Optical-electrical Co-sensing System and Reciprocal Temperature Compensation

Huanyu Yang[a], Zhi Zhou[b]

[a] Faculty of Infrastructure Engineering, Dalian University of Technology, Dalian, Liaoning Province, China

[b] Hainan University, School of Civil and Architectural Engineering, Haikou, Hainan Province, China

INTRODUCTION

Structural health monitoring (SHM), especially, real-time strain monitoring, has been widely used to identify structural mechanical properties, and evaluate the safety performance and service life of civil infrastructure . To monitor the strains of these structures, there are several types of strain sensors that can be used in the field, including electrical resistance gauges, piezo-electrical sensors, and fiber optic sensors . Fiber optic sensors have attracted intensive attention among these strain sensors due to the advantages of high sensitivity, small size, and immunity to corrosion and electromagnetic interference .

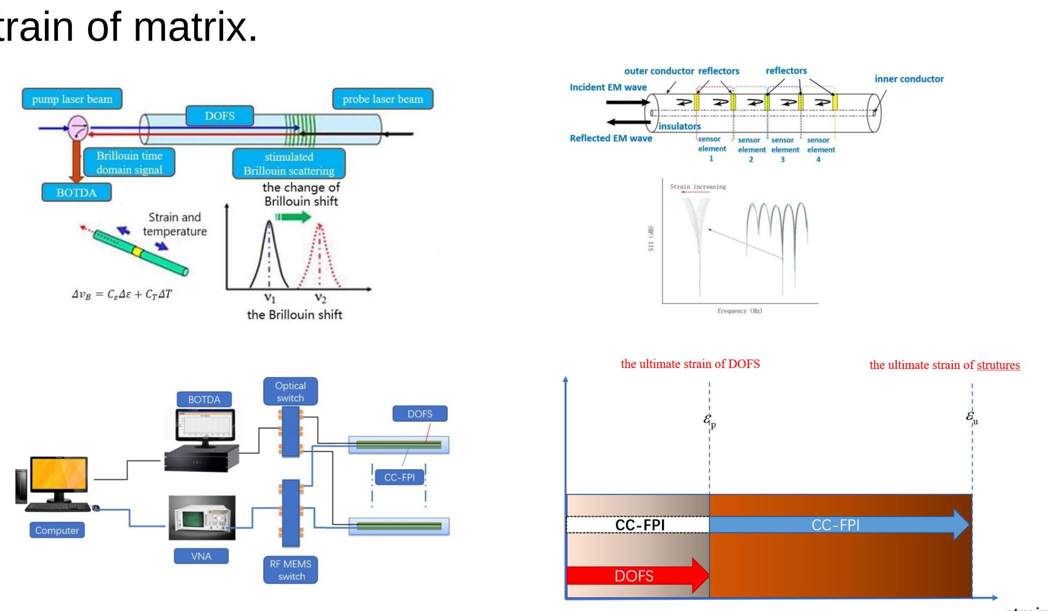
Due to the low measurement range of the optical fiber, all the current optical fiber cannot monitor the strain of the structure throughout the loading course until its complete failure, and thus cannot assess the damage degree of the structure under extreme load conditions.

This limitation is mainly determined by the material properties of low-elongation. Coaxial cable with high elongation (strain up to 15%, more than steel yield deformation) have similar electromagnetic (EM) theory to optical fiber except for the frequency of the electromagnetic waves that travel within them, which has been greatly developed in recent years. CC-FPI sensor has the advantages of small spatial resolution and adjustable gauge length, which is superior to other coaxial cable sensors. The DOFS sensors and CC-FPI have good complementarity in strain measurement. The former has high accuracy with a small measuring range, whereas the latter has a high measuring range but low accuracy.

Given the analysis above, this study proposes an optical-electrical co-sensing system (OESC system). It can simultaneously measure the small strain at the initiation stage of structural damage with high accuracy and fully cover the whole process information of material failure with relatively lower accuracy. Firstly, the sensing principle of the OESC system is introduced. Secondly, the strain sensing performance of the OESC system is tested by a translation table tensile test. Finally, a laboratory test was conducted to verify the reciprocal temperature compensation of DOFS and CC-FPI in OESC system.

CONCEPTUAL DESIGN OF THE OESC SYSTEM

The optical-electrical co-sensing method is to package a cascade of CC-FPI sensors and DOFS on the same matrix. The CC-FPI sensors and DOFSs are arranged parallel to the axis of the matrix at a certain distance and thus the two kinds of sensors can measure the same strain of matrix.



At the structural damage initiation stage, the strain was mainly measured by the DOFS belong to its high accuracy and the measurements of CC-FPI were used as a supplement. When the structural damage develops until the deformation exceeds the ultimate tensile strain of DOFS, CC-FPI replaces DOFS for subsequent large deformation measurement. At this stage, the measurement accuracy can be appropriately reduced, and CCFPI can meet the needs of both measurement accuracy and range.

The temperature and strain of the substrate can be realized by solving the equation below, so as to realize reciprocal temperature compensation.

$$\begin{cases} \Delta v_B = C_\varepsilon \Delta\varepsilon + C_T \Delta T \\ \Delta f = K_\varepsilon \Delta\varepsilon + K_T \Delta T \end{cases}$$

STRAIN SENSING PERFORMANCE

In order to evaluate the strain sensing performance of the proposed optical-electrical co-sensing system, three sets of tensile tests with strain ranging from 0 to the value that both DOFS and CC-FPI will break were performed.

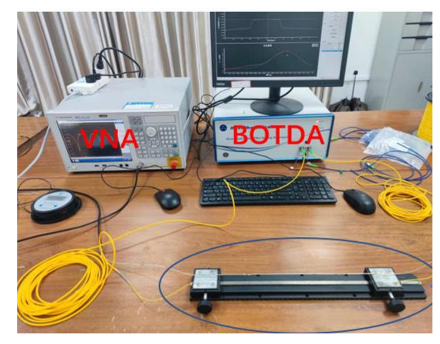
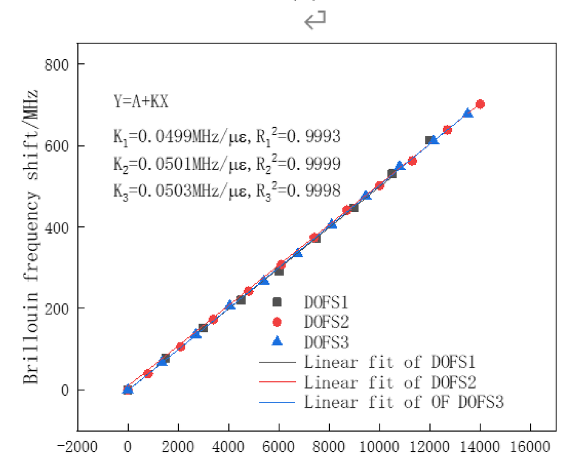


Diagram of the experimental set-up for ultimate tensile tests

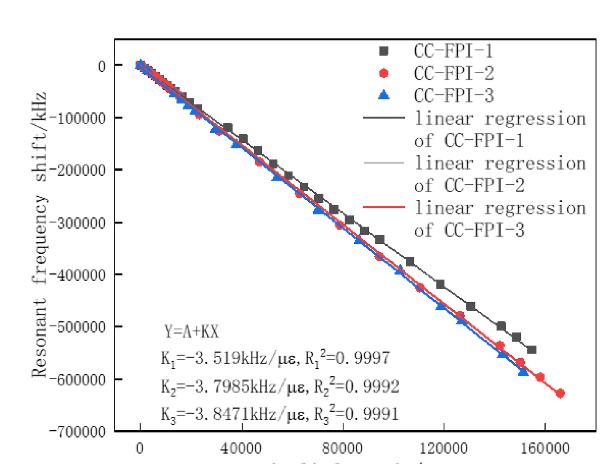
In the ultimate tensile tests, the tensile strain is gradually applied to the DOFS and CC-FPI up to the value that DOFS will break at a step of 1500 με (germination process of damage) and then gradually increased to the value that CC-FPI will break at a step of 9000 με (development process of damage).

The Brillioun frequency shift of DOFS increases linearly with increasing strain. It is evident from the figure that the responses of different DOFS to strain is highly consistent. Due to the stripping of the fiber coating, the ultimate tensile strains of the three groups of DOFS were relatively low, which were 12000 με,14000 με and 13500 με. The resonant frequency shift of CC-FPI decreases linearly with increasing strain. The strain sensitivities of three CC-FPI are -3.519 kHz/με, -3.803 kHz/με and -3.848 kHz/με respectively, and its ultimate tensile strain is as high as 140000 με, 150000 με,160000 με respectively.

(a)



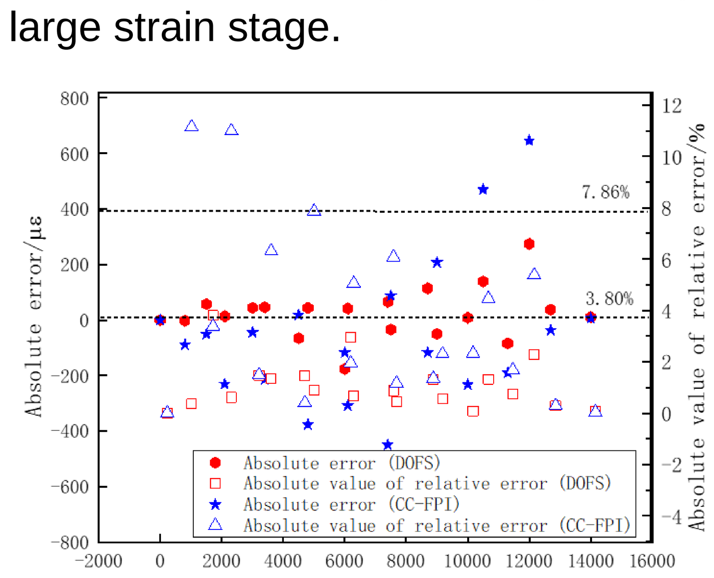
(b)



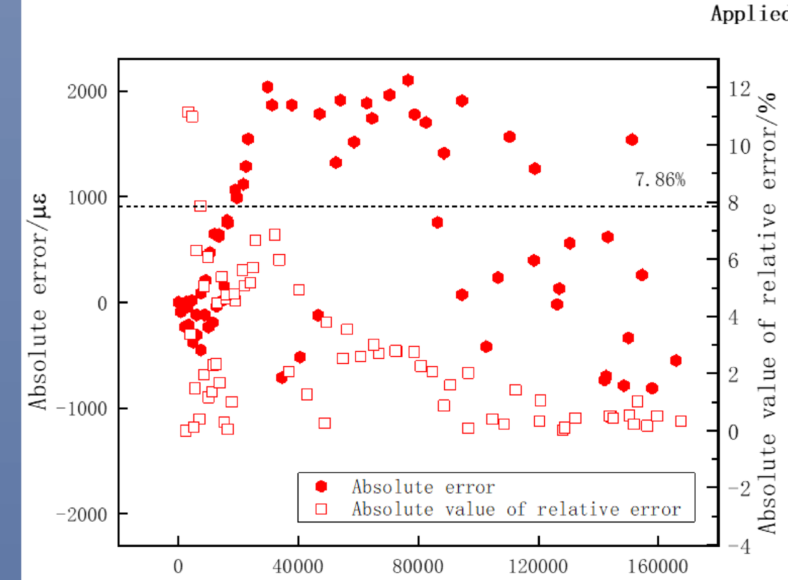
Signal responses of DOFS and CCFPI in OESC system. (a) DOFS in OESC system, (b) CC-FPI in OESC system.

The absolute errors of DOFS are within ± 274 με, and the relative errors are less than 3.8%. However, the absolute errors of CC-FPI are larger, up to ±773 με, in the same measurement range, and most of the relative errors are less than 7.86%.

The maximum strain of CC-FPI is over 160000 με and its absolute strain errors are within ±2100 με, and the relative errors at the small strain stage are generally higher than those in large strain stage.



Comparison between the measurements of DOFS and CC-FPI in small strain monitoring.

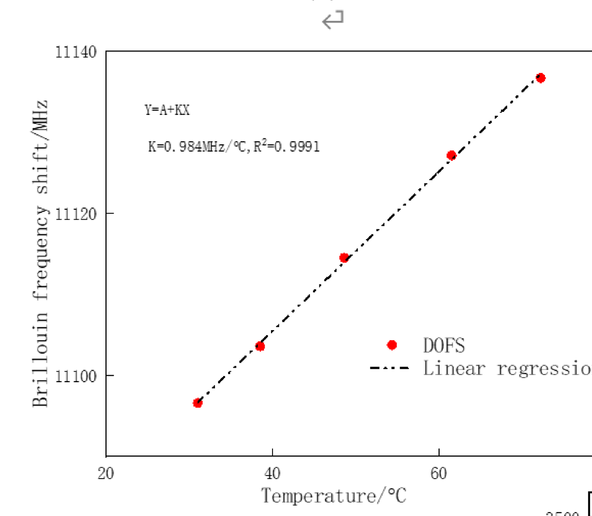


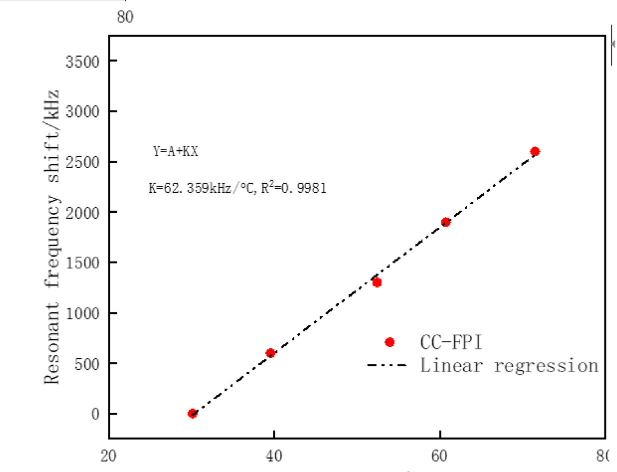
The measurement error of CC-FPI over the whole process.

RECIPROCAL TEMPERATURE COMPENSATION

A laboratory test was conducted to verify the reciprocal temperature compensation of DOFS and CC-FPI in optical-electrical co-sensing system. The tensile device with a DOFS and CC-FPI glued on parallel to the axis at a certain distance with a gauge length of 350 mm was placed in a constant temperature and humidity chamber. Slide the tensioner slider outward until the sensor was straight. Then the temperature was raised from 30 ℃ to 70 ℃ with an increasing step of 10 ℃.

(a)

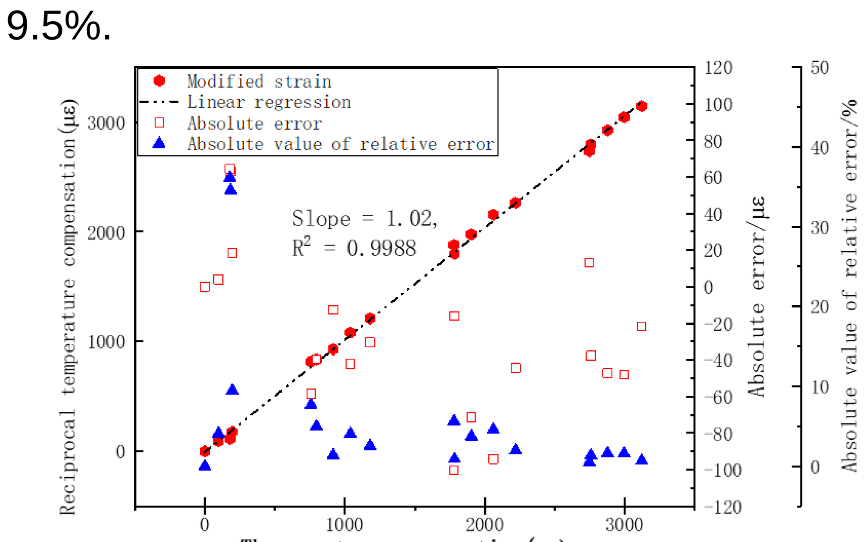




(a) Temperature-frequency shift curves of DOFS (b) Temperature-frequency shift curves of CC-FPI

The frequency shifts of DOFS and CC-FPI increase almost linear as the temperature increased, with a slope of about 0.984 MHz/℃ and 62.359 kHz/℃, respectively.

The displacement increments were raised from 0 to 0.4mm, 0.8mm, 1.2mm by step. The temperature was raised from 30 ℃ to 70 ℃ with an increasing step of 10 ℃ after each step of displacement increasing. Compared with the thermometer compensation method, the absolute errors of reciprocal temperature compensation are within ± 94 με, and most of the relative errors are less than 9.5%.



Comparison between reciprocal temperature compensation and thermometer compensation

Conclusions

This paper introduces an OECS system which can simultaneously provide the accurate strain measurement in a limited range and the rough strain measurement throughout the entire range. The strain sensing performance of the OESC system is tested by a translation table tensile test. And the reciprocal temperature compensation of DOFS and CC-FPI in OESC system has been investigated.

Acknowledgments

This work was financially supported by the National Natural Science Foundation of China under Grant No. 5217082790

周智教授课题组（Prof. Zhi Zhou-group）

大连理工大学 DALIAN UNIVERSITY OF TECHNOLOGY