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Abstract

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Improving the Measurement Accuracy of FBG Sensor Using Adaptive filters

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Abstract —**Adaptive filters are presented for improving the wavelength detection accuracy of FBG sensors within a sensing system which use tunable laser source. Simulation results demonstrated that by using this technique the Bragg wavelengths of the FBG sensors can be accurately detected. In addition, the filter with NMLS-OCF adaptive algorithm performs faster convergence than the other algorithms.**

I. INTRODUCTION

Fiber Bragg grating (FBG) has been considered as an excellent sensor element, which are currently receiving more and more research interest [1]. In order to measure strain/temperature variations with high accuracy, the ability to detect small shifts in Bragg wavelengths becomes an essential requirement for a FBG sensing system. However, in practical applications, various types of noise will occur that significantly limit the precision of wavelength detection [1]. For the FBG sensing system using broadband sources, the power of reflected signal is always low. This phenomena result in low signal to noise ratio (SNR), especially for the sensing system which using time division multiplexing (TDM) technique. Recently, tunable narrow band laser source have been introduced as the light sources for interrogating Bragg wavelength. The advantage of using the tunable laser source is that it can achieve relatively high signal power. At the same time, interferometric noise will be introduced to this kind of system [2]. In order to solve this problem, digital low-pass filters have been applied to improve the measurement accuracy of FBG sensors [3]. However, the improvement is limited because the noise components within the pass band remain after filtering and affect the measurement accuracy.

In this paper, we report the results of using adaptive digital filters to improve the measurement accuracy of FBG sensor within a sensing system which use tunable laser source. The system model of FBG sensing system using tunable laser source is introduced in Section 2. The implementation of adaptive filters for improving the measurement accuracy is presented in Section 3. The simulation result is shown in Section 4 and the conclusion is given in Section 5.

II. SYSTEM MODEL

A typical FBG sensing system based on tunable laser source is shown in Fig.1.

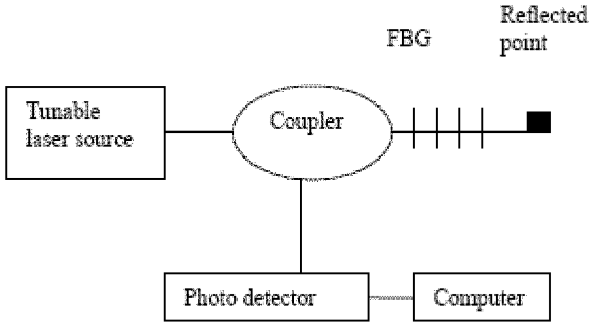

Fig.1.System diagram

The narrowband laser light is transmitted to the sensor FBGs via a directional coupler. A FBG sensor reflects the light to the coupler along the transmission optical fiber and reaches the photo detector. The tunable laser source is driven by a laser PZT actuator to scan over the spectral range which includes the spectrum of FBG sensor. During an individual scanning process, the central wavelength of the laser light varies with time, it can be expressed as:

$$\lambda(t) = \lambda_0 + Kt \qquad (1)$$

where λ_0 is the initial wavelength of the laser light, K is a proportional constant. Because the linewidth of tunable laser source is much narrower than that of FBG. The spectrum of the laser light during the scanning process can be regarded as an impulse sequence $I_0\delta(\lambda - \lambda(t))$.

As the tunable laser source scans across the spectrum of FBG, the light intensity at the photo detector can be expressed as:

$$\begin{aligned} I_{FBG}(\lambda(t)) &= \frac{1}{4}\int_{-\infty}^{+\infty} I_0\delta(\lambda - \lambda(t))R_{FBG}(\lambda, \lambda_B)d\lambda \\ &= \frac{1}{4} I_0 R_{FBG}(\lambda(t), \lambda_B) \end{aligned} \qquad (2)$$

where I_0 is the intensity of the light source, 1/4 is the coupler coefficient, $R_{FBG}(\lambda, \lambda_B)$ is the reflective

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spectrum of FBG. Therefore, $I_{FBG}(\lambda\ (t))$ has a waveform that is the same as the shape of $R_{FBG}(\lambda, \lambda_B)$. Furthermore, by recording the central wavelength of laser light when a peak in the reflected intensity is detected, we have:

$$\lambda_B = \lambda\ (t_p) \tag{3}$$

where $I_{FBG}(\lambda\ (t))_{t=t_p} = Max\,(I_{FBG}(\lambda(t)))$. Using this method, Bragg wavelength can be detected.

However, unwanted interferometric noise will occur in this system. This kind of noise is caused by the interference between the FBG signal (reflected from the FBG) and the residual reflected signal (reflected from fiber connectors, i.e. the "reflection point" as shown in Fig.1. The interferometric signal can be expressed as [2]:

$$I_{noise}(\lambda(t)) = \frac{I_0}{2}\sqrt{R_{FBG}(\lambda(t), \lambda_B)\beta^2}(1 - R_{FBG}(\lambda(t), \lambda_B)) \cdot \cos(\frac{2\pi}{\lambda} n\Delta L) \tag{4}$$

where β^2 is the intensity reflectivity of reflection point, and $n\Delta L$ is the optical path difference between the FBG and the reflection point. If there are multiple reflection points in the system, multiple interferometric noises will also appear. The total contribution of these interferometric signals can be regarded as the sum of them. As the interferometric signal appears in the system, the detector will detect a combined signal $I_{noise}(\lambda(t)) + I_{FBG}(\lambda(t))$ and wavelength detection accuracy will be affected. Digital low pass filters are efficient to eliminate the noise signal if Bragg signal and noise signal have independent frequency spectrum. However, the performance is limited if the noise components overlap with the Bragg signal in the frequency domain and the measurement error will up to 16 pm [3]. In order to solve this problem, in the following section, we use adaptive filter to improve the measurement precision of Bragg wavelength.

III. Applying Adaptive Filters on Tunable Laser Source Based FBG Sensing System

An adaptive filter is defined as a self-designing system that has the ability to design itself using a recursive algorithm [4]. With such a device we can process signals whose complete statistical information is unknown. The most widely used adaptive filtering algorithm is the least mean squares (LMS) algorithm. The advantage of this algorithm is that it is computationally simple, but it has the drawback of slow convergence. Advanced algorithms such as the normalized least mean square (NLMS) algorithm, affine projection algorithm (APA), NLMS with orthogonal correction factors (NLMS-OCF) and normalized data-reusing LMS (NDR-LMS) algorithm have been developed to solve this problem [5]-[7]. In this paper, these algorithms are used to eliminate the unwanted interferometric noise in the FBG sensing system.

In order to apply adaptive filtering algorithm to the combined signal $I_{noise}(\lambda(t)) + I_{FBG}(\lambda(t))$, we sample $I_{FBG}(\lambda(t))$ and $I_{noise}(\lambda(t))$ in time domain, then we obtained two discrete sequences:

$$I_{FBG}(n) = \frac{I_0}{4} R_{FBG}(\lambda(n\Delta t), \lambda_B) \tag{5}$$

and

$$I_{noise}(n) = \frac{I_0}{2}\sqrt{R_{FBG}(\lambda(n\Delta t)\ , \lambda_B)\beta^2}(1 - R_{FBG}(\lambda(n\Delta t), \lambda_B)) \cdot \cos(\frac{2\pi}{\lambda(n\Delta t)} n\Delta L) \tag{6}$$

where Δt is sample interval. Based on these two discrete sequences, adaptive filters can be used to improve the measurement precision of Bragg wavelength.

The operation mode of adaptive filtering is shown in Fig.2. Combined signal $I_{noise}(n) + I_{FBG}(n)$ is regarded as the input signal $x(n)$. A Bragg signal $I'_{FBG}(n)$ with a different Bragg wavelength compared with $I_{FBG}(n)$ is regarded as the desired signal $d(n)$. $y(n)$ is the output signal, $e(n)$ is the estimated error. The input signal is filtered by the adaptive filter operating on a recursive algorithm. After the weight value converged, the expected output signal is obtained.

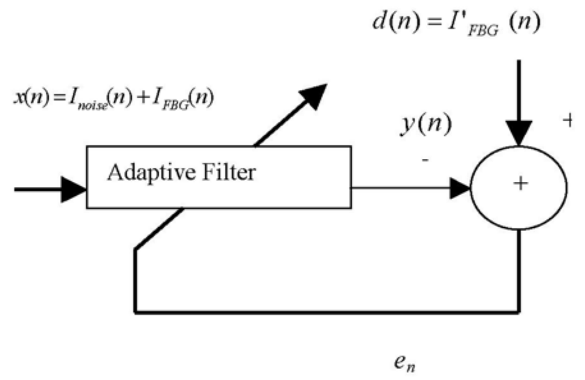

Fig.2 Block diagram of adaptive filter

We can describe the relationship of the input signal and output signal as:

$$y(n) = \sum_{k=1}^{M} x(n-k+1)w_k(n) \tag{7}$$

and

$$e(n) = d(n) - y(n) \tag{8}$$

where M is the order of the filter, $w^T\ (n) = [w_1(n), w_2(n), ...w_M(n)]$ is the adjustable tap weight vector at nth instant. The adaptive algorithm is the mechanism for adjusting the tap weight vector along the time axis. The most widely used LMS algorithm adjusts the weight as follows:

$$w(n+1) = w(n) + 2\mu e(n)x(n) \quad (9)$$

where $x^T(n) = [x(n), x(n-1)...x(n-M+1)]$, $\mu > 0$ is a constant called step size.

LMS algorithm is simple, but it has the drawback of converging slowly with the average mean square error (MSE), because its convergence depends on the input signal and the order of filter. The advanced adaptive algorithms, such as NLMS, APA, NLMS-OCF and NDR-LMS, have faster rates of convergence than LMS. Their weight adaptation algorithms are expressed as follows:

NLMS:

$$w(n+1) = w(n) + 2\frac{\mu}{\|x(n)\|^2} e(n)x(n) \quad (10)$$

APA:

$$D_n = [d(n), d(n-1), ..., d(n-M+1)] \quad (11)$$

$$X_n = [x(n), x(n-1), ..., x(n-M+1)]$$

$$x^T(n) = [x(n), x(n-1)...x(n-M+1)])$$

$$E_n = D_n - w_n^H X_n$$

$$w(n+1) = w(n) + \mu X_n [X_n^T X_n]^{-1} E_n$$

where ^{T} and ^{H} denote the transposition and complex conjugate transposition.

NLMS-OCF:

$$w(n+1) = w(n) + \mu_0 x_n + \mu_1 x_n^1 + ... + \mu_M x_n^M \quad (12)$$

where x_n is the input vector at the nth instant, x_n^k (k=1,2…M) is the component of x_{n-kD} that is orthogonal to $x_n, x_{n-D}, x_{n-2D}, .. x_{n-(k-1)D}$.

$$e_n = d_n - w_n^H x_n \quad (13)$$

$$e_n^k = d_{n-kD} - w_n^{kH} x_{n-kd}, \qquad (k = 1,2.....M)$$

$$w_n^k = w_n + \mu_0 x_n + \mu_1 x_n^1 + ... + \mu_{k-1} x_n^{k-1}$$

$$\mu_k = \begin{cases} \dfrac{\mu e_k^*}{x_n^H x_n} \; for & k = 0, if \; \|x_n^k\| \neq 0 \\ \dfrac{\mu e_n^{k*}}{x_n^{hH} x_n^k} \; for & k = 1,2,..., M, \\ & if \; \|x_n^k\| \neq 0 \\ 0 \quad Otherwise & \end{cases}$$

where * denotes the complex conjugate.

NDR-LMS:

$$k_0 = w_n \quad (14)$$

For i=0,1,…,R-1

$$k_{i+1} = k_i + \mu_{0,i} x_n + \mu_{1,i} x_{n-1} + ... + \mu_{M,i} x_{n-M}$$

$$w_{n+1} = k_R$$

where $\mu_{j,i} = \dfrac{(d_{n-j} - k_i^T x_{n-j})}{\|x_{n-j}\|^2}$,

$$x_n^T = [x(n), x(n-1)...x(n-M+1)]$$

IV. Simulations

Computer simulation was carried out to demonstrate the effectiveness of adaptive filter techniques. The reflection spectrum of the FBG can be expressed by Gaussian distributions as:

$$R_{FBG}(\lambda, \lambda_B) = R_0 \exp(-4\ln 2(\frac{(\lambda - \lambda_B)^2}{\alpha^2}) \quad (15)$$

where α is the spectral full width at half-maximum (FWHM) of FBG. Therefore, (5) can be expressed as:

$$I_{FBG}(n) = \frac{I_0 R_0}{4} \exp(-4\ln 2(\frac{(\lambda(n\Delta t) - \lambda_B)^2}{a^2}) \quad (16)$$

In simulation, the coefficients of the input signal were assumed as: I_0 =5 *mw*, R_0 =0.8, λ_B =1550 *nm*, α =0.1 *nm*, $n\Delta L$ = 5 *cm* and β^2 =0.01, in which case the frequency spectrum of $I_{noise}(n)$ is overlapped with that of $I_{FBG}(n)$. A Bragg signal $I'_{FBG}(n)$ with a Bragg wavelength of 1530 *nm* is regarded as the desired signal. The input signal and desired signal were sampled into 500 samples in 0.5 *nm* spectral range as shown in Fig. 3.

We firstly establish an adaptive filter using LMS algorithms. To begin with, we need to select the proper step size and order of the filter, which determines the speed of convergence and the stability of the algorithm. Large step size and low filter order imply fast convergence speed but large misadjustment in steady-state. In contrast, a small step size and high filter order lead to little misadustment in steady-state but a slow convergence speed. After using different coefficients to test the convergence speed and misadjustment in steady-state, we selected the coefficients of filter as: μ =0.006, M=12. The input signal is then applied to the LMS adaptive filter. After the MSE is converged to a constant, the filter stops working and the output signal is shown in Fig.4. The measurement error of the Bragg wavelength is 4 *pm*. Then, ten $I_{FBG}(n)$ with different Bragg wavelengths are added to the different $I_{noise}(n)$ (using $n\Delta L$ from 5*cm* to 10 *cm* with an interval of 0.5*cm*) and applied to the filter. As a result, the average measurement error is 3.7 *pm* (RMS value), which is much lower than that of the classical digital filter (16*pm*) under the condition where the frequency spectrum of the noise overlaps that of the FBG signal.

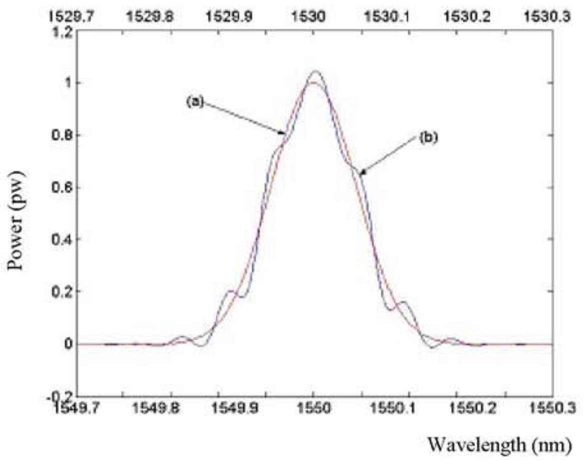

Fig.3 Input signal (a) and desire signal (b) for adaptive filtering

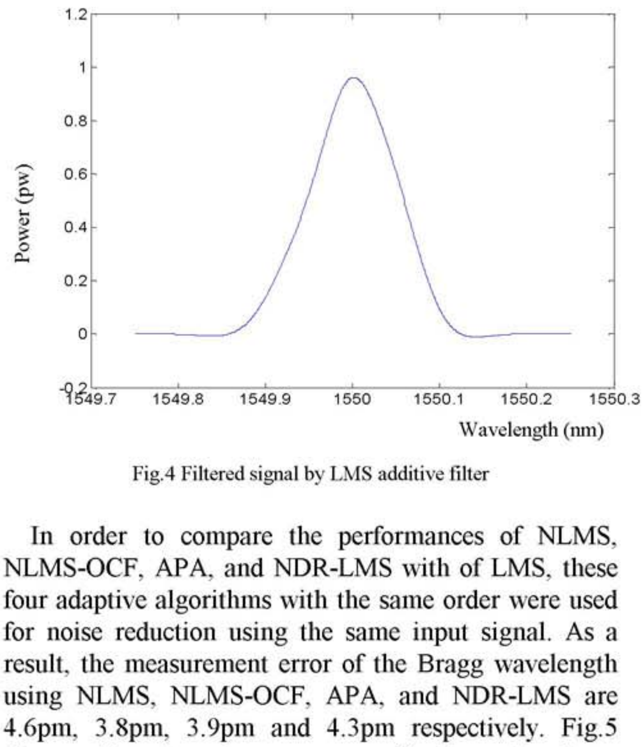

Fig.4 Filtered signal by LMS additive filter

In order to compare the performances of NLMS, NLMS-OCF, APA, and NDR-LMS with of LMS, these four adaptive algorithms with the same order were used for noise reduction using the same input signal. As a result, the measurement error of the Bragg wavelength using NLMS, NLMS-OCF, APA, and NDR-LMS are 4.6pm, 3.8pm, 3.9pm and 4.3pm respectively. Fig.5 shows the learning curves of the algorithms corresponding to the given system. It is evident that NLMS-OCF has the fastest convergence and that LMS has the slowest convergence among the algorithms being compared.

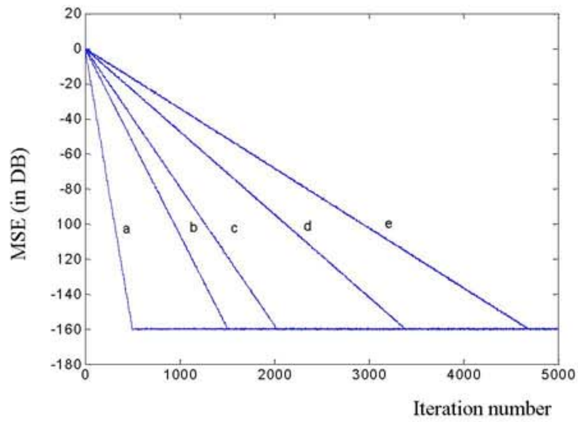

Fig.5 Learning Curves for five algorithms: (a) NLMS-OCF, (b) APA, (c) NDR-LMS, (d) NLMS and (e) LMS

V. Conclusion

Adaptive filters have been used to improve the measurement precision of the FBG sensors. The simulation results indicate that by using adaptive filters we can accurately detect Bragg wavelengths even when the noise components overlap with the Bragg signal in the frequency domain. In addition, the filter with NMLS-OCF adaptive algorithm performs faster convergence than the other algorithms.

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