Fiber optic strain twin-sensor-array for smart structural health monitoring

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Abstract : A multiplexed white light interferometric fiber optic twin-sensor-array was designed to monitor the structural health of large buildings. In this sensing system , based on a Michelson interferometer , an optical path matching technique is used to demodulate each twin-sensor. Each twin-sensor-array consists of a 2 × N sensing element linked by a 3 dB coupler. When one of the twin-sensor is used to measure strain , variations caused by temperature can be compensated for by referencing the other twin-sensor. The multiplexing capacity of the sensing scheme has been analyzed and experimental results with a 2 ×3 twin-sensor-array are given.

Keywords : fiber optic sensor ; white light interferometer ; multiplexing technique ; twin-sensor-array ; temperature compensation ; Michelson interferometer
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There has been considerable interest recently in the development of fiber optic sensors based on white light interferometry[1-2]. The use of such a technique for distributed strain or temperature sensing in advanced composite or other structural materials has been discussed in several recent articles[3-5]. Fiber optic Michelson sensor arrays are of particular interest for such applications because a number of reflective-type sensors networked either in a serial or a parallel topology may be interrogated by use of a common path-length variable reference , thus keeping the system cost down. Several schemes have been reported for multiplexing this type of sensors. These include coherence turning[6] , time-division[7] , spatial division[8] , duplicate fiber optic switch[3] and 1 × N star coupler[4] multiplexing technique.

In this paper , we propose and demonstrate a white light twin-sensor-array scheme that measures the absolute optical path lengths of each fiber segment end reflective surfaces.

1　Michelson based fiber optic interferometric twin-sensor-array

The sensing principle is shown in Fig. 1. The broadband LED source is directly coupled into the fiber optic Michelson interferometer by passing thorough a 3 dB coupler and lunched into the twin-sensor-array. The twin-sensor-array consists of 2 × N fiber segments (N twin-sensors) connected in series with partial reflectors in-between the adjacent fiber segments , configuring a Michelson interferometer based multiplexed fiber optic sensor array. The reflected signals of each sensor pair retune and travel in the same path towards the PIN detector end. One arm of the fiber optic Michelson interferometer as optical path adjusting part has been used to demodulate the twin-sensor-arrays. So that each individual sensor pair is corresponding to a unique interference peak because the optical path length is different from each other. For a sen-

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sor pair, if one of the twin sensors is used as a strain sensor, the other sensor can be used as a temperature compensated sensor.

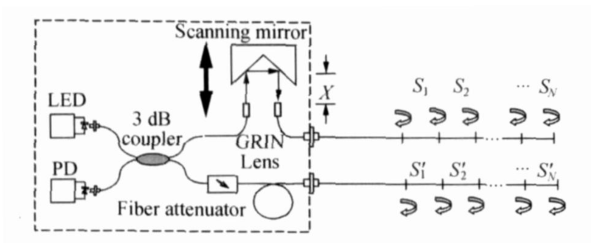

Fig. 1 Working principle of the twin-array Michelson fiber optic interferometric strain sensing system

Therefore, the proposed sensing scheme will be useful for temperature compensation of distributed strain measurement. An important application of the sensing system could be deformation sensing in smart structures.

2 Sensing principle

Fig. 2 shows a twin-sensor-arrays embedded in a concrete structure. A number of fiber segments pairs l_i and l_i' are connected in serial to form the twin-sensor-arrays, which is further connected to a lead in/out fiber of length L_0 and L_0'. In the sensing system, the length of the two lead in/out fiber cables has been chosen as nearly equal, and the same as each fiber segment pairs, i.e.:

$$\begin{cases} L_0 \approx L_0', \\ l_i \cong l_i', \\ l_i \neq l_j, \\ l_i' \neq l_j'. \end{cases} \quad (i, j = 1, 2, \cdots, N). \tag{1}$$

The optical path length of the reference arm L_0' can be varied through the use of a moving graded index (GRIN) lens or a scanning right angle mirror. One adjusts the optical path of the reference arm to match and trace the change of the twin-fiber-sensor gauge length in each sensing pairs. When the optical-path difference (OPD) between the sensing branch and the reference branch falls within the coherence length of the light source, a white light fringe pattern is produced. The central fringe, which is located in the center of the fringe pattern and has the highest amplitude, corresponds to the exact path match of the two optical paths. Thus, we have

$$nL_0 + \sum_{i=1}^{k} nl_i = nL_0' + \sum_{i=1}^{k} nl_i' + X_k. \tag{2}$$

The shift of the white light interference peak ΔX_k corresponds to the variation of the k-th twin-sensor, i.e.:

$$\Delta X_k = \sum_{i=1}^{k} [\Delta(nl_i) - \Delta(nl_i')]. \tag{3}$$

For the case shown in Fig. 2, the sensor array was embedded in the structure. The corresponding twin-sensor array was put in a pipe near the sensing fiber sensors in order to compensate the variation of the refractive index of the fiber induced by temperature changes and the elongation of the fiber caused by thermal expansion. The ambient temperature could be considered the same because the twin sensor array has been arranged very close.

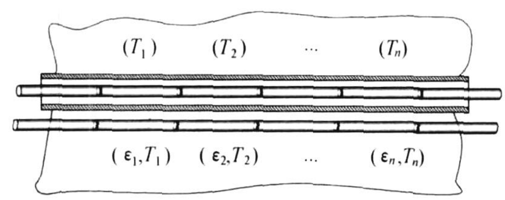

Fig. 2 For the case of the twin sensor array arrangement in the structure

In the Fig. 2, the sensor array has been embedded in the concrete material, while the reference array has been put on the pipe in free state nearby the sensor array.

When the strain and its environmental temperature change, the length of the sensing fiber gauge will increase (or decrease) as a result of both strain and elevated temperature. The optical path elongation can be expressed as

$$\Delta(nl_i) = [n\Delta l_i(\varepsilon) + \Delta n(\varepsilon) l_i] + (n\Delta l_i(T) + \Delta n(T) l_i]. \tag{4}$$

The compensation sensor array will surely increase as a result of elevated temperature

$$\Delta(nl_i') = [n\Delta l_i'(T) + \Delta n(T) l_i']. \tag{5}$$

Substitute equation (4) and (5) into equation (3) and note the condition given in equation (1) $l_i = l_i'$, we get

$$\Delta X_k = \sum_{i=1}^{k} [n\Delta l_i(\varepsilon) + \Delta n(\varepsilon) l_i] = \sum_{i=1}^{k} n_{\text{equivalent}} l_i \varepsilon_i, \tag{6}$$

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where

$$n_{equivalent} = \left\{ n - \frac{1}{2} n^3 [(1-\mu) p_{12} - \mu p_{11}] \right\} \quad (7)$$

represents the equivalent refractive index of the fiber core. For silica materials at wavelength λ = 1 550 nm, the parameters are $n = 1.46$, $\mu = 0.25$, $p_{11} \approx 0.12$, $p_{12} \approx 0.27$ [10], and the equivalent refractive index can be calculated as $n_{equivalent} \approx 1.19$.

This means that the peak shift ΔX_k only depends on the changes of the fiber optic sensing gauge length l_i and the refractive index due to coaxial strain, and it is independent of the optical path variations caused by the elevated temperature. Therefore, the changes due to the environmental temperature fluctuation of the fiber path can automatically be compensated.

Thus, the distributed strain can be measured by

$$\varepsilon_i = \frac{\Delta X_i - \Delta X_{i-1}}{n_{equivalent}\, l_i}. \quad (8)$$

3 Analysis of signals intensity

The signals intensity is different for the schemes shown in Fig. 1. The signal intensity from sensor pair j that is due to the coherent mixing between the reflected signals from the two partial reflectors that define the sensor may be expressed as

$$P_{D1}(j) = \frac{1}{8} P_0 \eta(X_j) \left[R_{j+1} \prod_{i=1}^{j} (T_i \beta_i) \right]^2, \quad (9)$$

where the 2 × 2 coupler is assumed to be 3 dB coupler and the insertion losses are neglected. β_j represents the excess loss associated with sensor j because connection loss between the sensing segments. T_j and R_j are respectively the transmission and reflection coefficient of the j-th partial reflector. T_j is in general smaller than $1 - R_j$ because of the loss factor β_j. $\eta(X_j)$ is the loss associated with the moving GRIN lenses systems and is a function of X_j.

Theoretical simulations were conducted for typical parameters: $\beta_j = 0.9$ ($j = 1, 2, \cdots, N+1$), $R_j = 1\%$, $T_j = 0.89$. The average attenuation of the moving GRIN lens part is taken as 6 dB, i.e. $\eta(X_j) = 1/4$. The power coupled into the input fiber is P_0. The normalized signal intensity for each sensor in the 10 sensors array is shown in Fig. 3.

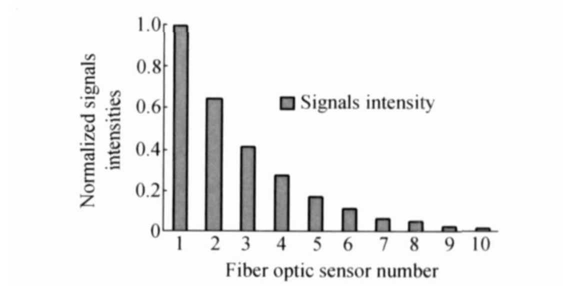

Fig. 3　Normalized signal intensity for i-th sensor in the twin-sensor-array.

4 Experimental results

A three twin-sensor-array was demonstrated in our experiments. In the sensing system, the LED light source power is 30 μW with drive current 50 mA, and the insertion losses of moving GRIN lens part is in the range of 4 dB to 8 dB as the gap distance from 3 mm to 70 mm (corresponding the optical path change within the range 6 mm to 140 mm). And each individual sensor's gauge length is about 1 000 mm (1 meter single mode optical fiber patchcord).

The PIN-detector output when the value of X is varied from 15 mm to 21.5 mm is shown in Fig. 4. The four major peaks correspond, respectively, to the sensor pair being matched of the three twin-sensor-array.

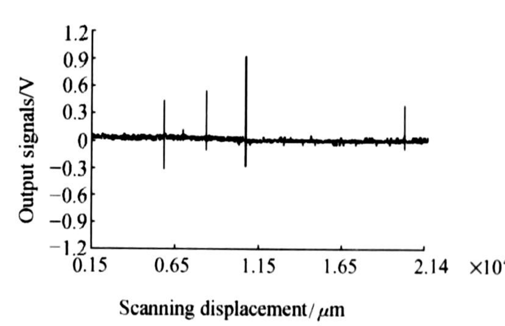

Fig. 4　Three twin-fiber-sensor array experimental scanning peak signals

In order to show the compensation efficiency of the sensor system, the experiments were performed under the two different circumstances of temperature conditions. The test coupon is depicted in Fig. 5. The load was supplied from a load cell to the test coupon and introduced a uniform stress field σ. Then the corresponding strain will

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be subjected from test coupon transfer to the optical fiber. As the strain increased, the resulting shift of the interference peaks from the fiber optic interferometer was measured. The testing result is given by Fig. 6, which corresponds to the distribution strain measured by each fiber sensor.

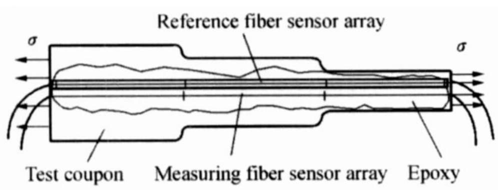

Fig. 5 Experimental setup for the twin-sensor-array test

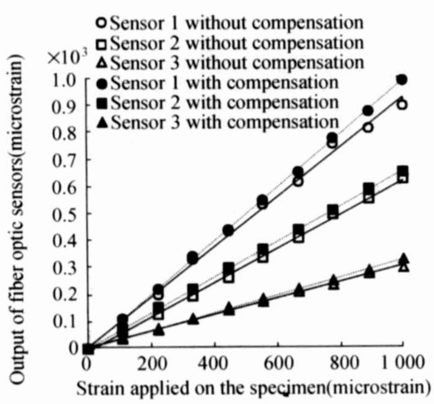

Fig. 6 The performance of the twin fiber optic strain sensors array in testing for both compensated and without compensated case with the ambient temperature of the test coupon changes from 15 ℃ to 35 ℃

5 Conclusions

Fiber optic white light interferometric twin sensor array multiplexing technique has been demonstrated, in which the matching multi-wave was demodulated by a moving GRIN lens or a right-angle mirror. The fiber optic sensors multiplexing capacity strongly depends on the light source power of the sensing system.

The proposed sensing scheme will be useful for the measurement of temperature or strain. An important application could be deformation sensing in smart structures. By incorporating fiber optic twin sensor array into structures such as large-scale buildings, bridges, dams, tunnels and highways, smart structures can be realized for situations where material strains must be monitored throughout the lifetime of the structure.

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