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EXPERIMENTAL TESTS ON LOCAL DAMAGE DETECTION USING OPTICAL FBG SENSORS

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In this study, the fiber Bragg grating (FBG)-sensor based local damage detection method is proposed under circumstances with temperature and external loading variations. To compensate the environmental effects, principal component analysis (PCA) is utilized and also the performance of PCA is compared with that of the conventional linear adaptive filter (LF) model. Laboratory tests with a 1/20 scale model of a jacket-type offshore structure with six jacket-legs and a heavy super structure have been carried out for investigating the performance of the proposed damage detection method. From the experimental tests, it is observed that the local damage feature is mostly hidden and difficult to identify due to the environmental effects. By utilizing the conventional LF and PCA models, the effects of the undesirable environmental effects can be efficiently eliminated, and it is also found that the performances of the LF and PCA models are very similar and competitive to each other. However PCA model does not require the information on the temperature and external load variations, hence it can be concluded that the PCA-based local damage detection can be more efficiently applied for FBG-based local damage detection under temperature and external loading variations.

Keywords: Linear adaptive filter, Principal component analysis, Environmental effects, Optical sensors.

1 INTRODUCTION

Jacket-type offshore structures are exposed to high levels of external loads such as waves, wind, earthquakes, ship-berthing impacts, and many kinds of operational loads. Moreover, maintenance, repair, and rehabilitation works for offshore structures are much more difficult than for large land-based infrastructures due to the difficulty of access and the inherent characteristics of harsh offshore environments. Therefore, preventative management is very important for achieving a sufficient level of structural safety and operational serviceability for offshore structures, and structural health monitoring (SHM) systems with reliable sensors and data processing units can play an important role in preventative management.

Many recent SHM-related studies on large scale infrastructures are focusing on the utilization of smart sensors such as MFC and FBG sensors to monitor structural health and detect structural damages. In particular, the FBG sensors for jacket-type structures are very useful and also important for evaluating the possibility of fatigue damages at locally distributed failure critical members due to the excessive vibrations and severe external loadings (Chan *et al*. 2006, Hill *et al*. 1978, Inaudi *et al*. 1998, Meltz *et al*.

1989, Udd, 1995). Although it is important to understand the effect of FBG sensor signals on structural conditions, these characteristics are also heavily governed by environmental changes including temperatures and external loadings, as well as structural conditions. Therefore, the environmental effects on sensor signals are now being very intensively investigated and discussed among structural health monitoring societies.

To compensate the effects of environmental changes, two different filter models, i.e. the LF and PCA models, are utilized in this study. More details on these two models can be found in many references (Ding and He 2004, Jolliffe 2002, Moore 1981, Sohn *et al*. 1999). And the damage detection method is developed using the trace of the residuals between predicted and measured sensor signals from the FBG sensors.

2 EXPERIMENTAL STUDY

Laboratory tests were carried out to investigate the proposed damage detection algorithms using optical FBG sensors with a 1/20 scaled model of Uldolmok tidal current power plant as shown in Figure 1. To simulate the periodically exciting tidal current loading on the structure in horizontal direction with about 12 hours period which is a main external loading, static horizontal loads with a maximum 3 kN was applied as shown in Figure 2. The temperature was changed between 18.9 – 31.8°C to consider the environmental effects on optical FBG sensor signals and also the damage detection algorithms. 9 FBG sensors were instrumented for measuring static strain responses at distributed 9 points on the column legs and additional temperature compensating FBG sensor were also installed at point a as shown in Figure 2. Sensors 4, 8, and 9 were mainly laid in the tensile stress under external horizontal loading while sensors 1, 2, 3, 5, and 6 were under compressive stress condition.

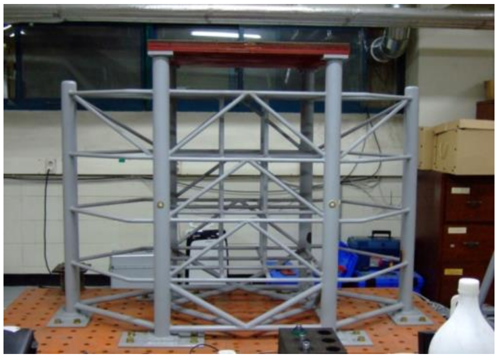


Figure 1. 1/20 lab-scaled steel jacket test structure.

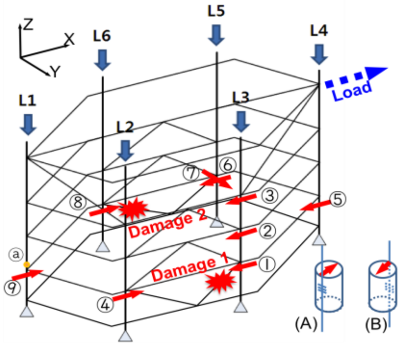
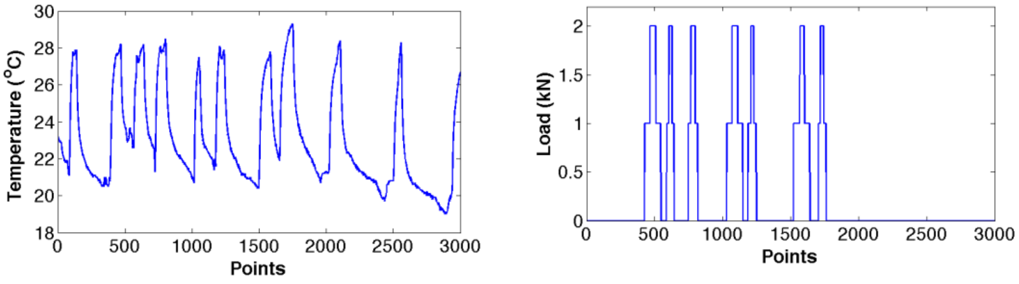


Figure 2. FBG sensor and damage locations.

FBG sensor signals were measured with ambient temperature every 5 minutes for about one month of experiemntal period under various temperatuer and static loading conditions (see Figure 3). For evaluating the damage detection performance of the proposed algorithms, two different damage scenarios were considered. Damage Case 1 is simulating 20% of sectional area reduction daamge in a main diagonal memebr near Sensor 1 and Damage Case 2 is simulating similar area reduction in the member near

Sensor 8 in the opposite location for Damage Case 1. As seen in Figure 4, the damage-induced signal change is much smaller than the change according to the changes in temperatur and loading conditions, therefore it is very difficult to distinguish the damge occurance time from the measured signals.



(a) Temperature variations (b) External loads

Figure 3. Environmental Changes.

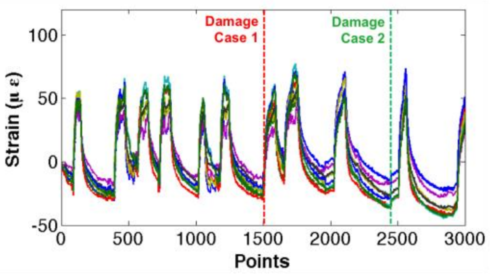


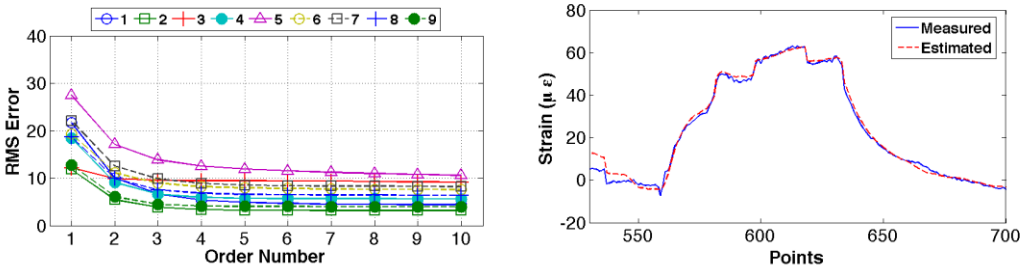
Figure 4. Measured data from the FBG sensors.

3 ELIMINATION OF ENVIRONMENTAL EFFECTS UNDER INTACT CASE

LF model is applied to the raw FBG signals to obtain the prediction model using response signals in the intact case with loading information which is usually difficult to measure directly from sensors. Figure 5 shows the verification on the prediction model with temperature and loading condition. RMS errors are gradually reduced as model order is increased up to the model order of 4 as shown in Figure 5(a), which means that the model order of 4 is optimal number for the linear adaptive filter model used in this study. Figure 5(b) shows the comparisons between measured and estimated strain data at Sensor 1 for the number of model order of 4, and it can be observed that the estimated strain data are fitted well.

Figure 6 shows the relationship between principal components (PCs) and environmental changes. In this study, totally 9 PCs are obtained by PCA and Figures 6(a) and 6(b) show the comparison results between 1st PC of measured signals and temperature and between the 2nd PC and external loads, respectively, and it can be obviously found that the 1st PC is highly correlated with temperature change while the

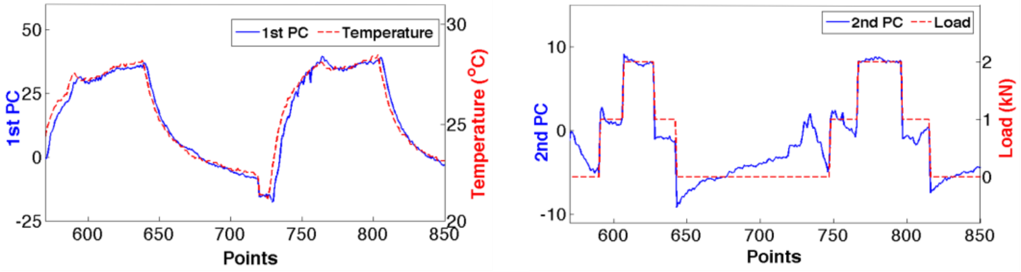
2nd PC is also significantly correlated with external loads. The correlation coefficients (CCs) between two PCs and environmental changes are summarized as in Figure 7, and it is found that the only 1st PC has very high CC value with respect to the temperature change while both of 1st and 2nd PCs have relatively high CC values with external loads. It is noticed that the environmental effects are mainly included in the lower 2 PCs, i.e., the 1st and 2nd PCs, and it can be expected that the damage-sensitive feature can be obtained from the remaining PCs such as summation from the 3rd to the 9th PCs.



(a) RMS error between measured and estimated data at each node

(b) Comparison between measured and estimated data at Node 1 (order number n=4)

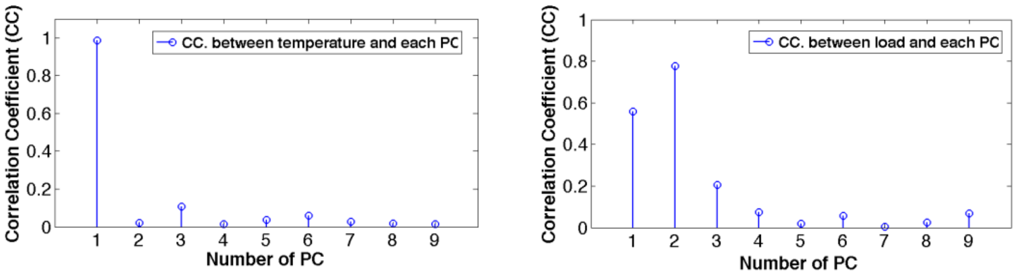
Figure 5. Verification of a model considering both of temperature and external loads.



(a) 1st PC vs. temperature

(b) 2nd PC vs. external load

Figure 6. Comparison between each PC from Node 1 and environmental changes (zoomed).



CC between temperature and PCs

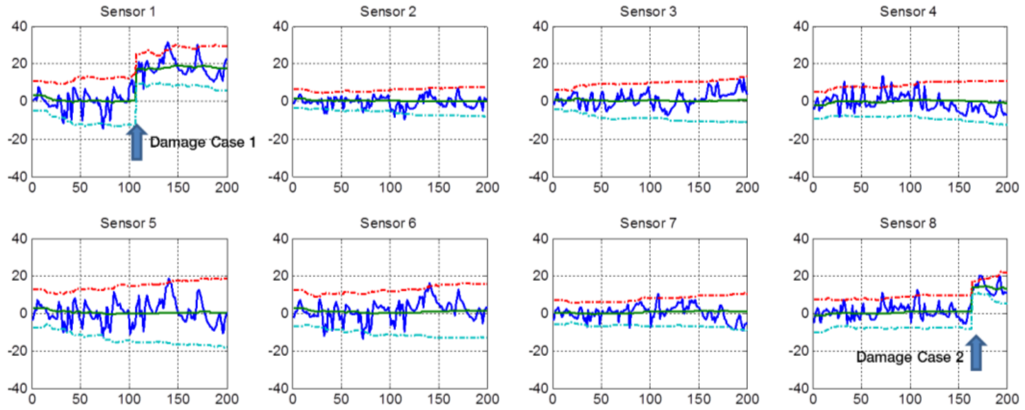
CC between external load and PCs

Figure 7. Correlation coefficients between environmental changes and principal components.

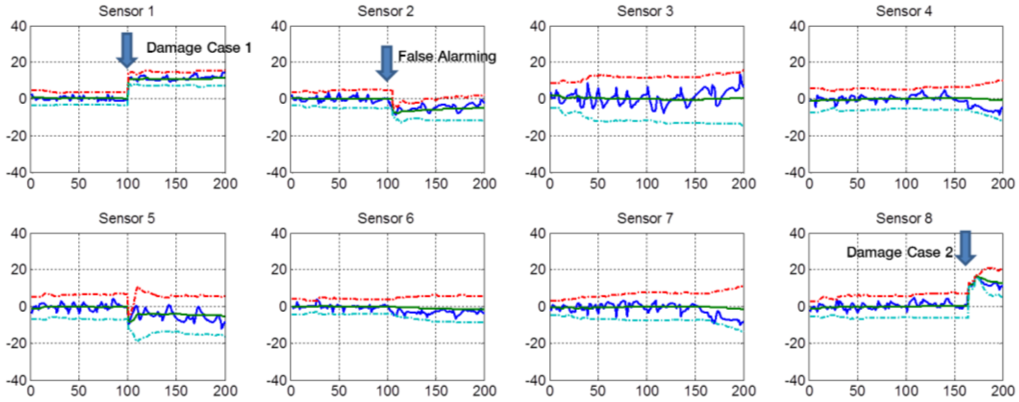
4 DAMAGE DETECTION RESULTS

Figure 8 shows the damage detection results using the LF and the PCA Models. The dotted lines represent the upper and lower threshold values and the solid line represents the mean of mean residual values. It can be observed that the inflicted Damage Cases 1 and 2 are successfully detected by both different Models and there is no false alarming error in the results of the linear adaptive filter model while one false alarming error in the PCA model. This false alarming error in PCA model can be less significant than damage missing error in the conservative-concept point of view.

The gap between lower and upper threshold values for Sensor 3 is relatively larger than other cases, which means that responses from Sensor 3 is highly noise-contaminated and unreliable. It can also be observed that the gaps between thresholds for PCA Model is relatively smaller than those for linear adaptive filter models, which means that the environmental effects including temperature and external load changes are more efficiently eliminated by using PCA Model.



(a) Linear Adaptive Filter Model



(b) PCA Model

Figure 8. Damage Detection Results Using Three Different Models.

5 CONCLUSION

In this study, two different filter models were applied to eliminate the effects of environmental changes contained in the measured signals from FBG sensors and the LF and PCA models are found to be very efficient for this purpose. And the residuals between estimated and measured sensor signals were utilized as damage indicator and two artificially inflicted damages are successfully identified using the proposed FBG-based damage detection method with two different filter models. Even though there is one false alarming error in PCA model, it can be concluded that the PCA model is more efficiently utilized for damage detection because PCA model do not require the environmental information, especially on external loads which are usually very difficult to measure directly.

Acknowledgements

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