Variability of Dynamic Characteristics of a Cable-Stayed Bridge Subject to Traffic-Induced Vibrations

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ABSTRACT

Due to large flexibility in cable-stayed bridges, vibrations induced by traffic and wind loads are more significant than those in other types of bridges. These vibrations may cause structural damage, such as fatigue in stay cables. The objective of this paper is to investigate dynamic characteristics of the Kao Ping Hsi cable-stayed bridge subjected to different traffic conditions. Experimental data were measured from a structural monitoring system installed upon this bridge. The techniques of system identification, including random decrement (RD) technique and Ibrahim time-domain (ITD) identification, were used to analyze the experimental data. The first eleven modes of the bridge were identified in three main directions. Then, the traffic induced variations in dynamic characteristics of Kao Ping Hsi cable-stayed bridge can be evaluated in the torsional modes. The results indicated that the traffic flow would not significantly change the natural frequencies of the cable-stayed bridge. However, the damping ratios are sensitive to the vibration intensity.

Keywords: cable-stayed bridge, dynamic characteristics, structural monitoring, traffic-induced vibration

斜張橋受車致振動之動力特性變化

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摘要

斜張橋由於輕質柔軟之特性，在營運階段承受的車流與風力作用下，引致的振動反應遠比其他類型橋梁明顯，此對斜張橋安全具有某種程度之威脅，尤其是對纜索元件可能造成直接之疲勞損傷。本文主要是利用動態監測系統，針對南部第二高速公路高屏溪斜張橋進行現地長期動態反應監測，並統計尖峰車流與離峰車流作用下之動力反應變化。同時，斜張橋的動態反應可進一步利用系統識別的方法求得斜張橋的動力特性參數，探討斜張橋在不同車流作用下之動力參數變化情形。由本文之研究結果可知，斜張橋在不同車流作用下，自然頻率變化並不明顯，但對於各振態阻尼比則有較明顯之改變，此一結果將有利於未來斜張橋之安全監測之參考。
關鍵字：斜張橋，動力特性，結構監測，車流振動，系統識別

文稿收件日期 99.2.9; 文稿修正後接受日期 99.7.16; *通訊作者
Manuscript received February 9, 2010; revised July 16, 2010; *Corresponding author

●I. INTRODUCTION

Rapid developments of structural sensing and control, data acquisition and processing, and computer technologies have made it feasible to monitor the structural health of large-scale structures in real time. Structural health monitoring (SHM) of large-scale infrastructures has increasingly attracted extensive interests from both fields of scientific research and industrial application. In general, the structural health of a cable-stayed bridge in its service lifetime is of particular importance to maintain the functions of the bridge. The bridge may sustain damage when it is subjected to various external loading, such as wind, earthquake or traffic. Damage to the existing bridge can be reflected on its natural frequencies, damping ratios and modal shapes [1]. The dynamic characteristics of a structure can often be identified from its dynamic responses. Therefore, it is an important issue to accurately measure the dynamic responses and to determine the dynamic characteristics of the bridge while it is in service.

Two primary approaches have been used to identify system parameters of the bridge. Regarding the analysis of measured data, techniques in frequency domain appear to be most frequently used in the literature. Although spectral analysis may be a straightforward method for identifying the natural frequencies of a system, identification of the damping ratios or mode shapes requires complicated mathematical analysis, especially for highly damped systems, as well as systems with severe modal interference. On the other hand, system identification in the time domain can provide accurate results if the measured signals are clean, i.e., with less noise contamination [2]. A technique in time domain that combines the random decrement (Randomdec or RD) technique [3] and the Ibrahim time-domain (ITD) identification technique [4] has been adopted to analyze the data collected from field testing. This procedure is quite straightforward and simple because the measured responses in time domain can be directly used without any additional mathematical transformations. In addition, the procedure is well established and has been successfully applied to identify the dynamic characteristics of real structural systems [5-6].

The random decrement (RD) is an averaging technique that can be used to extract the free decaying response of a vibrating body from its random excited stationary response. It was empirically developed in the late sixties by Cole [7] as a method of identifying system parameters of structures under ambient loading. Vandiver *et al.* [8] showed that the RD can be obtained from the multiplication of auto-correlation functions. Asmussen *et al.* [9] introduced the so-called vector RD method by using a vector triggering condition to more efficiently compute free decays from random responses. Huang and Yeh [10] showed that the RD signature of an acceleration response is nonequivalent to the free vibration response since a singular point exists in the RD signature. Based only on few records of floor acceleration response from earthquakes, Lin *et al.* [11] successfully identified the dynamic characteristics of the torsionally coupled buildings using a modified random decrement method together with the Ibrahim time domain technique. Their conclusions indicated that the randomdec acceleration signature is equal to a free decay acceleration response with certain initial displacement and velocity. Recently, many advanced studies have extensively applied the random decrement technique for damage detection [12-13], structural system identification [14-16], and structural health monitoring in civil [17] and offshore [18] engineering.

In this work, data from field measurements can be processed by the Random Decrement technique to yield the free vibration response, followed by the ITD technique. Both ambient vibration testing and structural monitoring techniques are used to obtain the dynamic response of the system. The aim is to determine the dynamic characteristics of the bridge from two sets of field data under normal traffic load. Then, the traffic induced variations in dynamic characteristics of Kao Ping Hsi cable-stayed bridge can therefore be evaluated.

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●II. DESCRIPTION OF

BRIDGE

The bridge tested is called the Kao Ping Hsi cable-stayed bridge. This bridge crosses the middle stream of Kao Ping Hsi river, and connects Tashu Village of Kaohsiung County and Chiuru Village of Pingtung County. The bridge was open to traffic on December 30, 1999. As shown in Fig.1, this bridge is an asymmetric single tower cable-stayed bridge. The bridge has a main span of 330m, and has a side span of 180m. The inverse Y-shaped pylon has a height of 183.5m from the foundation to the top of pylon. It is known that an ideal structural system for an asymmetric cable-stayed bridge is a hybrid system, utilizing different materials for main span and side span in order to balance the bridge on both sides. The side span was built with heavier concrete material, and the main span with steel, relatively lighter than concrete. A total of 30 sets of cables arranged on two planes are used to connect the girders to the pylon.

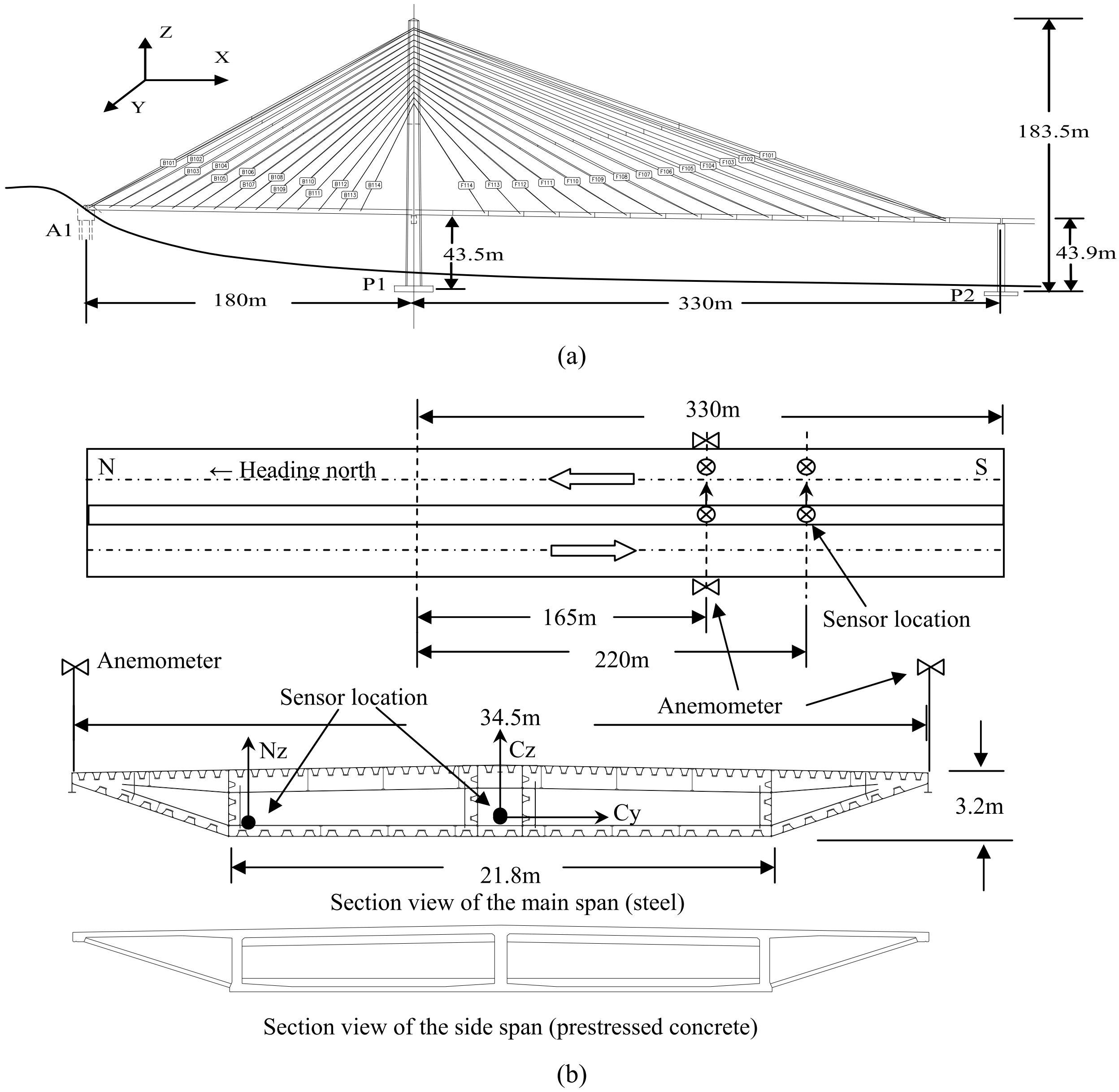


Fig.1. Layout of the Kao Ping Hsi cable-stayed bridge: (a) plane view; (b) sensor locations of the structural monitoring system.

III. MONITORING MEASUREMENTS

A typical structural health monitoring technique was adopted to measure the dynamic responses of the bridge. The structural monitoring systems were installed on the bridge and the data were collected between June 2006 and August 2008. The all-weather measurements were carried out in normal traffic conditions by using the structural monitoring system. Six sensitive servo-velocity sensors were installed within the bridge's box girder. Table 1 lists the layout of the velocity sensors.

As shown in Fig.1(b), the sensors were placed in two sections of the main span: at the center of the main span and at a point that is two-thirds away from the center pylon. The resolution of the sensors was up to 10^{-4} cm/s with full range of 10 cm/s. The recording system was an auto-trigger data acquisition system with 6 channels, and was able to convert analog signals to digital data and restore the measured data in the digital format. Due to limitation on the number of channels that could be simultaneously used during test, the dynamic responses of deck could only be measured in two vertical directions and one transverse direction within each section. For long term monitoring, the data from the 6 sensors could be recorded simultaneously, at a sampling rate of 100 Hz. Because the bridge was in service during testing, the dynamic responses in a torsional direction could only be obtained by using the difference between the two vertical responses measured within the same section. Since the modal shape of the structure could not be determined from the array of sensor locations in Fig.1(b). This work focuses on identification of natural frequencies and their corresponding damping ratios.

Table 1. Layout of servo-velocity sensors

Channel	Symbol	Position & direction
1	1/2L Nz	at 1/2 main span, northbound line, in vertical direction
2	1/2L Cz	at 1/2 main span, central of section, in vertical direction
3	1/2L Cy	at 1/2 main span, central of section, in transverse direction
4	2/3L Nz	at 2/3 main span, northbound line, in vertical direction
5	1/2L Cz	at 2/3 main span, central of section, in vertical direction
6	1/2L Cy	at 2/3 main span, central of section, in transverse direction

In the entire monitoring process, the bridge was under normal traffic conditions. A set of typical measured velocity data with corresponding auto-spectra from the field tests is shown in Fig.2. Figure 2(a) reveals large amplitudes in the bridge deck, which may be induced by a heavy truck passing through the bridge. Therefore, as can be seen, the bridge responses rapidly increase in the time history.

IV. EXPERIMENTAL MODAL ANALYSIS

The recorded velocity data from the 24 hours of measurement were processed with the RD technique. Then, the ITD technique was applied to these Randomdec signatures to extract the natural frequencies and damping ratios for the bridge.

4.1 Randomdec technique

Basically, the RD technique is a signal processing technique for obtaining ensemble averages of pre-segments of random response signals. As shown in Fig.3, assume that $\{X(t)\}$ and $\{Y(t)\}$ are two stationary random processes, and that $x(t)$ and $y(t)$ are two samples of $\{X(t)\}$ and $\{Y(t)\}$, respectively. If x_s is a threshold level of chosen, and $x(t_i) = x_s$ for i=1,2, ….,N, are found from the measured data, then the RD technique gives the signals defined as [19]

$$\delta_{xx}(\tau) = \frac{1}{N}\sum_{i=1}^{N} x(t_i + \tau), \tag{1}$$

$$\delta_{xy}(\tau) = \frac{1}{N}\sum_{i=1}^{N} y(t_i + \tau), \tag{2}$$

where $\delta_{xx}(\tau)$ is the unbiased estimation of auto-Randomdec signature of $x(t)$, and $\delta_{xy}(\tau)$ is the unbiased estimation of the cross-Randomdec signature of y(t) with respect to $x(t)$. The threshold value of RD is set to be the RMS (root-mean-square) value of the measured signals [10]. The time shift factor of ITD is selected among the non-proportional relationships [20]. To obtain the randomdec signature close to true free decay response, the number of average segments N in equations (1) and (2) must be greater than 500 [11]. However, the greater the number of superposition, the more accurate free decay responses can be determined.

4.2 Ibrahim time domain identification

The RD technique is applied to extract the free vibration signals from the vibration monitoring measurement. Then, the ITD technique is applied to identify the natural frequencies, modal damping ratios, and modal shapes of the system from the free vibration signals. Based on the analytical solution of the free vibration response for a linear system, in terms of the state variables, one is able to construct a system matrix [G] from the measured data in the least square sense, defined as

$$[\mathbf{G}] = [\overline{\mathbf{u}}][\tilde{\mathbf{u}}]^T \left([\tilde{\mathbf{u}}][\tilde{\mathbf{u}}]^T\right)^{-1}, \quad (3)$$

where $[\overline{\mathbf{u}}]$ and $[\tilde{\mathbf{u}}]$ are $2m$*s matrices, and $[\tilde{\mathbf{u}}]$ represents the free vibration response of s time steps for m degrees of freedom. The dimension of m is chosen to be large than the total number of degrees of freedom of the system to eliminate the influence of ambient noises on the identified results. As long as the number of station n, that is used to measure the free vibration responses of the system, is smaller than $2m$, the data for the rows with a sequential number larger than n are filled up using a time-shift scheme described in Pappa and Ibrahim [4]. The elements in $[\overline{\mathbf{u}}]$ differ from those in $[\tilde{\mathbf{u}}]$ by a time shift.

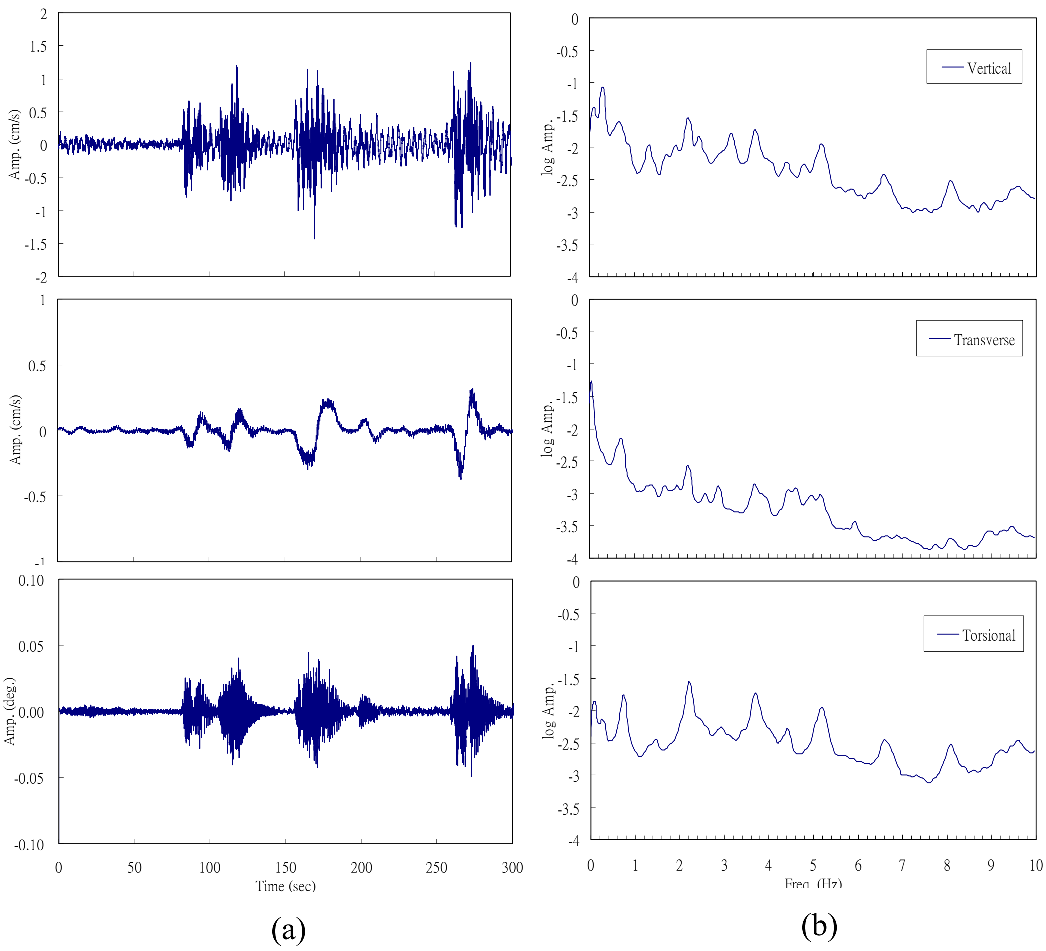


Fig. 2. Typical set of recorded data from monitoring system with corresponding auto- spectra in the three directions. (a) Time history, and (b) corresponding auto-spectra.

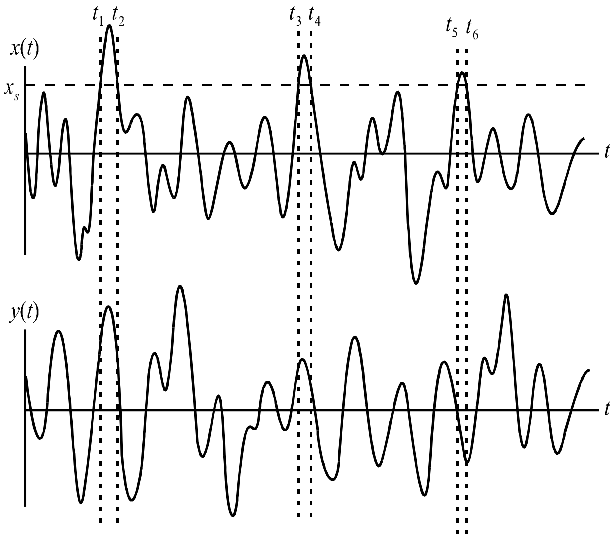


Fig. 3. Construction of Randomdec signatures [19].

The eigenvectors of [**G**] in Eq. (3) describe the mode shapes of the structural system of interest in the form of state variables, whereas the eigenvalues of [**G**] relate to the natural frequencies and damping ratios. Let λ_k and $\{\psi_k\}$ represent the *k*th eigenvalue and eigenvector of [**G**], respectively. The eigenvalue, λ_k, is a complex number, and can thus be expressed as a_k+ib_k. The complex conjugates of λ_k and $\{\psi_k\}$ are also an eigenvalue and eigenvector, respectively. The natural frequency and modal damping of the system, as in Eq. (3) are given by

$$\tilde{\beta}_k = \sqrt{\alpha_k^2 + \beta_k^2}\ , \tag{4}$$

$$\xi_k = -\alpha_k / \tilde{\beta}_k\ , \tag{5}$$

where $\tilde{\beta}_k$ is the pseudo-undamped circular natural frequency; ξ_k is the modal damping ratio;

$$\beta_k = \frac{1}{\Delta t}\tan^{-1}(\frac{b_k}{a_k})\ , \tag{6}$$

$$\alpha_k = \frac{1}{2\Delta t}\ln(a_k^2 + b_k^2)\ , \tag{7}$$

and Δt is the time shift between $[\bar{\mathbf{u}}]$ and $[\tilde{\mathbf{u}}]$.

Hence, the responses measured in the field test can be established by the ITD method. The modal parameters of such a structural system can be determined using the foregoing method.

4.3 Data processing and identification results

A set of typical measured velocity data with the corresponding auto-spectra from the field monitoring data is shown in Fig.2. The ITD technique was applied to the Randomdec signatures to determine the dynamic characteristics of the bridge. The natural frequencies and modal damping ratios of the first eleven modes in the three directions determined from structural monitoring test were listed in Table 2. As can be seen, the frequencies of lower modes identified in Table 2 correspond very well with those associated with peaks of the auto-spectra shown in Fig.2(b). However, the frequencies for higher modes given in Table 2 cannot be directly identified from the auto-spectra. Regarding the analysis of measured data, techniques in frequency domain appear to be most frequently used. Although spectral analysis may provide an easy method for identifying the natural frequencies of a system, identification of the damping ratios and mode shapes are not as straightforward, especially for highly damped system and systems with severe modal interference. Therefore, the peak value of spectrum may not be obvious at the locations where the measurement stations were setup (i.e. at 2/3 main span for asymmetric modes or at 1/2 main span for symmetric modes).

To compare the identified results from different dynamic tests, the data from the previous study by ambient vibration tests (in vertical and transverse directions) and monitoring system(in torsional direction) conducted in the same stage (May 2007) [21] were adopted. The modal parameters can be identified by using the continuous wavelet transform for the Kao Ping Hsi cable-stayed bridge, and are also listed in Table 2. As can be seen, good correlation exists in general between the two sets of experimental data from ambient vibration test and structural monitoring system. Herein, the data recorded form the present study are useful and correct with the current structural monitoring system, which can then be processed by the RD technique to yield the free vibration response, followed by the ITD technique. The dynamic properties can hence be established rationally for the Kao Ping Hsi cable-stayed bridge.

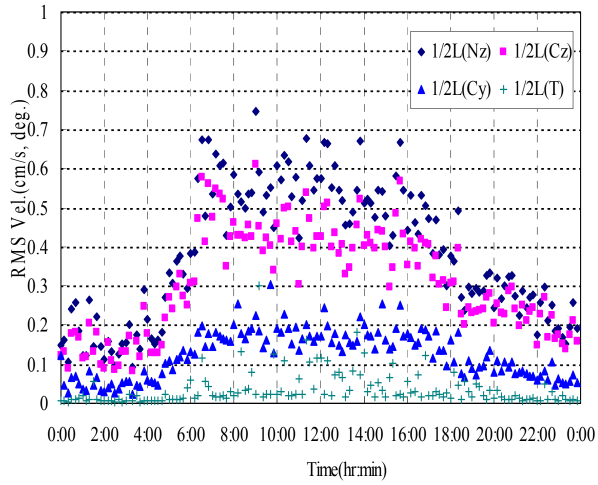
Table 2. Dynamic characteristics of the Kao Ping Hsi bridge

Mode	The present		Chen and Ou [21]			Mode shape description
	Field test#		Field test*		FEM	
	f (Hz)	ξ (%)	*f* (Hz)	ξ (%)	*f* (Hz)	
1	0.284	2.8	0.284	2.9	0.293	Z1
2	0.533	3.8	0.574	3.7	0.561	Z2
3	0.686	2.0	0.643	3.3	0.646	Y1
4	0.758	2.2	0.754	1.8	0.771	T1
5	0.97	4.6	0.92	4.4	0.93	Z3
6	1.41	1.7	1.46	1.1	1.43	T2
7	1.50	3.6	1.54	3.9	1.52	Z4
8	1.65	3.3	1.64	2.9	1.68	Y2
9	1.88	3.3	1.81	3.0	1.79	Z5
10	2.15	2.9	2.17	3.2	2.15	Y3
11	2.21	1.2	2.18	1.3	2.25	T3

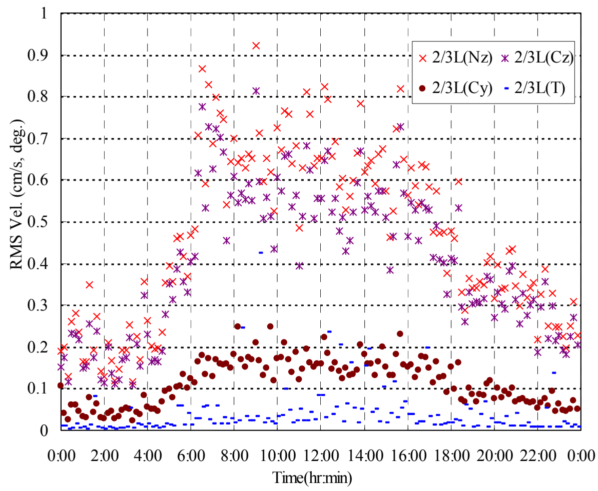
* Two field-based approaches were used to measure the dynamic responses of the bridge: an ambient vibration test approach, used to obtain the deck responses in the transverse and vertical directions; and a structural health monitoring approach, used to measure the deck responses in the torsional direction. # The same torsional data were adopted to analyze torsional modes in this paper.

V. VARIABILITY OF DYNAMIC CHARACTERISTICS

To obtain the dynamic characteristics with corresponding variable traffic loading conditions, the long-term structural health monitoring system has been run for over 24 months. The all-weather measurements were carried out in normal traffic conditions by using the structural monitoring system. A set of 24 hours recording data was adopted to determine the dynamic characteristics of the bridge. To reduce the effect of wind-induced vibration in this work, the measured data with the average wind velocity less than 3 m/s at the middle of main span are adopted to identify the dynamic characteristics of the bridge. The data measured in 24 hours are divided into 144 data segments, with each segment containing 10-minute velocity recordings. Ten-minute root mean square (RMS) values for deck velocity are presented, as a measure of vibration amplitude. Consequently, all statistics presented in this paper was computed using a ten-minute averaging time. Figure 4 illustrates the RMS of the velocity response of the deck within 24 hour. The results indicate that the RMS of the responses measured at each channel presents considerable variations in a day. In general, the maximum RMS values occur in rush hour from 6:00 to 18:00. Changes in these RMS values are mainly due to the varying traffic loading since the wind velocity can be considered quite low and exhibited limited change.



(a)



(b)

Fig.4. Variation of measured responses with time within a day at: (a) 1/2 of main span; (b) 2/3 of main span

In this work, the variability of dynamic characteristics can be determined under traffic loading flows, which can be addressed in torsional modes. Each data segment was obtained by an interval between the two hours from 144 data segments in a day. Thus, the natural frequencies and damping ratios are identified by using Randomdec technique from 12 data segments with each segment containing 10-minute velocity recordings. The frequency and damping ratio of each of those measured global modes exhibits some variations within a day, as plotted in Figs. 5 and 6, respectively. Figure 5 reveals that different modes present different frequency variations in the torsional direction and most of these variations are less than 1.5%. As can be seen, roughly, the frequencies of some modes (eg. modes 2 and 3) become slightly higher during 22:00 to 4:00; the period during which the velocity RMS values are relatively small. It is noted that such frequency variation could also be due to in part to the slightly lower temperatures at night, although no attempt was made to capture the temperature effect in the current test. Figure 6 indicates that different modes present different damping ratio variations in the torsional direction. As can be seen, the damping ratios of each mode become higher during 8:00 to 18:00; the period during which the velocity RMS values are relatively large. It is noted that such damping ratio variation could be due to large amplitude by traffic-induced vibration; a geometric nonlinear effect.

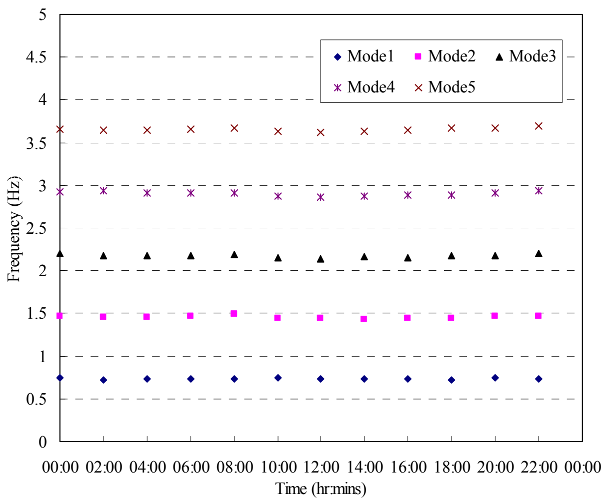


Fig.5. Variation of frequencies identified with time of day in torsional direction

Figure 7 shows the frequency of each mode which is related to the velocity RMS values of the deck in the torsional direction. The excellent agreement of the identified results from different traffic conditions indicates that the traffic flow would not significantly change the natural frequencies of the cable-stayed bridge. Further, the damping ratio of each mode is related to the velocity RMS values of the deck, as plotted in Fig. 8. It shows that the vibration intensity increases with damping ratios in the torsional direction. The possible reason is that the high capacity of energy dissipation of the cable element provided some additional contribution for the development of extra structural damping.

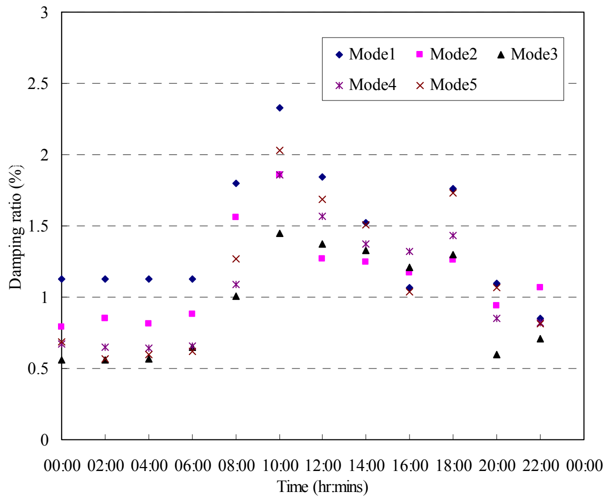


Fig.6. Variation of damping ratios identified with time of day in torsional direction

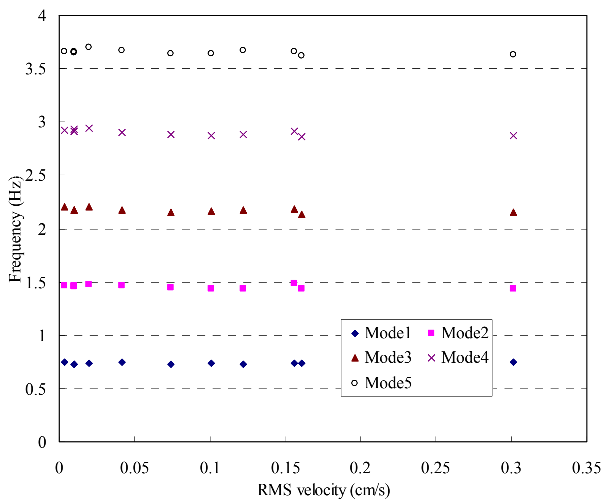


Fig.7. Variation of frequencies identified vs RMS velocity in torsional direction

VI. CONCLUSIONS

In this work, dynamic characteristics of the cable-stayed bridge was determined by using structural health monitoring system under different traffic flows. The data from field measurements processed by the Random decrement (Randomdec) technique to yield the free vibration response, followed by the ITD technique. The first eleven modes in three main directions, namely transverse, vertical and torsional, were identified for the Kao Ping Hsi cable-stayed bridge from the various recording data. Then, the traffic induced variability in dynamic characteristics of Kao Ping Hsi cable-stayed bridge can be evaluated in the torsional modes. The excellent agreements from different traffic conditions indicate that the traffic flow would not significantly change the natural frequencies of the Kao Ping Hsi cable-stayed bridge. However, the damping ratios are sensitive to the vibration intensity of the deck. The reason may be that the high capacity of energy dissipation of the cable element provided some contribution for the development of extra structural damping. Furthermore, the current observations from the monitoring data provide the possible variation for only a small range in the dynamic properties of the bridge under routine traffic conditions. Extended investigations are needed to obtain more general results on the traffic-induced variability of the cable-stayed bridge. It is considered that the traffic-induced vibration on the stay cables is an important issue and requires further study in the future.

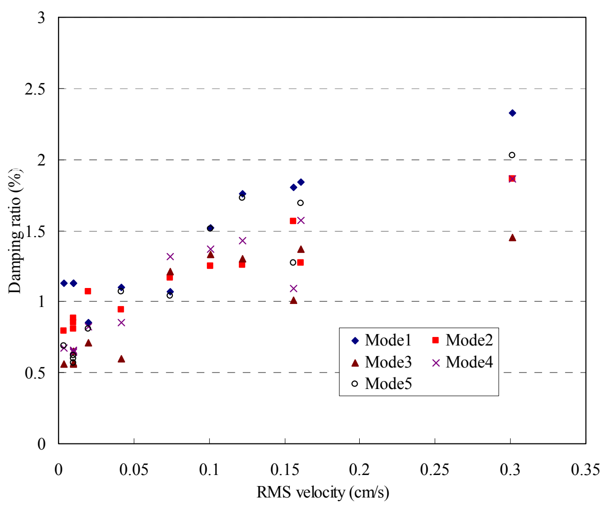


Fig.8. Variation of damping ratios identified vs RMS velocity in torsional direction (at 1/2 of main span)

ACKNOWLEDGEMENT

The authors would like to thank the National Science Council of the Republic of China for financially supporting this research under Contract No NSC 96-2628-E-390-011-MY3.

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