A sensing signal time-division multiplexing interrogation method of fiber Bragg grating sensor arrays

Shengchun Liu, Youlong Yu, Jintao Zhang

Abstract—A sensing signal interrogation method of time-division multiplexing system for high-resolution fiber Bragg grating sensors array is developed. Electric switch controlled by the CPLD is used in this scheme to interrogate simultaneously each sensing signal of the FGB sensors array based on different transmission times of each sensing signal from the modulator to the match switch. More than ten FBG sensors are real-time interrogated and demodulated with a sensing resolution of the 6 nε by the unbalanced Michelson interferometer. The sensing sensitivity of this system is 1.658 Deg/με, experimentally. The interrogation frequency of the system could reach 1 KHz.

Index Terms—fiber sensor, fiber Bragg grating, time-division multiplexing, signal interrogation.

I. INTRODUCTION

In-fiber Bragg sensors have more advantages than conventional sensors[1], especially in net-sensing[2]. Coded with wavelength, sensing information is immunity to interference of the electromagnetic and the harsh environments, and independent of source power swing. The wavelength-coded cascaded FBGs makes the sensor array with highly attractive for surface attachment or embedding into materials for structural health-monitoring, and the superiority of a FBG sensors array for many point sensing information is with minimize the number of entrance and exit point into smart structure.

Many multiplexing interrogation methods of the FBG sensors array have been proposed[3-7], two mostly methods of them are wavelength-division multiplexing (WDM) and time-division multiplexing (TDM). Nevertheless, the number of sensors applying to the WDM system is often limited by bandwidth of broad band source (BBS) and the wavelength shift range of every FBG sensor that determine the range of dynamic sensor. In a TDM system, the sensing information of each sensor is explored by the detector according to the time of the sensing pulse to be reflected from FBG sensor element in the sensors array. So the TDM system has not strict bandwidth demand to the source and permits FBG sensors with nominally same central wavelength serial writing in a fiber. Recently years, many TDM signal interrogation frames and techniques have been reported[8-11]. However, most of these methods are far from convincing for practical application, due to over-complex signal interrogation requirements. The shortcoming of the TDM system limits application of the system. For instance, it is too expensive to application, and all of TDM system read out only the selected sensor at peculiar time slot and cannot monitor the strain change of every sensor signal simultaneously.

In this paper, a new method of time-division multiplexing signal interrogation is introduced. The light of the BBS is modulated into pulse light by a modulator, which is controlled by a complex programmable logic device (CPLD). The pulsed light is injected into the sensor array. The interrogation of the sensing signal from FBG sensors element can be realized by using a Single-Pole Double-Throw (SPDT) switch array that controlled by the same CPLD. The CPLD generate the electrical pulsed signals, which is used to control the modulator and the switches array, simultaneously. Using an all-fiber unbalanced Michelson interferometer (UMI), the wavelength shift of the sensor G, will demodulate into the phase change of the output signal. The proposed system has a high capability/price ratio.

II. THEORY

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different wavelength-codes. The reflection sensing signals are launched into an UMI. Acting as a demodulator, the wavelength shift of the sensor \( G_i \) will demodulator into the phase change of the sensor \( G_i \), the interferometer is with an arm-length difference of \( L \). Its output intensity is

\[
I = \sum_{i=1}^{m} I_{np}(1 + k_i \cos(\phi_i - \frac{4\pi n L}{\lambda_i} (1 - p_i) \varepsilon_i))
\]

(1)

Where, \( I_{np} \), \( i=1,2,\ldots,m \) is the light signal intensity of the sensor \( G_i \) with the center wavelength \( \lambda_i \), \( k_i \) is the interference fringe visibility at \( \lambda_i \), \( \phi_i \) is the static phase difference of the UMI, \( \varepsilon_i \) is the axial strain of \( G_i \) and \( P_e \) is the effective elasto-optic coefficient. The light signals of the sensors, which received by the detector, transduce the electrical signals with \( A \) times gain.

The electrical sensing signals can pass directly through the output-channel of the SPDT switches array that is controlled by delay pulse of CPLD. The observed signal \( I \), will pass through the switch channel \( S_i \) with little loss and arrive to the phase-meter. The channel \( S_i \) refuses the other signals at \( ti - ti + \Delta t \) time slot. The output signal contains the high frequency signals of the modulation pulse as injected light pulse and sensing signal. The band-pass filter (BPF) will eliminate high frequency part of the signal. Therefore, the output signal of the channel \( S_i \) is

\[
I_i = A \varepsilon_i (1 + k_i \cos(\phi_i - \frac{4\pi n L}{\lambda_i} (1 - p_i) \varepsilon_i))
\]

(2)

Where, \( A \) is the gain times of the detector. The sensor signal of Eq.(2) received by a phase-meter. After wiping the direct current component off, the shift of the phase in Eq.(2) will be displayed. It depends on the measured strain \( \varepsilon_i \), that applied on the \( G_i \) axially. The strain can given

\[
\Delta \phi = -\frac{4\pi n L}{\lambda_i} (1 - p_i) \varepsilon_i
\]

(3)

The unbalanced Michelson interferometer is suitable for measuring the dynamic phase change. To generate the dynamic reference phase, A PZT driven by with a toothed-wave signal is stick on the short arm. Thus, a sinusoid dither is mix into the observed sensing signal. The reference signal of the phase meter is the saw-toothed wave, which is with the same frequency as the sinusoid dither, thus the sinusoid dither can eliminate by the phase meter. From Eq.(4), obviously, the measured strain can be achieved base on the phase-shift of the phase meter.

III. TIME-DIVISION MULTIPLEXED SCHEME

To ensure the reflection-sensing signal of the \( G_i \) pass through the output-channel \( N_i \) of the SPDT switch, the delay time of sensing signal of the \( G_i \) form modulator to the switch channel \( S_i \) should be measured in advance. The switch is analog, so the sensing signals pass through the switch with attenuation only and without distortion, and the phase shift of output signal of the output-channel \( N_i \) is corresponding to the axial stress acted on the \( G_i \). The on/off state of the output-channel \( N_i \) of the switch was controlled by the delay time control signals of the switch array (DP). The MP and DP signals are generated by the Boolean algebra operation of the internal octal counter of the CPLD. An example of ispMACH4064 is shown as the Fig. 2, which is the principle scheme of the generation of the MP. The clock of ispMACH4064 input from the SCLK pin is used to the system clock. The output of eight AND gate is high level when the time slot match with the setting of the ispMACH4064, contrarily the output of eight AND gate is low level. Fig.2 (b) is the principle of generating the signal period of MP and DP, the modulation signal with the certain period and duty factor can be produced by MP, as Fig.2(a) shown, the same ten modulation signal channel is used to enhance drive power of the modulator.
Experimental setup is shown in Fig.1, the optic-spectrum of BBS is flatten using the gain flatting filter and spectral power density has drop to less than 1dB ripple at range 1530-1565nm. The isolator prevents the reflected light of the FBG return the BBS, the isolation degree is 42dB. The interval of the ten gratings series in a fiber is 10m, whose center wavelength of FBGs are 1537.125 nm, 1539.475 nm, 1543.456 nm, 1545.336 nm, 1547.153 nm, 1549.171 nm, 1551.455 nm, 1553.107 nm, 1555.393 nm, 1557.740 nm, respectively. The length of FBG is 1 cm; the reflectance and the bandwidth of FBGs are all 90% and 0.15 nm, approximately. The reflectance of the end mirrors, the average arm length, the arm length difference and the interference fringe visibility of the UMI are near to 85%, 111 cm, 3.19 mm and 0.3, respectively. The signal frequency of the PZT-actuator is 1 kHz, the peak-peak value is 9.2V and the D.C. is 10V. The resolution of the phase meter is 0.01 Deg. the optimal response band of the detector is 1200-1650 nm, and gain is 24 V/mw. The bandwidth of the band-pass filter is set to 950-1050 Hz. The extinction ratio of the modulator is 37.5 dB and its insertion loss is 3.6 dB.

In this experiment, the frequency, the duty factor, the peak-peak volts and the volts of D.C. of the modulation signal, which is generated by the ispMACH4064, are 500 KHZ, 2%, 3.6V and 0V, respectively. The channel S_i of the switches may be on-state or off-state when the delay time control signal is high level or low level, so the sensing signals I_9 can pass through the corresponding channels S_i on the arriving switch time sequence of the sensing signal of the FBG sensors. The delay time of the first FBG sensor form the modulator to the electric switch is 91.2ns and the interval time of every reflection signal is 96.7ns. The different signals of the system are shown in Fig.4.

Fig.4 the different signals for interrogation the sensing signal of the G_9
1. Modulation pulses of the modulator; 2. delay time control signal of the 9th channel; 3. Sensing signal of FBGs; 4. output signal of the 9th channel

To testify the system faculty of real-time interrogation and monitoring the strain change of the FBG sensors, one side of the G_9 fix on a motionless stage and another side fix on the ultra-precision linear motor stages whose minimum step is 0.1 μm. The experimental plot of ∆Φ_9 vs ε_9 is shown as Fig.5. The slope between ∆Φ_9 and ε_9 in Fig.5 is 1.659 Deg/με, it is closely matches the theoretical value of 1.669 Deg/με. The minor error of the system was mainly due to the fluctuation of the surrounding temperature.

![Fig.5 Experimental curve of ∆Φ_9 vs ε_9](image)

Fig.5 Experimental curve of ∆Φ_9 vs ε_9

V. Conclusions

An interrogation method for the sensing signals of the fiber Bragg grating array is successfully designed, it make the signals pass through the corresponding channels using the parallel analog switch array, which controlled by CPLD. The stress changes of the FBG sensors array demodulated by the UMI. The system successfully interrogates and monitors the multi-sensors simultaneity. The sensing sensitivity of this system is 1.659 Deg/με, the metrical range of the stress is due to the stress endurant capacity of FBG in fiber, and the experiment result proved that the range is [-4000, 4000] με. This system has the resolution power of 6nε, theoretically.

The DP and the MP can be generated the same CPLD and be managed the same clock. So this method avoids effectively chaos of time sequence. The CPLD have advantage of programmable online, therefore the delay time control signals of the switch array can be modified online base on the transmitting time practically, and this time is the time of the sensing signal from the modulator to the certain switch. It extends greatly applying flexibility of system. The intervals of the between FBG sensors can be very short and be distributed with different optic path spacing. It is easy to interrogate over ten FBG sensors in practice; more important, this system has the capability of monitor the sensing elements in real-time, which is unprovided in the most of other FBGs net-sensing technique. This technology will deduce the cost remarkably and also make the TDM sensing system become more practical.

References