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Structural Health Monitoring in Changing Environmental Conditions using Macro-strain measurement

N.H.M. Kamrujjaman Serker[1] and Z.S. Wu[1]
1 Department of Urban & Civil Engineering, Ibaraki University, Hitachi, Japan

ABSTRACT: In this paper, a new structural health monitoring (SHM) strategy based on the data sensed by long-gage fiber Bragg grating (FBG) sensors in changing environmental conditions is presented. The main concept of the proposed damage identification technique is that the ratio of the modal macro strain (MMS) between two measurement locations is constant for a certain condition of the structure and is independent of the magnitude and location of the load. Therefore, damage can be identified in a certain zone of a structure from the change in the MMS ratio. Two important issues regarding civil SHM, localized damage and changing environmental conditions, are discussed here and the proposed damage identification strategy treats these factors. The proposed SHM technique was implemented to a highway bridge in Japan and the obtained results shows the potentials for the long-term SHM.

1 INTRODUCTION

Structural health monitoring (SHM) is an active field of research aimed at detecting, localizing and assessing the extent of damage in a structure so that its remaining life can be known and possibly extended. Development of new sensing technologies, sophisticated data analysis systems and damage identification algorithms has directed SHM to the present on-line monitoring approach. Recently, SHM is being implemented all over the world to increase the safety and integrity of civil, mechanical as well as aeronautical structures (Ko and Ni, 2005). Most SHM research to date has focused the application of modal parameters using structural dynamic responses or the static load and deflection measurements. However, for the monitoring of bridges, actual and future trends in this domain are the use of vibration signals under ambient, unknown excitation due to wind or traffic and the use of very large arrays of sensors. Concerning civil structures, some critical issues are presently facing the development of health monitoring systems including: (1) large size of the structure, (2) the damage is usually localized and (3) structural responses are affected by the variation in the environmental parameters as well as the operational conditions.

Vibration-based global SHM techniques use typical acceleration measurements to obtain structural modal parameters which are too "global" to detect the damage that is an intrinsically local phenomenon in structures. Traditional local inspections are sometimes effective but cost and labor-intensive. Moreover, large structures with inaccessible critical components limits the application of local inspection, therefore, the integrated information for the overall structure may not be obtained. Strain sensing has been proved to reflect the local behavior change of the structure. However, it is so "local" that the influence of damage on strain measurement cannot be reflected effectively unless the area where strain sensor is fixed covers the damaged region. Therefore, to detect arbitrary and unforeseen damage in a large and complex structure, strain sensors have to be installed in a distributed way. Conventional electrical strain gages which are of very small gage length compared to the size of the structure to be monitored can not serve this purpose and strain sensors with long gage length and distributed sensing capacity is required to meet the purpose. Recent developments in the fiber optic sensing technology have opened the door of distributed sensing with gage length up to several meters. (Li and Wu, 2007)

In last few years, several field and laboratory experiments have been carried out to investigate the variability in modal parameters due to the change in environmental conditions. Among the large number of environmental parameters, temperature change is considered to be the most responsible for the variation in structural modal parameters. Current literature survey reveals that the modal frequencies can be varied up to 10% only due to the environmental temperature change (Rohrmann *et al.*, 2000). However, the effect of temperature on mode shapes has been reported as non-significant. In addition, through numerical studies Serker and Wu (2007) showed that some of the proposed vibration based damage identification techniques can not localize the damage successfully, especially, when the damage degree is low. Recently some techniques have been proposed to consider or filter out the environmental temperature effect for structural damage identification. Most of these techniques consider the modal frequencies, most sensitive to temperature change among the modal parameters, as the damage sensitive parameter. This paper is aimed at presenting a new approach for damage identification in civil engineering structures based on data sensed by the distributed long-gage fiber Bragg grating (FBG) sensors under the varying environmental condition.

2 DISTRIBUTED LONG-GAGE FIBER OPTIC SENSING SYSTEM

Long-gage FBG sensors developed at the Structural Engineering and Dynamics laboratory of Ibaraki University, Japan (Li and Wu, 2007) was deployed as the sensing device for the distributed dynamic strain sensing, as shown in Figure 1. In spite of high precision and excellent dynamic measuring ability, the ordinary FBG faces an unfavorable problem is that its inherent gauge length is around 1-2cm, which makes FBG work as a traditional "point" strain gauge and difficult for distributed placement. After special packaging the gage length was extended to 1.0 meter by using a tube to sleeve the optical fiber and then fixing at two ends of the tube. For a general long-gage sensor, the in-tube fiber has the same mechanical behavior and hence the strain transferred from the shift of Bragg center wavelength represents the uniform average strain or the macro-strain over the sensor gauge length (Figure 1(a)). A FBG sensors array for distributed macro-strain measurements can be achieved after connecting the long-gage sensors in series as shown in Figure 1(b). In addition, the macro-strain from long-gage FBG sensors is related with rotational displacements. The most important feature is that macro-strain measurements are very sensitive to damage and can be directly applied for damage detection with no requirement for a detailed analytical model.

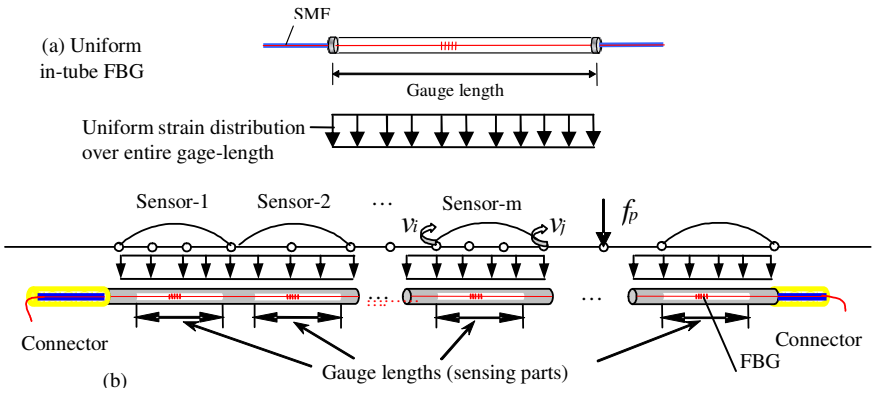

Figure 1. Long-gage FBG sensors array

3 DAMAGE IDENTIFICATION STRATEGY IN CHANGING ENVIRONMENTAL CONDITIONS

3.1 Damage Detection using the Modal Macro Strain-ratio (MMSR)

A very simple but effective way of detecting damage using the macro strain is presented in this section. The basic concept of the proposed damage detection technique (Figure 2(a)) is that the ratio of strains measured at two different locations under a certain loading configuration is constant.

$$\frac{\varepsilon_i}{\varepsilon_R} = k_i \tag{1}$$

where ε_i and ε_R are respectively the strains measured at a distance x_i and x_R from the same reference, k_i is a constant whose value depends on the location of the measurements. Similarly, the strain ratio between a damaged section and the undamaged reference section can be written as

$$\frac{\varepsilon_i^*}{\varepsilon_R} = \frac{1}{\beta} k_i \tag{2}$$

where ε_i^* is the strain at location x_i after damage, β $(0 \le \beta \le 1)$ is the ratio of the effective flexural rigidities at damaged and intact conditions. It is apparent from Equations (1) and (2) that the damage can be identified from the change in the strain ratio. The above relationship is valid for a single point time invariant loading and it is possible to generalize the concept by replacing the strain with modal macro strain (MMS), δ_{ar}, which can be obtained from the macro-strain modal analysis (Li and Wu, 2008). To conceptualize MMS, the macro-strain modal analysis is described here in brief. Consider a beam-like structure installed with a series of long-gage FBG sensors distributed over the length and each sensor covers at least one element (Figure 2(b)). The average strain or the macro-strain, $\bar{\varepsilon}$, over any sensor with a gage length L_m, can be obtained from the rotational displacement with a reasonable assumption that at each element the distance from the inertia axis to the bottom of the beam where sensors are to be installed is the same.

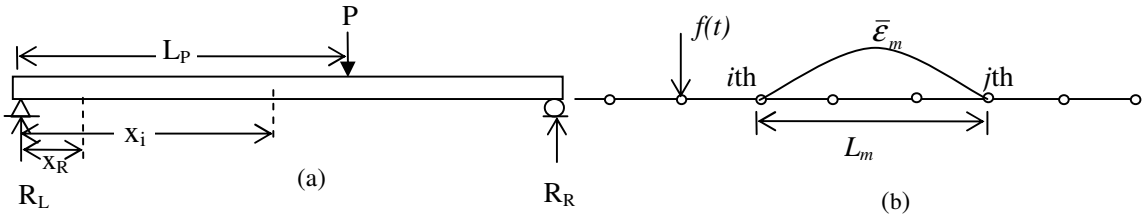

Figure 2. (a) Fundamentals of the strain-ratio approach (b) beam structure model

$$\bar{\varepsilon}_m(t) = \frac{h_m}{L_m}[\theta_i(t) - \theta_j(t)] \tag{3}$$

or, in the frequency domain,

$$\bar{\varepsilon}_m(\omega) = \frac{h_m}{L_m}[\theta_i(\omega) - \theta_j(\omega)] \tag{4}$$

where h_i is the distance measured from the neutral axis of the beam to the sensor location. θ_i and θ_j are the rotational displacements of the m^{th} sensor at i^{th} and j^{th} node respectively.
The macro-strain FRF, $H_{ip}^{\bar{\varepsilon}}$, between the measurement from the i^{th} sensor and the excitation at the p^{th} DOF can be achieved by

$$H_{mp}^{\bar{\varepsilon}}(\omega) = \frac{\bar{\varepsilon}_m(\omega)}{P_p(\omega)} \tag{5}$$

Submitting Equation (4) into Equation (5) with $\eta_m = h_m / L_m$

$$H_{mp}^{\bar{\varepsilon}} = \eta_m . \frac{\theta_i(\omega) - \theta_j(\omega)}{P_p(\omega)} = \eta_m \left(H_{ip}^{d}(\omega) - H_{jp}^{d}(\omega) \right) \tag{6}$$

where H_{ip}^{d} and H_{jp}^{d} are the displacement FRFs at the *i*th and *j*th DOF. Equation (6) can be further expressed as:

$$H_{mp}^{\bar{\varepsilon}} = \sum \frac{{}_r A_{mp}^{\bar{\varepsilon}}}{\omega_r^2 - \omega^2 + 2j\xi_r\omega_r\omega} \tag{7}$$

in which the macro-strain modal constant can be written as

$${}_r A_{mp}^{\bar{\varepsilon}} = \frac{\varphi_{pr}}{M_r}\delta_{mr} \tag{8}$$

and $$\delta_{mr} = \eta_m \left(\varphi_{ir} - \varphi_{jr} \right) \tag{9}$$

is the modal macro-strain at m^{th} sensor under the r^{th} mode.

Therefore, by replacing the strain measurement with MMS, Equation (1) can be modified and modal macro strain ratio can be obtained as

$$\frac{\delta_{ar}^{t_1}}{\delta_{Rr}^{t_1}} = \frac{\delta_{ar}^{t_2}}{\delta_{Rr}^{t_2}} = \text{.....} = \frac{\delta_{ar}^{t_m}}{\delta_{Rr}^{t_m}} \tag{10}$$

If more than one mode is used

$$\frac{\sum_{r=1}^{N}\delta_{ar}^{t_1}}{\sum_{r=1}^{N}\delta_{Rr}^{t_1}} = \frac{\sum_{r=1}^{N}\delta_{ar}^{t_2}}{\sum_{r=1}^{N}\delta_{Rr}^{t_2}} = \text{.....} = \frac{\sum_{r=1}^{N}\delta_{ar}^{t_m}}{\sum_{r=1}^{N}\delta_{Rr}^{t_m}} \tag{11}$$

where $\delta_{ar}^{t_m}$ and $\delta_{Rr}^{t_m}$ are the MMS obtained from the measurement of macro-strain data at any time t_m at a target and a reference location respectively. N is the number of mode.

3.2 Application of the MMSR for SHM in Changing Environmental Conditions

The damage detection technique is presented graphically in Figure 3. In this approach, features (MMS) will be extracted from the measurement over a period of time. Next, the extracted feature of a target location will be plotted against that of a reference location. It is obvious from Equation (10) that all data points of the feature plot lie on a same line for every condition of the structure. However, every structure experiences the varying operational and environmental conditions during its life which may cause some variation in the extracted features. It is expected that only structural damages can cause a significant and permanent change in the local as well as global behavior of the structure. Statistical approaches can be incorporated to account for the variability in the measured responses due to changing environmental condition.

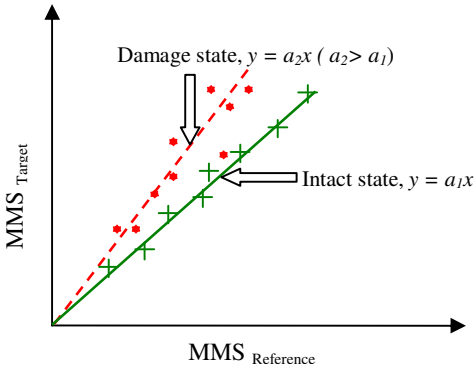

Figure 3. SHM in a changing operational and environmental condition

Let the extracted features of a target zone and the reference zone for a set of measurements follow a linear variation and can be expressed as

$$M_{Target} = a_1 * M_{Reference} \tag{12}$$

where a is the slope of the regression, M_{Target} and $M_{Reference}$ are the extracted features from a target zone and a reference zone respectively. Let the statistical model for another set of measurement for a target zone be

$$M_{Target} = a_2 * M_{Reference} \quad (13)$$

From Equation (2) it is obvious that damage causes an increase in the value of the strain ratio. Therefore, damage is likely to be present if the regression line shift to new position with an increased slope i.e. $a_2 > a_1$.

4 EXPERIMENTAL RESULTS FROM KAWANE BRIDGE

The Kawane Bridge, shown in Figure 4, is located in Ibaraki Prefecture, Japan. It is approximately aligned in the north south direction. This RC bridge, constructed in 1963, has six independent spans and each span consists of a concrete deck supported by four girders. The roadway, carrying two traffic lanes, in a span is 6.5 m wide and 21.3 m long. Along the length of each span, five cross-beams are equally spaced. No damage was observed during the visual inspection of the bridge. To investigate the effectiveness of the proposed damage identification technique, the measurement data on Kawane Bridge is considered for assessment. Six long-gage FBG sensors of gage-length 1.0 meter have been installed on one interior girder of the bridge. Details of the sensor installation are shown in Figure 4.

4.1 Monitoring Results

Experimental results obtained from the Kawane Bridge due to the normal traffic are presented here. The Bridge is located on the approach road to an expressway. Therefore, the traffic is significantly composed of passenger cars, though the bridge also serves for heavy trucks. Response data due to movement of passenger cars as well as small and heavy trucks was collected randomly. In addition, the collected response was due to the vehicles on just each lane as well as on both lanes. The sampling rate of data collection was different for different days. The sampling frequency was between 250 and 1000 Hz. The first data set was collected on August-19, 2008. The second and third data set were obtained respectively on September 17 and 18, 2008. The first and second data collection days were clear and sunny. The weather on the third data collection day was different and it was raining during the data collection period. Air temperature was recorded using a digital thermometer. The average air temperature on the 1st, 2nd and 3rd data collection day was recorded as 27.3^{o}C, 26.4^{o}C and 23.3^{o}C, respectively. First mode frequency of the bridge was obtained as 4.81, 4.91 and 5.02 Hz, respectively on August 19, Sept 17 and Sept 18, 2008.

MMS was extracted from the measured macro-strain responses. Scatter plots of the obtained results are shown in Figure 5. Sensor F7 was selected as the reference sensor. The slopes and R^2 values are listed in Table 1. It is obvious from Table 1 that the extracted features from different sensors are in good agreement with that of the reference sensor. By considering the measurement data of August 19, 2008 as the reference data set, the corresponding fit lines regarded as the reference to make some comparison among the results extracted from three different data sets. From Figure 5 and Table 1, it can be seen that there is no significant change in the slope of the fit lines of different zones. However, slight frequency shifts were observed from day to day measurements. Visual inspection reveals no damage in the bridge. Therefore, the shifting of the first mode frequency is due to the environmental changes.

5 CONCLUSIONS

In this paper, a new SHM strategy based on the data sensed by long-gage distributed FBG sensors in changing environmental and operational conditions is presented. Experimental results from a highway bridge in Japan are presented as feasibility proof of the proposed technique. All data was collected under the ambient traffic condition as well as in different environmental conditions. In addition, some change in the first modal frequency was noticed from daily measurements. Visual inspection reveals that the experimental bridge is in healthy condition. The experimental results using the proposed approach confirmed the same. However, the reference model for damage identification should be calibrated using a large number of data set.

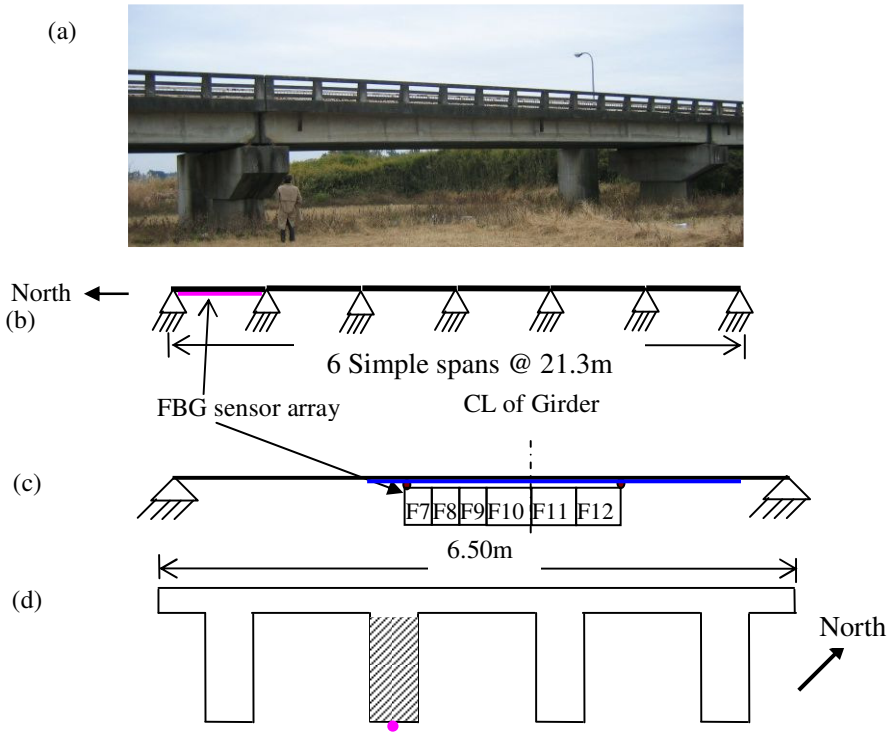

Figure 4. (a) A view of the Kawnae Bridge (b) line diagram of a girder (c) FBG sensors installed (d) cross section of the bridge

Table 1. Slope and R^2 values of the fit lines

Sensing zone	Date of Experiment					
	August-19		September-17		September-18	
	Slope	R^2	Slope	R^2	Slope	R^2
F8	1.08	0.998	1.08	0.997	1.09	0.993
F9	1.10	0.997	1.10	0.995	1.09	0.985
F10	1.18	0.997	1.18	0.996	1.19	0.987
F11	1.19	0.997	1.20	0.996	1.18	0.987
F12	1.14	0.996	1.12	0.993	1.14	0.984

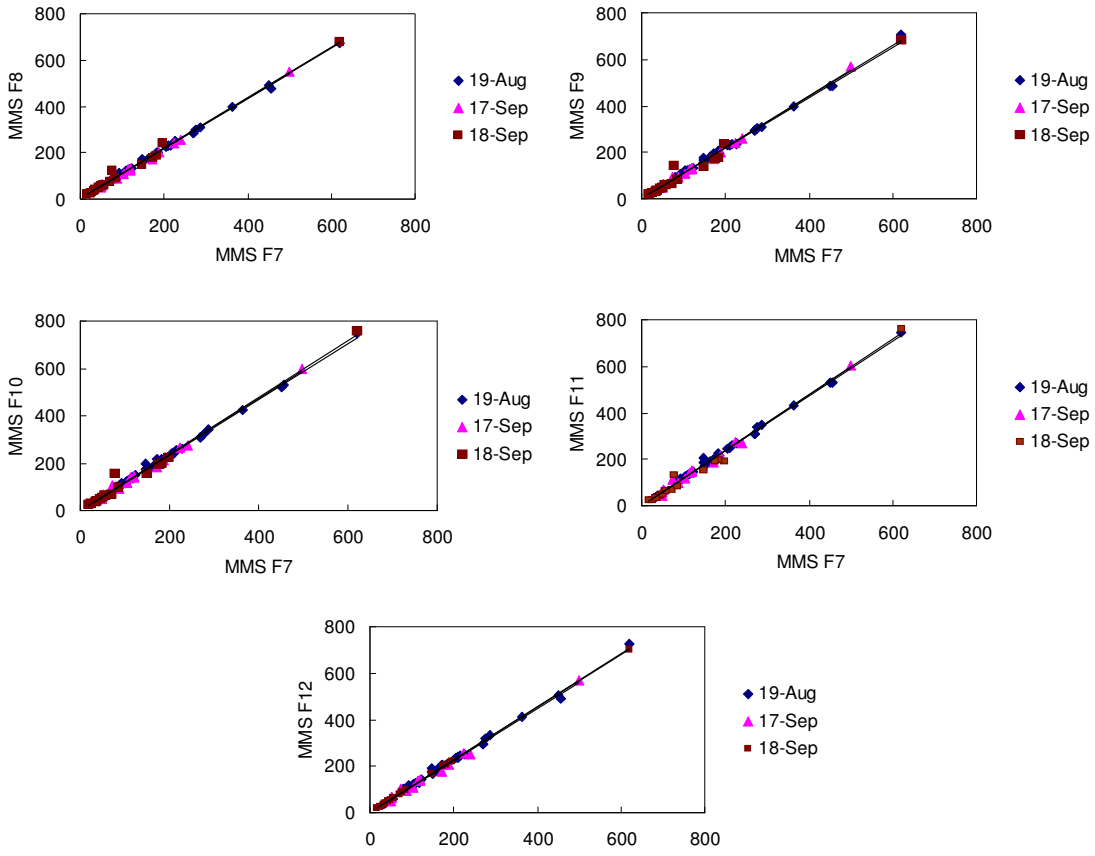

Figure 5. Monitoring results from Kawane Bridge

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