MONITORING RESULTS OF A SELF-ANCHORED SUSPENSION BRIDGE

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Abstract: Automatic measurement of instrumented civil engineering structures is now widely applied for behavior monitoring during construction in field as well as long-term monitoring for lifetime assessment of bridge structures.
This paper presents schematically the monitoring system installed in Yeongjong Bridge, a self-anchored suspension bridge located in the expressway linking Seoul and Incheon International Airport. Since (1) appropriate instrumentation, (2) reliable signal processing and (3) intelligent information processing constitute the major features to be considered for deploying proper monitoring system, corresponding general guidelines and suggestions are also proposed.
In addition, a representative example of results that can be acquired through structural health monitoring system is presented by means of data measured during 2 years after the opening of the bridge.

Key words: Monitoring system, bridge condition, assessment, health monitoring, sensor

1. INTRODUCTION

Automatic measurement of instrumented civil engineering structures is becoming more common for both diagnostic system identification purpose and in-field behavior monitoring during construction. In order to deploy a successful monitoring system, the required considerations are: proper instrumentation, reliable signal processing and knowledgeable information processing. Since instrumentation, which includes sensory device and data acquisition system (DAQs), obtains raw data from the real structure, sensor

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technology is of critical importance in the development of a monitoring system.

A number of sensor and sensing techniques have been developed in recent years which bear the potential for meeting the eventual need of an automatic monitoring system. These fall into the domain of remote sensing and nondestructive testing. Selection and installation of proper sensors constitute key considerations. Beyond the sensory system itself, some additional facilities need to be located in the field as well as in the control space. These facilities consist of DAQs, temporal data storage device, telecommunication facilities, and other auxiliary devices.

Sensor signal must be processed and interpreted. Immense volume of often noisy signals generated by a multiple-channel sensory should be manipulated concurrently and interpreted intelligently in both hardware and software. The signal processing procedure consists of numerous operations beginning from signal acquisition, generation, to interpretation. In order to assess the current condition of the structure based on signals, called as information processing, it is necessary to devise appropriate computational abstractions and support environments. To develop comprehensive computational environments for these purposes, a model of the information describing the system is required. This model must support a meaningful and computable representation of the components and their complex interrelationships that are characteristic of engineering system, such as physical configurations, sensors, signal processing, and diagnostic knowledge **[1]**.

2. BRIDGE DESCRIPTION

Yeongjong Bridge, completed in November, 2000, is a part of the Incheon International Airport Highway which connects Seoul and Incheon International Airport. Being the first bridge foreign visitors meet when arriving in Korea, particular attention has been paid on its design with unique features such as three-dimensionally profiled suspension cables, self-anchoring, and double decks for both automobile and train traffic.

The last design draft established in 1993 has been reviewed and completed in 1998 to fulfill the revised specifications and improve the structural safety and efficiency of construction. Yeongjong Bridge, shown in Figures 1, is a three-span continuous double deck self-anchored suspension bridge with a center span of 300 m long and side spans of 125 m long. Table 1 summarizes the principal characteristics and dimensions of the bridge.

Figure 1. Overview of Yeongjong Bridge

Table 1. Features of Yeongjong Bridge

Length	550 m (125+300+125 m)
Type of superstructure	Double deck Warren truss (height 12 m, width 35 m) - Upper deck: 6 roadway lanes - Lower deck: 4 roadway + 2 train lanes
Type of pylon	Diamond shaped steel pylon
Type of pylon foundation	Pneumatic caisson foundation
Suspension cable	3D cable (φ467.4 mm @ 14 strands) with dehumidification system - Vertical sag: 60 m - Lateral sag: 13.57 m

3. HEALTH MONITORING SYSTEM OF YEONGJONG BRIDGE

Health monitoring systems in Korea at the very beginning were installed in existing bridges in order to collect field data by full scale load capacity tests for design verification and, subsequently, evaluate the health of the structure. Immediately after the collapse of Seongsu Bridge, this first generation of monitoring systems has been applied in existing bridges, such as Namhae Bridge and Jindo Bridge.

Unlike earlier applications of health monitoring system, where conventional sensors, loggers and transmission methods were used and individual system served each bridge independently, recent systems that are usually adopted in newly built bridges, including Yeongjong Bridge, employ many modern technologies from sensing to processing. And also, an attempt to integrate health monitoring systems of several bridges together has been made in order to reduce the total cost and to increase efficiency of management. This integrated system includes Bridge Management System (BMS) for inspection, evaluation, estimation and rehabilitation **[2]**.

A total of 393 sensors, including static and dynamic strain gauges, and 23 data loggers are distributed over the bridge. The hardware system was designed to remote collect data, and the software system was developed to process data and to display the results in a custom-designed format. The sensors installed in the bridge are categorized based on their locations and physical parameters measuring as listed in Table 2.

Table 2. Description of the sensors installed in Yeongjong Bridge

Category	Measurand	Sensor	Quantity	Location
Load	Temperature	Thermometer	21 ea.	Cable & Deck
			12 ea.	Tower
	Wind Speed/ Dir.	Anemometer	5 ea.	Tower, Cable, Deck
	Earthquake	Accelerometer	3 ea.	Tower foundation
Response	Geometry	Laser Disp. Sensor	5 ea.	Girder
		Potentiometer	4 ea.	Expansion joint
		Tiltmeter	10 ea.	Tower
	Hanger Tension	Accelerometer	12 ea.	Hanger
	Strain	Static Strain Gauge	32 ea.	Anchor bolt
			42 ea.	Deck cross section
			40 ea.	Anchor plate
			8 ea.	Link shoe
		Dyn. Strain Gauge	76 ea.	Deck cross section
			99 ea.	Etc.
	Acceleration	Accelerometer	4 ea.	Tower
			10 ea.	Deck

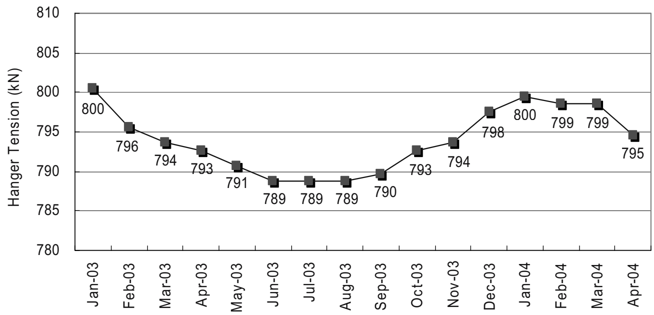
4. HEALTH MONITORING RESULTS

The monitoring system has been completed in 2001 and a huge volume of signals has been collected up to date. These signals were carefully analyzed for verifying the system performance and implementing further use for bridge health assessment. During the system stabilization period, signals showed regular pattern of fluctuation along with the daily and seasonal temperature changes. Some typical signal patterns are described here.

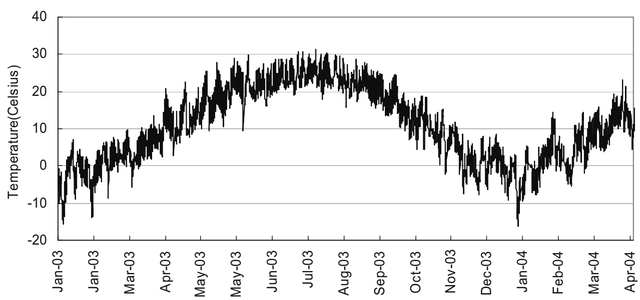
4.1 Hanger Tension Force

Hanger tension forces are obtained using the ideal vibrating chord theory **[3-4]**. As listed in Table 2, accelerometers were mounted on 12 representative hangers to evaluate tension forces. Frequencies computed from responses measured under ambient vibration by these accelerometers were used to obtain tension forces.

No particular trend was observed from the analysis of the tensile force in each of the 12 hangers separately. However, the average of tension force for the whole set of hangers presented similar shape to the fluctuation of ambient temperature, as shown in Figure 2. This average ranged between 789 kN and 800 kN, which corresponds to a variation of ±1.4% compared to the overall mean value.



(a) Averaged hanger tension



(b) Ambient temperature

Figure 2. Averaged hanger tension and ambient temperature observed during 15 months

4.2 Displacement of Expansion Joints

Joint displacements of both ends were seen to be essentially affected by temperature changes. Figure 4 plots the quasi-linear relationship observed between joint displacement and temperature. Displacement of the expansion joints averages 46 mm for a thermal variation of 10°C in ambient temperature.

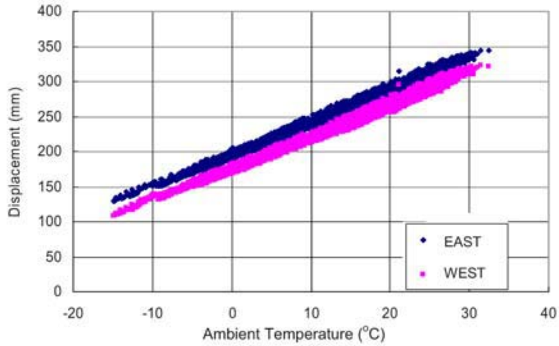


Figure 4. Joint displacement and ambient temperature measured in Yeongjong Bridge

4.3 Vertical and Lateral Displacement of Stiffening Girder

Vertical and lateral displacements at mid span measured by laser displacement sensor presented also the same seasonal pattern according to temperature changes. Vertical bars in the figures represent monthly fluctuation. Fluctuations of the vertical and lateral displacements ranged from –4 to 47 mm and from 2 to 43 mm, respectively.

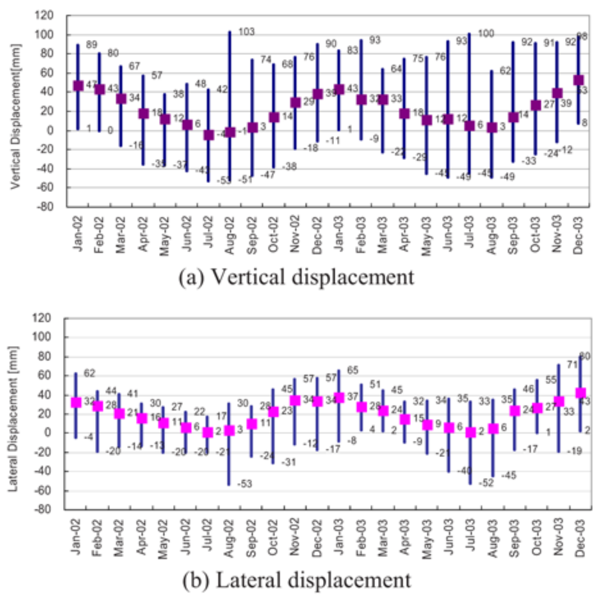


Figure 3. Displacements at mid span observed during 2 years

4.4 Acceleration and Frequencies

Dynamic properties have been analyzed using acceleration data under ambient vibration as shown in Figure 5. Measured frequencies of the 1st and 2nd modes are 0.494 and 0.831 Hz, which show almost no difference compared to the field vibration test results, 0.487 Hz and 0.810 Hz. Since temperature changes have direct influence on the dynamic properties of bridge structure **[5]**, temperature effects on the dynamic properties will be investigated in the future.

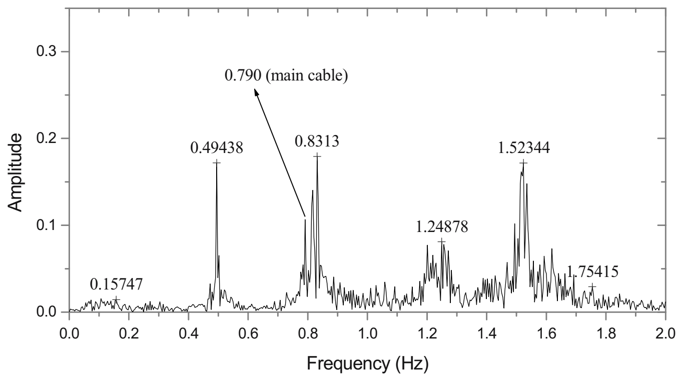


Figure 5. FFT spectrum of ambient acceleration signals measured in Yeongjong Bridge

5. DATA ANALYSIS: CONSIDERATION OF TEMPERATURE EFFECT

In Chapter 4, long-term responses of Yeongjong Bridge were seen to be governed by daily and yearly variations of temperature. Following, researchers aimed the assessment of the actual state of the bridge through the analysis of structural responses regard to temperature.

For this purpose, functional relations between temperature and structural response are defined before analyzing currently measured signals. Structural change or damage is found to occur when measured signals do not agree with the so-predefined temperature-response relationships **[5-6]**. Various kinds of system identification methods including neural networks, statistical method, and optimization method can be employed to construct a mathematical function. Among them, the ARX model, a statistical time series analysis method, is used for Yeongjong Bridge's data analysis.

Figure 6 plots the vertical displacements measured at center span during 30 months from July 2001 until December 2003. It is observed that vertical displacements show a recurrence period of 1 year. Similarly, vertical displacements also show a daily periodicity as seen in Figure 7. Since Figure 6 as well as Figure 7 presents similar patterns to the temperature data shown in Figure 2(b), a strong correlation between temperature and displacement can be expected.

Temperature data measured during 18 months from July 2001 at 18 locations (12 at both pylons, 6 at cables) have been utilized together with the vertical displacement data measured during the same period to construct the ARX model. Then, the constructed ARX model was used to analyze data measured during the remaining 12 months.

The ARX model appeared to simulate closely the new displacement responses as shown in Figure 7. The slight differences between measured and simulated responses, plotted in Figure 8, may be explained by the effects of other loadings like vehicle load that were not considered when constructing the model. Assuming that these differences are normally distributed, evaluation of the health of the structure can be done through threshold values expressed by a mean, standard deviation, and appropriate confidence level. An example of threshold values for 99% confidence ($\mu \pm 2.58\sigma$) is shown in Figure 8. In case measured data exceed the threshold values or biased responses are continuously acquired, investigation should be performed to determine if such errors are caused by dysfunction of sensor, increase of traffic volume or, in worst case, structural change or damage.

When data fall within the confidence range, as shown in Figure 8, it can be assumed that the structure is healthy and that no structural change or damage occurred.

In addition, deflection that does not consider thermal effects (Figure 9) is seen to be produced essentially by traffic loads. Following, comparison of such deflection with the one induced by design loads makes it possible to evaluate the margin or excess of the actual traffic regard to design values.

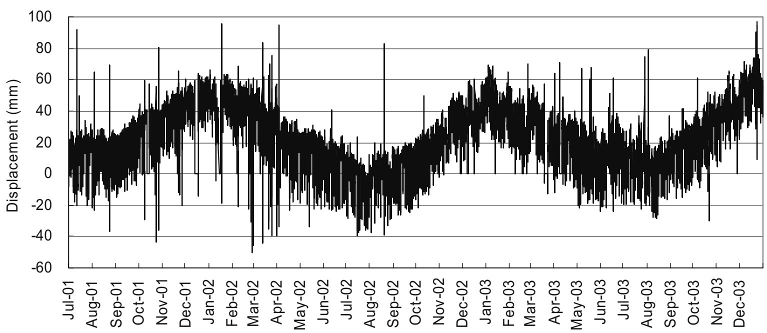


Figure 6. Vertical displacements of center span in Yeongjong Bridge

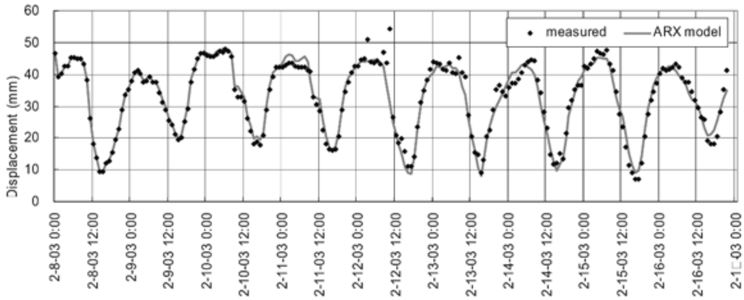


Figure 7. Comparison of displacements computed and measured during 10 days

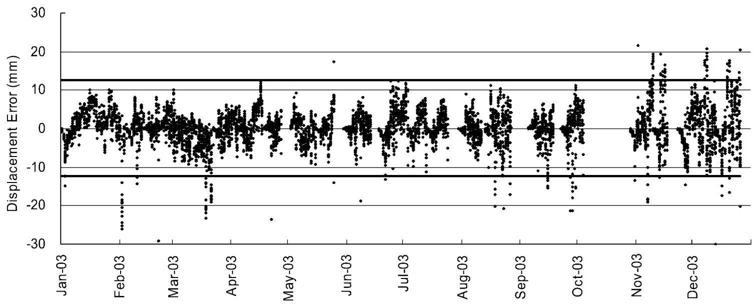


Figure 8. Difference between displacements computed and measured during 1 year

6. CONCLUSIONS

The monitoring system installed in Yeongjong Bridge is an integrated structural health monitoring system which is composed of sensors, data acquisition systems, signal transmission devices, signal control systems, and computer networks. This system has been successfully installed based on a proper development strategy. After its complete installation, test operation was performed on the system during one year, making it possible to stabilize the system and bring several rearrangements and minor changes in its configuration. The stabilized system produced valuable data to be used for health assessment of the bridge. The analysis of measured data verified that the behavior of the bridge is essentially governed by yearly and daily fluctuations of the temperature. Detailed analysis results of current signal data reveal that the bridge behaves as expected. Other research directions have also been addressed to improve future performance of the monitoring system.

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