The 2014 World Congress on
Advances in Civil, Environmental, and Materials Research (ACEM14)
Busan, Korea, August 24-28, 2014

Damping Analysis on Steel Strand Cables of A Cable-Stayed Bridge Based on Field tests

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ABSTRACT

Stay cables are the main components of cable-stayed bridges. Stay cable vibrations are considered one of the major concerns in long-span cable-stayed bridges. Inadequate damping of stay cables is a primary cause of these vibrations. There are two types of cables, parallel wire cables and steel strand cables. Available studies on stay cables have focused on parallel wire cables, but there has been little testing conducted and data accumulated for the damping of steel strand cables. This paper focuses on steel strand cables and their damping features based on field testing. A total of three types of steel strand cables, M8, M13 and M18 on Tongling Bridge (under construction) were tested to investigate the cables modal damping. Vibrator-induced and human-induced vibrations on the cables upon free decay were recorded, as well as the ambient vibrations. The present experiment results of the first 3 modal damping of each cable were compared with those from references of the similar types of cables. The comparison results revealed that: i) at the same mode, the longer the cable, the lower the value of damping; ii) for the same cable, the higher the mode, the lower the value of damping; and iii) modal damping of steel strand cables is of similar features but slightly larger than that of parallel wire cables.

1 Introduction

Cables are commonly used engineering material with featured advantages such as lightweight high strength capacity, etc. Cables have been widely used in cable-stayed bridges, suspension bridges, tower mast structures and other civil engineering and space structures. In the field of bridge engineering, cables are universally used as load-bearing components in cable-stayed bridges. Due to their great flexibility, light weight and minimal damping, cables of large bridges are easily excited by the external environment. Continuous vibrations of cable may be the cause of strand fatigue and corrosion. Pedestrians on the cable-stayed bridge may question the safety of these bridges because of the vibrations that the cables create. The vibrations can cause fatigue fractures in the cables, and thus affect the safety of bridges. Cable-stayed bridges become longer and so, long-span cable-stayed bridges under construction also lengthen. Engineering research found that cable-stayed bridge can be built up to a span of 1400m. The greater the span, the greater the length of the cables used, which in turn become more susceptible to environmental excitement and vibrations. Considering these possibilities, the study of vibration features of cables is extremely important for developing control of these cable vibrations.

Current research in the field of vibration control has been conducted primarily upon the parallel wire cable structure. Yamaguchi conducted vibration test on Tatara Bridge (using parallel wire cables) and derived its modal damping (Yamaguchi and Ito 1997,Manabe, Sasaki et al. 1999). Xie Xu, Shen Yonggang, Chen Shuisheng also conducted a similar study (Shui-sheng, Ming et al. 2003, Xu, He et al. 2008, Yong-gang 2008). There has been little research conducted on steel strand cables and little data, measure damping features, acquired.

In recent years steel strand cables have been gradually become more commonly used in the construction of cable-stayed bridges, because of their many advantages. By pulling the wire through an extrusion and flattening process, internal voids and outer diameter of strands are greatly reduced. This allows the density to improve and simplifies anchoring (Sheng-hai 2005).

Steel strand cables consist of an assemblage of wires laid helically around a core. Some researchers studied the advantages of strand cables and developed methodical explanations. Various investigations address the improvement of dynamic analysis of the cable, and study the effects of internal dry friction between helical wire layers of a cable playing a significant role in the dynamic behavior of cables. Based on the hypothesis that the losses are caused by a hysteretic phenomenon in the flexural rigidity of the cable, Denis U. Noiseux (Noiseux 1992) proposed laws to justify the internal losses in cables. Xin Liu (Liu and Knapp 2005) developed a mathematical cable model to predict cable vibrations and the attendant reduction in vibration amplitudes that occur due to internal friction caused by relative wire slippage.

Since researchers have discussed the better dynamic behavior of strand cables and found few problems in cable-stayed bridge with strand cables, it is necessary to conduct experiments on bridges that use steel strand cables.

Tongling Bridge is a cable-stayed bridge using steel strand cables. It has three cable planesand uses strand stay cables. Strand diameter is 15.2mm, tensile strength is 1860MPa. It has 228 cables, the shortest cable is 100m and the longest one is 336m. Figure 1 shows Tongling bridge and the cables tested during the experiment.

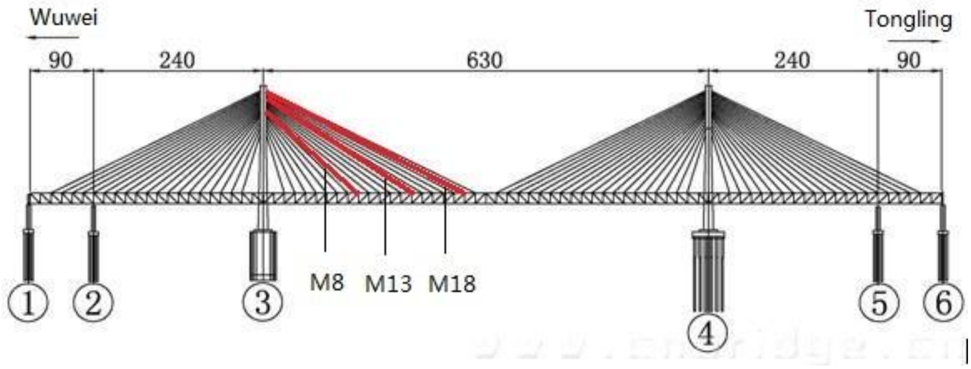

Fig.1 Tongling bridge

2 Field testing on Tongling Bridge

Three steel strand cables of Tongling Bridge, M8, M13 and M18 were excited in order to acquire their logarithmic decrement.

There are 3 cable planes in this bridge. In consideration of the experimenters’ safety, the middle cable planes were chosen for study. The bridge was still under construction during the experiment so the last and longest cable, M19, was not yet installed. Figure 2 shows the vibrator used in the experiment. Figure 3 indicates the sensors locations installed in the cable specimens. Figure 4 gives the sensors’ locations near the edge of the sleeve.

Fig.2 Vibrator attached to the cable

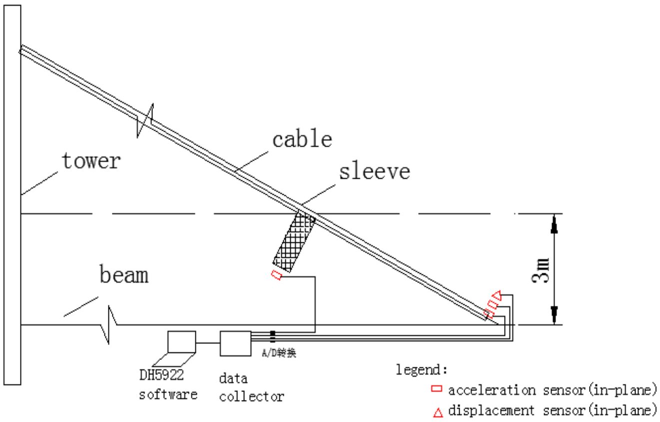

Fig.3 Sensor locations on the cable

Fig.4 Sensors near edge of sleeve

Table 1 shows the parameters of the 3 tested cables. Length and inclination of the cables can be got from the design of the bridge, the vibrator position is measured with a meter rule. By measuring the horizontal length from the end of cable to the end of vertical position of steel wire rope, the position of artificial excitation can be easily measured. The higher the excitation position, the better its effect, but because of the limitation of crane, 3 meters is the highest vibrator position in the field test.

Table1 Parameters of the cables

Cable No.	length(m)	inclination	Position of the vibrator	Position of the artificial excitation
M8	180.9	41.43°	3 meters to deck	1/5 position of the cable
M13	248.7	31.57°		
M18	320.6	25.85°		

Table2 Shows the effects of both the artificial excitation and the vibrator excitation. It shows that each excitation method has its advantages and disadvantages. In a word, vibrator excitation is better for higher modes and artificial excitation is better for lower modes.

Table 2 Effects of excitation

mode	Vibrator excitation	Artificial excitation
1	The cable vibrated slightly, there was no evident vibrating and decaying process in the acceleration curve	Vibration of cable was larger than excitation by vibrator, there was evident vibrating and decaying process in the acceleration curve
2	The cable vibrated violently, there was evident vibrating and decaying process in the acceleration curve	The cable vibrated violently, there was evident vibrating and decaying process in the acceleration curve
3	The cable vibrated violently, there was evident vibrating process in the acceleration curve and the vibration decay pretty quickly	Artificial excitation could not output the force of so high frequency

The vibrator is made up with a vibrating mass and a cable fixed device. When the mass vibrates with certain input frequency, the inertial force will excite the cable to vibrate. This inertial force is proportionate to the input frequency; therefore the higher the frequency, the better the effects of excitation. This creates difficultly for the vibrator to excite a cable of lower frequency. The method of artificial excitation involves using a steel wire rope to excite the cable. The rope can be placed at a height of one-fifth of the cable length. At this position, it is much higher than that of the vibrator. Although this method is considered better for lower modes, to use it for higher modes, the frequency of human interaction cannot ensure higher than 2Hz. Figure 5 shows artificial excitation. In this experiment, we used vibrators to excite higher modes, and we used artificial excitation to excite lower modes.

Fig.5 Artificial excitation

Conditions scenarios during the experiments are listed in Table 3. As the vibrator has a vibrating mass, it may change the features of the cable, so environmental excitation with and without vibrator should be tested to consider the effect of vibrator. Each of the condition scenarios should be repeated 3 times and use their mean value to diminish the errors. As environmental test will take a very long time, so environmental excitation will be repeated 2 times. First 3 modes of each cable are tested using both vibrator excitation and artificial excitation to make sure the all 3 modes will get the best vibrating samples.

Table 3 Conditions scenarios

Condition No.	Excitation	Explanation	Times
Cable No.-1	Environmental excitation	Without vibrator	2
Cable No.-2		With vibrator	
Cable No.-3	Vibrator excitation	1 mode	3
Cable No.-4		2 mode	
Cable No.-5		3 mode	
Cable No.-6	Artificial excitation	1 mode	
Cable No.-7		2 mode	
Cable No.-8		3 mode	

3 Logarithmic decrement of cable

Free decay method (Fukuwa, Nishizaka et al. 1996) was used to calculate the damping of the cable. Random Decrement Technique/ERA method (Fang-lin, Xu-hui et al. 2002,Li·qun and Jin-ping 2004, Hua 2006) was used to identify the damping features of the cables using the data of ambient vibrations.

(1) Free decay method

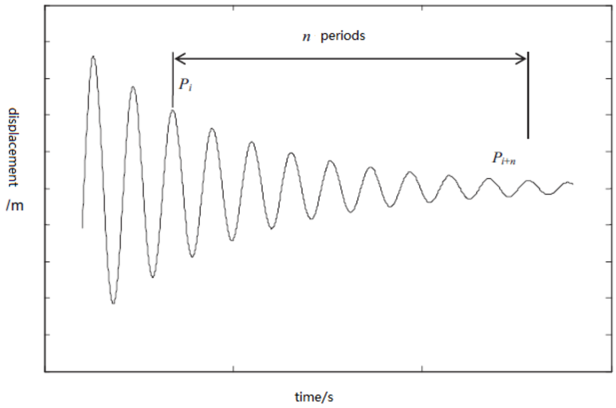

Fig.6 Free decay curve

According to the definition of logarithmic decrement ratio, if there is a free decay curve in Fig.6, and if the ratio of two neighbored peaks is η, then the logarithmic decrement ratio δ is the natural logarithm of η：

$$\delta = \ln\eta = \ln\frac{P_i}{P_{i+1}} = \frac{\pi\xi}{\sqrt{1-\xi^2}} \tag{1}$$

Usually we choose two peaks between several cycles to minimize the error：

$$\delta = \frac{1}{n}\ln\frac{P_i}{P_{i+n}} = \frac{\pi\xi}{\sqrt{1-\xi^2}} \tag{2}$$

According to this formula we could get the logarithmic decrement using the data from the free decay curve found in the experiment. Figure 7 shows the 2nd acceleration time series and its Fourier spectrum of cable M8 by artificial excitation. The 2nd modal damping was calculated and shown in Fig.8. Each point in Fig.8 was calculated using 100 periods.

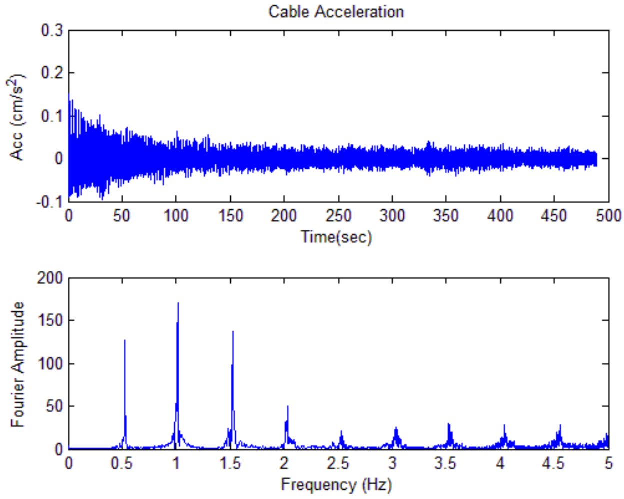

Fig.7 Free decay curve / its Fourier spectrum

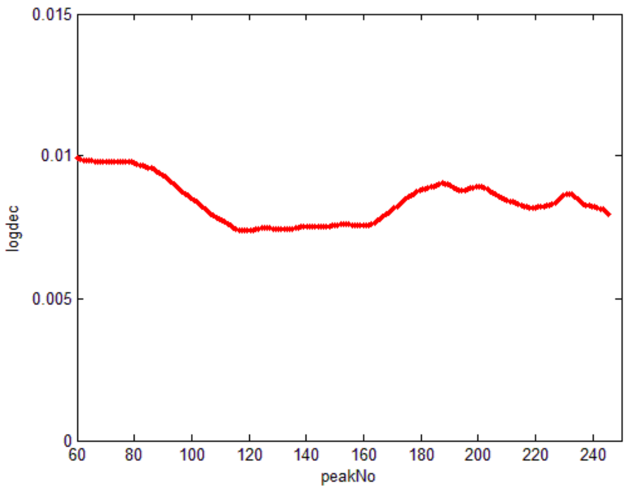

Fig.8 Logarithmic decrement of 2nd mode

From the Fourier spectrum in Fig.7 it is found that the frequency of the free decay curve is not single, a result caused by the imprecision of artificial excitation. To get a free decay curve with single frequency, Butterworth filter was used and Fig.9 shows the filtered 2nd mode decay curve. In Fig.9 the acceleration curve is separated into 3 parts: 1) unstable, 2) free decay, and 3) environmental vibration. It is important to choose the right part of the curve for calculating. Figure 10 shows the logarithm of the peak or valley in Fig.9.

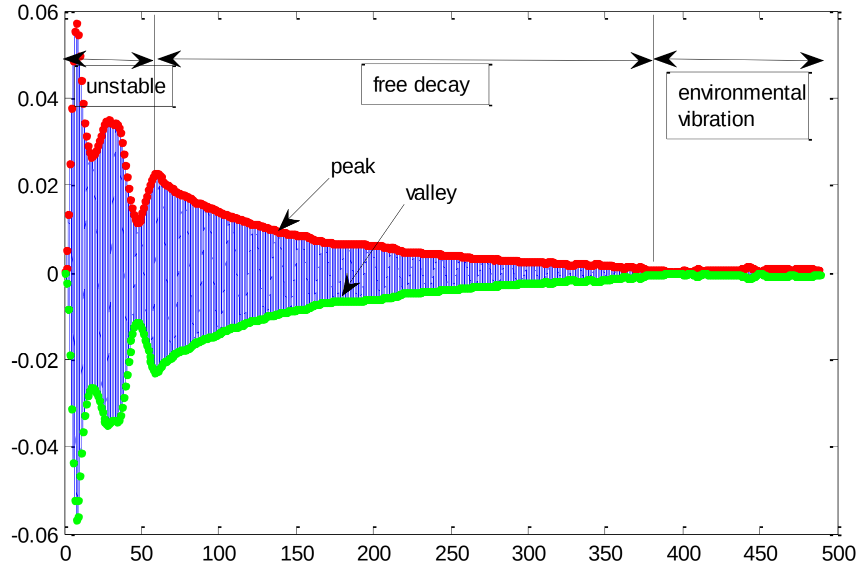

Fig.9 Filtered acceleration of 2nd mode

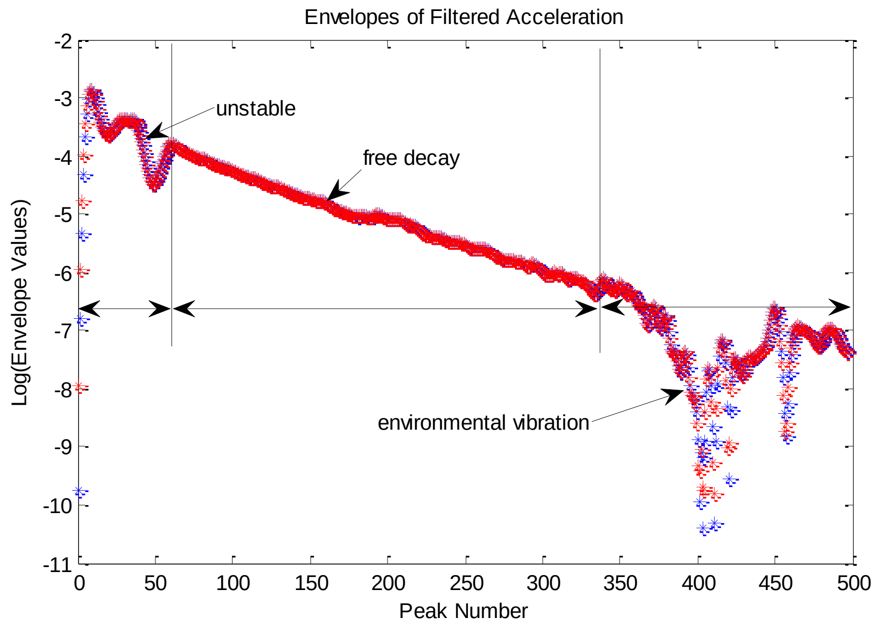

Fig.10 Logarithm of the peak (valley)

Figure 8 shows that the logarithmic decrement is not a constant value but a value that changes with the amplitude of acceleration. To avoid the errors brought by different acceleration amplitudes, each acceleration time series is cut and then started with the same acceleration amplitude. The final logarithmic decrement was calculated with the approximate linear free decay part in Fig.10.

(2) The Random Decrement Technique/ERA method

Sometimes both, the vibrator and the artificial excitation, cannot excite the lower mode of the cable. Other methods are needed to calculate the damping of the cable. This paper uses the Random Decrement Technique/ERA method to identify the damping of cables with environmental vibration acceleration.

The Random Decrement Technique(Ji and Xiao 2006) is a method used to identify structures under ambient loadings. It helps extract free-decay response data that can be further used as input to other modal identification methods. The basic idea of this method is to pick out time segments and take an average at each time segment to achieve a response that satisfies the initial condition. The ERA method (Fang-lin, Xu-hui et al. 2002, Li·qun and Jin-ping 2004, Caicedo 2011) is a time-domain method using the principles of minimum realization to obtain a state-space representation of the structure. A realization is the estimation of the system matrices A, B, and C acquired from the structure responses. There are an infinite number of matrices A, B, C, and D, each of which have different dimensions that can be used to describe the state space of the structures. One of these matrices is a case with the smallest number of states. This realization is called a minimum realization and can be used to create the discrete state space model of the system. The minimum realization can be calculated by Hankel's matrix decomposition. The discrete state space model can then be changed into a continuous model. The Eigen values of this continuous state space model can be used to determine the natural frequency and the damping ratio of the structure. There are also some problems with the ERA method. For example, often times, many false modes will appear among the identification results. Users must make their own judgments to remove the false modes (Hua 2006).

Figure 11 shows the acceleration time history and its Fourier spectrum of cable M8 under environmental excitation. The frequency of each mode can be read from the peak of the Fourier spectrum. Using the Random Decrement Technique/ERA method, damping of cable can be identified with white noise vibrations (environmental vibrations). First, the original signal is dealt with the Random Decrement Technique. Reaching a signal similar to that of the free decay is shown in Fig.12. This signal was used as the input of the ERA method. Frequency and the damping with false modes of the cable are then identified. With the natural frequency getting found in Fig.11, false modes can be eliminated. As a result, we can get the real modal damping of each mode.

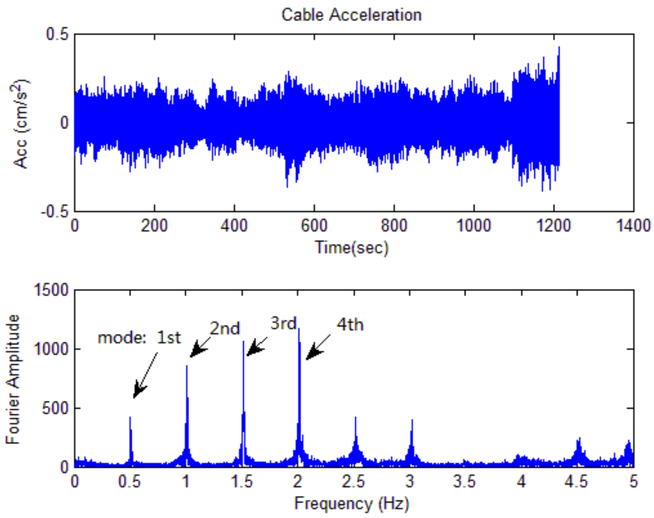

Fig.11 Environmental vibration and Fourier spectrum

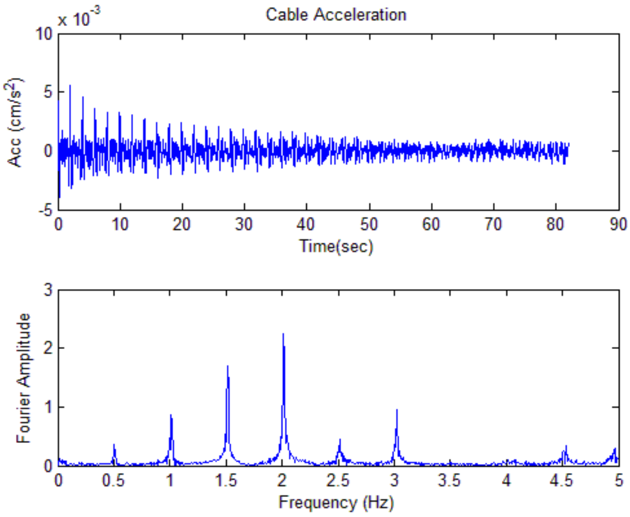

Fig.12 Acceleration after using RDT

Logarithmic decrements calculated above are listed in Table 4 to Table 6. Both artificial excitation and vibrator excitation belongs to free decay method and frequency of each mode is read from the Fourier spectrum. ERA method can calculate both frequency and logarithmic decrement and the frequencies are close to that read from Fourier spectrum.

Table 4 Damping of M18

Mode	M18				
	Frequency (Hz)	δ (Free decay)		ERA (Environmental excitation)	
		Artificial excitation	Vibrator excitation	Frequency (Hz)	δ
1	0.366	△	△	0.348	0.0050
2	0.659	△	△	0.665	0.0018
3	1.001	0.0012	0.0015	1.000	0.0022

Table 5 Damping of M13

Mode	M13				
	Frequency (Hz)	δ (Free decay)		ERA (Environmental excitation)	
		Artificial excitation	Vibrator excitation	Frequency (Hz)	δ
1	0.415	△	△	0.419	0.0164
2	0.806	0.0095	△	0.796	0.0142
3	1.196	0.0088	△	1.193	0.0054

Table 6 Damping of M8

Mode	M18				
	Frequency (Hz)	δ (Free decay)		ERA (Environmental excitation)	
		Artificial excitation	Vibrator excitation	Frequency (Hz)	δ
1	0.513	0.0098	△	0.530	0.0122
2	1.001	0.0083	0.0056	1.012	0.0073
3	1.514	0.0127	0.0122	1.518	0.0030

"△"means there is no result under this condition

The logarithmic decrement of each cable in illustrated in the Fig.13 to Fig.15 to compare different methods with their mean value and also to compare the difference of logarithmic decrements of different cables.

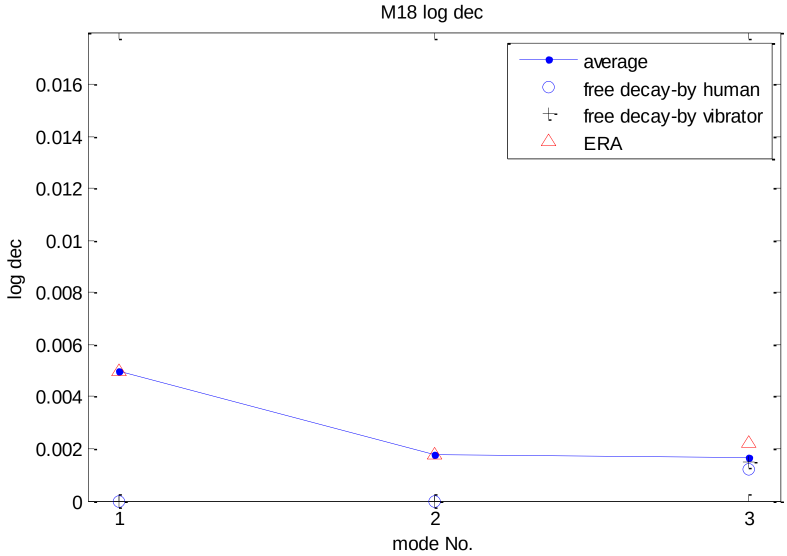

Fig.13 The logarithmic decrement of M18

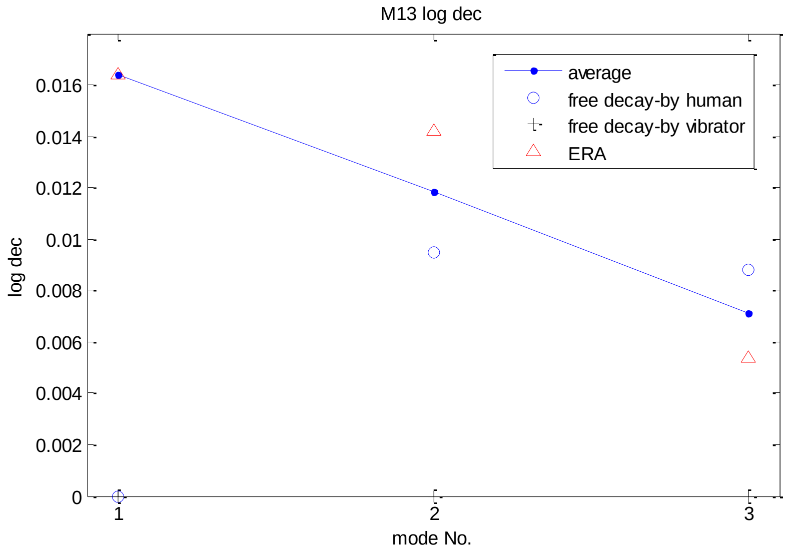

Fig.14 The logarithmic decrement of M13

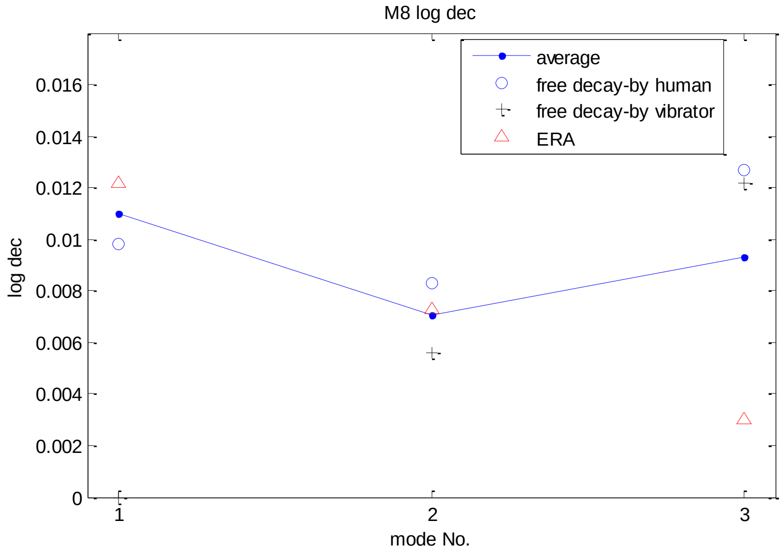

Fig.15 The logarithmic decrement of M8

The results show that for the same mode, the longer the cable, the lower its damping. For the same cable, the results show that the higher the mode, the lower its damping. The damping is calculated by different methods that are close to each other, with the exception of the 3rd mode of M8, the 1st, and the 2nd mode of M18.

4 Comparison of steel strand and parallel wire cable

The first 3 modal damping of steel strand cables that were calculated from this experiment, was compared with the damping of Tatara bridges (containing parallel wire cables) by field vibration testing (Manabe, Sasaki et al. 1999, Yong-gang 2008) and the results of SHI Chen (Chen 2004). Results are shown in Table 7 and Fig.16.

Table 7 Damping of steel strand cables and parallel wire cables

Cable No.	1st mode	2nd mode	3rd mode	Length(m)	Cable type
Tatara Bridge					Parallel wire cable
C1	0.013	0.0021	0.0018	265.9	
C38	0.011	0.005	0.003	347.8	
reference[14]					
215m cable	0.005	0.0021	0.0012	215.6	
present					Steel strand cable
M8	0.0122	0.0069	0.0125	180.9	
M13	0.0164	0.0095	0.0088	248.7	
M18	0.005	0.0018	0.0013	320.6	

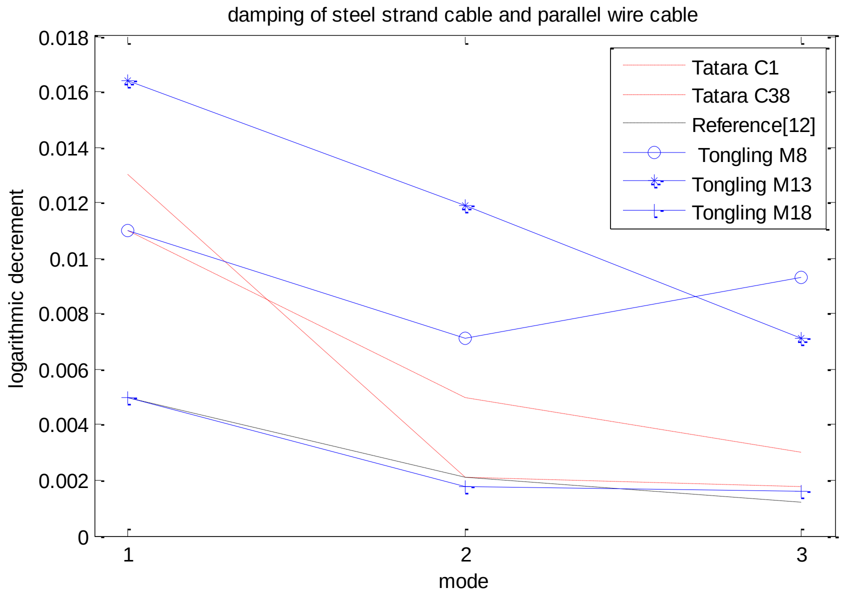

Fig.16 Comparison of steel strand cables to parallel wire cables

Compared to the parallel wire cables, the 1st and 2nd modal damping of steel strands has higher a damping, while the 3rd modal damping (M8 and M13) is almost the same value. In general, the modal damping of steel stand cables and parallel wire cables have no significant difference.

5 Conclusions

This paper used 2 methods to investigate the experimental estimation of modal damping. The methods used include: 1) the free decay method using the acceleration time series under artificial excitation and vibrator excitation, and 2) the Random Decrement Technique/ERA method using the acceleration of environmental vibration. With the modal damping observed by these two methods, we could conclude that:

1) Choosing the right excitation method is very important to achieve better results. According to the working principle of the vibrator along with the feature of artificial excitation, lower modes should be excited by artificial excitation methods while higher modes should be excited by a vibrator.

2) According to the results, the free decay method has clear principles and makes full use of the data, and consequently acquires reliable results. The Random Decrement Technique/ERA method could use the acceleration of environmental vibration, so it is useful when free decay signal is not available. For lower modes it was difficult to excite during the experiment. The Random Decrement Technique/ERA method could solve such problems. But there are also problems using the ERA method. Many false modes infiltrate and users must judge by themselves to eliminate the false modes.

3) Results of the experiment showed that for the same mode, the longer the cable, the lower its damping. Results showed that for the same cable, the higher the mode, the lower the value of damping.

4) The 1st and 2nd mode damping of steel strand cables is a little higher than parallel wire cable. The 3rd modal damping is almost the same value. In general, modal damping of steel strand cables is of similar features but slightly larger than that of parallel wire cables.

Acknowledgment

This work has been supported by Bridge Monitoring and Vibration Control Department, Tongji

University and Liuzhou OVM Machinery Co. The writers would like to thank Dr. ZHOU Yi, XU Bin, WU Jiaxin for their participation in the experimental set-up and implementation, and professor XIE Zhenyuan and engineer HUANG Yongjiu for their support.

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