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# **INNOVATIVE MONITORING INSTRUMENTS ON ALL CABLES OF CABLE-STAYED BRIDGES**

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# ABSTRACT

To evaluate the cable tensions of a cable-stayed bridge, conventionally piezoelectric sensors or forcebalanced sensors are applied to measure the vibration signal spectrum of cables. Connected to a signal analyzer (such as a PC) through electrical wires in parallel, those sensors are tied-up to the cable-tendon to be measured. However, with limited sensors and signal channels, the measurements of all cable vibration could only be implemented part by part. Practically, it is difficult to measure all cable vibration simultaneously. For overcoming the mentioned difficulties, an innovative optic-fiber health monitoring system on the cables of a cable-stayed bridge is designed in this article. Herein this paper will not only introduce the mechanism of the new system but also the application to a real cable-stayed bridge. With the new device, it becomes possible to monitor all cables of a cable-stayed bridge economically, simultaneously, and regularly, even in wind-rain weather condition.

Keywords: Cable-stayed bridge, FBG sensor

# **INTRODUCTION**

The main structure components of a cable-stayed bridge include pylons, decks, abutments, and cables. Through cables, the weight of the decks are transferred into the pylons and thereof the foundations. Therefore the tension force of the cables is one of the important health indexes of a cable-stayed bridge. To evaluate the cable forces, there are three methods applied in field: (1) a jack pulling out the anchor, (2) a load cell imbedded between the anchor and anchor seat, and (3) cable force estimation by the natural frequencies of a cable. Practically, only the method (3) is applied in-situ both during and after the completeness of a cable-stayed bridge construction. To carry out the method (3), an engineer has to be equipped with vibration sensors together with a signal analyzer. Connected to a signal analyzer through electrical wires in parallel, piezoelectric sensors or force-balanced sensors are conventionally applied and tied-up to the cable-tendon to be measured. However a typical cablestayed bridge has more than one hundred cables, and with limited sensors and signal channels, the measurements of all cable vibration could only be implemented cable by cable or part by part, as shown in Fig.1. It takes many man-hours to finish the work. Furthermore the environment may vary

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dramatically during the long-hour measurement, such as temperature, wind and rain, so the measured data are not under the same environmental condition. Besides, if the conventional vibration sensors are installed permanently for all cables, with so many sensors and electrical wires, the system will cost a fortune and affect the aesthetic view of the bridge. For overcoming the mentioned difficulties or drawbacks of conventional vibration measurement system, an innovative optic-fiber health monitoring system on the cables is designed in this article. Herein this paper will not only introduce the new system but also the application to a real cable-stayed bridge. With the new device, it becomes possible to monitor all cables of a cable-stayed bridge economically, simultaneously, and regularly, even in wind-rain weather condition.

#### FIBER BRAGG GRATING SENSOR

Fiber Bragg grating (FBG) sensors are highly attractive recent years for their inherent wavelength response, immune from electrical wave or magnetic wave, and their multiplexing capability for the distributive sensing network in a series of arrays along a single optical fiber. The Bragg phase-matching condition determines the Bragg wavelength of a fiber grating. The wavelength shifts of a fiber Bragg grating subjected to physical disturbance can be expressed as followed:

$$\frac{\Delta\lambda_B}{\lambda_{B,0}} = (1 - p_e)\Delta\varepsilon + (\alpha + \xi)\Delta T \tag{1}$$

in which  $P_e$ ,  $\Delta \varepsilon$ ,  $\alpha$ ,  $\xi$ ,  $\lambda_{B,0}$  and  $\Delta T$  are the effective photoelastic constant, axial strain, thermal expansion coefficient, thermal optic coefficient, the initial wavelength of fiber Bragg grating, and temperature shifts, respectively. These coefficients generally depend on the type of optical fibers and the wavelengths at which they are written and measured. For typical FBG sensors, the effective photoelastic constant is about 0.21. Suppose the temperature shifts keep constant during a dynamic measurement, Eq(1) can be expressed as followed:

$$\Delta \lambda_{B} = (1 - P_{e}) \cdot \lambda_{B,0} \cdot \Delta \mathcal{E}$$
<sup>(2)</sup>

Eq(2) simply relates the axial strain with the wavelength shifts of a fiber Bragg grating subjected to axial force.

#### THE STRAIN IN A ROD SUBJECTED TO MOVING BOUNDARIES

Consider a rod subjected to the moving boundaries on two cables in the same gravity plane, as shown in Fig.2. According to the mathematical analysis, the longitudinal displacement response of any point on the rod includes so-called: (1) qusi-static terms and (2) dynamic terms. The former is governed by the transverse vibrations in gravity plane of the two cables, and each cable's transverse vibration is characterized by its own mechanism, such as tension force, length density, section rigidity and gravity. On the other hand, the latter is comprised of the modal responses of the rod subjected to fixed ends, and each modal response has the essential natural frequencies described as the following equation:

$$f_n = \frac{n}{2l} \sqrt{\frac{E_t}{D}} \tag{3}$$

Where  $E_t$  is the tangent Young's Modulus, and D is the length density of the pretension wire. If the all natural frequencies in Eq(3) are much higher than the interested natural frequencies of the two qusistatic terms induced by the two cables, only the two cables' characteristic frequencies show up in the interested frequency spectrum of the sensing optic fiber as illustrated in Fig.3. If so in Fig.3, then it would be possible to monitor the cable force of the two cables just by one single FBG.

# APPLICATION OF FBG SENSING SYSTEM ON THE CABLES OF A CABLE-STAYED BRIDGE, EXISTING OR UNDER CONSTRUCTION

FBG sensing system is featured with its multiplexing capability for the distributive sensing network in a series of arrays along a single optical fiber. By connecting the cables of an existing cable-stayed bridge by pretension wires with FBG sensors, installed permanently as illustrated in Fig.4, all the cable vibration can be measured simultaneously under the same environment condition: the wind condition, the temperature condition, and the passing-by vehicle condition. Moreover such an idea could also be applied to a cable-stayed bridge under construction as illustrated in Fig.5. The engineers in field can monitor the cable force or the balance of the bridge at any moment and very quickly, without spending hours or even a day to measure the cable vibration by conventional vibration sensors. Except the efficiency, Table I compares the advantage between the FBG sensing system and conventional vibration sensors for a cable-stayed bridge.

# APPLICATION EXAMPLE-I ON GI-LU CABLE-STAYED BRIDGE

Gi-Lu Bridge, crossing the longest river in Taiwan, is a modern design pre-stressed concrete cablestayed bridge. The bridge has a single pylon, two-row harped cables, and a streamline-shape main girder with 2.75 meters in depth and 24 meters in width. The main girder rigidly connects with the pylon and spans 120 meters to each side bent as shown in Fig.4. On September 21, 1999, Gi-Gi Earthquak seriously struck central Taiwan. Fig.6 indicates both the epicenter and the site of Gi-Lu Bridge. Gi-Lu Bridge experienced the strong near-fault ground motion much greater than its seismic design level 0.28 G. The observed damage of Gi-Lu Bridge was observed: the concrete cover of the pylon spalled off, one cable fell onto the deck, the soffit of the girder at the juncture with the pylon cracked, the rebar inside the girder compressively failed, the cap beams of the two side bents were ruined by the vertical and lateral pounding force. After the retrofit of the concrete structure and the cable force adjustment in 2001 and 2004 respectively, the bridge now is opened to the public traffic. For monitoring the cable forces and studying the wind-rain induced vibration in the future, the authors applied the above mentioned FBG sensing system to the three longest cables, R33, R31 and R29, as shown in Fig.7. In Fig.7 two FBGs connect R33-R31 and R31-R29 respectively, while two velocimeters independently measure the vibration of R33 and R31. Fig.8 shows the beginning 10second data within the 6-minute measurement. Both Fig.8 (a) and Fig.8 (b) indicate the wavelength variation of the two FBGs, while Fig.8 (c) and Fig.8 (d) show the velocity history of Cable R33 and R31 at the points connecting the pretension wire between R33 and R31. Marked with characteristic frequencies, Fig.9 shows the Fourier Spectrum of those 6-minute measured signal. From Fig.9(c) and Fig.9 (d), measured by conventional sensors, not only the characteristic frequencies of Cable R33 and R31 could be identified respectively, but also the natural frequencies of the deck could be recognized. On the other hand, measured by FBG sensors, Fig.9 (a) apparently composes of Fig.9(c) and Fig.9 (d) except the natural frequencies of the deck, and Fig.9 (b) simultaneously shows the characteristic frequencies of Cable R31 and R29. It is demonstrated that the proposed FBG sensing system could replace the conventional electronic sensors. Those identified characteristic frequencies in FBG sensors help to monitor the cable vibration and cable force.

# APPLICATION EXAMPLE-II ON GI-LU CABLE-STAYED BRIDGE

Fig.10 presents another installation of FBGs sensors between cables and the girder. One quarter cables (17 cables) are equipped with FBGs sensors measuring the cable vibration as well as the deck vibration. Fig.11 shows the measurement data collected when a truck passed the deck. From Fig.11, it is recognized that the truck caused stronger cable vibration, and that the oblique line implies the speed of the truck. Fig.12 presents the Fourier Spectrum of the vibration time history in Fig.11. From Fig.12, not only the characteristic frequencies of each cable, but also the characteristic frequencies of the girder could be recognized. By the proposed instruments, all cables of a cable-stayed bridge could be monitored economically, regularly, simultaneously.

# CONCLUSIONS

From the above simple field application on Gi-Lu Cable-Stayed Bridge, it's verified the proposed "optic-fiber health monitoring system on the cables of a cable-stayed bridge" works. Being unafraid of raindrop, permanent installation, low cost, and other important features listed in Table I, the suggested system is superior to the conventional vibration sensor system with electrical wires. In the future, the proposed optic-fiber monitoring system could not only be applied to study the cable vibration induced by wind-rain weather condition, but also to a cable-stayed bridge under construction.

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# Table 1. Advantage comparison between the FBG sensing system and conventional vibration sensors on Cables of a Cable-Stayed Bridge

FBG sensing system	Conventional sensor system
Simple installation	High resolution
Not afraid of raindrop	Technology mature
Not afraid of lightning	Independent measurement
Low equipment cost / few man-hours needed	Being equipped with wireless transmission
Permanent installation	Applicable under bridge construction
Wavelength encoded	
Low/no transmission lost	
High sampling rate	
Applicable under bridge construction	
Immune from electrical wave or magnetic wave	
All cable vibrations are measured under the same environmental condition.	
Little influence on the aesthetic scenery of a cable-stayed bridge	



Figure 1. With limited sensors and signal channels, the measurements of cable vibration can only be implemented cables by cables (Right bottom is the PC recorder)



Figure 2. A pretension wire subjected to the moving boundaries on two cables. The displacement response of any point on the wire includes: (1) qusi-static terms and (2) dynamic terms



Figure 3. Idealized frequency spectrum of the optic fiber on the pretension wire in Figure 2



Figure 4. Proposed Fiber Bragg Grating monitoring system on the cables of a cable-stayed bridge



Figure 5. Proposed Fiber Bragg Grating monitoring system on the cables of a cable-stayed bridge under construction



Figure 6. The epicenter of Gi-Gi Earthquake and the site of Gi-Lu Bridge (On the same star point in this Taiwan map)



Figure 7. FBG sensing system together with velocimeters on Cable R33, R31, and R29



Figure 8. The beginning 10-second data within the 6-minute measurement data



Figure 9. The Fourier Spectrum of those signals in Fig.8 (all 6-minute measurement data)



Figure 10. Seventeen FBG Sensors are installed between the cables and the girder.



Figure 11. Signals recorded when a truck passed the deck. The oblique line implies the speed of the truck.



Figure 12. The characteristic frequencies of each cable could be recognized.