Application of Optical Fiber Sensors for Structural Monitoring and Control

K.C. Chang, T.K. Lin and Y.B. Lin

ABSTRACT

Experimental result of a full scale-steel frame with a smart active control system under shaking table test has been carried out in this paper. Newly, the concept of smart structure has been broached to the extent of structure control. The NEURO-FBG control system, which is composed of both neural networks and fiber Bragg grating sensors, has been theoretically analyzed and simulated to effectively control the structure under the strike of arbitrary earthquake. However, the feasibility of implementing the NEURO-FBG control system in actual structure is not yet proven.

To this intention, a full-scale steel frame with the NEURO-FBG control system is examined by earthquakes simulated from a 5x5 shaking table. Minute schedule with several representative earthquakes is arranged to appraise the performance and robustness of the NEURO-FBG control system. As expected, signals detected from fiber Bragg grating (FBG) sensors have shown their superior characteristics in structure surveillance than conventional strain gauges. Moreover, experimental data recorded from earthquake excitation have also demonstrated the benefit of using NEURO-FBG control system than traditional active control. The results have demonstrated that the NEURO-FBG control system can be applied to buildings after the whole testing process.
INTRODUCTION

Active control, basing on its charmingly interactive characteristics, has pour new energy to the realm of structure control over the last decade. Unlike the numerous restrictions such as achievability of damping ratio, serviceability and prospective consideration of the architecture in passive control, hydraulic actuators with proper control force can effectively and rapidly alleviate the excitation caused by whether quake or wind. Accompanying with this basic concept, large amount of optimal control theory in calculating the control force have been proposed. The linear optimal control, pole assignment, independent model space control, instantaneous optimal control, pulse control and predictive control are the most reprehensive ones among them. [1-6]

Although these control theories have been numerically demonstrated to control the structure effectively, the implementation of active control is still bothered by some serious problem. Among these annoying conditions, the time delay problem and the reliability problem are the most common ones occurred in practical situation. The inherent time delay caused by hydraulic actuator may be largely accumulated when the building faces long-duration earthquake excitation.[7 ]Therefore, the structure system may become instable and diverse instantaneously. On the other hand, due to the high power output of actuator, the reliability of active control system also needs to be considered more carefully than that of passive control system. Any unexpected condition should be evaluated carefully before installing the control device into a practical building thus the control system will not be the inhabitant's nightmare someday.

With these uncertainties and difficulties, most of the researches seem to focus on developing a new control theory. Only few of them have been implemented in practical experiment and most of the works were also confined in the small-size specimen. Therefore, it might be impossible to evaluate the actual performance of any proposed control theory when it is applied to a practical building. In order to demonstrate the advantages of the proposed smart control system in practice, a smart control system, composed of the NEURO-FBG CONVERTERs and NEURO-CONTROLLER, were applied on a full-size three-story specimen in National Center for Research on Earthquake Engineering(NCREE) and all the experimental procedure and results will be carried out in this paper.
NEURO-FBG CONTROL SYSTEM

The complete concept of the proposed NEURO-FBG control system is shown in the block diagram as Figure 1. As the definition of smart structure, there are three parts in the block diagram: the structure surveillance system, the NEURO-FBG CONVERTERs and the NEURO-FBG CONTROLLER. The left-hand part is the structure surveillance system with the optical fiber network and the right-hand sides are the NEURO-FBG CONVERTERs. The NEURO-FBG CONTROLLER, which connects the sensors and the buildings, locates in the bottom of the diagram.

By distributing sensors as many as possible in the important parts of buildings, FBG sensors can be applied in structure scrutiny as well as representing the dendrites for both NEURO-FBG CONVERTERs and NEURO-FBG CONTROLLER. These FBG sensors can detect the response of the structure element almost simultaneously with huge numbers and simplified wires when the structure is subjected to ruinous excitations. Therefore, the structure damage can be rapidly assessed after these strikes.

Furthermore, structure response can be alleviated by the system of NEURO-FBG CONVERTERs and NEURO-FBG CONTROLLER. With the support of the NEURO-FBG CONVERTERs, a broad viewpoint in the time domain can be obtained. The NEURO-FBG CONVERTER can convert local FBG sensor readings into global
system indices and the NEURO-FBG CONTROLLER, built under the aid of the CONVERTER, can then control the structure as designed.

That is, the NEURO-FBG CONTROLLER is far different from the traditional active control by integrating the smart structure concept. Besides reducing the structural response during the external excitation such as earthquake or wind, structural serviceability and comfort of the residents are also considered in the design of NEURO-FBG control system. In other words, the health condition of the structure can be easily monitored by the FBG-based system.

EXPERIMENTAL RESULTS

The structure surveillance system

Twelve FBG sensors, installed on the full scale specimen, has comprised a perfect structure surveillance system in the form of network to monitor the health condition of the building. By taking the advantages of optical fiber communication technology, these FBG sensors were simply stringed by an optical fiber and a clear data flow can be simultaneously obtained.

In order to demonstrate the superior characteristic of the FBG-based surveillance system as described in theory, this system was then examined experimentally by comparing with the data collected from the RSG-based system. Both of the systems were operated under several typical earthquake excitations with different level of PGA values and the results are depicted below. With these arrangements, the assorted PGA values can be used to evaluate the influence of the inevitable noise fluctuation contained in the measured data.

The whole time history of the twelve FBG sensors under El Centro earthquake excitation with PGA value 100 gal is shown in Figure 2. Due to the symmetrical distribution of these sensors in two steel columns, whether the tensional mode is participated can be easily examined by the recorded data. It is shown that the time histories of FBG1 and FBG 7, which should present similar responses under only longitude-direction excitation, have reflected approximate records during the experimental disturbance. This phenomenon has prove the feasibility of simplifying the whole specimen as a 3-degree-of-freedom building in the longitude direction and each set
of the six FBG sensors on different columns can be used as the feedback source for the smart control system.
For the monitoring function of the system, the sensor readings under different scale of PGA values are also compared. As analyzed, the responses of each sensor should be kept in a proportional relationship under different PGA values when the behavior of structure remains linear. In other words, the distributed sensors can easily be used to detect if inelasticity has occurred in any part of the specimen and the replacement of the component can be considered.

**NEURO-FBG CONTROLLER**

The NEURO-FBG CONTROLLER, which is the most important part of the smart control system, was applied on the specimen for alleviating the structural response under earthquake. To elaborately evaluate its performance, the specimen protected by the developed NEURO-FBG CONTROLLER was excited by several different ground excitations under various PGA scale. This experimental schedule can be used to simulate the actual condition of the structure during the strike of random earthquake. Moreover, to compare the result with those of the uncontrolled building, the specimen with no actuators on it was also tested on the table to its maximum susceptible intensity. These data were then scale up as the controlled cases to represent the bare frame response.

Four different earthquakes were used in the experimental scheme. They are: the El Centro earthquake, Kobe Earthquake, SYL earthquake, and New Hal earthquake. Each of these earthquakes represents the geological characteristics of different quake zone and offers a broader perspective for assessing the smart control system.

**Comparison with LQG Method:**

To emphasize the advantage of using this smart control system, it is necessary to make a comparison between the responses of three conditions including the uncontrolled,
NEURO-FBG CONTROLLER, LQC control.

The comparison of all the control results and control efficiencies is clearly listed in Table 1. The uncontrolled structure response is removed here so that the comparison between these two control methods can be enlarged as detail as possible. It is observe that trends of these two control methods appear to be very close in the experiment. Obviously, one of the advantages of using the proposed smart control system, which is largely improving the control efficiency with the same level control force as other method, was not experimentally implemented and the reason is discussed.

Unlike the prevailing LQG control method, the proposed neural-based control system was firstly applied to a full-size specimen. Though it had been successfully verified by a down-scale model before the experiment, the high-frequency control force generated by the NEURO-FBG CONTROLLER based on purely theoretical analysis during ambient vibration still caused the unstable situation. Thereby, Choice between the system stability and optimal control force became an annoying dilemma. To solve this problem temporarily, the control efficiency was sacrificed. The NEURO-FBG CONTROLLER was downgraded its performance for the successful process of the experiment. However, even with this situation, the out performance of NEURO-FBG control system still worked well and this research will keep on improving the system to its optimal performance in the future.

<table>
<thead>
<tr>
<th>El Centro Earthquake</th>
<th>Uncontrolled</th>
<th>NEUR-FBG CONTROLLER</th>
<th>Control efficiency</th>
<th>LQG control</th>
<th>Control efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative displacement(mm)</td>
<td>3rd floor</td>
<td>65.587</td>
<td>32.341</td>
<td>50.69%</td>
<td>37.92</td>
</tr>
<tr>
<td>2nd floor</td>
<td>49.412</td>
<td>25.444</td>
<td>48.51%</td>
<td>14.858</td>
<td>69.93%</td>
</tr>
<tr>
<td>1st floor</td>
<td>25.774</td>
<td>15.974</td>
<td>38.02%</td>
<td>14.858</td>
<td>42.35%</td>
</tr>
</tbody>
</table>

| Absolute acceleration (g) | 3rd floor | 0.4 | 0.26 | 35.00% | 0.260 | 35.00% |
| 2nd floor | 0.278 | 0.22 | 20.86% | 0.212 | 23.74% |
| 1st floor | 0.299 | 0.255 | 14.72% | 0.225 | 24.75% |

<table>
<thead>
<tr>
<th>SYL Earthquake</th>
<th>Uncontrolled</th>
<th>NEUR-FBG CONTROLLER</th>
<th>Control efficiency</th>
<th>LQG control</th>
<th>Control efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative displacement(mm)</td>
<td>3rd floor</td>
<td>105.188</td>
<td>57.222</td>
<td>45.60%</td>
<td>52.594</td>
</tr>
<tr>
<td>2nd floor</td>
<td>75.358</td>
<td>43.585</td>
<td>42.16%</td>
<td>37.679</td>
<td>50.00%</td>
</tr>
<tr>
<td>1st floor</td>
<td>38.037</td>
<td>21.841</td>
<td>42.58%</td>
<td>19.018</td>
<td>50.00%</td>
</tr>
<tr>
<td>Absolute acceleration(g)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>--------------------------</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>3rd floor</strong></td>
<td>0.846</td>
<td>0.355</td>
<td>58.04%</td>
<td>0.316</td>
<td>62.65%</td>
</tr>
<tr>
<td><strong>2nd floor</strong></td>
<td>0.642</td>
<td>0.240</td>
<td>62.62%</td>
<td>0.316</td>
<td>50.78%</td>
</tr>
<tr>
<td><strong>1st floor</strong></td>
<td>0.536</td>
<td>0.281</td>
<td>47.57%</td>
<td>0.207</td>
<td>61.38%</td>
</tr>
</tbody>
</table>

**CONCLUDING REMARKS**

A full-size smart active control system based on both neural networks and optical fiber sensors has been implemented. To demonstrate the superior advantages shown in the theoretical analysis, the practical performance of the structure surveillance system, the NEURO CONVERTERs and the NEURO-FBG CONTROLLER were examined by a shaking table test.

In the first part, the surveillance system composed of twelve FBG sensors showed its outstanding performance in monitoring structure with more precise resolution and the damage condition after any strike can be easily assessed. Meanwhile, the NEURO CONVERTERs were also trained by data collected from the surveillance system installed on the steel structure. After establishing these NEURO CONVERTERS, they were evaluated by using several different excitations. The results have given good compatibility with theoretical analysis and demonstrated the feasibility of using NEURO CONVERTERs in the active control field.

Moreover, the final NEURO-FBG CONTROLLER was finished and a full-size structure experiment was done on the shaking table in NCREE. Four different earthquakes were used to evaluate the performance of the NEURO-FBG CONTROLLER and the results were compared with the LQG control algorithms. Once again the NEURO-FBG CONTROLLER had been proved to be effectively controlling the structure. The structure can be controlled by the NEURO-FBG CONTROLLER in a more smooth and effective way when comparing to the traditional active control.

However, there is still something unsolved. The instability problem during the stand-by step was not jet solved after the experiment and the best performance of the NEURO-FBG CONTROLLER was not realized. There is a belief that the NEUR-FBG CONTROLLER can perform better after solving the problem and the technology of this smart active control can be applied in the near future.
Reference:


