Study on FBG Vibration Sensor

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Abstract-To overcome the demerits of electromagnetic vibration sensors, the authors, using double-cantilever beam structure, fabricate a fiber Bragg gratings (FBG) vibration sensor based on matching filtering demodulation. This sensor with function of temperature compensation combines vibration sensing and dynamic wavelength demodulation. To study its sensing characteristics the authors have done some experiments and the results show that the sensor has good sensing properties, which can meet the demand of long-term and long-range monitoring for large scale engineering structure.

Keywords- FBG vibration sensor; matching filtering; demodulation; temperature compensation

I. INTRODUCTION

Vibration is a common feature in the nature. Vibration sensors are widely used in the large scale engineering structure[1]. The application of traditional vibration sensors, such as piezoelectric, magnetoelectric, eddy current sensors, is severely limited because of evident flaws---weak output signal, short transmission distance and easily interfered by electromagnetism[1,2]. FBG vibration sensor avails itself of strain mechanism to calculate the acceleration by measuring change of wavelength[3,4]. FBG vibration sensor has such characteristics as long transmission distance, high measuring precision, long-term stability, not interfered by electromagnetism, easily connected to network, combining sensing with transmission, so it is very fit to be applied in the monitoring for large scale engineering structure.

Vibration measurement belongs to dynamic measurement technology, which requires the sensors not only high sensitivity and good spectral response, but also higher speed of wavelength demodulation and better ability to resist temperature disturbance[5]. To solve the above-mentioned problems, a fiber Bragg grating (FBG)vibration sensor with double-cantilever beam structure is designed and matching filtering demodulation technology is applied in the paper[1]. The experimental results indicate the sensor has good sensing properties.

II. SENSING PRINCIPLE

The sensing principle of FBG vibration sensor based on matching filtering demodulation is shown in Fig1. A forced vibration system is made up of cantilever beam B1 ("main beam") and mass block O. FBG1 is pasted on main beam. When the system under the action of vibration, B1 is forced to vibrate because of inertia effect and cyclic strains build up, which results in periodical change of the center wavelength of FBG1. FBG2 is pasted on another cantilever beam B2 (“queen beam”). The deflection of free end of B2 can be adjusted by tuning plug F, thus the center wavelength of FBG2 can be also adjusted. The light from broadband light source LED transmits to FBG1 via 3dB coupler. After deflected by FBG1, it transmits to FBG2 via 3dB coupler again, and after filtered and transmitted by FBG2, it is received by light power meter PD. Adjust the center wavelength of FBG2 by F to make that of FBG1 just right in range of linearity of transmission spectrum of FBG2. As is shown In Fig2, the reflected light of FBG1 transits to FBG2, it will be filtered and transmitted by FBG2 and the light power received by PD will make linear change with the shift of the center wavelength of FBG1. The upper is called wavelength demodulation, that is to say; the signal conversion from wavelength to power.
The reflectance spectrum of FBG1 in Gaussian function is given by
\[ R_1(\lambda) = R_0 e^{-\frac{4\ln 2}{\delta\lambda_1^2} (\lambda - \lambda_c)^2} \]  
(1)
where \( R_0 \) is peak value reflectance of incident light, \( \lambda_c \) is center wavelength of FBG1, \( \delta\lambda_1 \) is bandwidth of FBG1 at half peak value.

The transmission spectrum of FBG2 is given by
\[ T_2(\lambda) = 1 - R_0 e^{-\frac{4\ln 2}{\delta\lambda_2^2} (\lambda - \lambda_c)^2} \]  
(2)
where \( R_0 \) is peak value transmittance of incident light, \( \lambda_c \) is center wavelength of FBG2, \( \delta\lambda_2 \) is bandwidth of FBG2 at half peak value. Suppose incident light power per unit wavelength is \( I_0 \). After the light transmitting to 3dB coupler twice, the total light power received by PD is given by
\[
P = I_0 \int_{\lambda_1}^{\lambda_2} T_1(\lambda) \cdot R_1(\lambda) d\lambda = R_0 \cdot \delta\lambda_1 \sqrt{\pi} \frac{R_1 \cdot \delta\lambda_2}{2\sqrt{\ln 2}} e^{-\frac{4\ln 2}{\delta\lambda_1^2} (\lambda - \lambda_c)^2 - \frac{4\ln 2}{\delta\lambda_2^2} (\lambda - \lambda_c)^2} \]  
(3)

Given \( I_0 = 1 \text{mW/}\text{nm}, R_1 = R_2 = 0.9, \delta\lambda_1 = \delta\lambda_2 = 0.2 \text{nm} \), from formulation (3), we can get the relation between output light power and wavelength deference \( (\lambda_c - \lambda_c) \), as shown in Fig3. It is the curve of complementary function of Gaussian function. There exist two linear-approximation ranges on both sides of the curve trough, which is made right use of by matching filtering demodulation. Its optimal operating point can be obtained from formulation (3) by second derivative of \( (\lambda_c - \lambda_c) \), thus the optimal operating wavelength deference is given by
\[
(\lambda_c - \lambda_c) = \sqrt{\frac{(\delta\lambda_1^2 + (\delta\lambda_2^2)}{8\ln 2}} \]  
(4)

If the 3dB wavelength bandwidth of FBG1 and FBG2 is both 0.2nm, from formulation (4), the optimal operating wavelength deference is 0.12nm. In practice it is very difficult to ensure wavelength deference just right, therefore, to obtain optimal operating condition, a tuning plug must be designed to adjust wavelength deference in the process of development of the sensor.

Because FBG1 and FBG2 are under the same temperature condition and pasted on the same thermal expansion coefficient material, the center wavelength of them changes in phase with temperature. So the wavelength deference is unchanged and the optimal operating condition of the sensor is free from temperature. In addition, to overcome self-resonance of cantilever beam structure, damper fluid is injected into the sensor, thus, higher response sensitivity and better spectrum character can be obtained.

III. EXPERIMENTAL STUDY

To study the characteristics of FBG acceleration sensor, the authors make a series of experiments. The vibration monitoring and analysis system is provided by COINV, and a standard piezoelectric acceleration sensor is used as a reference and contrast object in the experiments. Fig4 is block diagram of experimental equipment. Vibration exciter device(VD) is driven by signal generator(SG) and power amplifier(PA). VD engenders sine wave and square-wave vibration, which is monitored by FBG vibration sensor(VS) and piezoelectric
acceleration sensor (AS) simultaneously. VS is connected with LED and PD like Fig1, and AS connected with charge amplifier (CA) by coaxial-cable. The output voltage signals from PD and CA is inputted in different channels of data acquisition device (MD) simultaneously. The data collected by MD is imported to computer by parallel port, processed and analyzed by software, displayed in the screen at last.

**A. Vibration Waveform**

When vibration device makes simple harmonic vibration at 0.5Hz and 10 Hz, the output voltage graphs of VS and AS are shown in Fig5 (a) and Fig5 (b). Whether in Fig5 (a) or in Fig5 (b), the output voltage graphs of VS and AS are approximately same. The sensitivity of the former is slight over that of the latter in fig (a), but that is on the contrary in fig(b). So the FBG vibration sensor is more suitable to measure low-frequency vibration.

**B. Frequency-Amplitude Characteristic**

When testing frequency-amplitude characteristic of FBG vibration sensor, diverse damping liquid is injected into the sensor to get different damping ratio. Three frequency-amplitude characteristics because of different damping ratio is shown in Fig6. The vibration acceleration value in the test is 0.5g, which is measured by standard acceleration sensor and remain unchanged in the process of the test. The measured frequency band is 0.1~40Hz. From Fig6, acceleration amplitude is flat region from 0.1Hz to 14 Hz, resonance region from 14Hz to 24 Hz, and attenuation region over 24Hz. So working region is from 0.1Hz to 15 Hz, and natural frequency is approximately 20 Hz. In addition, acceleration amplitude is free from damping ratio in working region, but it is obvious to diminish with augment of damping ratio, and if damping ratio is chosen about 0.7, the resonance which causes the sensor damaged or invalid, can be avoidable.

**C. Output Characteristic**

The calibration curve of FBG vibration sensor is shown in Fig7. Input acceleration value is gained from the standard acceleration sensor and output voltage value is read from the computer. From the Fig7, the relation between acceleration and voltage is linear within the limit of 2g, and the linearity is 0.9996, sensitivity is 189mv/g, but beyond 2g the relation between them is nonlinear. So measuring range of FBG vibration sensor is 2g.

**D. Repeatability**

During the experiment, VS is fixed on the vibrator. When it vibrates with varying frequency and amplitude, the vibration acceleration is changing and we can get measuring acceleration value according to upper calibration coefficient of the sensor. At the same time, AS is served as a reference. The experiment is done thrice and the results are shown in table1.
IV. CONCLUSIONS

FBG vibration sensor designed in the paper, using double-cantilever beam structure, overcomes the interference brought by temperature successfully, and solves availably the problem of dynamic wavelength demodulation by applying the technology of matching filtering demodulation. So the sensor is a blend of vibration sensing, dynamic wavelength demodulation and temperature compensation. Also the authors study sensing characteristics of the sensor by some experiments and draw the conclusions: the sensor works from 0.1Hz to 15Hz, acceleration range of measurement is 2g, sensitivity is 189mv/g; linearity is superior to 99.9%, repeatability is less than 2.0%, and the maximal cross-axis anti-interference is 33dB. To sum up, the sensor is fit for measuring low frequency vibration, can serve as an effective monitoring way for large-scale structures, instead of electromagnetical acceleration sensors.

REFERENCES