High-Speed Fiber Bragg Grating Demodulation System Based on MEMS Mirror

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Abstract

Demodulation systems constructed using F-P filters exhibit relatively slow demodulation frequencies, which generate demodulation errors when measuring physical quantities with high variation frequencies. Therefore, it is essential to improve the demodulation frequency while guaranteeing demodulation precision. To this end, this paper proposes a demodulation system based on MEMS micromirrors, which includes constructing a demodulation system built with MEMS micromirrors, utilizing fiber optic wavelength etalons to address the problem of nonlinear errors between the driving voltage controlling the MEMS micromirror and the output wavelength that affect demodulation accuracy, and demodulating sensor stress wavelength values by means of the central wavelength positioning principle and peak-finding algorithm. Finally, static performance testing of the demodulation system is conducted using an equal-strength cantilever beam, where a motor-driven flexible plate performs sinusoidal motion at frequencies of 1 Hz and 5 Hz respectively, and the motion curves are acquired using the demodulation system. Experimental results demonstrate that the linearity of this demodulation system is 0.85%, and fitting of the acquired wavelength curves yields a maximum R^2 value of 0.9847.

Full Text

High-Speed Demodulation System for Fiber Bragg Grating Based on MEMS Scanning Mirror

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Abstract

The demodulation frequency of systems based on F-P filters is relatively slow, leading to demodulation errors when measuring physical quantities with high rates of change. Therefore, it is essential to improve the demodulation frequency while ensuring demodulation accuracy. This paper proposes a demodulation system based on MEMS scanning mirrors, which includes constructing such a system and employing a fiber optic wavelength etalon to address the nonlinear error between the driving voltage and output wavelength of the MEMS mirror that affects demodulation precision. The sensor' s stress wavelength values are demodulated using the principle of center wavelength positioning and a peak search algorithm. Finally, static performance testing of the demodulation system is conducted using an equal-strength cantilever beam, while a motor-driven flexible plate executes sinusoidal motions at frequencies of 1 Hz and 5 Hz, with the demodulation system acquiring the motion curves. Experiments demonstrate that the linearity of the demodulation system is 0.85%, and the maximum R^2 value for fitting the acquired wavelength curves is 0.9847.

Keywords: fiber Bragg grating; fiber etalon; tunable optical filter; optical fiber sensing

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Introduction

Fiber Bragg Grating (FBG) sensors, as optical sensors, offer numerous advantages including light weight, small size, high reliability, high sensitivity, excellent chemical stability, good electrical insulation, and strong immunity to electromagnetic interference. They can measure various physical quantities such as temperature, strain [1], vibration [2], and pressure [3], and have been widely applied in chemical engineering [4], construction [5], aerospace [6], bridges [7], and other fields.

Currently, the most widely used fiber grating demodulation systems are constructed based on Fabry-Perot (F-P) filters. The principle involves applying a varying voltage to drive the F-P resonant cavity, which changes the cavity length to convert broadband light into narrowband light with varying wavelength. The wavelength of the light reflected by the FBG sensor is then determined based on the correspondence between the driving voltage of the F-P filter and the filtered wavelength. Wen et al. from North University of China [8] employed an etalon to reduce demodulation errors caused by the creep and hysteresis characteristics of piezoelectric ceramics in F-P filters, demonstrating through experiments that the measurement accuracy of the tunable filter demodulation system could reach 2.59% after incorporating the etalon.

Yin et al. from Central South University [9] utilized an improved wavelet threshold denoising algorithm to smooth the raw data sequence and applied a Gaussian fitting algorithm to obtain reliable peak sequences, enabling FBG sensors to monitor building cracks. Comparative experiments with a micrometer showed that the absolute measurement error remained relatively stable at approximately 0.25 mm.

Zhen from the China Academy of Launch Vehicle Technology [10] developed a demodulation system based on F-P filter technology, achieving a demodulation accuracy of 1 pm when the demodulation frequency was below 10 Hz. F-P filters use piezoelectric ceramics to adjust the spacing of the F-P cavity, and these ceramics exhibit creep and hysteresis characteristics that affect demodulation accuracy when measuring physical quantities with high rates of change [11].

Wen et al. from Shanghai Jiao Tong University [12] simulated the vibration of wind turbine blades under impact, finding that the surface vibration frequencies were concentrated around 27 Hz and 91.8 Hz, while the edge vibration frequencies were around 22.4 Hz. Therefore, when using F-P filter-based demodulation systems to detect wind turbine blade vibrations, insufficient sampling frequency becomes a problem [13,14].

To meet the demand for detecting high-frequency varying physical quantities using FBG sensors, it is necessary to improve the measurement frequency of the demodulation system. This paper proposes constructing a high-speed fiber grating demodulation system with a MEMS scanning mirror as the core component, simultaneously introducing a fiber wavelength etalon for wavelength calibration to resolve measurement errors caused by the nonlinear relationship between the driving voltage and output wavelength of the MEMS mirror. Finally, static performance testing experiments based on an equal-strength cantilever beam and dynamic performance testing experiments based on a motor and flexible plate were conducted to verify the demodulation accuracy and speed of the system.

1.1 Principle of FBG Sensors

The schematic diagram of an FBG sensor is shown in Figure 1 [Figure 1: see original paper]. When the sensor undergoes deformation due to applied strain, the grating period changes, and the refractive index of the fiber core changes due to the elasto-optic effect. The combined effect of these two factors alters the reflected wavelength value.

The Bragg wavelength, denoted as λB, is calculated using Equation 1:

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

where n_{eff} represents the effective refractive index of the fiber grating, and Λ represents the grating period of the fiber grating.

When the incident light is a broadband source, the FBG sensor reflects light with a center wavelength that satisfies Equation (1), while light at other wavelengths is transmitted. When the fiber grating is subjected to strain, causing changes in n_{eff} and Λ, the reflected wavelength value of the FBG sensor shifts. This shift is denoted as $\Delta\lambda B$*, the change in grating period as* $\Delta\Lambda$*, and the change in fiber refractive index as* Δn{eff}. The wavelength shift is calculated using Equation 2:

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

Changes in external temperature also cause shifts in the reflected wavelength of the FBG sensor. Combining the effects of temperature and strain, the wavelength shift of the FBG sensor' s reflected light is calculated using Equation 3:

$$\Delta\lambda_B = \lambda_B(1 - [\rho_{12} - \mu(\rho_{12} + \rho_{11})])\varepsilon + \lambda_B(\alpha + \xi)\Delta T$$

where represents the Poisson' s ratio of the material, _{11} and _{12} represent the axial and transverse elasto-optic coefficients respectively, represents the strain applied to the sensor, α represents the thermal expansion coefficient, represents the thermo-optic coefficient, and ΔT represents the temperature change of the sensor.

1.2 Optical Path Principle of the Demodulation System

The optical path configuration of the constructed demodulation system is illustrated in Figure 2 [Figure 2: see original paper]. The control board drives a tunable optical filter with a varying voltage to filter the broadband light from an ASE source into narrowband light with changing wavelength. After passing through an optical splitter, one path of light goes through a fiber wavelength etalon and is then collected by a photodetector for intensity measurement. The remaining beams pass through optical circulators to the FBG sensors, where light at the Bragg wavelength is reflected back through the circulators into photodetectors. The control board analyzes the light intensity collected by the photodetectors at different times within the acquisition period to resolve the Bragg wavelength of the FBG sensors.

[Figure 4: see original paper] Electromagnetically Driven MEMS Scanning Mirror

1.3 Tunable Optical Filter Based on MEMS Scanning Mirror

The working principle of the tunable optical filter based on MEMS scanning mirror is shown in Figure 3 [Figure 3: see original paper]. Light from the source becomes a parallel beam after passing through a lens, is diffracted by a grating into beams of different wavelengths, and is then reflected by the MEMS mirror onto the output lens.

[Figure 3: see original paper] Principle of Tunable Optical Filter Based on MEMS Mirror

The MEMS scanning mirror is an optical scanning device capable of high-speed torsional motion. Common driving methods include electrostatic, electromagnetic, piezoelectric, and thermal drives. This paper employs an electromagnetically driven MEMS scanning mirror, whose schematic diagram is shown in Figure 4 [Figure 4: see original paper].

When current passes through the driving coil, it interacts with the magnetic field generated by the magnetic material to produce an Ampere force. This force creates torque about the rotation axis of the reflective surface, driving its torsional motion. By controlling the current applied to the driving coil, the reflective surface can be made to perform high-speed periodic torsional oscillations [15].

1.4 Demodulation Principle Based on Fiber Wavelength Etalon

The MEMS mirror achieves light reflection through torsional motion. When the voltage across it is near zero, a control dead zone exists, causing nonlinear errors between the output wavelength and control voltage that affect measurement accuracy. Particularly during high-speed scanning, additional uncertainties arise due to the inertia of the rotating mirror. To address these issues, a fiber wavelength etalon is introduced to calibrate the reflected light wavelength values from the FBG sensor.

[Figure 2: see original paper] Optical Path Principle of Demodulation System

The fiber wavelength etalon contains an internal grating that reflects incident light at specific wavelengths, with each reflected wavelength spaced at equal intervals. It is minimally affected by strain and temperature variations [16], with a wavelength fluctuation rate due to temperature of approximately 5 pm/80°C. Its reflection spectrum is shown in Figure 5 [Figure 5: see original paper].

[Figure 5: see original paper] Reflection Spectrum of Fiber Wavelength Etalon

The spectral data received by the demodulation system’ s control board is obtained through discrete sampling of the continuous spectrum of light reflected from the FBG sensor by photodetectors. As shown in Figure 6 [Figure 6: see original paper], the intensity distribution of the FBG sensor’ s reflected light approximates a Gaussian distribution [17].

[Figure 6: see original paper] Principle of Center Wavelength Positioning

The relationship between wavelength value λ and corresponding light intensity I(λ) is expressed as:

$$I(\lambda) = I_0 exp[-4ln2(\frac{\lambda - \lambda_c}{\Delta\lambda})^2]$$

where I_0 is the amplitude of the reflected spectral intensity, λ_c is the center wavelength value of the reflected light, and $\Delta\lambda$ is the 3 dB bandwidth of the reflected spectrum. Gaussian curve fitting is performed on the collected spectral data to determine the acquisition point position of the FBG sensor’ s reflected light center wavelength.

The tunable optical filter scans and outputs narrowband light under periodic driving voltage generated by the control board. After passing through the optical splitter, one path goes through the fiber wavelength etalon to a photodetector, while the other paths enter the FBG sensors via circulators, with reflected light returning through the circulators to photodetectors. The control board synchronously acquires signals from all photodetector channels. The transmission wavelength range of the tunable optical filter is divided into a short band of 1525-1550 nm and a long band of 1550-1565 nm based on different driving voltage pins, with each band having a scanning voltage range of 0-47 V. The short band contains 28 peaks. Due to significant linear distortion in the relationship between transmission wavelength and driving voltage at low voltages, the peak spacing is not uniform in the left portion. The fiber grating sensor' s reflected light has two peaks: one corresponding to strain and the other to temperature. As shown in Figure 7 [Figure 7: see original paper], within one driving voltage scanning period, photodetector signals are acquired on the rising edge. As the driving voltage increases, the center wavelength of the tunable filter' s transmitted light gradually decreases from 1550 nm. At the corresponding wavelength where light passes through the etalon with minimal attenuation, the photodetector acquires the maximum signal value.

To eliminate errors in etalon peak detection, the average of N solutions is taken, and the FBG wavelength λ_{FBG} is calculated as:

$$\lambda_{FBG} = [\sum(\Delta n_i \cdot + \lambda_{si})$$

2. Construction of the Tunable Filter-Based Demodulation System

The schematic diagram of the fiber Bragg grating demodulation system based on the tunable filter method is shown in Figure 8 [Figure 8: see original paper]. The system comprises three modules: the optical module consists of an ASE light source, a MEMS mirror-based tunable optical filter, optical splitters, optical circulators, etalons, and FBG sensors.

[Figure 8: see original paper] Principle of Demodulation System

The data processing module consists of photodetectors (PD), current/voltage operational amplifier modules, ADC acquisition modules, a control board demodulation system module, DAC driving voltage modules, and voltage amplifier modules. The constructed demodulation system is shown in Figure 9 [Figure 9: see original paper].

[Figure 7: see original paper] PD Acquisition Spectrum Diagram

Based on the linear relationship between the driving voltage of the tunable optical filter and the transmitted wavelength, the wavelength and sampling points can be considered linearly correlated when using sawtooth or triangular waves as driving voltages. As shown in Figure 6, assuming the transmission peak wavelength interval of the etalon is $\Delta\lambda s$*, the i-th peak is p_i with a reflection peak wavelength of* λ{si}, the number of sampling points between it and the (i+1)-th peak is K_i, and the number of sampling points between it and the FBG reflection peak p_{FBG} is Δn_i. Assuming the etalon has N peaks, each peak can be used to calculate the corresponding FBG wavelength.

[Figure 9: see original paper] Schematic Diagram of Demodulation System

The upper computer communication module consists of an Ethernet communication module and a PC. The control board controls the DAC to generate sawtooth scanning voltage to drive the tunable optical filter. Broadband light from the ASE source is filtered by the tunable optical filter into narrowband light with different center wavelengths. The splitter divides this narrowband light: one path passes through the etalon into a photodetector (PD1), while the other paths enter corresponding optical circulators. When passing through the FBG sensors, a portion of the light is reflected back through the circulators into photodetectors (PD2, PD3, etc.). The PD output electrical signals undergo I/V conversion, are acquired by the ADC, and transmitted to the control board demodulation system to resolve the center wavelength of the sensor' s reflected light. The data is then transmitted to the PC via the Ethernet module. The system's 0.954% error indicates that when demodulating fiber optic sensors, this demodulation system achieves better accuracy than devices using piezoelectric sensors.

The optical module determines the fundamental specifications of the entire demodulation system. The ASE source used in this paper has a maximum output power of 50 mW and a stable output band of 1528-1563 nm (C-band). The tunable optical filter has a free spectral range of 1510-1590 nm and a 3 dB bandwidth of 0.46 nm. The etalon operates in the wavelength range of 1525-1565 nm with a wavelength spacing of 0.8 nm.

3. Experimental Verification

To verify the accuracy of the demodulation system, comparative tests were first conducted using an equal-strength cantilever beam and a strain gauge sensor system. Furthermore, to validate the high-speed measurement capability of the demodulation system, a dynamic performance test apparatus was constructed and high-speed sampling verification experiments at 100 Hz were carried out.

3.1 Static Performance Testing A large-strain equal-strength cantilever beam test bench with 3000 microstrain was used to evaluate the demodulator' s performance. FBG sensors were attached to the equal-strength beam, and five weights of 5 N each were sequentially loaded and unloaded to induce varying degrees of strain in the cantilever beam, causing the attached FBG sensors to experience the same strain. The wavelength shift of the sensor' s reflected light resolved by the demodulation system was recorded, and the results from three experimental runs were analyzed. Simultaneously, the proposed demodulation system was compared with a piezoelectric sensor-based system.

[Figure 10: see original paper] Static Performance Test Experimental Setup

The weights were sequentially loaded and unloaded three times, and the average wavelength values for loading and unloading were calculated. The total travel wavelength average was then determined, and a fitting curve was obtained using the least squares method. The test results for this system and the comparison system are shown in Figure 11 [Figure 11: see original paper].

[Figure 11: see original paper] Static Performance Test Results

By fitting the strain measured by the piezoelectric sensor with the wavelength change of the fiber grating sensor and scaling the fitting errors to the same scale for comparison, the results show that the proposed demodulation system has smaller fitting errors compared to the piezoelectric sensor. The calculated linearity is 0.85%, which is superior to the 0.954% of the comparison demodulation system, indicating that the proposed system demonstrates better accuracy when demodulating fiber optic sensors than devices using piezoelectric sensors.

3.2 Dynamic Performance Testing of the Sensing Demodulation System The dynamic performance test apparatus for the demodulation system proposed in this paper is shown in Figure 12 [Figure 12: see original paper]. Fiber sensors were attached to a flexible plate, which was fixed at one end and connected to a motor via a linkage at the other end. The motor' s rotation caused the flexible plate to undergo periodic bending.

[Figure 12: see original paper] Dynamic Performance Test Experimental Setup

Due to the motor' s rotational motion, the strain curve detected by the sensor attached to the flexible plate can be approximated as a sinusoidal curve, making the stress wavelength collected by the sensor approximately a sinusoidal signal. As shown in Figure 13 Figure 13: see original paper, the data collected by the FBG sensor was scaled to match the range of data collected by the piezoelectric sensor. The results show that when the motor rotation frequency is 1 Hz, sinusoidal fitting of the wavelength data output by the demodulation system yields a coefficient of determination (R^2) of 0.9657, which is better than the 0.9635 of the comparison demodulation system. Additionally, Fourier curve fitting produced an R^2 of 0.9861, also superior to the comparison system' s 0.9847. When the motor rotation frequency was increased to 5 Hz, as shown in Figure 13(b), sinusoidal fitting of the demodulated wavelength data yielded an R^2 of 0.9435, better than the comparison scheme' s 0.9342. Fourier curve fitting produced an R^2 of 0.972, again superior to the comparison scheme' s 0.9663. These results demonstrate that the proposed scheme exhibits better dynamic detection capability than F-P filter-based demodulation schemes across different frequencies.

[Figure 13: see original paper] Dynamic Performance Test Results

4. Conclusion

This paper proposes a tunable filter-based demodulation system that employs a MEMS scanning mirror instead of an F-P filter to address the slow wavelength

scanning frequency of F-P filters. Simultaneously, a fiber optic etalon is used to solve the problem of low demodulation accuracy caused by the nonlinear relationship between the scanning mirror’ s driving voltage and output wavelength. With the demodulation system operating at 100 Hz, static and dynamic performance tests demonstrate that the proposed system achieves fast demodulation speed while maintaining demodulation accuracy, showing practical significance for detecting wind turbine blade vibrations.

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Note: Figure translations are in progress. See original paper for figures.