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Signal Analysis from a Long-Term Bridge Monitoring System in Yongjong Bridge

영종대교 계측시스템의 신호데이터 분석

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국문 요약 >> 영종대교에 설치된 교량 모니터링 시스템의 구성특징을 살펴보고 이로부터 계측, 수집된 각 신호들의 특성을 조사 분석하였다. 3차원 자정식 현수교인 영종대교에 설치, 운영되는 모니터링 시스템의 구성은 *센서-현장하드웨어-광통신망-계측서버-관리자*로 연결되는 자동화된 시스템으로써 개통 이후부터 교량의 거동 및 하중효과를 대변하는 물리량을 측정하고 있다. 이 논문 에서는 시스템의 구성 및 측정항목에 대한 소개와 온도변화에 의한 시그널에의 영향을 감시 할 수 있는 알고리즘의 개발과정을 언급한다. 또한, 행어 케이블의 장력측정 방법의 일환으로 길이가 짧고 장력이 큰 케이블에 대해 정적으로 장력산정이 가능한 장치 및 알고리즘의 개발에 대해 소개한다. 특히 이 교량의 공용중에 이루어진 철도통행을 위한 설비의 추가로 교량 구조계의 변화를 계측 신호를 바탕으로 분석, 제시하였다. 이러한 각종 계측 및 모니터링 결과는 향후 교량의 상태판정의 기본자료로 활용되어 효율적 유지관리를 가능하게 할 것으로 기대된다.

주요어 영종대교, 모니터링 시스템, 장력산정, 구조계 변화

ABSTRACT >> This paper presents schematically the monitoring system installed in Yongjong Bridge, a self-anchored suspension bridge located in the expressway linking Seoul and Incheon International Airport. 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. A representative example of results that can be acquired through structural health monitoring system is presented by means of data measured during a few years after the opening of the bridge. In order to effectively measure the tension force for hangers that have relatively short length or high tension force, a static tension measurement device has been explored. Newly equipped railway system on the existing bridge results in change of dead load, consequently dynamic characteristics have also been changed. This result can be detected by the monitoring system during and after railway construction.

Key words Yongjong Bridge, monitoring system, tension measurement, structural change

1. Introduction

Automatic measurement of instrumented civil engineering structures becomes 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.(1) 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.(2,3)

Unlike earlier applications of health monitoring system, where conventional sensors, loggers and transmission methods were used and individual system served each

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본 논문에 대한 토의를 2007년 2월 28일까지 학회로 보내 주시면 그 결과를 게재하겠습니다.

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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)

Yongjong Bridge Health Monitoring System has been successfully instrumented and operated for 5 years since the bridge has been opened to public in 2000. During the last 5 years of operation, the system has provided meaningful signals in stable manner. Typical measurement results acquired by the system have been briefly introduced in this paper.

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.(4) 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 Yongjong Bridge's data analysis.

Since this bridge experienced severe structural change by newly equipped railway, measured signals from the monitoring system accordingly show changes especially on the dynamic characteristics. This result is also introduced.

2. Monitoring System Configuration

2.1 Bridge Description

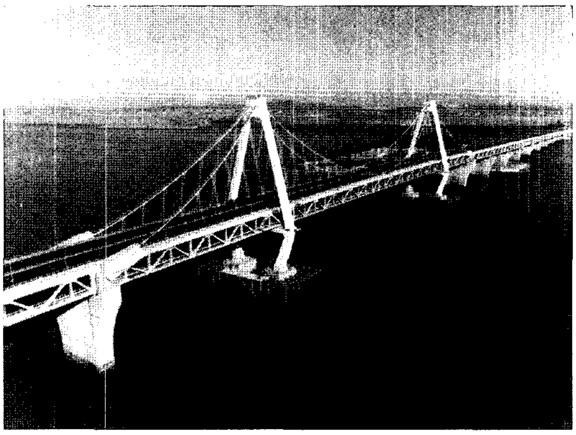
Yongjong Bridge, completed in November 2000, is a part of the Incheon International Airport Highway which connects Seoul and Incheon International Airport. Being the first bridge foreign visitors meet when arriving in Korea, particular attention has been paid on its design with unique features such as 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. Yongjong 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. Figure 2 renders the typical views and dimensions of the bridge.

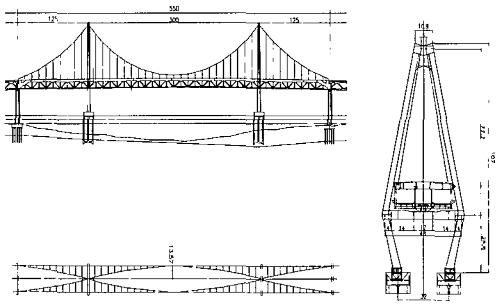
Railway has been constructed in the lower deck after 5 years of bridge operation because of lack of traffic demand and budget situation. As shown in Figure 3, because of newly equipped railway, the dead load of superstructure has increased a total of 19.06 kN/m, which is 3.8% of the total dead load.

2.2 Monitoring System

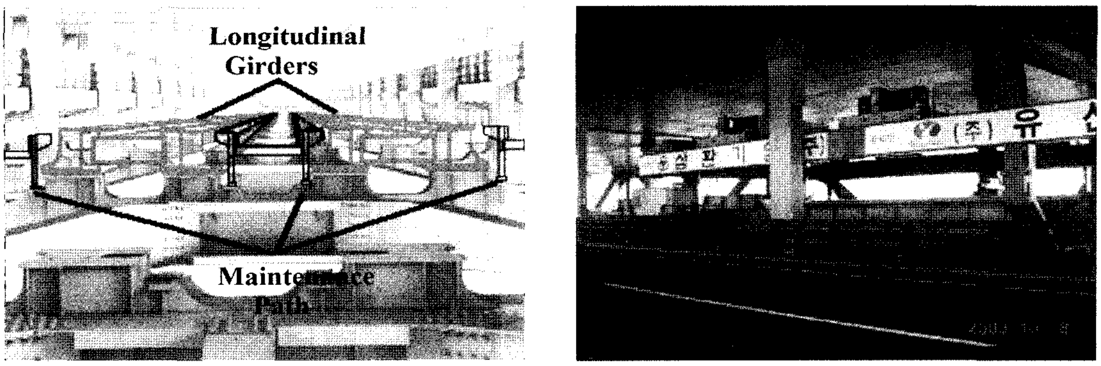
A total of 393 sensors, including static and dynamic strain gauges, and 23 data loggers are distributed over the bridge. The hardware system was designed to collect data remotely, and the software system was developed to



〈Figure 1〉 Overview of Yongjong Bridge.



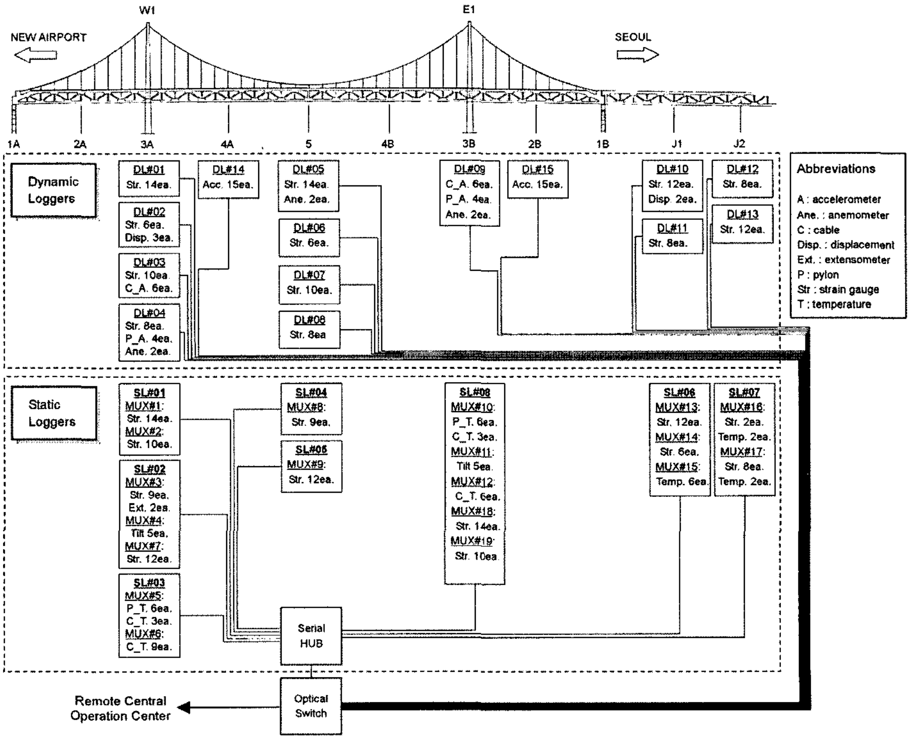
〈Figure 2〉 Typical Dimension (M).



〈Figure 3〉 Railway Construction.

〈Table 1〉 Description of the sensor installation.

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



〈Figure 4〉 Hardware System Configuration.

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 1.

The monitoring system is composed of four parts of subsystems, which are sensors and sensor network, data acquisition system and related accessories, devices for signal transmission, and computer system and control devices in remote operational room. Hardware configurations in bridge field and signal transmission scheme are depicted in Figure 4.(5)

3. 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 during, before and after railway construction are described here.

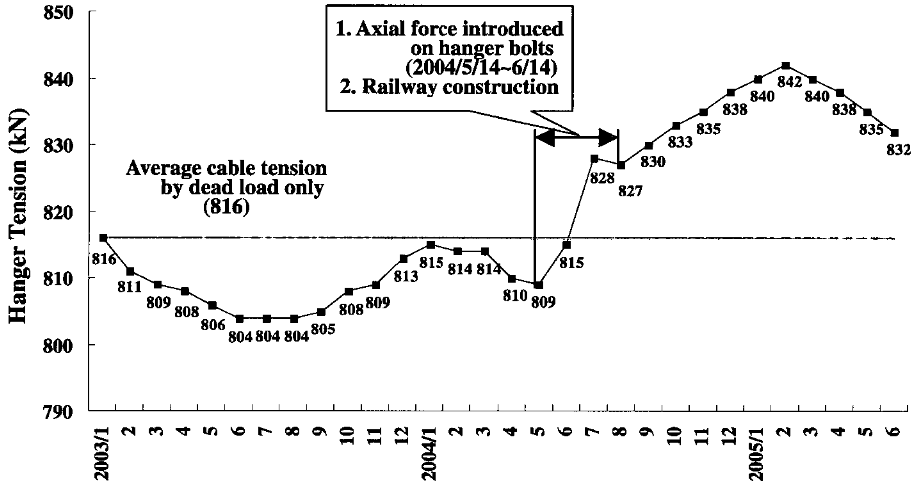
3.1 Hanger Tension Force

Hanger tension forces are obtained using the ideal vibrating chord theory.(6) As listed in Table 1, 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 5. Before railway construction, this average ranged between 789 *kN* and 800 *kN*, which corresponds to a variation of ±1.4% compared to the overall mean value. After completion of railway construction on May 2004, hanger tension has been increased by 2.9% (Table 2).

3.2 Displacement of Expansion Joints

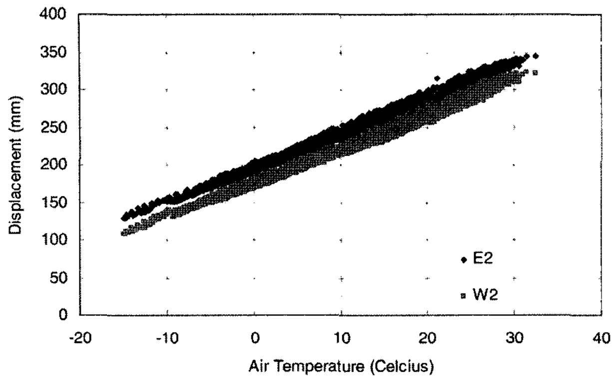
Joint displacements of both ends were seen to be essentially affected by temperature changes. Figure 6 shows the quasi-linear relationship observed between joint displacement and temperature. Displacement of the



<Figure 5> Averaged hanger tension.

<Table 2> Changes of Hanger Tension Force.

	Field Test	From Monitoring System	Numerical Analysis(7)
Change of the Tension Force	+2.55 (Ton)	+2.54 (Ton)	+2.73 (Ton)
Remarks	A total of 32 Hanger cables (8 locations)	12 hanger cables (12 locations)	312 hanger cables (78 locations)

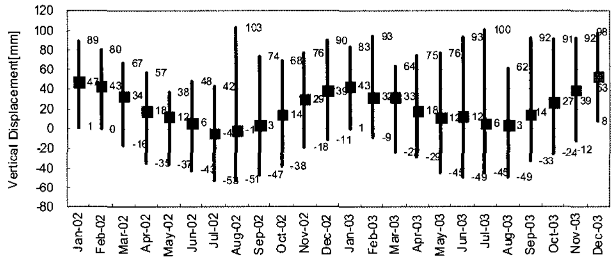


〈Figure 6〉 Joint displacement and ambient temperature.

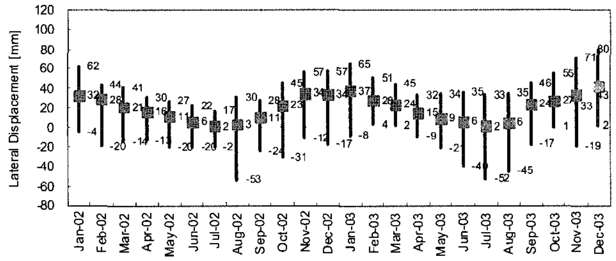
expansion joints averages 46 mm for a thermal variation of 10℃ in ambient temperature.

3.3 Vertical and Lateral Displacement of Stiffening Girder

Vertical and lateral displacements at mid span measured by laser displacement sensor presented 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 as shown in Figure 7. Because of the increased dead load by railway, vertical displacement accordingly increased about 41.4 mm as depicted in Figure 8.



(a) Vertical displacement

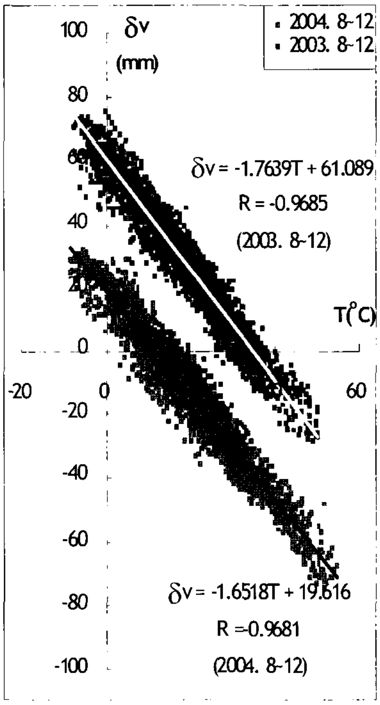


(b) Lateral displacement

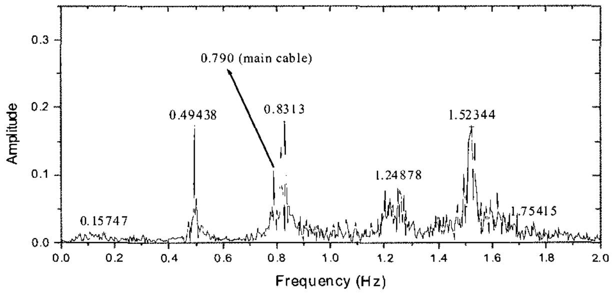
〈Figure 7〉 Displacements at mid span observed during 2 years.

3.4 Acceleration and Frequencies

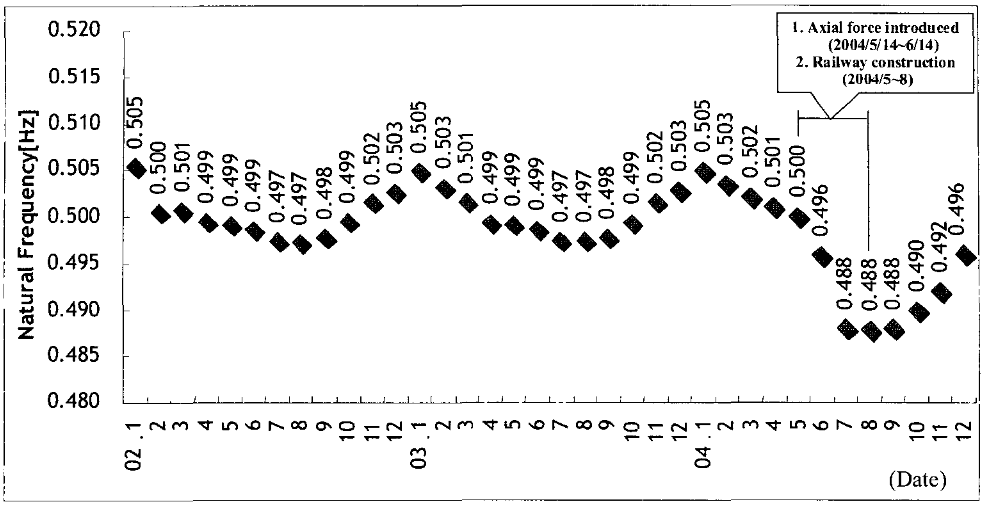
Dynamic properties have been analyzed using acceleration data under ambient vibration as shown in Figure 9. Measured frequencies of the 1st and 2nd modes are 0.494 and 0.831 Hz, which show almost no difference compared to the field vibration test results, 0.487 Hz and 0.810 Hz. The effect on natural frequencies by railway mass addition shows 1.84% decrease for the first bending mode. Since temperature changes have direct influence on the dynamic properties of bridge structure(8), temperature effects on the dynamic properties have been investigated and results are addressed in detail in elsewhere.(9) The change of the natural frequencies of the stiffened girders by the additional railway dead load is listed in Table 3



〈Figure 8〉 Shifting of the Girder Displacement.



〈Figure 9〉 FFT spectrum of the ambient acceleration signals measured.



〈Figure 10〉 Changes of the Natural Frequencies of the Bridge.

〈Table 3〉 Comparison of the Natural Frequencies.

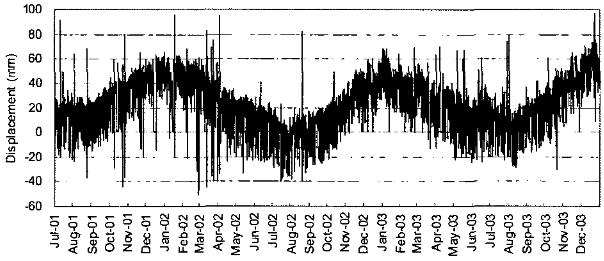
	Modes	From Monitoring System [Hz]	Numerical Analysis [Hz]	Field Test [Hz]
Before Railway Construction	Bending #1	0.498	0.496	0.487
	Bending #2	0.836	0.830	0.810
	Torsional #1	1.074	1.066	1.060
	Torsional #2	1.703	1.705	1.700
After Railway Construction	Bending #1	0.483	0.487	-
	Bending #2	0.817	0.815	-
	Torsional #1	1.057	1.060	-
	Torsional #2	1.698	1.700	-

and Figure 10.

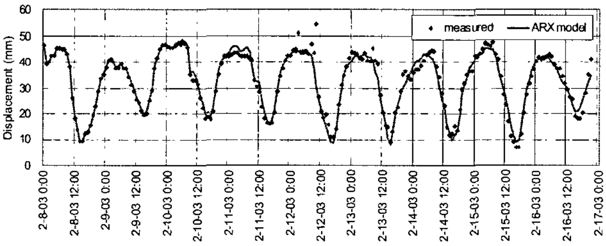
4. Consideration of Temperature Effect

Correlations 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.(4) 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 Yongjong Bridge's data analysis.

Figure 11 depicts 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 12. Since both figures present normal sine curve a strong correlation between temperature and displacement can be expected.



〈Figure 11〉 Vertical displacements of the mid span.



〈Figure 12〉 Comparison of the displacements computed and measured during 10 days.

ARX model consists of 3 components, i.e. auto-regressive output $y(t)$, exogeneous input $u(t)$, and white noise $e(t)$. The First component, auto-regressive output, reflects the property of a dynamic model. The second, exogenous input, explains the external stimuli. The last, white noise, is the equation error term modeling the disturbances that act on the input-output process. So this white noise contains measured disturbances, unmeasured disturbances and measurement noise.

The equation of ARX is

$$y(t)+a_1y(t-1)+\cdots+a_{n_a}y(t-n_a)=b_1u(t-n_k)+b_2u(t-n_k-1)+\cdots+b_{n_b}u(t-n_k-n_b+1)+e(t) \tag{1}$$

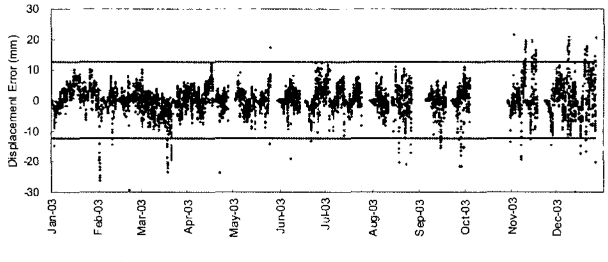
The left side of Eq.(1) contains only auto-regressive output terms, which is the linear combination from an output of the present time t, $y(t)$, to an output of the past n_a steps, $y(t-n_a)$. The right side sums up white noise, $e(t)$, and linear combination of n_b exogenous inputs which have time delay as long as n_k, $u(t-n_k),\cdots,u(t-n_k-n_b+1)$.

As Eq.(1) shows, there are two divisions to be determined in the ARX model. One is the model orders, n_a, n_b, n_k, and the other is a parameter vector, θ, that is defined as following Eq.(2).

$$\theta=\left[a_1\ a_2\ \cdots\ a_{n_a}\ b_1\ b_2\ \cdots\ b_{n_b}\right]^T \tag{2}$$

The parameter vector is usually determined by 'least square method' that minimizes the sum of squared errors between calculated and measured responses. Since the calculation of the parameter vector is straightforward once the order of the model is fixed, determining the order is more important in construction of the ARX model. Inappropriate order of the model can cause improper expression of the system or over-fitting problem. Following methods are frequently used to determine the model orders; Akaike's information theoretical criterion (AIC), Akaike's final prediction error criterion (FPE), Rissanen's minimum description length (MDL) and cross validation.(10)

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.



〈Figure 13〉 Difference between displacements computed and measured during 1 year.

The ARX model appeared to simulate closely the new displacement responses as shown in Figure 12. The slight differences between measured and simulated responses, plotted in Figure 13, 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 13. 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 malfunction of sensor, increase of traffic volume or, in worst case, structural change or damage.

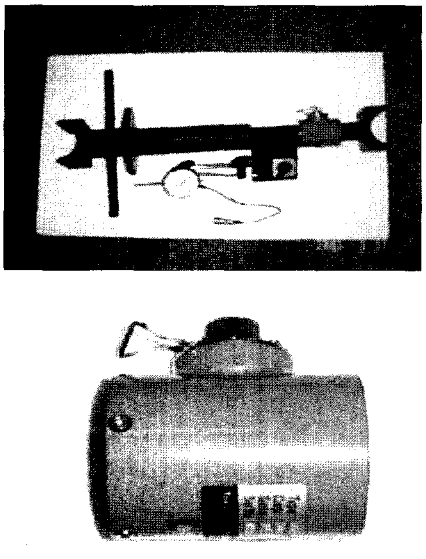
When data fall within the confidence range, as shown in Figure 13, it can be assumed that the structure is healthy and that no structural change or damage occurred. In addition, deflection that does not consider thermal effects is seen to be produced essentially by traffic loads. Thus, comparison of 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.

5. Static Measurement of Hanger Tension Force

Vibration method can be successfully applied when the cable has a simple support condition and can be easily excited.(7,11) Furthermore, when the large number of natural frequency modes can be obtained and used for calculation, the accuracy of measured tension force would be greatly enhanced. When those conditions, however, are not expected, the vibration method gives poor results or even not applicable. Actually, for short cables or cables having the complicated support conditions, vibration method is hardly applicable because of the poor quality of signals or limitation of theoretical formula. As one of the alternatives to the vibration method, a static method can be considered. In this static method, the necessary data for tension estimation would be the lateral deflections and bending moments at various locations in the tensioned tie rod under the different lateral loads. A static method for tension estimation of short length hanger cables in Yongjong bridge is addressed in here.

5.1 Measuring Devices

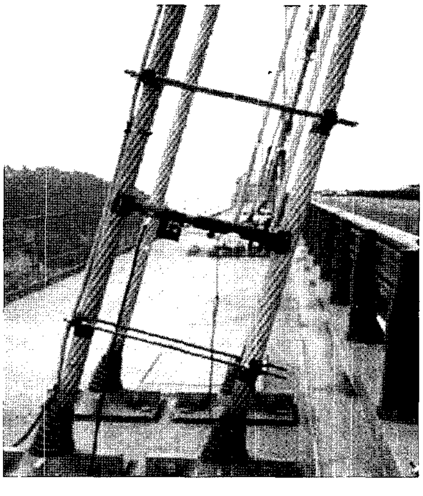
Measuring device is fixed between two hanger cables as shown in Figure 14 and designed to apply lateral force on the cable when the grip is turned. Other devices are constraint devices, and they are installed at lower and upper location of measuring device. Signals from load cell and LVDT are stored on notebook computer in real time in the field. The load cell has the maximum capacity of 200 kN. LVDT used in experiment can measure the deflection from 0.01 mm to the maximum 5 cm. The measuring device is in compression when applying lateral force. Therefore, precise manufacturing is necessary to avoid any eccentricity or buckling.



〈Figure 14〉 Measuring Devices.

5.2 Field Measurement

The theoretical equation reveals good results for longer distance between two constraint devices.(12,13) However, it is often said that limitations in installation distance exist because of the free length of the hanger cable or for the purpose of the easy treatment of constraint device. Lower constraint device is usually installed at 5 cm above from collar of hanger and is at a right angle to the cable as shown in Figure 15. Upper constraint device is installed at the maximum height without subsidiary equipments. Usually the distance between two constraint devices is appropriate to be 120 cm. Rod of constraint device is threaded at both ends. When installing the constraint devices on the cable, devices are moderately fixed by bolts, so as not to slip down on the cable. Over-tightening the bolts leads to induce the additional tension on the cable. Under-tightening the constraint devices will give rise to slip down or obtain the unstable initial deflection or lateral force. Measuring device is fixed on the middle point between two constraint devices in parallel and also tightened by the turn grip. After installing the devices on the cable, calibrations are followed in the measurement software installed on the notebook computer. It is convenient that LVDT is set to zero on the dial to identify the introduced deflection in real time. From theoretical point of view, there is no need to do calibration. However, calibration helps us to obtain the reliable and consistent signal. After calibration, lateral force and deflection are recorded on notebook computer by turning the grip on



〈Figure 15〉 Installation of the measuring device.

〈Table 4〉 Comparison of Tensile Forces (unit: tonf)[13]

Hanger ID	Design Tension	Vibration MethodStatic Method		
		Ambient Vibration	Forced Vibration	
NTS24	81.870	-	79.4	84.6
NTS25	81.624	-	86.2	83.2
NTS37	83.023	80.5	95.2	82.3

measuring device.

In Table 4, hanger tensions obtained from conventional vibration method and proposed static method are compared with design tension forces. As shown in Table 4, reasonable values could be obtained by suggested method.

From the field test, the obtained conclusion is that the boundary conditions by the constraint devices coincides well with the theoretical ones and the proposed static method can estimate the hanger cable tension more precisely regardless of the cable length or flexural rigidity. Although there are some minor problems to be resolved such as the determination of flexural rigidity of cable, the distance between two constraint devices, etc., proposed method and manufactured device show feasibility and applicability of static method for estimation of cable tension. The detailed numeric results of tension estimation are described in elsewhere.(10,11)

6. Conclusion

The monitoring system installed in Yongjong 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. After completion of railway on the existing bridge, the monitoring system detects changes of measurements which are identical as expected in the analysis. Other research directions have also been addressed to improve future performance of the monitoring system.

Acknowledgement

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