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MULTIPLEXED FIBER OPTIC OTDR SENSORS FOR MONITORING OF SOIL SLIDING

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Abstract: Fiber optic optical time domain reflectometry (OTDR) sensors are suitable to apply the distributed measurement by multiplexing configuration. OTDR sensor system with displacement sensors has been developed to monitor slope stability in soil layers. The displacement was determined from the difference between the reflected signal of the sensing optical connector and the signal of the reference optical connector. Laboratory tests indicate that displacements can be measured with the resolution of several mm and the maximum measurable displacement is about 10 cm, which is enough to apply for the monitoring of soil movements.

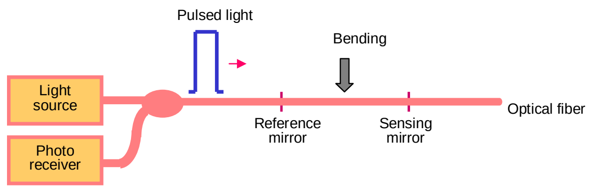
Keywords: OTDR sensor, displacement, multiplexing

1. INTRODUCTION

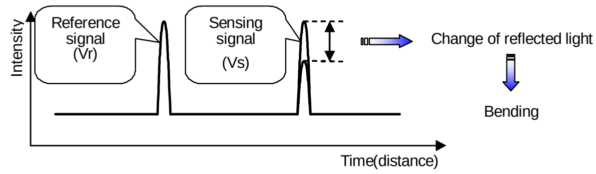
Fiber optic sensors have many advantages for structural health monitoring. One of these advantages is the electro-magnetic immunity because these sensors use light as a medium influenced by the external effects. Also, another advantage is that a fiber line can be used to measure physical quantities at various points[1]. In 1976, Barnoski and Jensen reported a method to measure the loss of light nondestructively by an analysis of Rayleigh back scattering in time domain [2]. This optical time domain reflectometry (OTDR) utilizing Rayleigh back scattering can detect the location information from the traveling time of the pulsed light. However, this sensor needed a high sensitive photo-receiver. So, the cost was very high. Yuan suggested a novel approach of quasi-distributed strain sensing with white light interferometry, which was constructed by one optical fiber having several low reflected mirrors[3]. This sensor shows the length change between mirrors. This sensor tracks all length changes between mirror pairs. Gauthier considered a single mode fiber optic bend-type sensor[4]. This sensor used the bend loss of an optical fiber, which is affected by the external effects. This bend-type sensor could not use various numbers of the sensor heads on one optical fiber. Therefore, in this study, we considered a multiplexed fiber optic bend-loss type sensor for measuring displacements. The sensor head of this sensor was constructed with two connectors and a bending mechanism, which was operated by the external displacement. Five sensor heads on an optical fiber were distinguished by the reflected signals with optical time domain reflectometry.

2. PREPARATION OF THE PAPER

Multiplexed optical loss based fiber optic sensor use pulsed lights like optical time domain reflectometry (OTDR) as shown in Fig. 1 (a). If the pulsed light meets the reference mirror and the sensing mirror, then some portion of the pulsed light shall be reflected at two mirrors. These reflected lights were shown in Fig. 1 (b) as a reference signal (Vr) and a sensing signal (Vs). If the external effects such as displacement induce the bending of the optical fiber between the reference mirror and the sensing mirror, then the bending makes some optical loss between two mirrors shown in Fig. 1 (b). This optical loss can be detected as the decrease of the sensing signal. Therefore, if the relation between the external effect and the change of the sensing signal can be found, then the displacement can be determined from this kind of fiber optic sensors.



(a) Schematics of optical loss based fiber optic sensor



(b) Reflected signals from reference mirror and sensing mirror

Fig. 1. Operation of multiplexed optical loss based fiber optic sensor

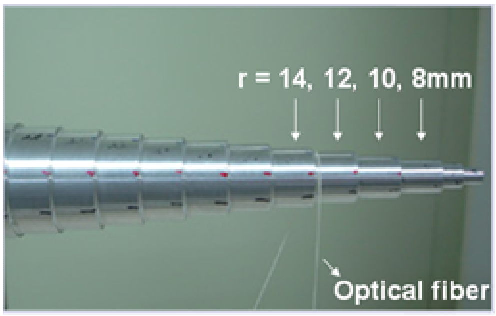
If many sensor heads are installed on one fiber line, then the reference signal is necessary to normalize the sensing signal, because the sensing signal can be changed by the bending losses of other sensor heads. The displacement can be easily calculated from this reference signal and sensing signal by using the following equation.

$$\delta = C\left\{\left(\frac{V_r - V_s}{V_r}\right)_i - \left(\frac{V_r - V_s}{V_r}\right)_0\right\} \qquad (1)$$

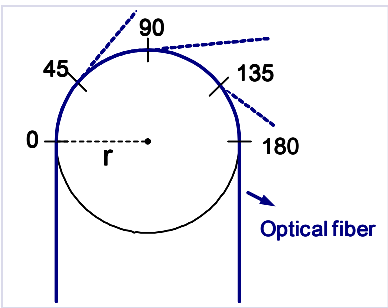
where C is the proportional constant between displacement and the normalized signal ratio. δ is the displacement of the sensor head. The normalized signal ratio of $\left(\frac{V_r - V_s}{V_r}\right)_i$ is the value at some measuring instant, and the normalized signal ratio of $\left(\frac{V_r - V_s}{V_r}\right)_0$ is the value at the starting time.

3. OPTICAL LOSS EVALUATION OF SINGLE MODE FIBER

For making the sensor head, the loss of single mode fiber was investigated at the condition of bending the fiber by using a cylindrical bar shown in Fig. 2. The optical fiber of bending part was prepared with a portion wiped on the cylindrical bar between the reference mirror and the sensing mirror. When the pulsed light was launched in the optical fiber, the light was reflected at the reference mirror and the sensing mirror. The reference signal (Vr) comes from the reference mirror and also the sensing signal (Vs) comes from the sensing mirror. In order to show the change of bend loss, the normalized OTDR signal was calculated as (Vr-Vs)/Vr shown in Fig. 3 (a). The loss was increased due to the increase of the bending arc angle of the optical fiber when the diameter was less then 14 mm. Also, the repeatability was investigated by the change of bend arc angle at one bending diameter of 8 mm. The loss was almost fully induced at the diameter of 8 mm. Therefore, the effective sensing signal could be obtained in the diameter range of 8 ~ 14 mm.

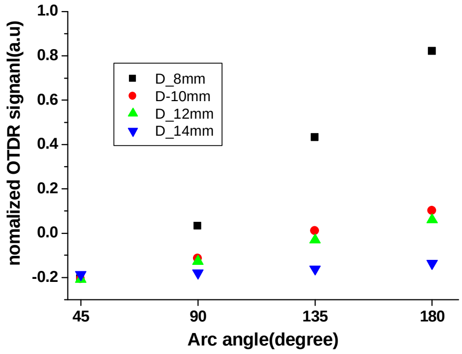


(a) Cylindrical bar

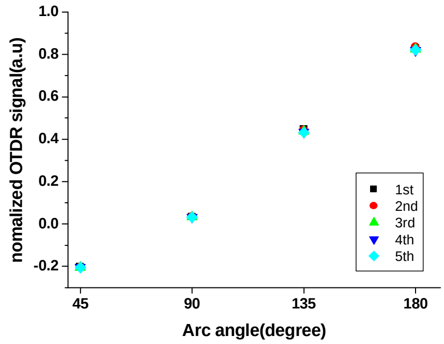


(b) Bend arc angle

Fig. 2. Fiber bending on cylindrical bar



(a) Cylindrical bar



(b) Optical loss

Fig. 3. Normalized OTDR signal due to fiber bending

4. FABRICATION OF SENSOR HEAD

The sensor head was fabricated with two aluminum cylinders and one weight as shown in Fig. 4. The optical fiber was bonded on a circumferential point of the small cylinder with epoxy. Two mirrors were installed at the end of the bending fiber with conventional optical connectors. The displacement was going to rotate the big cylinder by the circumferential string of the cylinder. If the displacement was changed, then the big cylinder was to be rotated. Then, the bending arc angle of the optical fiber should be changed. After all, the optical loss was to be changed and the sensing signal was also changed, and the displacement could be determined from the normalized OTDR signal.

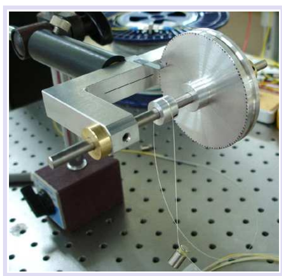


Fig. 4. Sensor head

The reflected signals from two mirrors of the sensor head were shown in Fig. 5. This figure showed that the sensing signal was well distinguished from the reference signal.

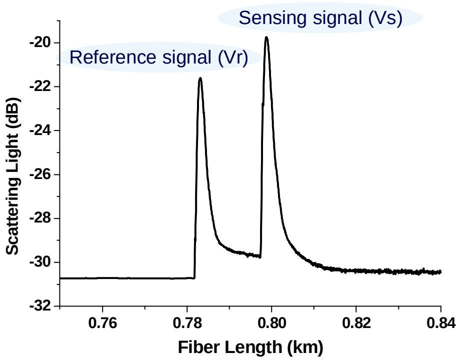


Fig. 5. Reference signal and sensing signal

5. MULTIPLEXING EXPERIMENT

Five displacement sensor heads were prepared to perform the multiplexing operation in one optical fiber after the fabrication of sensor heads. Each sensor head was constructed with a bending part of 5 m fiber length and two optical connectors, and was separated by the dummy optical fiber of 200 m as shown in Fig. 6.

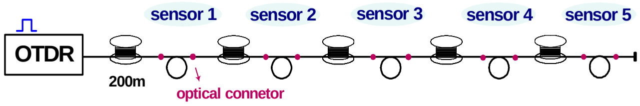


Fig. 6. Multiplexing of five displacement heads in one optical fiber

The reference signals and the sensing signals from the sensor heads were shown in Fig. 7. The width of the pulsed light was 5 ns. The proportional constant of each sensor was determined by calibration experiments.

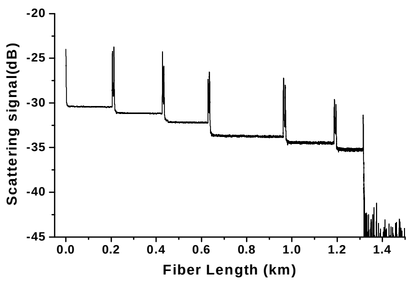


Fig. 7. Reflected signals from each sensor

Four cases of induced displacements were investigated to test the multiplexing performance. The first case was that the displacement of 3 cm was induced at Sensor#1 and sensor#5, and also 5 cm was applied at Sensor#3. The second case was that the displacement of 7 cm was induced at Sensor#1 and Sensor#4. The third case was that the same displacement of 5 cm was induced at Sensor#1, Sensor#3, and Sensor#5. In the fourth case, the same displacement of 5 cm was induced at Sensor#2, and Sensor#4.

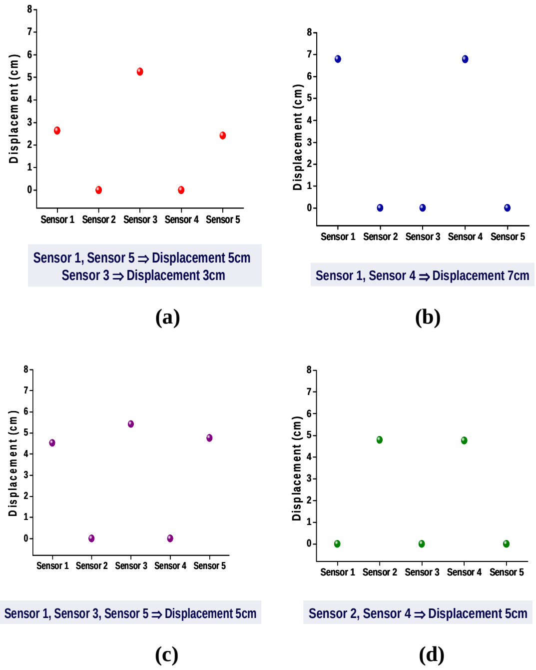


Fig. 8. Displacement sensing results

From these tests, the displacements acquired from the sensors were shown in Fig. 8. In this figure, the displacement of 5 cm, which was given at each sensor, was well determined by the fiber optic sensors. So, we could confirm that each sensor could operate independently and well measure the applied displacement. Finally, we investigated the unity of the sensor signals at one displacement condition.

6. CONCLUSION

Multiplexed optical loss based fiber optic sensor with 5 sensor heads was constructed by using only one optical fiber sensing line in order to point-wisely measure the displacement of large structures such as bridges and buildings. In these studies, the detailed results are obtained as following: 1) Fiber optic displacement sensor was fabricated with two reflected connectors and one bending mechanism. The displacement sensitivity was investigated, and also the maximum measurable displacement was about 6 mm. 2) Multiplexing was tested by 5 channel displacement sensor heads installed on one fiber line. The displacements were given on the sensor heads. The displacements were independently well sensed by the fiber sensor. Therefore, it showed that the multiplexing was successfully operated.

ACKNOWLEDGWMENTS

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REFERENCES

[1] E. Udd, *Fiber Optic Smart Structures*, John Wiley and Sons Inc., 1995.

[2] M. K. Barnoski, and S.M. Jensen, 1976. “Rayleigh scattering on an optical fiber,” *Applied Optics*, Vol. 15,No. 9, p. 2112-2115, 1976.

[3] L. Yuan, L. Zhou, and W. Jin, “Quasi-distributed strain sensing with white light interferometry: a novel approach,” *Optics Letters*, Vol. 25, No. 15, p. 1074-1076, 2000.

[4] R.C. Guthier, and C. Ross, “Theoretical and experimental considerations for a single-mode fiber optic bend-type sensor,” *Applied Optics*, Vol. 36, No. 25, p. 6264-6273, 1997.