STRUCTURAL HEALTH MONITORING SYSTEM FOR BUILDINGS WITH AUTOMATIC DATA MANAGEMENT SYSTEM

Akira Mita¹, Toshiaki Inamura² and Shiro Yoshikawa²

ABSTRACT

A structural health monitoring system based on MATLAB Web Server is proposed and its prototype system is presented. In addition, a simple networked sensor system to be used for the health monitoring system is also proposed. The system transfers the data automatically through the Internet and is configurable through the network with the help of XML-based data transfer. The system is now under operation.

Keywords: Health monitoring, MATLAB, data management, database

INTRODUCTION

Many researchers have realized the necessity of structural health monitoring (SHM) systems for assessing the health of large structures such as bridges and buildings. However, designers and contractors are kind of reluctant to release the relevant information to third parties. In contrast, the purchasers, users or owners of buildings have been eager to know the safety and reliability of the structures. Thus, the feasible SHM systems should take into account of such a variety of stakeholders. Given these backgrounds, a prototype SHM committee decided to conduct a feasibility study using the SHM system presented in this paper. The system has been developed by Mita laboratory, Keio University and it acquires response data on-line by using automatic sensor systems and upload tools. Eight buildings are currently monitored by the system.

We use the networked sensor system and the MATLAB-based server. The MATLAB Web Server is an ideal deployment tool as Web applications for release of the identified results as we already have many damage detection tools coded for MATLAB. For example, the story stiffness is identified using complex modal properties obtained by numerical algorithm based on subspace state space system identification [Lennart Ljung 1999, Yoshimoto et al. 2005]. This algorithm is implemented to the system.

MATLAB-BASED HEALTH MONITORING SYSTEM

System Outline

The outline of the MATLAB-based health monitoring system is depicted in Figure 1. The response data recorded at a building is automatically transmitted to the server through the Internet when the monitored response exceeds the prescribed trigger level. The trigger setup and other configurations for the sensor system can be done through this server so that the users do not need to configure the sensors at each building. The software architecture for the data transfer and configuration for this networked

¹ Professor, Keio University, Yokohama, Japan, mita@sd.keio.ac.jp
² Former graduate student, Keio University, Yokohama, Japan
The acquired data need to be accompanied with the meta-data that explain the relevant information of the data such as date, location, building name, sensor name, trigger and so on. The minimum information of the data was decided be embedded in the name of the file as denoted by:

\[ \text{sname}_\text{yyyyymmddhhmss}_\text{chname}.txt \]

where:

- **sname**: name of building
- **yyyyymmddhhmss**: year, month, day, hour, minute, second
- **chname**: channel name such as accFLx+
In each file, the physical value of the data at each time step is stored in one column. If the sensor has three outputs, the corresponding number of files should be 3. However, the meta-data embedded in the file name are not enough to identify the nature of the data. We need more meta-data to pinpoint the data needed for evaluation. Thus we should carefully design the data model for the meta-data for quick and rational search of the data. The meta-data other than those included in the file name should be stored with the raw response data. They can be categorized into several groups of meta-data. Each group has certain relations with other groups. The structure of the meta-data to indicate the relationships among groups has an important role for the efficient data search. A typical data model we developed is depicted in Figure 3. In this case, the meta-data are stored in a relational database.

Most of these meta-data are stored in the memories of the sensors in XML formats. They are transferred to the relational database via conversion software. What we would like to achieve in the near future is automatic generation of the sensor database by gathering the sensor meta-data through the network. We are currently testing the mechanism to automatically transfer the meta-data stored in each sensor to the database server including the configurations for each observation. By introducing this system, we do not need manual generation of database. Once sensors are connected to the SHM network, the relevant data are automatically gathered into the database. The change of the configurations is also automatically reflected on the database.

The MATLAB Web Server was employed for data evaluation as shown in Figure 4. The stored data are processed using the applications developed at our laboratory. The MATLAB Web Server bridges web server and MATLAB and works as an API. The applications are combinations of MATLAB m-files, HTML input documents, HTML output documents, and graphics. The applications for health evaluation had been developed to be used off-line. They can be used for the MATLAB Web Server by adding the code to accept input from an HTML input document and to return the results to the HTML output document. Thus, accumulated resources can be effectively used. The MATLAB application resides on the server machine so that the users of health monitoring system do not need to know the MATLAB itself. The users do not need the license individually.

Figure 3. Data model for sensors
Figure 4. MATLAB web server.

PROTOTYPE SYSTEM

Figure 5. Standard tools for data evaluation.

A prototype system was constructed. This time, only one site out of eight buildings has the automatic sensor system. The other buildings use existing monitoring systems so that the selected data were manually uploaded to our server. The system is opened for the authorized users who agreed to the release policies. The system requires the standard authentication process for the access.
Standard Tools

The views on the web-server are listed in Figure 5 for a base-isolated building for the earthquake occurred on July 23, 2005. The standard view tools include time histories, power spectrum densities and coherence functions, transfer functions and parametric system identification using ARX models. Users can arbitrarily set the decimation rate and model orders. From the set of views we can evaluate the health of the building during this moderate earthquake.

Damage Index Example

As an example of damage indexes, the story stiffness of a building was employed. The algorithm used here requires a complex mode shape of any order [2]. Assuming the steady state motion in the depicted mode, the story stiffness is estimated. In order to test the performance of the implemented algorithm, a test structure consisting of four floors shown in Figure 6 was prepared. As the damaged case, four leaf springs used as the columns for the second story were cut at the bottom and top parts. The photo of the damaged leaf springs is shown in Figure 7. Five accelerometers were used to observe acceleration response of all the floors including the base. The modal parameters were identified using the base acceleration as an input and the four acceleration data at each floor as outputs. The subspace identification method was applied for the one-input and four-outputs system. The story stiffness was identified based on those modal parameters. An example of acceleration data in the damaged case is shown in Figure 8.

The estimated natural frequencies and damping ratios are shown in Table 1. We can observe that the 1st natural frequency fell about 7% compared with the healthy case by the damage introduced to the columns on the second floor. On the other hand, for the 2nd natural frequency, there is almost no change between the healthy case and the damaged case. This fact is confirmed from the transfer functions plotted in Figure 9. It is noted that the horizontal axis of the transfer functions is “period(s)” so that the most right peaks indicate the first modes for the healthy and damaged cases. The mode shapes also shown in Figure 9 include the information of the location and the degree of the damage in this structure. The damage degrees identified from the 1st mode and the 2nd mode are plotted in Figure 10. It is clearly understood that the stiffness of the second story was indeed reduced due to the damage. However, the results of the 3rd and 4th stories show the increase of the stiffness. This is not the desired scenario for this case. The method may need more robustness to clearly identify the damaged stories with improved accuracy.

In Figure 11, an example of desired view for showing the damage degree and location is depicted. Although, many sophisticated damage detection algorithms have been developed, complicated indexes are not appropriate for users of the buildings. We need to develop the communication tools to narrow the gaps between professional engineers and the public. The developed MATALB-based health monitoring system can be a promising test bed for verifying the newly proposed or developed damage detection algorithms. The most sophisticated algorithm may not be necessarily the best tool for convincing the public that some danger due to the damage exists in a particular building.

<table>
<thead>
<tr>
<th>MITAL</th>
<th>Healthy Frequency [Hz]</th>
<th>Healthy Damping [%]</th>
<th>Damaged Frequency [Hz]</th>
<th>Damaged Damping [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st mode</td>
<td>1.50</td>
<td>3.2</td>
<td>1.39</td>
<td>2.0</td>
</tr>
<tr>
<td>2nd mode</td>
<td>3.84</td>
<td>3.3</td>
<td>3.82</td>
<td>4.8</td>
</tr>
</tbody>
</table>
Figure 6. Test structure.

Figure 7. Leaf spring (L: healthy, R: damaged).

Figure 8. Time histories obtained from 4-story test model.

Figure 9. Transfer functions and mode shapes for healthy and damaged models.
CONCLUDING REMARKS

A MATLAB-based structural health monitoring system was proposed and its prototype system was developed. The system includes the automatic sensor system that transfers the data from the sensor through the Internet and the configuration of the system can be easily modified. The data transferred by the sensor system is managed by the data server based on the meta-data relevant to the acquired data. The automatic sensor network may contain the configuration data in XML formats to be transferred into the relational database to ease the management of the whole system.

The prototype system provides the standard evaluation tools to show time histories, power spectra, transfer functions and modal information. Though the current system provides the algorithm to locate and quantify the damage in some story, the robustness of the results needs to be improved.

The system presented here is a good test bed to evaluate the damage identification methods and data management algorithms for further promotion of such a system. The system should be evolved to meet the requirements on the public to provide easy understanding of the views for those do not have the engineering knowledge on the structural systems. It is our hope to use the system to make large structures safer and healthier.
REFERENCES
