed as:
From the equation (6), the relationship between FBG center wavelength shift and air gap spacing \( L_a \) has been built, so displacement vibration of the rotating shaft can be obtained by the FBG center wavelength shift.

\[
\frac{\Delta \lambda}{\lambda} = (1 - P_e) \frac{B_r^2 A_g D}{2 \mu_0 \pi^2 L \left( 1 + \frac{E_i A_f D}{\pi^2 L} \right) \left( 1 + \frac{B_r L_a}{\mu_0 L_{rm} H_c} \right)^2}
\]  

(6)

Fig. 2. The principle diagram of the FBG

Fig. 3. Physical map of sensor

2.2 Turbine rotor dynamic balance vibration measurement system

Before the turbine rotor official uses, it must be done dynamic balance vibration calibration experiment to ensure vibration of the rotor within normal operating range. The map of turbine rotor dynamic balance experimental platform system is shown in Fig. 4. The turbine rotor consists of 3rd and 12th blades, also it is supported by semi-watt bearing, and the support stiffness of rotors can be adjusted by using lateral preload handle of semi-watt bearing. Due to the limitation of actual working condition, the vibration sensors are placed on the same side of the rotor supported, up to 45° relative to the horizontal, as shown measuring point 1 (1st eddy current sensor and 1st FBG vibration sensor) and measuring point 2 (2nd eddy current sensor and 2nd FBG vibration sensor) in Fig. 4. In order to ensure that the eddy current sensor is not affected by permanent magnet magnetic interference of non-contact FBG vibration sensor, according to the requirements of the eddy current sensor technology, the center distance of the installation of the two sensors is greater than 60 mm as shown in Fig. 4.

In order to verify the performance of FBG vibration sensor, the eddy current sensor signal must be real-time collected. In this experiment, the signal of non-contact FBG vibration sensor is real-time acquired by FBG demodulator, also the eddy current displacement sensor signal is obtained by NI data acquisition card and Lab view collection system (Fig. 5).
3 Sensors calibration

The principle of designed FBG vibration sensor to monitor steam turbine rotor vibration is that the central wavelength change of the FBG vibration sensor can reflect the vibration from the equation (6). To realize this, it is necessary to calibrate the relationship between FBG wavelength shift and air gap spacing $L_{a}$. So the Non-contact FBG vibration sensors calibration system has built as shown in Fig. 6. The non-contact FBG vibration sensor, LK-G80 laser displacement sensor (Range: 30 mm, Resolution: 0.1 um) and experimental board are fixed on three coordinate...
guide. Using LK-G80 laser displacement sensor as reference standard, by adjusting the three coordinate guide to change the distance between the experimental model and sensor $L_a$.

The experiment is repeated 6 times, and calculates average value of all experiments. According to the fitting a straight lines from Fig. 7, they show that: sensitivity of 1st sensor in range of 3.00–3.80 mm is $-449.83$ pm/mm, linearity is 5.19%, linear fitting equation is $\Delta \lambda = -449.83 \times L_a + 2562.57$; sensitivity of 2nd sensor in range of 4.00–5.00 mm is $-430.95$ pm/mm, linearity is 3.31%, linear fitting equation is $\Delta \lambda = -430.95 \times L_a + 2860.38$.

4 Experiments and analysis

In the experiment, the turbine rotor is connected with electric motor by driver plate. At first, the electric motor is driven the turbine rotor at a given speed, and in order to avoid driver plate vibration interferes the turbine rotor dynamic balance testing, we make the turbine rotor separate itself from the electric motor in a state of free vibration. The experiments are divided into two groups. When the speed increased to 300 r/min and 400 r/min, we rapidly pull out driver plate, and make the turbine rotor in free vibration state. Also the vibration signal started after driver plate pulled
out, and stopped until rotor stopped. The indicators of FBG vibration sensor and eddy current sensor are shown in the Table I. In this experiment, the electrical measurement system sampling rate is 50 Hz, and the FBG vibration sensing sampling rate is 1 kHz, the experiment is repeated three times at each speed.

4.1 Time domain analysis
According to the fitting equation of the sensor are shown in the Table I, the two FBG vibration sensor center wavelength shift can be converted to displacement vibration. Fig. 8 and 9 show the vibration signal time domain of turbine rotor at the speed of 300 and 400 r/min. From the Fig. 8 and 9, it can be seen that the vibration time domain signal trend of FBG is consistent with eddy current sensor; then the domain signal amplitude exists certain differences, due to two independent systems and acquisition starting points are not synchronized. These conclusions qualitatively show that the sensor can realize vibration measurement.

| Performance indicators | Range/mm | Fitting equations |
|------------------------|----------|------------------|
| 1st FBG vibration sensor | 3.0~3.8  | $\Delta \lambda = -449.83 \times L_a + 2562.57$ |
| 1st eddy current sensor | 0.3~1.3  | $U = 20.018 \times L_a - 16.013$ (U means voltage) |
| 2nd FBG vibration sensor | 4.00~5.00 | $\Delta \lambda = -430.95 \times L_a + 2860.38$ |
| 2nd eddy current sensor | 0.3~1.3  | $U = 19.991 \times L_a - 15.998$ |

**Table I.** The indicators of FBG vibration sensor and eddy current sensor

![Graphs showing time domain analysis](image-url)
4.2 Spectrum analysis

Due to the acquisition systems of the FBG vibration sensor and eddy current sensor are independent. So in order to better evaluate the FBG vibration sensor properties, the time scale of two sensors’ signal could be matched. When the turbine rotor stops, there is a pulse response in two sensors. Time alignment reference point of FBG vibration sensor and eddy current sensor are shown in Fig. 10. The moment rotator stop is considered as a termination time reference point, and selected the same length for vibration signals of two sensors.

![Fig. 9. Vibration signal time domain of turbine rotor at the speed of 400 r/min](image)

![Fig. 10. Time alignment reference point of FBG and eddy current sensor](image)

We used FFT transform to dispose the time domain signal after time-match, and the spectrum of FBG vibration sensor and eddy current sensor signal at speed of 300 r/min and 400 r/min after time-match are shown in Fig. 11 and 12. From the two figures, we can obtain that: the fundamental frequency relative error between
FBG vibration and eddy current sensor in the 1st/2nd measuring point at the speed of 300 and 400 r/min are 6.32%/5.2% and 1.68%/1.68% (Table II), the fundamental frequency value of two kinds of sensors are almost the same; compare with eddy current sensor, the FBG vibration sensor is more sensitive to the multiple frequency of vibration signal. The Table III is the two types of sensors 1X frequency amplitude value after time-matched. From these we can see that the maximum relative error of the two kinds of sensors is 17.8% at the speed about 400 r/min in the 2nd measuring point; relative error is within 6% in the 1st measuring point. So it’s demonstrated that the non-contact FBG vibration sensor can be applied to measure the vibration of turbine rotor, but the accuracy and reliability of non-contact FBG vibration sensors could be further improved.

Table II. Two types of sensors dominating frequency value after time-matched

| Measuring point | 300 r/min | 400 r/min |
|-----------------|-----------|-----------|
| Wheel speed     | 1st       | 2nd       | 1st       | 2nd       |
| FBG vibration sensor | 4.88 Hz, 9.766 Hz | 5.859 Hz, 10.74 Hz | 5.859 Hz, 10.74 Hz |
| Eddy current sensor | 4.59 Hz, 4.639 Hz | 5.762 Hz | 5.762 Hz |
| Relative error of 1X frequency/% | 6.32 | 5.20 | 1.68 | 1.68 |

Fig. 11. Spectrum of FBG vibration sensor signal at speed of 300 r/min and 400 r/min after time-match

Fig. 12. Spectrum of eddy current sensor signal at speed of 300 r/min and 400 r/min after time-match
4.3 The time-frequency analysis

According to the vibration signal’s spectrum analysis of the two kinds of sensors under different speed, it can’t show the value of frequency versus the time, and make the multiple frequency clearly show in the figure. The time-frequency map of two kinds of sensors’ vibration signal is shown in Fig. 13. From the figures, we can find that: 1-8X multiple frequency of the eddy current sensor have an obviously change along with the time, but only 1-3X multiple frequency can be integrality obtained in the FBG vibration signal; the 1-3X multiple frequency of the FBG vibration signal is consisted with the eddy current sensor; when the turbine rotor runs at a lower speed, the eddy current sensor can greatly detect dynamic characteristics of turbine rotor, but FBG vibration sensor can only get part such as in the 4-5X multiple frequency. Some parameters still are different, so we could do the further research on the sensor’s performance to improve its performance.

| Measuring point          | 300 r/min | 400 r/min |
|--------------------------|-----------|-----------|
|                          | 1st       | 2nd       | 1st       | 2nd       |
| FBG vibration sensor     | 23.8 um   | 21.12 um  | 26.46 um  | 29.9 um   |
| Eddy current sensor      | 23.09 um  | 22.32 um  | 32.19 um  | 32.23 um  |
| Relative error/%         | 3.07      | 5.38      | 17.8      | 7.23      |

5 Conclusions

This paper has proposed a non-contact vibration sensor based on fiber Bragg grating sensing, and applied to detect vibration of steam turbine rotor dynamic balance experimental platform. The principle of the sensor has been introduced, it’s based on magnetic coupling principle and the FBG sensing to obtain the vibration.
Performance of non-contact FBG vibration sensor has been analyzed in the experiment, this experiment shows that: sensitivity of 1st sensor in range of 3.00–3.80 mm is $-449.83 \text{ pm/mm}$, linearity is 5.19%, linear fitting equation is $\Delta \lambda = -449.83 \times L_a + 2562.57$; sensitivity of 2nd sensor in range of 4.00–5.00 mm is $-430.95 \text{ pm/mm}$, linearity is 3.31%, linear fitting equation is $\Delta \lambda = -430.95 \times L_a + 2860.38$. In addition, turbine rotor dynamic vibration detection system based on eddy current displacement sensor and non-contact FBG vibration sensor have set; and compared with results of signals under analysis of the time domain, frequency domain and time-frequency changing. The contrast analysis of experimental data shows that: the vibration signal of non-contact FBG vibration sensor is basically the same as the results of eddy current displacement sensor; it verified that the sensor can be used for non-contact measurement of turbine rotor dynamic balance vibration.

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