RESEARCH ON BOTDR/A BASED DISTRIBUTED OPTICAL SENSING TECHNIQUE IN STRUCTURAL HEALTH MONITORING

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As a novel kind of optical sensing technology, BOTDR/A base distributed optical sensing technique draws lots of attention around the word. To fully utilized its distributed sensing advantage, and make it applicable in structural health monitoring applications. Temperature sensitivity test and strain sensitivity test were conducted; the results shown there are good linear relationships between temperature, strain and the Brillouin frequency. Temperature compensation method was studied; Then, one new kind of displacement sensing scheme using metal spring is proposed .Two little pulleys with inner diameter of 18mm were used to fix the optical circles together, then single mode optical fiber was winded along the pulleys into optical loops. When two pulleys were tensioned, optical fiber in loops will be tensioned. One end of metal spring with diameter of 5mm was connected to one pulley, with another end was fixed. If there is displacement change between fixed end of spring and the pulley that didn't attached to spring, metal spring could convert the displacement change to strain change of optical fiber in loops，that is Brillouin frequency change. the result show there are good linear relationship between displacement and Brillouin frequency. This kind of Brillouin displacement sensor is featured with cheap cost, long measurement range, and distributed sensing ability, which can be applied to field works on structural health monitoring.

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ABSTRACT: In this work, one novel kind of Fiber Optical Brillouin Displacement sensor was proposed and developed using metal spring. Two little pulleys with inner diameter of 18mm were used to fix the optical circles together, then single mode optical fiber was winded along the pulleys into optical loops. When two pulleys were tensioned, optical fiber in loops will be tensioned. One end of metal spring with diameter of 5mm was connected to one pulley, with another end was fixed. If there is displacement change between fixed end of spring and the pulley that didn't attached to spring, metal spring could convert the displacement change to strain change of optical fiber in loops. And then calibrating test was conducted to study the displacement sensitivity of the sensor, results show that there were good linear relationship between displacement and Brillouin frequency. This kind of Brillouin displacement sensor is featured with cheap cost, long measurement range, and distributed sensing ability, which can be applied to field works on structural health monitoring.

1 INTRODUCTION

Displacement monitoring is one of most important hot point of health monitoring for infrastructures[1] Furthermore, displacement is the key to the evaluation of structure safety, or prediction. Researchers around the world have conducted lots of research works to develop many kinds of displacement sensors, such as Linear Variable Differential Transformer (LVDT), laser displacement sensor, Fiber Bragg Grating (FBG) displacement sensor, etc. According to the sensing principle, there are sensors based on electrical resistance modulation method, electrical induction modulation method, electrical capacitance modulation method, photoelectric modulation method, etc. There are some problems on application of displacement sensors based on electrical modulation principle. Signal cannot be transmitted in long distance along signal wires, and with relatively big noise aroused by electrical jamming. Generally, there will be huge signal attenuation when the transmission distance beyond 200 meters. In recent years, optic displacement sensor based on Fiber Bragg Grating (FBG) sensing technique have been developed, with good durability, long transmission distance, high precision and immunity to electromagnetic interference[2] There were some successfully field works application reported, such as water cube of 2008 Beijing Olympic Games, and Tsing Ma Bridge in Hongkong[3] . Displacement can be monitored by this kind of optical displacement sensor precisely[4]. Furthermore, it is easy to establish sensing network using optical displacement sensor. Brillouin Optical Time Domain Reflectometer/Analyzer（BOTDR/A）is one novel kind of sensing technique for distributed monitoring of strain and temperature, which have received lots of attention around the world, recently. There are several advantages of this kind of technique, such as distributed sensing ability, low monitoring cost, good durability, etc. Common single mode fiber optic can be utilized as sensing component, which makes the monitoring cost lower. In this work, one novel kind of fiber optical Brillouin displacement sensor was proposed and developed using metal spring packaging method and also optical fiber winding method in order to develop displacement sensor with lower cost, and can be applied to build displacement sensing network conveniently, in field work.

2 EXPERIMENTAL DETAILS

Sensing principle of Brillouin fiber optical monitoring system is based on Brillouin Scattering theory. Brillouin scattering is one kind of optical scattering phenomena, which is caused by interaction of incident light wave field and media elastic acoustic field[5]. There is one frequency change called Brillouin frequency shift, which can be measured by BOTDA analyzer. Brillouin frequency shift caused by backward Brillouin scattering light can be described as:

$$f_B = 2nv_a / \lambda \tag{1}$$

In the formula 1, f_B- Brillouin frequency shift, n- refractive index of fiber core, v_a- sound speed, λ- wavelength of incident light. When there are temperature change or strain change, $f_B$will change. By monitoring the f_B, temperature and strain can be measured. There is linear relationship between f_B and temperature and strain, as shown in formula 2.

$$\Delta f_B = k_{ft}\Delta T + k_{f\varepsilon}\Delta\varepsilon \tag{2}$$

In the formula 2, ΔT is temperature change, $\Delta\varepsilon$ is strain change, k_{ft} is temperature coefficient of Brillouin frequency shift, $k_{f}\varepsilon$ is strain coefficient of Brillouin frequency shift. Formula 2 shows that Brillouin frequency can be change by both temperature and strain. In the field work of strain monitoring, temperature compensation should be considered. In another hand, BOTDR temperature sensor should be strain isolated.

Common single mode optical fiber was used to serve as sensing element. The Packaging structure of fiber optical Brillouin displacement Sensor was designed as figure 1 shows. There are two pulleys made of plastic used to support the optical fiber. Outer diameter of pulley is 27mm, and inner diameter is 18mm. Distance between to pulleys is 20cm. Firstly, optical fiber with length of 2m was winded around two pulleys with a little of pretension. Secondly, pulley-2 was attached with one end of metal spring. The displacement change between two ends of the packaging structure will convert to the stretch of metal spring, and then convert to the strain variation along the sensing optical fiber loops between two pulleys. Therefore displacement can be monitored by strain detection using optical Brillouin strain sensing technique. Metal spring with length of 10cm and diameter of 5mm was used in the test. Tube -1 and tube-2 were used to protect the sensing element inside.

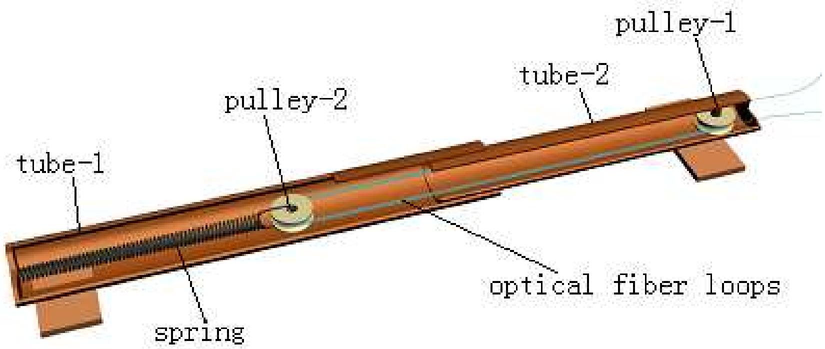


Figure 1. Packaging structure of fiber optical Brillouin displacement sensor.

Interrogator used in the test is Swiss made Ditest STA200 Brillouin optical time domain analyzer, as figure 2 shows. The strain accuracy is 20με, and temperature accuracy is 1°C. Distribution measurement distance is 30Km. minimum spacial resolution can be 0.5m.

Considering the device accuracy and reasonable spacial resolution, spacial resolution of 1m was used during experiments.

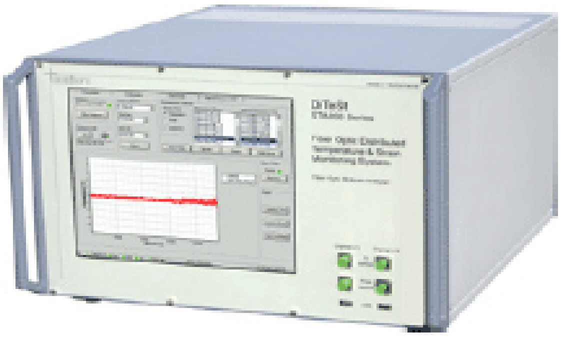


Figure 2.Ditest STA200 BOTDA.

To study the feasibility of displacement sensor, static load test was designed and conducted, as shown in figure 3. In the test, weights were loaded gradually on one pulley, from 0 to 0.5kg, with load step of 0.05kg. The aim of the test is to test the relationship between the static load and the Brillouin frequency change due to strain change along the optical fiber in winding loops. 2m length of single mode optical fiber was winded around two pulleys, which is similar to packaging structure of displacement sensor. Spacial resolution used during the test of BOTDA is 1m. One extra wheel of single mode fiber was used to build the optical loop for measurement. Brillouin Frequency was measured along whole optical loop of the test, including sensing optical fiber in loops between two pulleys. Sensing optical fiber with length of 2m was located on the range from 36-38m of the whole optical loop of the test.

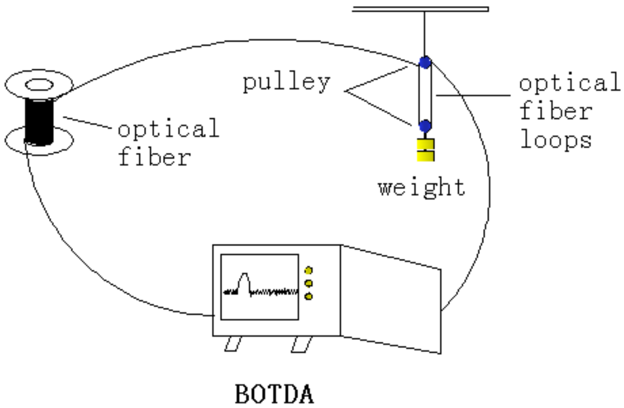


Figure 3. set up of static load experiment.

Displacement calibration test was designed and conducted to study displacement sensitivity of the sensor, as shown in figure 4. Optical operation stage was used to apply displacement on two ends of displacement sensor. Displacement sensor was tensioned a little bit, and then displacement from 0cm to 7cm was loaded and unloaded with load step of 1cm, respectively. Three load cycles were conducted to study the sensing ability and reproducibility of the sensor. One extra wheel of single mode fiber was used to build the optical loop for measurement. BOTDA was used to measure Brillouin frequency of optical fiber in whole optical loop in every load step.

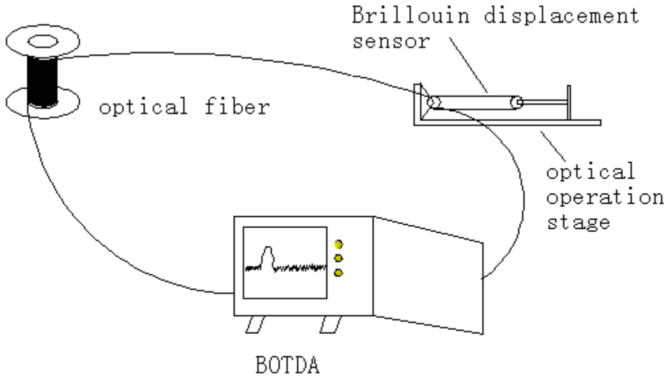


Figure 4. set up of displacement calibrating experiment.

3 RESULTS AND DISCUSSION

Figure 5 shows the Brillouin frequency result obtained in static load experiment. The sensing optical fiber with length of 2m was located in the area from 36-38m corresponding to the x axis, where there were 11 frequency peaks. The peaks increased as the load increased from 0kg to 0.5kg. There is good linear relationship between static load and Brillouin frequency response, which means that strain variation caused by static load along optical fiber loops can be monitored using winding method. By means of winding method, strain can be monitored just in sensing gauge length of 20 cm, which decrease the sensing length needed for common BOTDA device, dramatically.

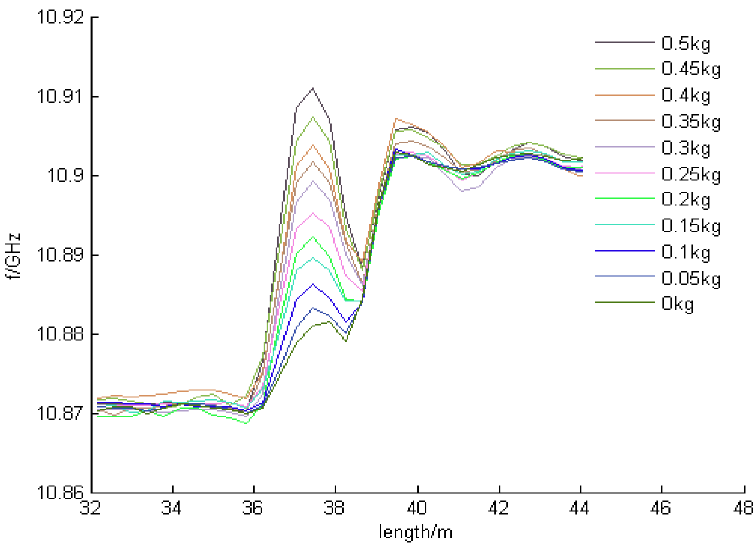


Figure 5. Brillouin frequency result of static load experiment.

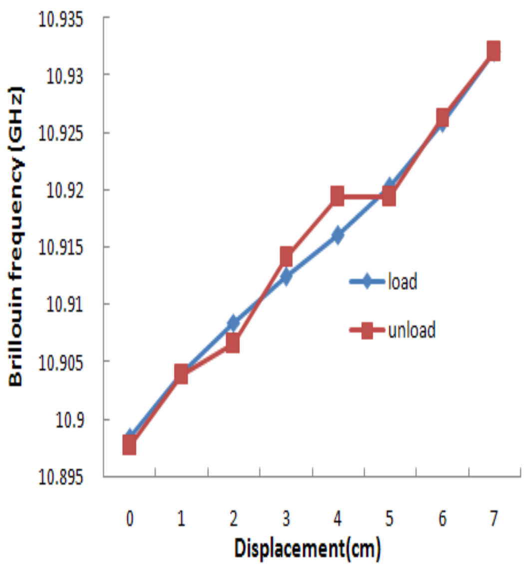
According to BOTDA's principle, the strain of a sampling point on the optical fiber actually is the average strain of the optical fiber within a certain range ahead of that point, and this range is called spatial resolution. For instance, the spatial resolution of BOTDA is 1.0 m, and that is to say the strain of a sampling point shows the average strain within 1.0 m ahead[6]. When static load was applied on one pulley, the strain will be basically constant in sensing optical loops. Therefore, when same axial strain was applied on sensing optical fiber with length of 2m, there must be one sampling point measurement can reflect the real strain in the fiber. Follow the increment of weights; strain along optical fiber in the loops will increase gradually. Then strain change will lead to change of Brillouin frequency. By comparison, suitable metal spring was selected. The stiffness of the spring is 0.5N/cm, which means that elongation of 10cm will lead to elastic force of 5N.

Maximum Brillouin frequency in the sensing gauge during displacement calibration experiment was obtained, as table 1 shows. Figure 6 shows the result of Brillouin frequency in load cycle 1. There are relative good linear relationship between displacement and frequency. In the load way, R^2 is 0.994, and displacement coefficient is 0.00048GHz/mm, and in the unload way, R^2 is 0.9822, displacement coefficient is 0.00049GHz/mm.

Table 1. Brillouin frequency results of calibration test (GHz).

Disp.	1st load	1st unload	2nd load	2nd unload	3rd load	3rd unload
0cm	10.89845	10.89762	10.89762	10.89815	10.89815	10.89719
1cm	10.90404	10.90386	10.90299	10.90425	10.90358	10.90404
2cm	10.90841	10.90649	10.90842	10.90927	10.90518	10.90785
3cm	10.91244	10.91407	10.9128	10.91271	10.91338	10.91242
4cm	10.91604	10.91932	10.91862	10.91816	10.91682	10.91723
5cm	10.92027	10.91932	10.92197	10.92095	10.92172	10.92129
6cm	10.92578	10.92636	10.92701	10.92715	10.92662	10.92621
7cm	10.93198	10.93198	10.92899	10.92899	10.92897	10.92897

Figure 7 shows the result of Brillouin frequency in load cycle 2. There are good linear relationship between displacement and frequency. In the load way, R^2 is 0.9909, and displacement coefficient is 0.00045GHz/mm, and in the unload way, R^2 is 0.9909, displacement coefficient is 0.00044GHz/mm.



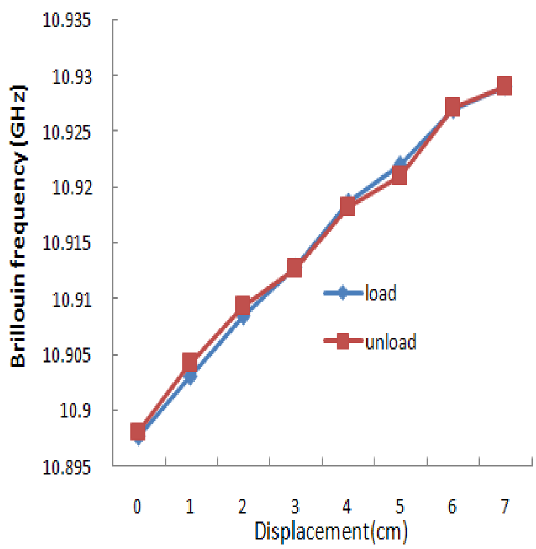
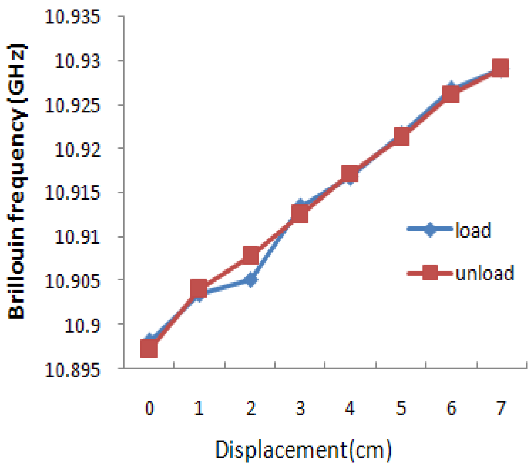


Figure 6.Brillouin frequency result of load cycle 1st. Figure 7.Brillouin frequency result of load cycle 2nd.

Figure 8 shows the result of Brillouin frequency in load cycle 3. There are good linear relationship between displacement and frequency. In the load way, R^2 is 0.9882, and displacement coefficient is 0.00044GHz/mm, and in the unload way, R^2 is 0.9941, displacement coefficient is 0.00045GHz/mm.



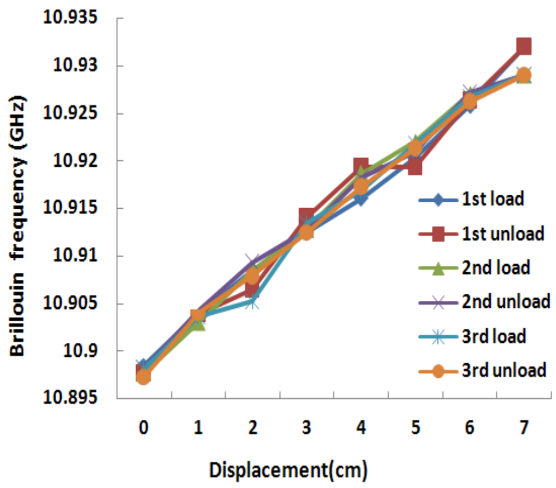


Figure 8. Brillouin frequency result of load cycle 3rd.

Figure 9. Brillouin frequency results of three load cycles.

Figure 9 shows that Brillouin frequency obtained during all the load cycles. There is good reproducibility of the frequency results. The average strain coefficient is 0.00046GHz/mm. The result shows that there are good linear relationships between Brillouin frequency and displacement applied. According to the strain sensitivity experiment[7], strain coefficient using Ditest STA200 is 0.484GHz/10000με. Strain precision of STA200 is 20με; strain change of 20με will lead to Brillouin change of 0.000968GHz. And Brillouin frequency of 0.000968GHz can be caused by displacement change of 2.1mm, according to the average displacement coefficient obtained in the experiment, which means that displacement resolution can be about 2 mm of this kind of optical Brillouin displacement sensor with metal spring packaging method and optical fiber winding method.

4 CONCLUSIONS

In this paper, one novel kind of Fiber Optical Brillouin Displacement sensor was developed using metal spring. In order to make the sensing gauge smaller and the displacement sensor more concise in size, one kind of method was proposed by winding the optical fiber into loops. Two little pulleys with inner diameter of 18mm were used to fix the optical circles together. Static load experiment result show there are good linear relationship between Brillouin frequency and static load. Displacement calibration experiment results show that there is good reproducibility of the frequency results. The average strain coefficient is 0.00046GHz/mm. and there are good linear relationships between Brillouin frequency and displacement applied. By means of STA200, the displacement sensor can monitor displacement with resolution of about 2mm. It is one good way to measure displacement of big measurement range using this kind of sensor. Further research should be conducted on accuracy enhancement using metal spring with bigger stiffness and comparison test with traditional displacement sensor in the field works of structural health monitoring. And also, distributed sensing networks composed of fiber optical Brillouin displacement sensor should also be studied in the future.

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