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Use of FBG Optical Sensors for Structural Health Monitoring: Practical Application

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Abstract

This paper describes the development of FBG Optical sensors for their practical application on structural health monitoring. The sensors were installed on the Tsing Ma Bridge for a trial run. The results using FBG sensors were in excellent agreement with those acquired by the bridge WASHMS.

Introduction. Previous research works have shown that FBG sensors have several inherent advantages over conventional electrical sensors such as small size, light weight, non-conductivity, fast response, resistance to corrosion, higher temperature capability, and immunity to electromagnetic noise and ratio frequency interferences. The distinct advantages of FBG sensors over other types of fiber optic sensors are their multiplexing capability and wavelength-encoded measurand information. A single string of optical fiber can accommodate up to many tens of FBG sensors. The meaurand information is encoded in wavelength, which is an absolute parameter and thus FBG sensor systems are less susceptible to signal amplitude fluctuations. Another attractive feature of FBG sensors is their inherent ability to serve as both the sensing element and the signal transmission medium which opens new possibilities in the field of reliable remote structural health monitoring. In this regard, application of this new technology would have a significant impact on health and efficiency of civil infrastructure systems. However, the practical applications of this kind of sensors to real civil engineering structures have not been widely adopted although the progress of fiber optic health monitoring is impressive [1].

Different types of Fiber Bragg Grating (FBG) sensors for simultaneous strain and temperature measurement and for temperature independent strain measurement have been developed by The Hong Kong Polytechnic University [2-5]. Fiber-laser-based wavelength-division-multiplexed (WDM) FBG sensor interrogation technique and a broadband light source-based multiplexed FBG sensor interrogation system have also been devised. The system can perform both static and dynamic strain measurement (up to a sampling rate of 52Hz), and allows ones to read the measurement data at locations tens of kilometers away from the monitoring site. After a series of successful laboratory test and verification, the system have been installed to different parts of the Tsing Ms Bridge and compared with the results obtained by a sophisticated long-term monitoring system, known as Wind And Structural Health Monitoring System (WASHMS), which was devised and implemented by the Highways Department of Hong Kong SAR Government to monitor the structural health and conditions of the three cable-supported bridges in Hong Kong, including the Tsing Ma Bridge, the Ting Kau Bridge and the Kap Shui Mun Bridge [6]. This on-structure instrumentation WASHMS system consists of a total of about 800 sensors of different types permanently installed on the three bridges, including strain gauges, GPS position sensors, accelerometers, level sensors, temperature sensors and weigh-in-motion sensors. Because the WASHMS was implemented several years ago, it has not been benefited from the newly developed optical fiber sensor technology. In order to investigate the feasibility of using the developed FBG sensors for structural health monitoring, a field test was carried out in May 2003, in which a number of such FBG sensors were installed on the Tsing Ma Bridge to conduct real time and full scale measurements. The results were assessed and compared with the conventional strain gauges obtained from the WASHMS.

In the field of fiber-optic sensors (FOSs) the FBG sensors are one of the most exciting developments in recent years. They have a unique property and many advantages over other FOSs due to their quasi-point sensing and multiplexing capability. The most important advantage of an FBG sensor is that the measurand is encoded directly in terms of wavelength, which is an absolute parameter and does not suffer from disturbances of the light paths [7]. Hence, the output signal is independent of the intensity of the source, and losses in the connecting fibers and couplers. Furthermore, each of the reflected signals will have a unique wavelength and can be easily monitored, an array of wavelength-multiplexed FBG sensor may thus be implemented for simultaneous multiple measurements using a single fiber.

Figure 1 Packaged FBG strain gauges boxed in ABS enclosures with two 3 mm fiber outlets (Inset shows the FBG sensors epoxied on nitinol sheets in an oven after baking at 80°C for 5 hr)

FBG Sensor Fabrication and Package Units. Standard telecommunication single mode fibers (Corning-SMF28) were used to fabricate FBG sensors. In order not to weaken the mechanical strength of the FBG, the outer coating of the fiber was removed by soaking a short length in warm acid bath instead of using mechanical stripper. After the FBG inscription, this short un-coated FBG was annealed. To facilitate the installation process while maintaining the straightness of the FBG, the FBG was mounted on nitinol (an acronym for NIckel TItanium Naval Ordnance Laboratory) strips with thickness of ~ 7.5 μm (0.0029") and dimensions of 6×110 mm, which were cleaned with high concentration isopropanol to remove grease stains. Nitinol is a room temperature super elastic metal which is corrosion resisting and can withstand 8% elongation without deformation. The FBG-nitinol sheet combo were sandwiched and pressed together using two Teflon sheets to minimize the thickness as well as evenness of epoxy between the FBG and the nitinol sheets. Figure 1 shows a packaged FBG strain gauges boxed in ABS enclosures with two 3 mm fiber outlets. Inset of Figure 1 shows the packaged FBG sensors epoxied on nitinol sheets in an oven after baking at 80 °C for 5 hours.

Trial Run. The Tsing Ma Bridge (TMB) is the longest suspension bridge carrying both highway and railway traffic. A structural health monitoring system, WASHMS, was installed and has been operating since the bridge opening. The structural health monitoring system for the TMB comprises sensors such as accelerometers, strain gauges, displacement transducers, level sensors, anemometers, temperature sensors and weigh-in-motion sensors, installed permanently on the bridges, and the data acquisition and processing system.

(1) Truss Girder (2) Hanger Cables (3) Rocker Bearing

Figure 2 Installed FBG Sensors

In this test, three different strategic locations: (1) truss girders (2) hanger cables, and (3) rocker bearing, on a section Chainage 23488 of lower deck respectively (Figure 2), were chosen to install FBG sensors. In addition, strain-free FBG sensors were also used to measure the temperature at different sensing points to provide temperature compensation for the measurements. The FBG DEMINSYS unit developed is a complete system with the capability to perform multiple optical FBG sensor measurement and provide a major advancement for mechanical and temperature sensing applications. The unit provides rapid measurement rate of hundreds of FBG sensors on several fibers. It includes an optical light source used to illuminate the FBG sensors, and an optical detector to measure the reflected optical signals on each sensor. An external portable PC provides the on-line calibration data display/storage of the FBG sensors under test. The system resolution and accuracy are 1 pm and 10 pm respectively. The sampling rate of the system is adjustable and can be increased up to 20 kHz.

Observation and Experience Acquired

Truss Girder *Measurement.* An array of 12 FBG sensors was mounted on different locations of Chainage 23488. The FBG sensors are placed close to the existing strain gauges for an optimal comparison. The signals from the FBG sensors are compared with the signals of the corresponding strain gauges. The sampling time is 0528 ms. A moving average filter of 10 points is applied to the data of the FBG sensors and the detection bandwidth of the FBG sensors is reduced to about 2 kHz. Although the sensors are not located at exactly the same location, great resemblance has been found. Zooming in the signal reveals that the noise in the FBG sensor signal is mainly caused by a 13 Hz component and can be reduced by appropriate filtering or placing the DEMINSYS outside the bridge. The resolution is found to be about 1 pm and can be reduced by further averaging. Using such filtering, sub-pm/με resolution can be achieved.

Hanger Cable Measurement. Six FBG sensors ***wer***e mounted on the hanger cables. One of the FBG sensors mounted on a hanger cable to the Ma Wan tower was monitored with the high-speed DEMINSYS interrogation system. Via another input fiber, an athermal packaged FBG sensor in a vibration-isolated case is used as reference. For the hanger cable measurement, the readout frequency is set to 0.106 ms. The measured histories from the two FBG sensors show clearly the train passages.

Rocker Bearing Measurement. Various measurements with the FBG sensors mounted on the rocker bearings were performed including an overnight measurement of about 20 hours with a sample time of 2.1 ms, the data from strain gauges on the rocker were also logged simultaneously. In the Tsing Ma Bridge construction, the rocker bearings are used to support and hold the deck. Therefore, the loading on the rocker is very complex and the strain depends strongly on the position of the sensor. Despite the FBG sensors and the strain gauges are not mounted on the exactly same location of the rocker, the signals of the 2 types of sensors, are founded to be very similar and the train passages can clearly be detected.

Conclusions. The background of Fiber Bragg Grating sensor technology was briefly introduced. The high-speed demultiplexing/interrogation system for FBG sensor arrays and the FBG sensor package units were developed. Field trial with FBG sensor arrays for measurement on hanger cable, rocker bearings and truss girder of the Tsing Ma Bridge was performed successfully. The application of FBG sensors and interrogation system to monitor the dynamic strain on the Hong Kong's landmark Tsing Ma Bridge has been demonstrated. The FBG package technique was proposed to apply for structural health monitoring application. It can clearly and correctly detect the dynamic strain responses of the bridge induced by the passage of trains on bridge. The measurement result of the interrogation system was in excellent agreement with those obtained by resistive strain gauge measurement.

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