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LONG-TERM MONITORING FOR THE CONTROL OF CABLE VIBRATIONS

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Abstract

The Seohae Bridge has had a structural health monitoring system since its completion in 2000. More than 170 sensors including accelerometers are installed at stay cables as well as the superstructure. Based on the data measured, the numerical analysis model was tuned to have the same dynamic characteristics, such as natural frequencies, as the real bridge had. A buffeting analysis was performed with this model in order to get the modal displacements at the location of the cable anchorages. From the results, the possibility of the parametric excitation of the bridge was verified and the capacities of the cable dampers were determined.

INTRODUCTION

Cable stayed bridges have become the structural form of choice for medium to long span bridges in Korea. The Seohae Bridge is a composite cable stayed bridge, which is 470m long in main span length and is 34m wide with 144 stay cables. Serviceability problems due to the vibration of stay cables in large amplitudes have occurred, leading to the adoption of the term ‘rain-wind vibrations’. However a few instances were considered as ‘structure induced vibration’ called as parametric excitation.

Without having full information concerning cable vibrations at the time of construction, the design of viscous dampers for 100 stay cables among 144 stays was carried out to mitigate cable vibration. Several dampers that were installed to the outer long cables have failed and been replaced repeatedly. The cause of these failures was investigated based on the following data:

- Global frequencies and modal shapes of the bridge itself,
- Anticipated amplitudes of modal displacements of the deck and pylon anchorages, obtained from the buffeting analysis of the complete bridge, and
- External conditions (wind speed and direction) provoking the bridge response.

Description of the Seohae Bridge

The Seohae Bridge, which was opened to the public in November 2000, is located approximately 65 km south of Seoul and is one of the longest bridges in Korea. This bridge crosses Asan Bay is 7.31 km long and consists of a cable-stayed bridge and two different types of PSC box girder bridges. The cable-stayed bridge, which is 990 m long, consists of three cable-stayed spans of 200 m + 470 m + 200 m and two 60 m-long simply supported end spans (Fig. 1). Since the side spans are shorter than half of the main span, the end spans are hinged to the end of the cable-stayed side spans to eliminate uplift at the intermediate piers, P40 and 41.

The cross section of the deck consists of two longitudinal steel girders spaced 34m apart and precast concrete panels. There are steel floor beams between those edge girders at every 4.1 m along the bridge. The two pylons are H-shaped concrete structures of 187 m high above sea level. The three cable-stayed spans are supported by a total of 144 cables, ranging in length from 54 ~ 247 m. The number of strands in cables vary from 37 to 91 and ϕ15.2 mm and seven-wire strand is used. The strands are galvanized, covered by wax, individually sheathed, and placed inside a HDPE pipe without grout.

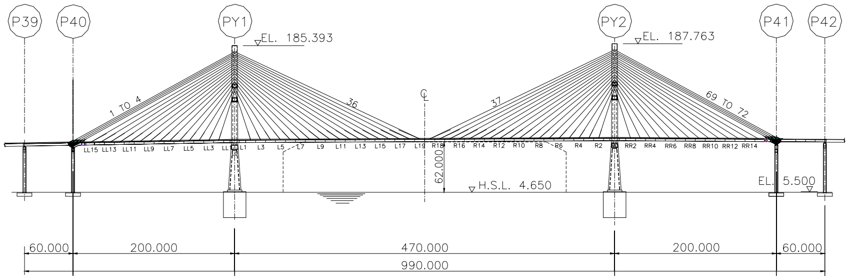


Figure 1. General view of the Seohae cable-stayed bridge.

Structural Health Monitoring System

The SSHMS (Seohae SHMS) consists of five subsystems, and they are the sensory system, data acquisition system, data processing and storage system, LAN-based networking system, and the display and control system. More than 120 sensors were installed on the superstructure, the pylons, and the stay cables. The data continuously collected from these sensors is transferred to the maintenance office, about 3 km away, through a fiber optic local area network. Because the SSHMS is a real-time online monitoring system, the user can easily grasp the situation of the bridge and any networking problem that might be occurring. An exclusive program to display the gathered data and control the system has been developed. This program also displays the processed real-time data and / or the stored data within the optional period through the Graphic User Interface technology.

The normal logging procedure is to sample dynamic data at 100 Hz and static data at 10-minute intervals. At the end of each 10-minute sampling period, the statistical data such as the maximum, mean, and minimum are computed for each sensor and stored in the database. The objectives of the SSHMS are: (1) to monitor the structural response and evaluate the performance of the bridge, (2) to provide information required for operating the computerized BMS, and (3) to provide useful information to the bridge engineers.

LONG-TERM MONITORING

Cable Forces

There are several techniques to evaluate cable forces, such as direct reading from a tensioning jack, measurement by a load cell or strain gauges, and elongation of cables. A simple and accurate method to measure cable forces is the indirect method using natural frequencies of stay cables based on the vibrating chord theory. Assuming that the cable is hinged at both ends and the flexural rigidity of the cable is not ignored; the equation below can be obtained:

$$\left(\frac{f_n}{n}\right)^2 = \frac{g}{4wl^2}T + \frac{EIg\pi^2}{4wl^4}n^2 = b + a \cdot n^2 \tag{1}$$

where f_n = n-th natural frequency, n = number of natural frequency, g = acceleration of gravity, w = weight of cable per unit length, l = effective length of cable, T = cable force, and EI = flexural rigidity of cable.

From Eq. (1), it is impossible to determine the exact flexural rigidity because of the twisting of a cable.

Then, the process to calculate the cable force is as follows:

(1) Calculate n modes and natura1 frequencies (f_n) of the cable.
(2) Plot n^2 and $(f_n /n)^2$ in x-y plane.
(3) Perform the linear regression analysis
(4) Determine the y-intercept from the linear line.
(The y-intercept corresponds to constant b in Eq. (1))
(5) Calculate the cable force T by substituting the known factors, g, w, and l to it.

In the case of the Seohae Cable-stayed Bridge, accelerometers that evaluate cable forces are installed in 24 cables out of 144 cables. Real-time accelerations of cables are gathered and processed. Using the Fast Fourier Transform algorithm, cable forces are automatically calculated and stored in the database at every hour. Table 1 shows the recent results and the initial cable forces. It can be seen that the cables show a sound behavior as the ratios of initial and measured cable forces lay between 94 % and 104 %.

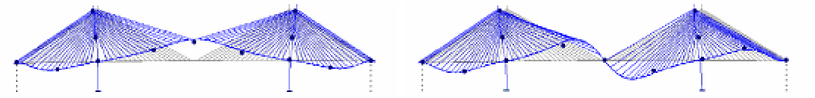
Table 1. Comparisons of cable forces (Unit: tonf)

Cable No.	Automatically measured in March 2004 (A)		Manually measured in April 2001 (B)		Measured by iso-tensioning jack in August 2000 (C)		Ratio of A/C	
	East	West	East	West	East	West	East	West
1	561.2	565.4	581.0	582.3	599.7	596.2	94%	95%
11	430.3	433.5	431.4	437.7	413.7	425.6	104%	102%
27	503.8	511.6	514.7	519.1	507.5	511.6	99%	100%
29	505.4	525.7	519.5	533.0	532.3	528.1	95%	100%
32	653.8	645.5	661.8	650.3	660.2	652.9	99%	99%
36	634.0	607.8	640.1	619.5	632.0	636.4	100%	96%
37	618.6	603.9	633.4	621.1	636.6	598.3	97%	101%
38	680.8	660.2	697.0	678.6	696.4	680.2	98%	97%
44	529.2	526.9	541.9	530.7	542.0	530.2	98%	99%
46	452.5	466.1	459.9	470.7	450.8	468.1	100%	100%
62	494.2	493.7	503.0	509.2	496.3	478.5	100%	103%
72	537.0	547.1	548.5	570.6	564.3	582.5	95%	94%

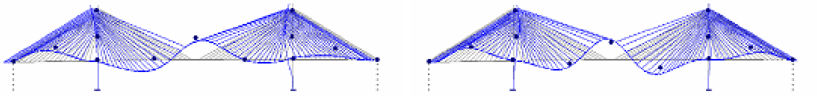
Dynamic Behavior of Structure

From the 12 accelerometers at deck, 8 accelerometers at pylons, and 24 accelerometers at 24 cables, real-time accelerations of cables are gathered and processed. Structural natural frequencies are automatically calculated and stored in the database at every 20 minutes using the Fast Fourier Transform algorithm (Pick-Picking method). The mode shapes from the FE analysis and measured data (depicted on the figures with dots) are shown in Figure 2.

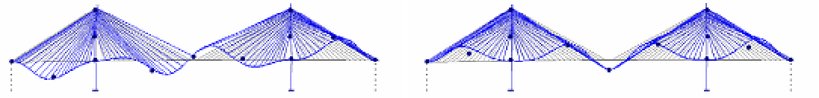
MAC (Modal Assurance Criterion) values from the AVT (ambient vibration test) and FE analysis are listed in Table 2. The data shows the validity of the data processing. Figure 3 shows the monthly average values of frequencies during 2001~2005. According to this table, there is no significant change in the long-term view. This indicates good structural health. On the other hand, there is a correlation between temperature and structural frequencies found in the short-term view, with the ratio of 0.00021Hz/°C (0.081%) for f_{v1} and 0.00011Hz/°C (0.034%) for f_{v2}.



(a) 1-st mode (b) 3-rd mode



(c) 7-th mode (d) 9-th mode



(e) 11-th mode (f) 13-th mode

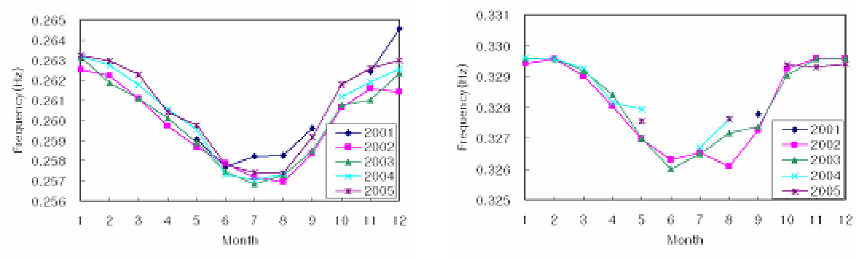
Figure 2. Comparison of vertical mode shapes.

Table 2. Theoretical and measured frequencies of the bridge

Mode No.	FE Model Frequency	2001 ~ 2005		2004.3.11		
		Measured Frequency	Frequency Error (%)	Frequency by PP	Frequency by ERADC*	MAC (deck only)
1st (f_{v1})	0.2654	0.2600	2.08	0.2625	0.2609	0.989
3rd (f_{v2})	0.3292	0.3281	0.33	0.3235	0.3200	0.954
7th (f_{v3})	0.4413	-	-	0.4517	0.4511	0.659
9th (f_{v4})	0.5371	-	-	0.5310	0.5279	0.927
11th (f_{v5})	0.5968	-	-	0.5800	0.5755	0.950
13th (f_{v6})	0.6319	0.6249**	1.12	0.6225	0.6252	0.940

* : Eigensystem Realization Algorithm using Data Correlation

** : Measured frequencies during 2004 ~ 2005



(a) Monthly average of frequency, f_{v1} (b) Monthly average of frequency, f_{v2}

Figure 3. Frequency variation in a year.

The frequency shift ratio of 1-st of The Seohae Bridge due to the removal of one cable is about 2%. If we compare this value with the temperature effect (3.24% / 40°C for f_{v1}), it is clear that the temperature should be considered when we evaluate the dynamic characteristics of cable-stayed bridges.

CABLE STAY VIBRATIONS

Cable stay vibration can be generated by the periodic displacement of anchorages, and consequently by oscillation of the bridge induced by the wind acting on the deck or pylons, or by the traffics. A given periodic displacement of an anchorage can be broken down into transverse and longitudinal displacements [1].

- Transverse displacement of an anchorage can generate the classical phenomenon of resonance in plane and out of plane. The response of a cable stay to classical resonance attains maximum amplitude when the angular frequency of excitation matches one of its modal angular frequencies. This amplitude is limited by damping the cable stay.

- Longitudinal displacement of an anchorage can generate the phenomenon of parametric resonance. This type of resonance that is similar to instability occurs when the angular frequency of excitation is half or twice as much of a modal angular frequency of the cable stay. To some extent, the amplitude of the response can be reduced by cable stay damping itself.

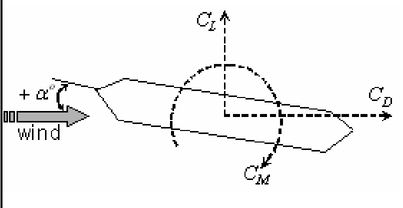
The parametric excitation analysis requires the response of the bridge for different wind speeds, which are obtained from a buffeting analysis. Only a limited number of dynamic modes are used in the buffeting response. To capture the bridge dynamic behavior precisely, a sufficient number of modes are required. On the other hand, the analysis of stay cables requires only the first 2 or 3 modes of the cables.

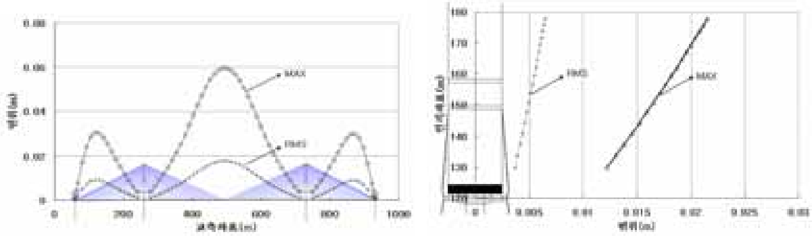
Based on the monitoring results, i.e. measured natural frequencies of the bridge and cables, it is found that there is no possibility of parametric resonance. But in several long cables near the anchor pier and mid of main span, the classical phenomenon of resonance could occur. In this case, there might be a problem in the capacity of the bladder used in the viscous damper due to high pressure developed by fast oscillation of the cable. In addition, it is necessary to consider the cable neutralization. It is natural for cable to deviate from the center of the guide tube due to long-term deflection of the bridge members and daily temperature variations. If we consider the stroke of cable damper, the strand bundle should be as centered as possible inside the guide tube.

Buffeting Analysis

In order to evaluate the possibility of parametric excitation and calculate the theoretical modal amplitude of the cable due to wind, aeroelastic buffeting analysis was carried out using flutter derivatives. The buffeting force was loaded only on the deck and the assumed 10-min wind speed was 20m/s at deck level in the analysis. Roughness length z_o and structural damping ratio ξ were assumed as 0.1m and 0.5% respectively. Aerodynamic coefficients from wind tunnel tests were shown in Table 4. One buffeting analysis was carried out with the 3-D FE model that is tuned to have the similar frequencies obtained from measurement. The results are shown in Figure 4.

Table 4. Aerodynamic Coefficient from Wind Tunnel Test

	Aerodynamic Coefficient	
	C_D	0.200
	C_L	-0.126
	C_M	0.059
	$dC_L/d\alpha$	6.331
	$dC_M/d\alpha$	0.172



(a) Vertical deflection at deck level (b) Horizontal deflection at tower

Figure 4. Max./RMS responses of cable anchorages (half side).

CONCLUSIONS

The Seohae Bridge has experienced serviceability problems with large amplitude vibrations of stay cables, leading to the adoption of the term ‘rain-wind vibrations’. However a few instances were considered as ‘structure induced vibration’ called as parametric excitation. In order to design proper damping devices to mitigate cable vibration, long-term monitoring data from the SSHMS was analyzed and a buffeting analysis was carried out based on the measured data.

From the experience of conducting BHMS for years, measuring cable forces with accelerometers is a quite effective and accurate method. This study confirms this idea. Also long-term data showed that the effect of ambient temperature on the dynamic characteristic should not be neglected.

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