Fiber Bragg Grating (FBG) Sensing Network Condition Monitoring of Harbour and Jetty Structures in Iran

Mohammad Reza Hedayati [a,*], Ali Asghar Amidian [b], Mohammad Hossein Amiri [c] and Fatemeh Khodadadi [d]

[a,b] Scientific-Applied Faculty of Post & Comm., Tehran, Iran

[a,c] Tehran North Branch, Islamic Azad University, Tehran, Iran

[d] Software Engineering, University of Hertfordshire, Hatfield Hertfordshire, UK

Submitted: 12 Feb. 2015 — Accepted: 12 Feb. 2015 — Published: 12 Feb. 2015

Abstract—Fiber Bragg Grating (FBG) technology, as an on-line-temperature and strain sensing system, has been attracting great attention because of its capability along with accuracy and precision. The following article proposes a signal processing system and explains its technical principles with special reference to the quay wall of the Shahid Rajaee Harbour at the Persian Gulf located in southern part of Iran. The use of a signal processing system using FBG sensors for monitoring dynamic strain and temperature of the target structure has been proposed. Implementation of fiber optic sensing (FOS) technology in the system has been advocated, as the use of traditional electrical strain gauges in large numbers in a sensing network, for structural and health monitoring of different buildings and civil engineering structures is found to pose special problems, and it is difficult and sometimes impossible to measure a fault or crack in the on-shore or off-shore constructions, due to prevailing environmental conditions.

Keywords—Fiber Bragg Grating (FBG); Condition Monitoring; Sensing Network; Expert System; Fiber Optic Sensing (FOS).

I. Introduction

OVER the past few years, besides a very high demand of optical fiber in telecommunication, we witnessed the powerful and high potency inventions in the field of Fiber Bragg Grating (FBG) technology and its multipurpose applications. The first gradient index fiber were designed and fabricated jointly by the Nippon Sheet Glass Co. and Nippon Electric Co. in 1969 [1]-[10]. The first commercial FBGs were available in 1995 and were pioneer in the design and mass production based on components for the gain flattening filters, 50 GHz and 100 GHz DWDM filters [2]. Including their applications in the optical communications such as optical filters, couplers, reflectors, dispersion comparators, they are also used as sensors in structural health monitoring (SHM) of civil engineering structures [3]-[4].

Though FBG cannot fully compete with sensors like metal strain gauges especially with regard to price, they provide some superior qualities suited to specific applications:

They are convenient and simple in installation and implementation in any structure because of their cylindrical geometry, compactness in size, inability to conduct electrical current, robust to environmental conditions, light in weight, with high sensitivity, easy to transmit the output signal over long distances, unaffected by electromagnetic interference and radio frequency interface.

* Corresponding Author: Mohammad Reza Hedayati, *PhD*

E-mail: hedayati.rov@gmail.com

Under the technical support of "Faculty of Applied Post and Communication" several practical measurement and health monitoring FBG packages are developed. Figure 1 shows the indoor laboratory test in the fiber optic Lab of above mentioned institute.

Figure 1. FBG sensors incorporated in the laboratory in door test setup

For the last two decades the loads on the harbours caused by the propeller effect of container vessels have increased. At first, this increase was ascribed to the scaling-up of the vessels. To guarantee public safety during the lifetime of a quay wall and to make an optimal economical maintenance it is necessary to monitor working condition of quay wall and structure integrally. The structure under study is located at Shahid Rajaee Port Complex in Bandar Abbas, with its unique geographical position at the closest point of entrance to the Strait of Hormuz and the Persian Gulf.

This paper reports the development of a new FBG test facility purpose-built by the authors to investigate the effect of imposed external vibration and unsteady dynamics of supper heavy marine thrusters on the quay wall behavior of Shahid Rajaee harbor in order to, mainly prevent undesirable events, reduce the maintenance cost and increase the shelf life. In the proposed method the rate of effective exerted force, vibration and other environmental condition are recorded using specially designed FBG based system of sensing and a dedicated expert system of the collected data.

II. CONCEPT OF FBG BASED MONITORING

Following are the main reasons for the quay wall monitoring:

- Find bugs in the design and construction of structures
- Grading to update and repair based on risk
- Identify and map sensitive areas before crash
- When monitoring the incident and determined the cause of the accident.
- Reducing the cost of reconstruction
- The possibility of warning to correct the situation back to normal at the time of heavy waterfront.
- Register loading conditions on the Quay Wall at a time interval that determines the behavior is applied to the structure.
- Enhance Life Wall [3].

In order to ensure the proper functioning of installed FBGs on the quay wall the ROV based vibration arm impose the localized vibration at different suspected area and positions of subsea structure as shown in Figure 2.

FBG shows good compatibility with concrete or steel made structures, but due to non-elastic nature and brittleness feature of FBG sensor. Without complete protection and encapsulation, application and installation of the sensors to the structures is not practically possible. The packaging and casing of the fine-spun fragile sensor in a metallic tube is essential and it is not sound and possible to use them without metallic cover and packaging. In order to make full use of FBG, indirect sensors device based on FBG and construction materials are fixed together using bolts and screws [8]-[14] .

The advantage of FBG sensors for the structural health monitoring (SHM) applications are listed as following:

Highly sensitive, protected against electromagnetic interference, WDM compatibility, resistance to corrosion and long life [4]-[5].

FBG spectral changes to their relationship (as a function of the separation of the network) contact with outside influences in sensing and very efficient. At present the FBGs are used at high levels in areas such as communications, signal processing and sensing applications. The advantage is that it is a small utility that can be easily implemented within the monitoring system on the surface or inside of the structures [6]-[7]. Schematic diagram of inner structure of an FBG sensor having an index modulation of Λ spacing inside a single-mode optical fiber is depicted in Figure 3. The general characteristics and operation of FBG sensor corresponding to the Incident Wavelength is shown in Figure 4.

Figure 2. Localized vibration imposed to the quay wall using ROV based vibrator and receiving FBGs notification installed on the quay wall at Shahid Rajaee harbour

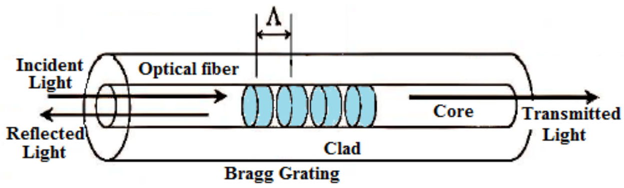

Figure 3. The interior structure of a FBG sensor

FBG include a periodic modulation of the refractive index in the core of an optical fiber in single-mode. FBG wavelength is expressed as "(1)".

$$\lambda_B = 2\, n\, \Lambda \quad (1)$$

λ_B free space in which the central wavelength of incoming light that is reflected from the Bragg grating will be an effective refractive index n fiber core at a wavelength Space Centre is free and Λ is the periodicity of the grid index Bragg. Applied load on a grid showing the stress/strain on a fiber optic linked to the object. Bragg changes the distance networks and an optical stress change due to changes in the refractive index is expressed as "(2)".

$$\Lambda\lambda_B = \lambda_B\,(1 - Pe)\,\varepsilon \quad (2)$$

where ε is the coefficient of elasticity and Pe an effective optical stress coefficient is defined as "(3)".

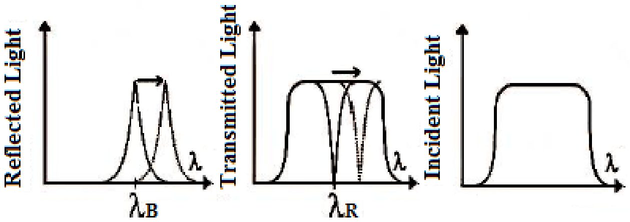

Figure 4. The comparison of Reflected, Transmitted and Incident Wavelengths in FBG sensor

$$Pe = n^2/2[P2 - v(P1 - P2)] \quad (3)$$

$P1$ and $P2$ in which the optical stress sensor element, n is the core index and v is Poisson rate. Asked for optical fiber $P1$ = 0.11, $P2$ = 0.25, v = 0.16 and n = 1.48, respectively. Using the Pe, the "(4)" is obtained.

$$\Lambda\lambda_B = (0.30)\lambda_B\, \varepsilon \quad (4)$$

Change $\Lambda\lambda_B$ when the pressure was detected on the fiber and the relationship between the measured pressure and $\Lambda\lambda_B$ that can be used in applications related to protection against pressure [5].

Installation of FBG sensor in a typical steel reinforced concrete structure is shown in Figure 5.

Figure 5. Installation of FBG sensor in a typical steel reinforced concrete structure

Each ship propeller load and movement are great and all vibrations along the walls, causing compression and changing port and docks along the Quay Wall bearing capacity [5]-[9]. In this research work FBG sensing elements with expert system has been used as a modern class of measurement system for structural health monitoring in civil infrastructures. The core problems focus on reliable FBG sensors with metallic casing and the high frequency, high accuracy and precision with distinguished cost effective characteristic.

This practical research work shows that FBG sensors have become one of the key sensors in structural condition monitoring and will take the place of some conventional electrical sensors.

In this work, the performances of a few commercially available alternative solutions, based on fiber Bragg-grating were tested and directly compared both in laboratory and in field conditions. The results are presented and discussed using specially designed and fabricated remotely operated vehicle (ROV) as an external sources of localized vibration on the subsea portion of the suspected quay wall, aiming at the assessment of generalization the main characteristics of this technology for conditioning the quay wall and other similar types of structural health monitoring applications, and also taking into account the principal requirements of in-field civil engineering applications. The effectiveness of proposed monitoring method based on long-gauge sensors is validated through an application on a quay wall in the Shahid Rajaee port of I.R. Iran.

III. APPLICATION OF KNOWLEDGE & RULE-BASED SYSTEM

In general the knowledge and rule based systems built in to an expert system may initiate and begin from the many origins and resources [9]-[10]. The preliminary resources of knowledge and rules for developing an expert system should be the domain expert [11]. To design, develop and construct the knowledge and rule based expert system, the specific knowledge domain or the subject domain is acquired with respect to the process of data accusation system. In this regard information related to healthy structures and probable error or faulty materials and structures are compared well before the analyzing the final knowledge domain. The knowledge domain is formed and stabilized so that the information algorithm can be shaped and constructed in the computer program for efficient and impressive utilization.

Taking the above consideration in to account, a knowledge administer and constructor obtains the knowledge through direct interaction with the process expert. To extract knowledge from the expert the knowledge engineer must become familiar with problem of vibration and strain analysis of structures. Figure 6 summarized the proposed methodology process of expert system in the FBG sensing and health monitoring network.

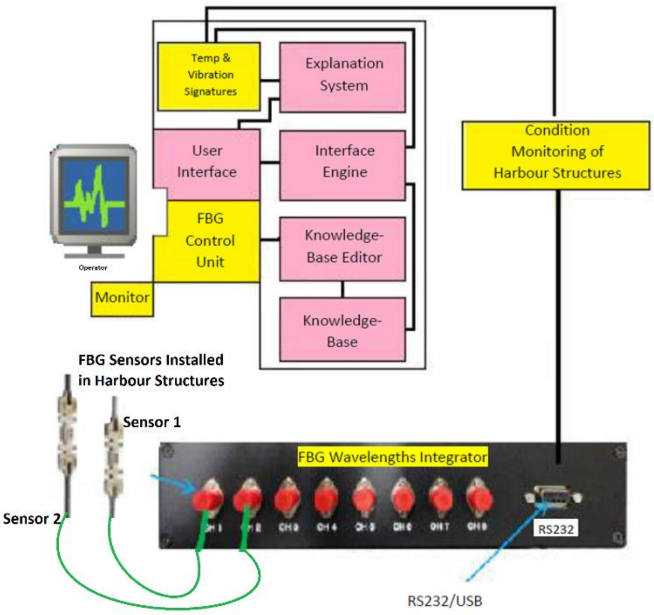

Figure 6. The most important FBG module of proposed rule-based expert system

The rule base system is goal driven using back ward chaining strategy to test the trueness of collected structure vibration and acoustic properties information which are in the form of wavelength deformation as stated earlier. The output data of the user interface when the typical strain imposed to the FBG sensor connected with channel 1/8 of integrator is depicted in Figure 7.

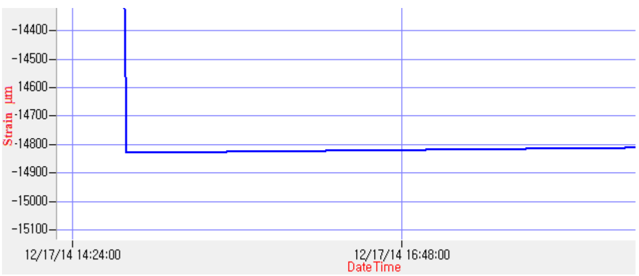

Figure 7. Output data of the "User Interface" software when the typical strain in cluding temperature sensed using the first (1/8) FBG sensor connected through channel 1/8

The case specific data plus the information obtained through proposed model i.e. Figure 6, with the help of explanation subsystem, allows the program to explain its reasoning to the user and will provide the expert system shell requirements. Significant difference can exist between the signals created by subsea concrete defects [12]. The respective wavelength deformation of the mentioned signals may exceed each other in a different way in repeated measurements of the same specimen in comparison with the different FBG sensors. This device serves as a base for development of expert system monitoring module [13].

Figure 8 shows the variation of strain when the proposed expert system analyzed the data using one of the eight sensors connected to the channel 1 of the integrator. The application of proposed expert system using FBG sensor calibrating the imposed temperature is shown in Figure 9.

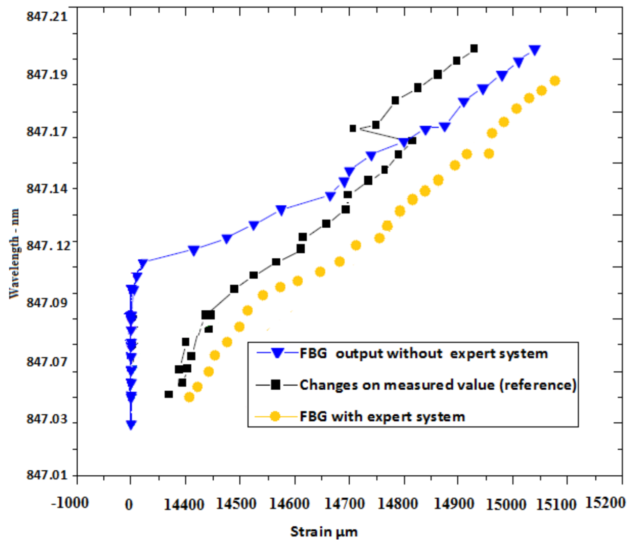

Figure 8. Typical comparison of the expert system output with direct FBG output

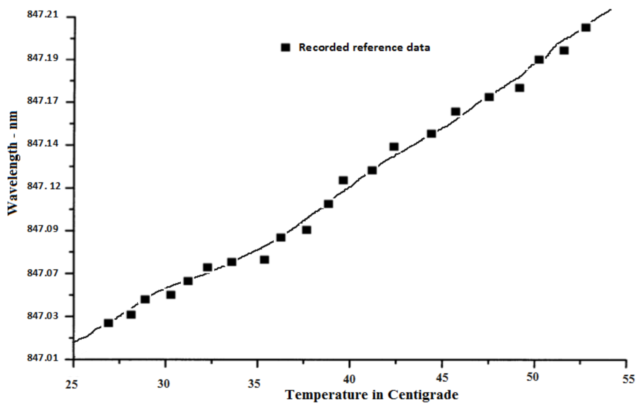

Figure 9. Typical comparison of the expert system output against FBG exposed to the temperature

IV. CONCLUSIONS AND REMARKS

In this research work FBG sensor along with proposed expert system has been used as an advance method of non-destructive testing and health monitoring particularly in the large composite and concrete civil infrastructures. The core problems focus on the novel proposed expert system using FBG sensors application. As a new method of measuring algorithm and sensor application for structural health monitoring system, Popularization and generalization of FBG and analysis of measured data is still a challenge for researchers.

This research work shows that FBG sensors have become one of the key sensors in structural health monitoring (SHM) in offshore and onshore structures and will take the place of many types of conventional electrical sensors.

In this work, the performances of a proposed solution, based on expert fiber Bragg-grating were tested and directly compared both the results of indoor laboratory validation and application of sensors on the quay wall structure which is the output of health monitoring system at Shahid Rajaee port in the] Persian Gulf, southern part of Iran. The outcome and consequences are deliberated and discussed, intending at the assessment of generalization the main attributes and properties characteristics of proposed expert system and FBG technology for quay wall and other similar types of SHM applications, and also taking into account the principal requirements in-field of civil engineering applications. The capability and productivity of the proposed measuring and monitoring system based on long-gauge sensors is illustrated and tested through an application of ROV based vibrator mechanism at the Shahid Rajaee port in Iran. For developing the present expert system, the knowledge domain is organized so that the information can be structured in the computer program for effective use and originated from source of knowledge should be the domain expert. To design and develop knowledge based expert system, the specific knowledge domain or the subject domain is acquired. In the proposed scheme the alteration and modification of reference FBGs signal with expert system, conclude that the normal condition of interior section of construction, structure or mechanism has changed or deformed and therefore the diagnosis is conformed.

REFERENCES

[1] W. Li, C. Xu, S. Ho, B. Wang, and G. Song, “Monitoring Concrete Deterioration Due to Reinforcement Corrosion by Integrating Acoustic Emission and FBG Strain Measurements,” Sensors, vol. 17, no. 3, p. 657, Mar. 2017.

[2] M. R. Hedayati, A. A. Amidian, S. A. Sadr, and A. Razazan, “Intelligent Ship Hull Inspection and NDT Using ROV Based Flux Leakage Expert System,” 2010 Second International Conference on Computational Intelligence, Modelling and Simulation, Sep. 2010.

[3] S. Mahadevan, V. Agarwal, K. Neal, D. Kosson, and D. Adams, “Interim Report on Concrete Degradation Mechanisms and Online Monitoring Techniques,” Sep. 2014.

[4] P. F. da Costa Antunes, H. F. T. Lima, N. J. Alberto, H. Rodrigues, P. M. F. Pinto, J. de Lemos Pinto, R. N. Nogueira, H. Varum, A. G. Costa, and P. S. de Brito Andre, “Optical Fiber Accelerometer System for Structural Dynamic Monitoring,” IEEE Sensors Journal, vol. 9, no. 11, pp. 1347–1354, Nov. 2009.

[5] M. Veldhuis, "Monitoring of Harbour Structures in The Netherlands," fift European Conference on Structural Control, June, 2012.

[6] Leslie Der Zhuang, Wong “Utilising Hydraulic Transient Excitations for SHM of pipeline with Distributed Optical Fiber Sensing” Doctor of Philosophy thesis, Monash University, Clayton Victoria, Australia Sep, 2016.

[7] A. F. Obaton, G. Laffont, C. Wang, A. Allard, and P. Ferdinand, “Tilted Fibre Bragg Gratings and Phase Sensitive-Optical Low Coherence Interferometry for refractometry and liquid level sensing,” Sensors and Actuators A: Physical, vol. 189, pp. 451–458, Jan. 2013.

[8] S. Javadpour and M. Hedayati, "traffic monitoring system parameters and external road in remote areas using radio frequency (RFID) And sensor Network Bragg grating (FBG)," in The First Congress on Intelligent Transportation Systems (ITS), Jan, 2013.

[9] M. R. Hedayati, A. A. Amidian, S. A. Sadr, and A. Razazan, “Intelligent Ship Hull Inspection and NDT Using ROV Based Flux Leakage Expert System,” 2010 Second International Conference on Computational Intelligence, Modelling and Simulation, Sep. 2010.

[10] C. Chin, “fiber-optic smart structures for monitoring and managing the health of transportation infrastructures,” Project Report, Apr. 2010

[11] X. Qiao, Z. Shao, W. Bao, and Q. Rong, “Fiber Bragg Grating Sensors for the Oil Industry,” Sensors, vol. 17, no. 3, p. 429, Feb. 2017.

[12] S. C. Ryu and P. E. Dupont, “FBG-based shape sensing tubes for continuum robots,” 2014 IEEE International Conference on Robotics and Automation (ICRA), May 2014.

[13] M. Nicolas, R. Sullivan, and W. Richards, “Large Scale Applications Using FBG Sensors: Determination of In-Flight Loads and Shape of a Composite Aircraft Wing,” Aerospace, vol. 3, no. 3, p. 18, Jun. 2016.

[14] X. Guo, W. Li, W. Wang, and X. Feng, “Development and Application of Fiber Bragg Grating Clinometer,” IOP Conference Series: Materials Science and Engineering, vol. 205, p. 012033, Jun. 2017.

Assistant Professor Dr. Mohammad Reza Hedayati obtained his MTech. & PhD in electrical engineering from IIT, Banaras Hindu University, India. At present he is faculty member of Communication department and deputy of research and education at Scientific-Applied Faculty of Telecommunication (Ministry of ICT) in Iran. He was assigned the position of the Dean of Faculty of Eng. at Islamic Azad University Tehran North Branch and also Central Branch in Tehran Iran. His main research interests include subsea NDTs including fabrication and application of Fiber Brag Grating sensors (FBGs) and fabrication and implementation of underwater remotely operated vehicle (ROV) in different subsea projects which particularly emphasized in the field of oil and gas exploration in Persian Gulf, Iran and health monitoring and assessment of near to shore constructions like quay walls.

Dr. Ali Asghar Amidian received his BS degree from K.N Tooosi University of Technology Tehran in 1986, and his PhD from Laval University, Quebec, Canada in 2002 in Telecommunication Engineering. Since 2003 he joined to the faculty of applied Science of Communication as an Assistant Professor and faculty member of Sharif University of Technology. He worked as Director General of Training Center of Telecommunication of Iran and many other governmental positions. Dr. Amidian has published a number of research papers and academic books.

Mohammad Hossein Amiri received his BTech in Information & Communication Technology (ICT-Optical communication) from Faculty of Applied Science of Post and Telecommunication and MSc in Electrical Communication Engineering from Islamic Azad University Tehran North Branch. He worked on optical sensors Fiber Bragg Grating (FBG) for more than six years in different national projects.

Fatemeh Khodadadi was born in Iran 1984. She received the MSc software engineering from university of Hertfordshire, UK, in 2013 and BSc Software Engineering from Azad University, Iran, 2008. Her main area of interest is computing and Data analysis.