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Full-scale experimental verification on the vibration control of stay cable using optimally tuned MR damper

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Abstract. MR dampers have been proposed for the control of cable vibration of cable-stayed bridge in recent years due to their high performance and low energy consumption. However, the highly nonlinear feature of MR dampers makes them difficult to be designed with efficient semi-active control algorithms. Simulation study has previously been carried out on the cable-MR damper system using a semi-active control algorithm derived based on the universal design curve of dampers and a bilinear mechanical model of the MR damper. This paper aims to verify the effectiveness of the MR damper for mitigating cable vibration through a full-scale experimental test, using the same semi-active control strategy as in the simulation study. A long stay cable fabricated for a real bridge was set-up with the MR damper installed. The cable was excited under both free and forced vibrations. Different test scenarios were considered where the MR damper was tuned as passive damper with minimum or maximum input current, or the input current of the damper was changed according to the proposed semi-active control algorithm. The effectiveness of the MR damper for controlling the cable vibration was assessed through computing the damping ratio of the cable for free vibration and the root mean square value of acceleration of the cable for forced vibration.

Keywords: MR damper; semi-active control; vibration mitigation of cable; full scale cable test

1. Introduction

Cable-stayed bridges have become popular in recent years for their high performance and cost-effectiveness, and the span of bridges increase significantly with the development of new materials and technologies. As the main force-bearing components in cable-stayed bridges, the length of stay cables increase as well. Thus, using passive dampers alone may not satisfy the control requirement of the stay cables and semi-active MR dampers have been proposed for the vibration mitigation of long stay cables for the advantage of lower energy consumption, adjustable input and wide control range (ex., Chen *et al*. 2001, Li *et al*. 2007).

MR dampers have been proved to be effective as control devices installed in building structures for resisting earthquake excitations (ex., Spencer *et al*. 1997, Dyke *et al*. 1998), and they have

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been applied to several real bridge projects, such as the Eiland bridge nearby Kampen. The Netherlands (Weber *et al*. 2005), the Dongting Lake Bridge (Chen *et al*. 2001, Wang *et al*. 2003, Duan *et al*. 2006), Third Qiantang River Bridge (Wu *et al*. 2004), Bingzhou Yellow River Highway Bridge (Li *et al*. 2007) and Sutong Bridge in China. However, their performance for mitigating cable vibration has yet to be evaluated.

Experimental tests have been conducted using scaled models to study the performance of MR dampers for mitigating cable vibrations where constant input current is applied (ex. Wu and Cai 2006, Christenson *et al*. 2006). Theoretical studies have been carried out on the semi-active control algorithms associate with MR dampers for cable vibration control, which mostly inherited from the control algorithms used for buildings, such as neural network (Ni *et al*. 2002), LQR (Li *et al*. 2007) and clipped optimal control (ex. Christenson *et al*. 2006). Weber *et al*. (2007a, b, c) applied the energy equivalent approach to model MR damper as equivalent linear viscous damper or nonlinear friction damper in the theoretical and experimental studies of cable vibration control using MR dampers.

The above studies showed that the high nonlinearity of MR dampers leads to a relatively complex representation of its mathematical model and makes them difficult to be applied to suppress cable vibration with an efficient control algorithm. Also, different from building structures, there is an optimal damping associated with each mode of cable vibration (Pacheco *et al.* 1993) and this special feature has not been fully utilized in the existing semi-active control algorithms of MR dampers. The authors (Huang *et al*. 2012) conducted a performance test on a popular MR damper and derived a simple bilinear mechanical model of the damper, consequently, proposed an efficient semi-active control strategy based on the universal design curve (ex. Pacheco *et al.* 1993, Krenk 2000) for linear dampers. Simulation study was carried out and showed that the MR damper is effective as a semi-active control device for the vibration mitigation of stay cable. However, the model of cable-MR damper system established in the simulation study was relatively ideal compared to the real situation, and on the other hand, it is difficult to conduct reliable field tests on an actual bridge to verify the performance of MR dampers installed on the cables. Hence, it might be more reasonable and meaningful to carry out experimental studies on the cable-MR damper system using a full-scale model.

In this paper, a full-scale cable test will be carried out to investigate the optimal damping performance of the cable-MR damper system and to verify the accuracy and efficiency of the proposed semi-active control algorithm for suppressing cable vibrations. A long stay cable fabricated for a real bridge will be set-up with a MR damper installed. The cable will be excited under both free and forced vibrations. Different test scenarios will be considered where the MR damper was tuned as passive damper with minimum or maximum input current, or the input current of the damper was changed according to the proposed semi-active control algorithm. The effectiveness of the MR damper for controlling cable vibration will be assessed through computing the damping ratio of the cable for free vibration and the root mean square value of acceleration of the cable for forced vibration.

2. Semi-active control algorithm

The semi-active control algorithm proposed in Huang *et al*. (2012) will be used in the full-scale experiment for the verification of the effectiveness of the MR damper. The essence of the algorithm will be summarized in the following and the detailed derivations can be found in (Huang *et al*. 2012).

The equation of motion of the cable-damper system is first established according to the classic theory of cable structure (Irvine 1981)

$$m\ddot{v}(x,t)+c\dot{v}(x,t)-Tv''(x,t)=f(x,t)+F_d(t)\delta(x-x_d) \tag{1}$$

It is based on a taut string assumption as shown in Fig. 1, where L is the length of the cable, m is the mass per unit length, c is the uniform inherent damping of the cable, and T is the cable force. The location of the damper is denoted as x_d, which is the distance from the damper to the anchorage of the cable. It is assumed that the cable force is unchanged under linear oscillations, the bending stiffness is negligible, and the effects of sag and inclination are ignored. In Eq. (1), $v(x,t)$, $\dot{v}(x,t)$ and $\ddot{v}(x,t)$ are the displacement, velocity and acceleration of the cable respectively, $v''(x,t)$ is the second partial derivative of $v(x,t)$ with respect to x, $F_d(t)$ is the damping force at the damper location, $f(x,t)$ is the uniform load applied over the cable, and $\delta(x-x_d)$ is the δ-dirac function.

The boundary conditions corresponding to the above equation of motion are $v(0,t)=v(L,t)=0$ for all t, $0\le x\le L$.

Assuming the series of solution to Eq. (1) are in the form of

$$v(x,t)=\sum_{j=1}^{r}q_j(t)\varphi_j(x) \tag{2}$$

where $\varphi_j(x)$ is the mode shape function with $\varphi_j(0)=0$ and $\varphi_j(L)=0$. Eq. (1) can be transformed to the modal coordinate system by substituting Eq. (2) into (1) using a standard Galerkin approach and integrating along the full length of the cable, as

$$M\ddot{q}+C\dot{q}+Kq=f_q+\varphi(x_d)F_d(t) \tag{3}$$

where

$$M=[m_{ij}],\ \ m_{ij}=m\int_0^L\varphi_i(x)\varphi_j(x)dx \tag{4}$$

$$C=[c_{ij}],c_{ij}=c\int_0^L\varphi_i(x)\varphi_j(x)dx \tag{5}$$

$$K=[k_{ij}],\ \ k_{ij}=-T\int_0^L\varphi_j''(x)\varphi_i(x)dx \tag{6}$$

$$f_q=[f_{qi}],f_{qi}=\int_0^L f(x,t)\varphi_i(x)dx \tag{7}$$

Using a control oriented model proposed by Johnson *et al*. (2007), the mode shape functions are

$$\varphi_0(x)=\begin{cases}x/x_d & 0\le x\le x_d\\ (L-x)/(L-x_d) & x_d\le x\le L\end{cases};\ \ \varphi_j(x)=\sin(j\pi x/L) \tag{8}$$

and the mass, stiffness and damping of the cable are expressed as

$$m_{ij} = \begin{cases} \frac{mL}{2}\delta_{ij} & i>0, j>0 \\ \frac{mL}{3} & i=0, j=0 \\ \frac{mL^3 \sin(kx_d\pi/L)}{x_d(\pi k)^2(L-x_d)}, & others, k=\max(i,j) \end{cases} \tag{9}$$

$$k_{ij} = \begin{cases} \frac{T\pi^2}{2L} i^2\delta_{ij} & i>0, j>0 \\ \frac{LT}{x_d(L-x_d)} & i=0, j=0 \\ \frac{TL\sin(kx_d\pi/L)}{x_d(L-x_d)}, & others, k=\max(i,j) \end{cases} \tag{10}$$

$$C = (c/m)M \tag{11}$$

Introducing a state vector $Z = \begin{bmatrix} q \\ \dot{q} \end{bmatrix}$, Eq. (3) can be transformed into the state-space representation of the cable-damper system as

$$\dot{Z}(t) = AZ(t) + GF_d + Bf_q(t) \qquad Z(t_0) = 0 \tag{12}$$

where

$$A = \begin{bmatrix} 0 & I \\ -M^{-1}K & -M^{-1}C \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ M^{-1} \end{bmatrix}, \quad G = \begin{bmatrix} 0 \\ M^{-1}\varphi(x_d) \end{bmatrix} \tag{13}$$

Eqs. (1)-(13) are adapted from (Johnson *et al*., 2007).

Expressing the control force or the damping force of MR damper as

$$F_d(t) = -LZ(t) \tag{14}$$

where L is the feedback gain matrix. Substituting Eq. (14) into Eq. (12), one obtains the state-space equation of the cable-damper system as

$$\dot{Z}(t) = (A - GL)Z(t) + Bf_q(t) \tag{15}$$

The feedback gain can be related to the optimal linear damping coefficient as

$$L = -\begin{bmatrix} 0 & C_{d,opt}\varphi^T(x_d) \end{bmatrix} \tag{16}$$

where $C_{d,opt}$ is the optimal linear equivalent damping of the MR damper, which can be determined using the Universal Damping Curve for linear dampers (Krenk 2000) as shown in Fig. 2. Horizontal axis is the dimensionless damping coefficient of damper represented as

Fig. 1 Cable-damper system (Johnson *et al.* 2007)

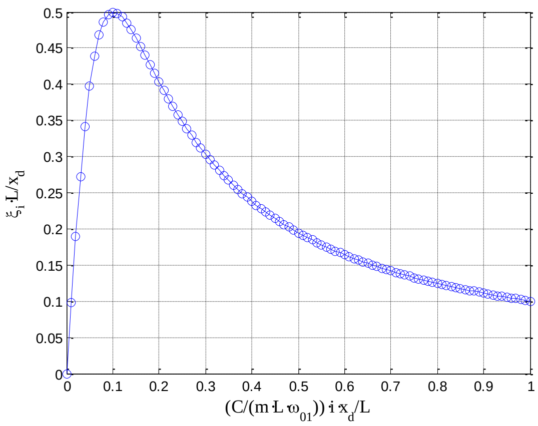


Fig. 2 Universal damping curve

$$\kappa = \frac{iC_{\mathrm{d}}(x_d / L)}{mL\omega_1} \tag{17}$$

where C_d is the linear damping coefficient of damper, ω_1 is the 1st natural angular frequency of the cable, and i represents the ith vibration mode, and vertical axis is the ratio between the damping ratio of cable ξ_j and the relative installation position of damper x_d / L, which can be approximately represented as

$$\frac{\xi_i}{x_d / L} \cong \frac{\pi^2\kappa}{(\pi^2\kappa)^2 + 1} \tag{18}$$

When the cable achieves the maximum damping ratio, Eq. (18) will be equal to 0.5, and the value of κ can be obtained as

$$\kappa = \frac{1}{\pi^2} \tag{19}$$

The corresponding optimal damping coefficient of the damper can be calculated from Eqs. (17) and (19) as

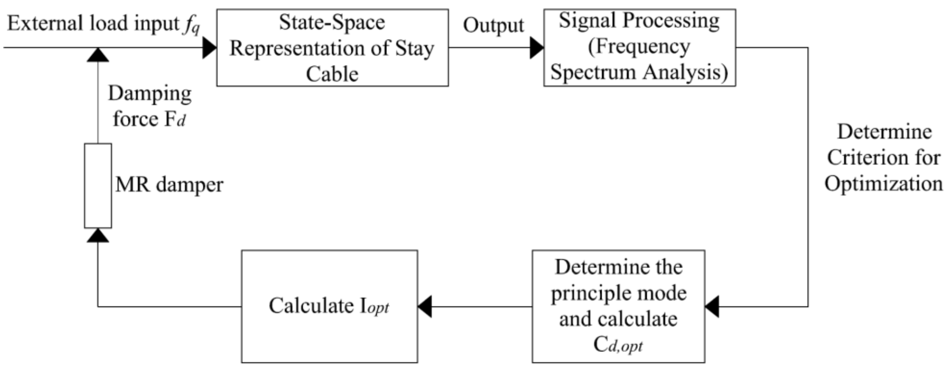


Fig. 3 Flow chart of the control algorithm

$$C_{d,opt} = \frac{mL\omega_1}{i\pi^2 (x_d / L)} \tag{20}$$

For the optimal tuning of MR damper, i is chosen as the dominant or principal vibration mode which can be identified by signal processing the displacement response using the following equation

$$i = index\{\max |q_j(t)|\} \tag{21}$$

where $q_j(t)$ is the modal displacement of j^{th} mode. In the experimental study, in order to reduce the feedback time of the controller, the principal mode is determined by examining the largest value of the power spectrum of displacement response vector.

After determining the optimal damping coefficient $C_{d,opt}$, the optimal input current I_{opt} for MR damper can be obtained using the following equations

$$C = C_e + \frac{F_e}{V_{\max}} \tag{22}$$

$$C_e = \begin{cases} c_1 I + c_2 & 0 \le I \le 0.5A \\ c_3 I + c_4 & 0.5A \le I \le 2A \end{cases} \tag{23}$$

$$F_e = \begin{cases} f_1 I + f_2 & 0 \le I \le 0.5A \\ f_3 I + f_4 & 0.5A \le I \le 2A \end{cases} \tag{24}$$

where C is the linear equivalent damping of the MR damper, C_e and F_e are coefficients bilinearly related to the input current, and $V_{\max}$ is the maximum velocity of the damper. The parameters c_1, c_2,

c_3, c_4, f_1, f_2, f_3, f_4 could be determined by curve fitting from the performance test presented in Huang *et al*. (2012). To compute the optimal input current I_{opt}, the bilinear relationship between $C_{d,opt}$ and I_{opt} are established where C is set to $C_{d,opt}$ and Eqs. (23) and (24) are substituted into Eq. (22).

The semi-active control algorithm for mitigating cable vibrations using MR damper can be summarized by the flow chart shown in Fig. 3.

3. Full-scale experimental test

Simulation studies have been carried out and presented in previous paper (Huang *et al*. 2012) to investigate the effectiveness of MR damper in mitigating cable vibration. However, the analysis was derived based on series of assumptions and simplifications on the cable system, and therefore, it is necessary to conduct experimental tests for further studies. In this paper, a full-scale experimental test on cable-MR damper system will be established to verify the theoretical and simulation studies.

The full-scale cable test was conducted in Liuzhou OVM Machinery Co., LTD. A 170 m galvanized steel wire strand cable (OVM250-37) with parameters given in Table 1 was used. The cable was manufactured for real bridge project and was tested before installed to the bridge.

3.1 Experimental set-up

The cable was tensioned horizontally using hydraulic jack as shown in Fig. 4, and therefore, the effects of sag and inclination can be ignored in the test. A MR damper (RD-1005-03) provided by Lord Company was used, which is a popular type of MR damper applied to actual stay cable. The parameters of the MR damper are summarized in Table 2 and its configuration is shown in Fig. 5.

Table 1 Parameters of cable

L [m]	T [kN]	m [kg/m]	D [mm]	f_1 [Hz]	x_d [m]	c [N·s/m]
170	3826	44.067	110.5	0.8756	3.4	0.31

Table 2 Parameters of MR damper

Compressed length （mm）	Tensile length （mm）	Body diameter （mm）	Axle diameter （mm）	Maximum force （N）	Maximum temperature （℃）
155	208	41.4	10	4448	71℃

Fig. 4 Full-scale cable

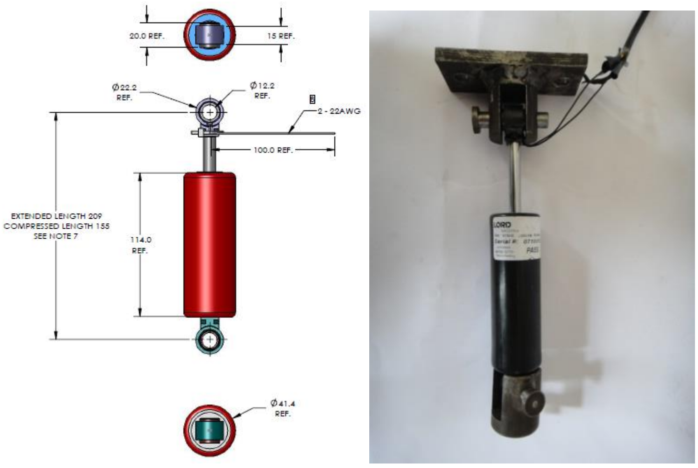


Fig. 5 MR damper

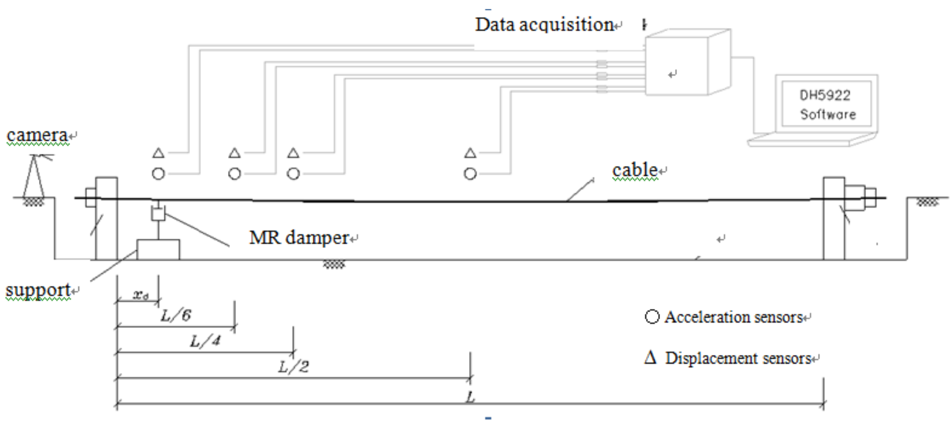


Fig. 6 Set-up of full-scale cable test

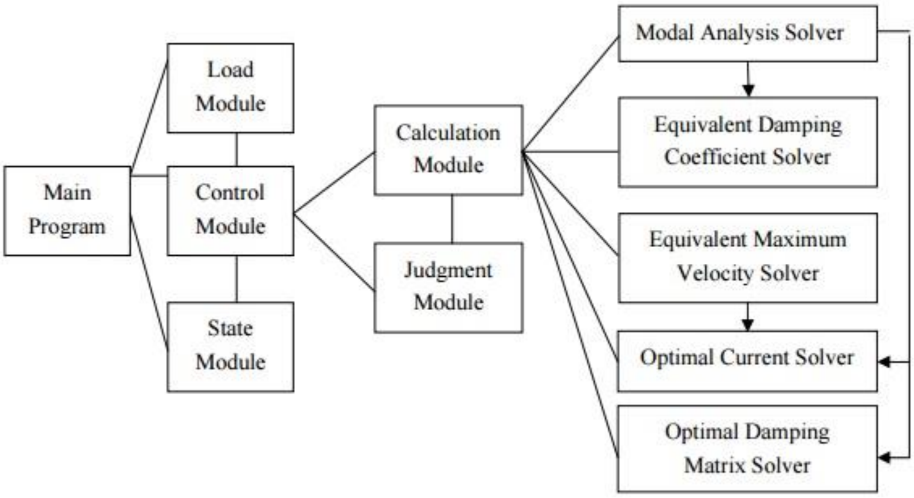


Fig. 7 Structure of semi-active control system

Theoretically, it is desirable to have dampers installed as higher as possible in order to achieve ultimate performance. However, realistically, the position of damper is usually limited to 2%-5% of cable length from the anchorage due to aesthetic concern. In this test, the MR damper was installed at 2% of cable length for free vibration and 4% of cable length for forced vibration.

Displacement sensors and accelerometers were installed to collect the dynamic responses of the cable during vibration test. The detail set-up is illustrated in Fig. 6.

3.2 Realization of semi-active control algorithm

The semi-active control algorithm proposed in Session 2 was compiled using SIMULINK, a subassembly of MATLAB, and realized through the integration of two major hardwares, a QUANSER active control system which outputs the optimal control voltage and a LORD Wonder Box which converts the voltage to the input current of MR damper. This synthesizes the feedback control loop given in Fig. 3 and builds up an efficient and refined semi-active control system specially designed for mitigating cable vibration.

The structure of the semi-active control system can be divided into four hierarchies as shown in Fig. 7 and the details will be explained as follows.

(1) The Main Program (Fig. 8) is the foundation of the semi-active control system, which consists of three modules, namely the Load Module, the State Module, and the Control Module.

- The Load Module inputs forces to the cable-MR damper system.
- The State Module gives the output of the system through the establishment of state-space equation.
- The Control Module computes the optimal control force to the system based on the output information.

(2) For feedback control, the majority of computation efforts contribute to the determination of optimal control force given by the Control Module (Fig. 9), which requires a Calculation Module and a Judgment Module.

- The Calculation Module (Fig. 10) contains different solvers corresponding to the equations given in Session 2 and computes the optimal input current of MR damper which will be transferred to a digital oscilloscope in order to monitor the semi-active control effect in real time. It also determines the optimal damping coefficient matrix which will be feedback to the State Module for next step computation.
- The Judgment Module is used to: (a) decide whether it is necessary to start the Calculation Module by setting a threshold on the amplitude of vibration, (b) to ensure the calculated optimal current falls into the interval set by the bilinear model of MR damper and (c) to prevent the input current of MR damper from exceeding its maximum allowable value.

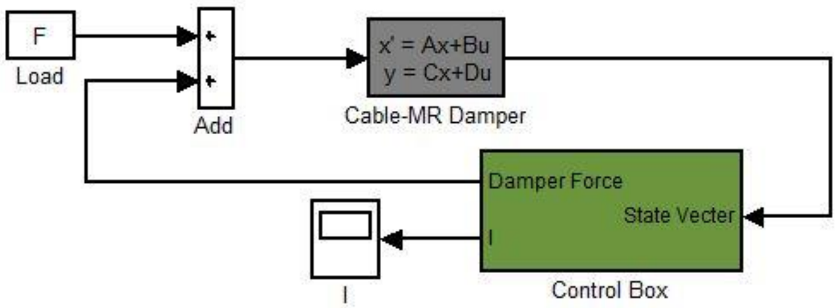


Fig. 8 Main Program of semi-active control system

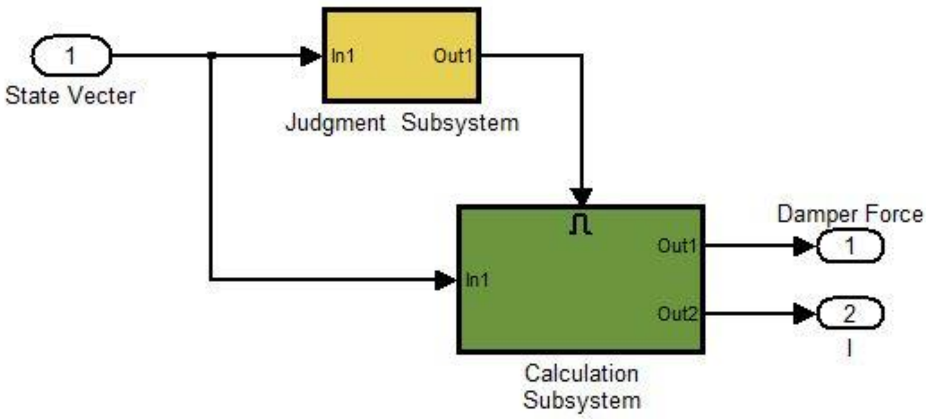


Fig. 9 Control Module

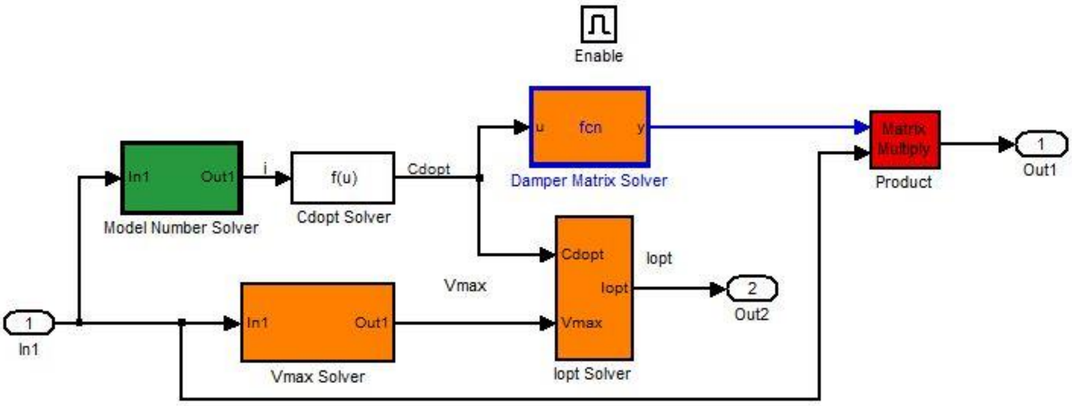


Fig. 10 Calculation Module

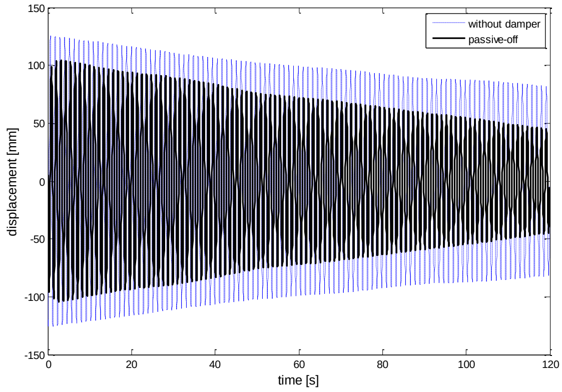
4. Test results

In the simulation study (Huang *et al*. 2012), it was found that the vibration of stay cable is dominated by lower modes under different external excitations and can be effectively controlled once the first few modes of vibration are suppressed. Therefore, in the full-scale cable test, only lower modes of cable vibration are considered. Both free vibration and forced vibration of the cable were generated and will be presented in this paper, where four different scenarios were considered as: (1) No damper (without installation of MR damper); (2) Passive-off (with installation of MR damper whose input current is 0A); (3) Passive-on (with installation of MR damper whose input current is the maximum working current of 2A); and (4) Semi-active (with installation of MR damper whose input current is calculated by the semi-active control algorithm).

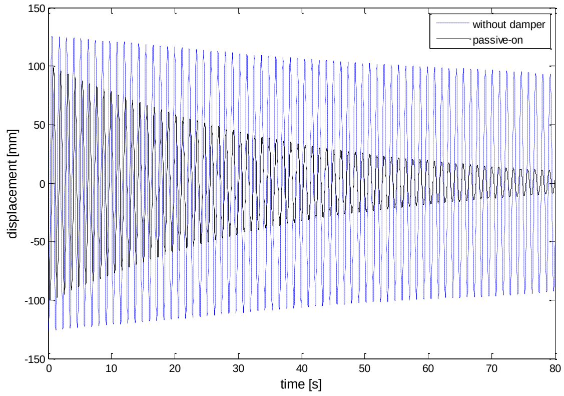
4.1 Free vibration

Free vibration was generated by first humanly pushing the cable up and down at its mid-span and then releasing it when the displacement at mid-span reached the maximum amplitude of first mode cable vibration. Afterwards, the cable was undergoing only the first mode vibration. In this test, the MR damper was installed at 3.4 m (2% of the cable length) from the anchorage of the cable.

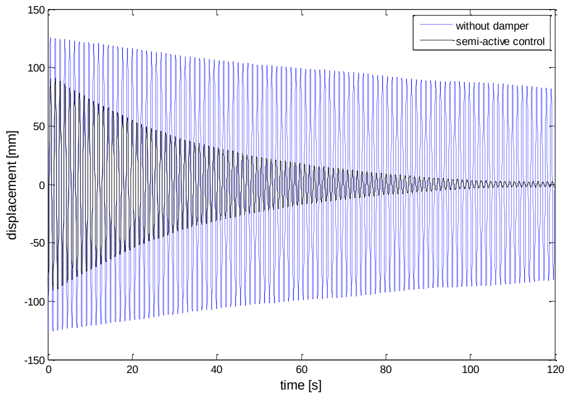
Displacement responses at the mid-span of the cable for different test scenarios are shown in Fig. 11 and the corresponding power spectrum density (PSD) are plotted in Fig. 12. The logarithmic decrement ratio of the displacement time-history and the peak value of PSD which represents the vibration energy were also obtained for each test scenario, presented in Table 3 and 4 respectively. It can be seen from Table 4 that the maximum reduction on cable vibration happened at the damper location. Figs. 11 and 12 and Table 3 showed that the effectiveness of the MR damper on suppressing cable vibration was similar when it was in the semi-active state or in the Passive-on state, and was much better than when it was in the Passive-off state. However, as the input current of the semi-active MR damper changes along with the cable vibration (Fig. 13) and is in general lower than the maximum working current (Passive-on state). Therefore, the overall performance of the MR damper is much better when it is working as a semi-active control device.



(a) Passive-off

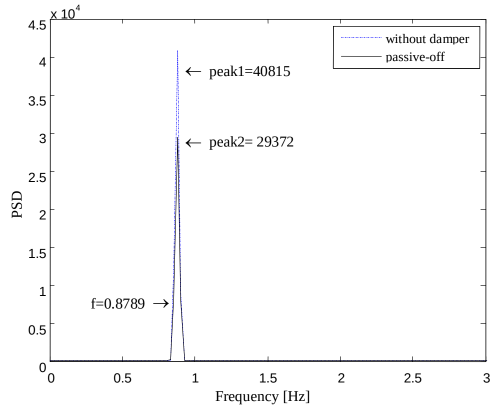


(b) Passive-on

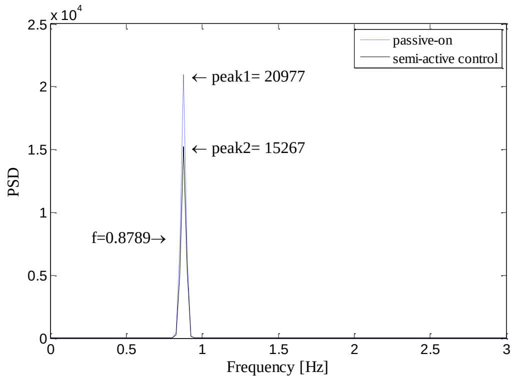


(c) Semi-active

Fig. 11 Displacement time history of free cable vibration at 1/2L



(a) No damper vs Passive-off



(b)Passive-on vs Semi-active

Fig. 12 Power spectrum of displacement response of free cable vibration

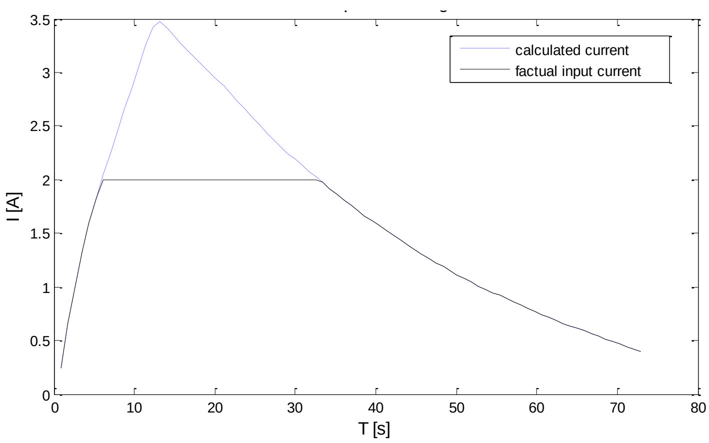


Fig. 13 Changes of input current of MR damper (Semi-active)

Table 3 Logarithmic decrement ratio and modal damping of first order vibration

Frequency（HZ）	Scenarios	Logarithmic decrement δ	Modal damping ratio ξ	Reduction ratio η
0.8789	No damper	0.0040	0.0006	1
	Passive-off	0.0079	0.0013	1.95
	Passive-on	0.0397	0.0063	9.84
	Semi-active	0.0385	0.0061	9.55

Remark: $\eta = \delta / \delta_{no\ damper}$

Table 4 Peak value of power spectrum

Scenarios	$L/2$		$L/4$		x_d	
	Peak p	Reduction rate ζ (%)	Peak p	Reduction rate ζ (%)	Peak p	Reduction rate ζ (%)
No damper	40815	--	16389	--	139	--
Passive-off	29372	28	12547	23	89	36
Passive-on	20977	49	8663	47	54	61
Semi-active	15267	63	6291	62	39	72

Remark: $\zeta = (p_{no\ damper} - p) / p_{no\ damper}$

4.2 Forced vibration

The forced vibration was generated using a VRS2 exciter manufactured by Solutions-Inc, Japan, as shown in Fig. 14. The frequency range of the exciter is 0~20Hz and the maximum force produced is 500 N. Common dynamic forces such as sinusoidal excitation, impulse load and white noise can be generated, however, due to the time limitation restricted by the manufacturer, only sinusoidal vibration was tested where the exciter was fixed at the location of $L/4$, and the second mode of cable vibration was generated. The loading period is around 100 to 120 seconds.

In this test, the MR damper was installed at 6.4 m (4% of the cable length) from the anchorage of the cable. Due to the limitation of test condition, the effect of the mass of exciter was not able to be completely removed during the test, and therefore, the frequency of the cable system was slightly shifted by a period of 60 seconds. This can be overcome in the analysis by considering the maximum amplitude of steady-state vibration.

Displacement responses at the $L/4$ of the cable for different test scenarios are shown in Fig. 15, and Fig. 16 plots the change of input current of MR damper when it is used as a semi-active control device. Also, the root mean square (RMS) values of acceleration at each measuring point are given in Table 6.

VRS2 Exciter

WF1974 Transmitter

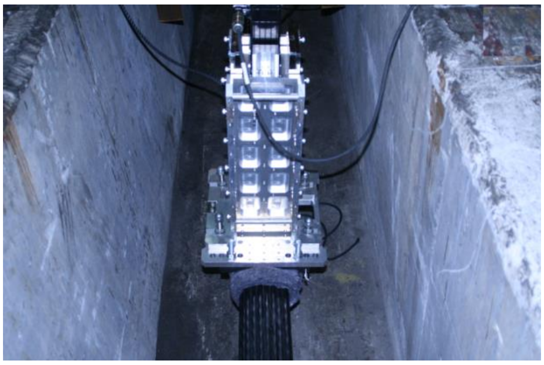


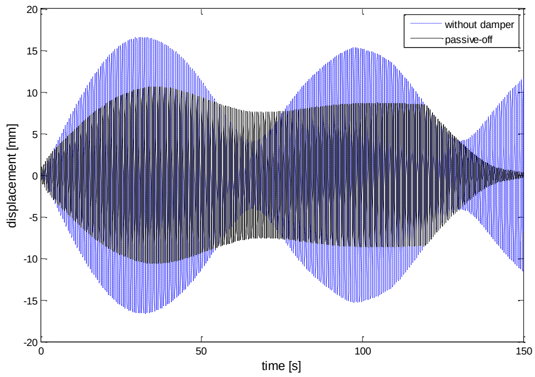
Fig. 14 Onsite installation of exciter

Table 5 Root mean square (RMS) value of acceleration at each measuring point

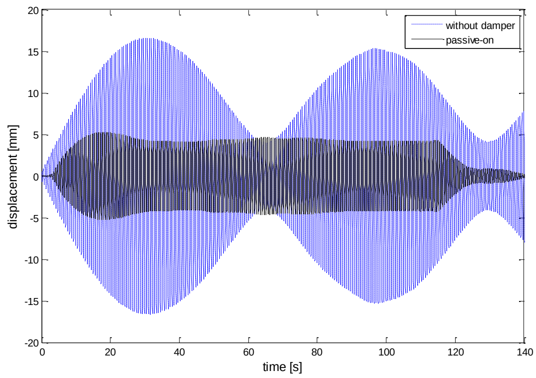
Scenarios	$L/4$		$L/6$		x_d	
	RMS (*g*)	ζ (%)	*RMS* (*g*)	ζ (%)	*RMS* (*g*)	ζ (%)
No damper	0.1031	0	0.0860	0	0.0255	0
Passive-off	0.0709	31	0.0590	31	0.0176	31
Passive-on	0.0371	64	0.0281	67	0.0043	83
Semi-active	0.0378	63	0.0289	66	0.0049	81

Remark: $\zeta = (RMS_{no\ damper} - RMS) / RMS_{no\ damper}$

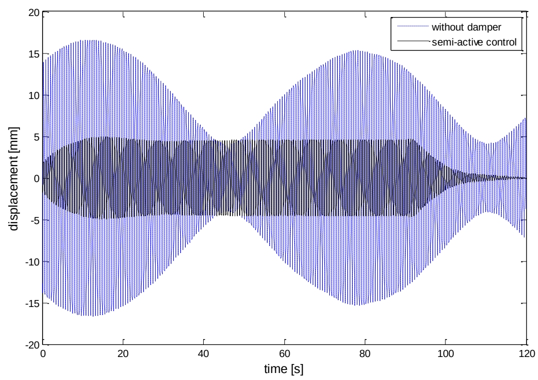
It can be seen from Fig. 15 and Table 6 that the maximum reduction on cable vibration still occurred at the damper location, and the Passive-on and semi-active MR damper are much more effective than the Passive-off MR damper for controlling cable vibration. Fig. 16 plots the variation of the input current of MR damper and it is set to zero when the calculated value is negative which indicates negative damping and is not applicable. The performance of Passive-on and semi-active MR damper are relatively similar, however, the semi-active MR damper used about 10% input current as that of the Passive-on MR damper (Fig. 16) for achieving the same control effect.



(a) Passive-off



(b) Passive-on



(c) Semi-active

Fig. 15 Displacement time history of forced cable vibration at 1/4L

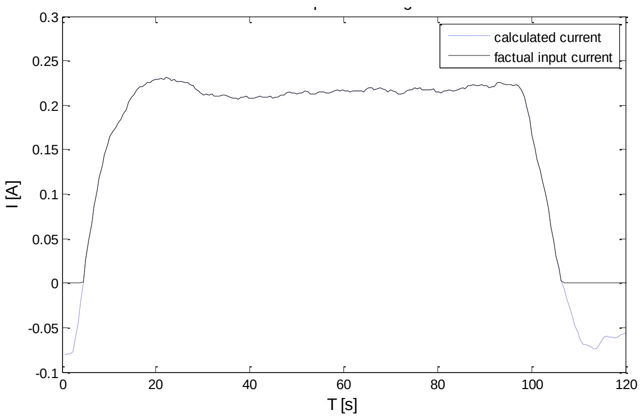


Fig. 16 Changes of input current of MR damper (Semi-active)

Table 6 Root mean square (RMS) value of acceleration at each measuring point

Scenarios	$L/4$		$L/6$		x_d	
	RMS (*g*)	ζ (%)	*RMS* (*g*)	ζ (%)	*RMS* (*g*)	ζ (%)
No damper	0.1031	0	0.0860	0	0.0255	0
Passive-off	0.0709	31	0.0590	31	0.0176	31
Passive-on	0.0371	64	0.0281	67	0.0043	83
Semi-active	0.0378	63	0.0289	66	0.0049	81

Remark: $\zeta = (RMS_{no\ damper} - RMS) / RMS_{no\ damper}$

Table 7 Comparison of simulation and experimental results

Scenarios		ζ (%)		*Relative error* (%)	
		x_d	$L/4$	x_d	$L/4$
Passive-off	Simulation	43	42		
	Experiment	31	31	-27.91	-26.19
Passive-on	Simulation	88	78		
	Experiment	83	64	-5.68	-17.95
Semi-active	Simulation	81	74		
	Experiment	81	63	0.00	-14.86

Remark: *Relative error* = (Experiment–Simulation) / Simulation×100

Table 7 showed the differences between experimental and simulation results. It can be seen that the control effect achieved in the experiment is lower than the one computed by simulation and this is possibly due to the time delay caused by actual devices. However, both studies verified that MR damper is effective for mitigating cable vibrations especially when its input current is turned on.

5. Conclusions

In this paper, a full-scale experimental test was carried out to verify the effectiveness of MR damper for vibration mitigation of stay cable. A long stay cable fabricated for a real bridge was set-up with MR damper installed. The cable was excited under both free and forced vibrations. Different test scenarios were considered where the MR damper was tuned as passive-off damper (0 input current), passive-on damper (maximum input current), or semi-active damper (varying input current). The test results showed that the MR damper is capable for controlling the vibration of stay cable. The performance of Passive-on and semi-active MR damper are relatively similar and much better than the Passive-off MR damper, however, the semi-active MR damper used lower input current than the Passive-on MR damper for achieving the same control effect as its current varies according to the proposed semi-active control algorithm.

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