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EXPERIMENTS ON REDUCTION OF CABLE VIBRATION USING MR DAMPERS

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ABSTRACT

An experimental study is described in this paper on cable vibration control with a MR damper. The performance of this damper is obtained experimentally with different loading frequencies and currents. A 7.16m-long stay cable with a prototype-to-model scale factor of eight is established for the vibration control study. Frequencies of the stay cable under different tension forces are measured and compared with those obtained through theoretical calculation. Then, by hanging a mass in the middle of the cable and by cutting the connecting rope, a free vibration control test is carried out and the acceleration time histories of the middle point and the 1/4th point of the cable are measured while the MR damper with different inside currents is installed at the 1/4th point. Also, a shaker is installed at 2.3% of the cable length close to the lower end to simulate a forced vibration control test. The measured data show that the damper is good for cable vibration control within its working current range (zero to maximum) though beyond some value, the control effect stays almost the same with increased current. It is also observed that the damper can reduce cable vibration under a variety of excitation frequencies, especially for the resonance cases.

Keywords: Magnetorheological (MR) damper, Cable vibration control

INTRODUCTION

There are over 20 major cable-stayed bridges in the U.S. and about 600 worldwide (Angelo 1997). Under certain combinations of light rain and moderate wind speeds (10 to 15 m/s), incidences of large-amplitude vibrations (on the order of 1 to 2m) of stay cables have been reported worldwide, including those located in U.S. as Fred Hartman, Weirton-Steubenville, Burlington, Clark, East Huntington, and Cochrane bridges (Ciolko and Yen 1999). These cables are otherwise stable under similar wind conditions without rain. This phenomenon is known as

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rain-wind vibration. As primary members of cable-stayed bridges, stay cables are the crucial members of the entire structure. Excessive cable vibrations will be detrimental to the long-term health of the bridges and will be a potential threat to public safety and national investment in transportation infrastructures. This issue has raised great concerns in the bridge community and has been a cause of deep anxiety for the observing public (Tabatabai and Mehrahi 2000).

Recognizing the severe condition of cable vibrations, researchers have investigated many ways to address this problem, such as providing mechanical dampers (Tabatabai and Mehrabi 2000), adding crossing ties/spacers (Langsoe and Larsen 1987) or treating cable surface with different techniques (Flamand 1995). The present paper is to use a Magnetorheological (MR) damper to reduce the vibration of a stay cable.

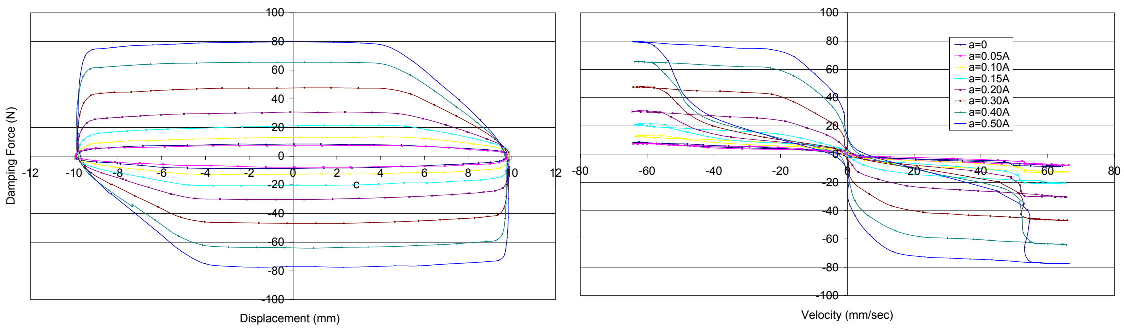
MR dampers are made from MR fluids, which typically consist of micron-sized, magnetically polarizable particles dispersed in a carrier medium such as water, oil or silicone. When a magnetic field is applied to the fluids, particle chains form and the fluids become semi-solid and exhibit viscoplasticity. It can be achieved in a few milliseconds for transition from MR fluids to rheological equilibrium and the maximum achievable yield stress of MR fluids is in an order of 0.1Mpa. The MR fluids can be readily controlled with a low power supply in the range of 2-50watts (Lord Corporation 2004). MR dampers have attracted many researchers' attention. Spencer *et al*. (1997) have investigated the phenomenological model of a MR damper. Fu *et al*. (2001) studied seismic control strategy of a six-story scaled building structure with shearing mode MR dampers, along with many other researches not mentioned here.

EXPERIMENT AND CHARACTERISTICS OF MR DAMPER

Universal Test Machine (UTM) with a maximum output force of 5KN is used to obtain the performance curve of the type RD-1097-01 MR damper provided by Lord Corporation. The damper is connected vertically to the frame with displacement control. The force and displacement time series data are read by the computer controlled data acquisition system. An ampere meter and a wonder box device controller are connected in series with the MR damper to measure and adjust the current in the MR damper, separately.

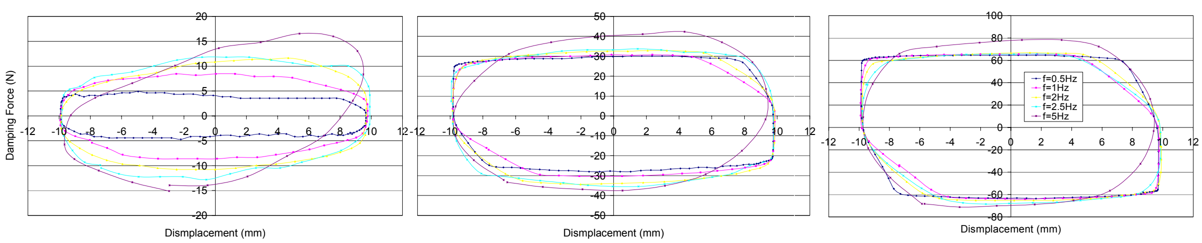
The performance of the MR damper with a variety of currents is provided in Fig. 1. The controlled displacement amplitude is 10mm and the loading frequency is 1Hz. It is observed from this figure that the maximum damping force is about 80N with the current of 0.5A. Even when there is no current in the MR damper, it still provides a damping force of about 10N. So the dynamic range (defined as the ratio of the peak force with a maximum current input of 0.5A to the one with zero current input) is about 8. Also, it is obvious that with the increase of the provided current, the damper can dissipate much more energy.

Fig. 2 shows the performance of MR damper under different frequencies. When there is no current provided to the MR damper, the damping force will increase when the exciting frequency increases (Fig. 2(a)). The ratio of peak force with a maximum exciting frequency of 2.5Hz to the one with 0.5Hz is about 2. When the current is 0.4A, the ratio becomes 1 in Fig. 2(c). This means that the MR damper can respond vibrations with different frequencies at almost the same force. According to the simple mechanical Bingham model for a controllable fluid damper (Stanway 1985 and 1987), this phenomenon means the Coulomb friction part of the force components is increased much with the increase of current so that it dominates the viscosity part, which is proportional to the velocity represented by the frequency here.



(a) (b)

FIG. 1. Performance of MR damper under different currents



(a) (b) (c)

FIG. 2. Performance of MR damper under different frequencies with: (a) a=0A, (b) a=0.2A, (c)a=0.4A

CABLE EXPERIMENT SETUP

Scaling Relations between the Prototype and Model Cable

According to scaling principles, to maintain the similarities between the prototype cable and experimental model, it is important to match scaling factors for all important physical variables. However, it is actually almost impossible to satisfy the scaling principle for all the parameters in majority cases (Tabatabai and Mehrabi 1999). Under these considerations, the following scaling relations shown in Table 1 are chosen according to the similarity principles (Tabatabai and Mehrabi 1999). Based on the experiment conditions, the scaling factor n between the prototype and the model is determined as 8.

Cable Setup

Fig. 3 shows the setup of the cable model system. The one strand steel stay cable is composed of seven wires with a cross section of 98.7mm^2. Both ends of the cable are anchored to two frames with different heights so that the two ends can be considered as fixed. Since the lower end goes though a hydraulic jack before it is anchored, an adjustable tension force can be put on the cable. Nine tension forces are chosen to measure the vibration control effect of the added MR damper under different tension forces. The geometric relation of some specific points is ready to get in the figure. Those points are positions for external vibration loadings, the damping device and the measuring sensors. The Cable Angle (α) in this figure is 11.27°.

Table1. Dynamic scaling relations

Parameter	Scaling factor (model/ prototype)	Parameter	Scaling factor (model/ prototype)
Dimension	1/n	Dynamic Time	1/n
Area	$1/n^2$	Velocity	1
Volume	$1/n^3$	Acceleration	N
Signal Frequency	n	Force	$1/n^2$

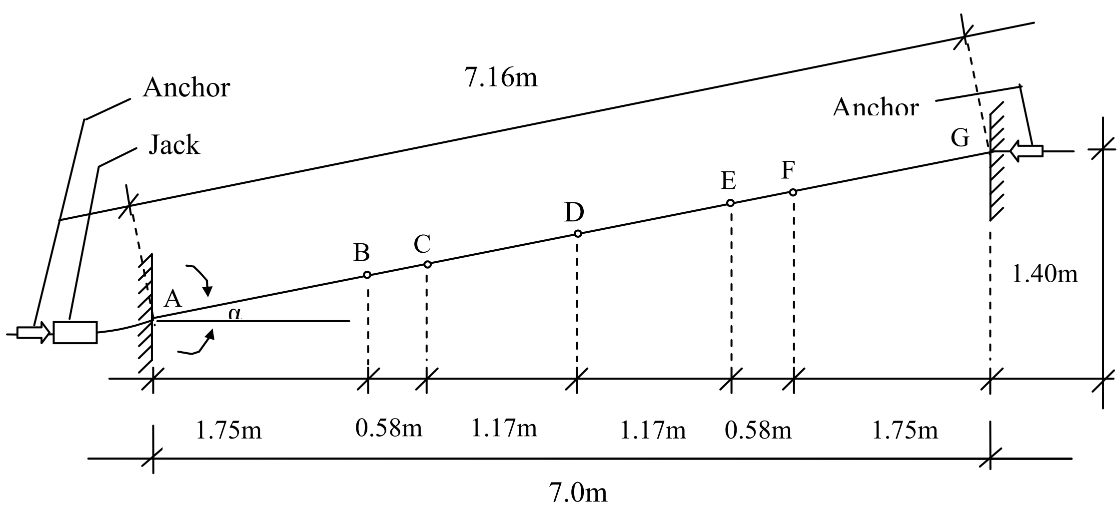


FIG. 3. Cable experimental setup

EXPERIMENT RESULTS

Characteristics of the stay cable

A mass weighted 93.4N is hanged at the middle point 'D' to give the cable a free vibration by cutting the chord connecting the mass. The acceleration time histories at points 'B' and 'D' are measured by two accelerometers and collected by a Photon® data acquisition system. FFT of those time history data is carried out to get the frequency spectra. From the frequency spectra, the basic natural frequency is obtained as 8.93Hz with a cable axial tension force of 16.06KN. Since the scaling factor used is eight, the frequency of the prototype should be 1.12Hz, which is within the reasonable range of the actual cable frequency (Tabatabai *et al.* 1998). Theoretically, the natural frequency can be calculated by the following equations (Irvine 1981):

$$\tan(\Omega/2) = \Omega/2 - (4.0/\lambda^2)(\Omega/2)^3 \qquad (1)$$

$$\Omega = 2\pi f L \Big/ \sqrt{T/m} \tag{2}$$

$$\lambda^2 = (\frac{mgL\cos(\alpha)}{T})^2 L \Big/ \frac{TL_e}{EA} \tag{3}$$

$$L_e = (1 + \frac{(\frac{mgL\cos(\alpha)}{T})^2}{8})L \tag{4}$$

in which, E is Young's modulus, T is the tension force, L is the cable length, α is the inclined angle, L_e is the deformed cable length (Assumed as a parabolic deflected shape), A is the cross section area, m is the mass for per unit length, λ^2 is proportional to the ratio of the axial stiffness to the geometric stiffness. It is a non-dimensional parameter to describe the dynamic behavior of the cable.

From the Eqs. (1)~(4), the frequency f can be calculated as 10.08Hz, which is 12.9% higher than the experimental result. If the tension force is changed, the natural frequency of the cable will also be changed. The theoretic and experimental frequencies versus tension forces are plotted in Fig. 4.

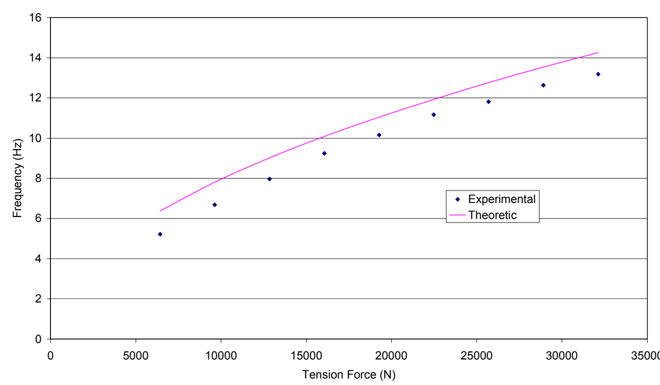
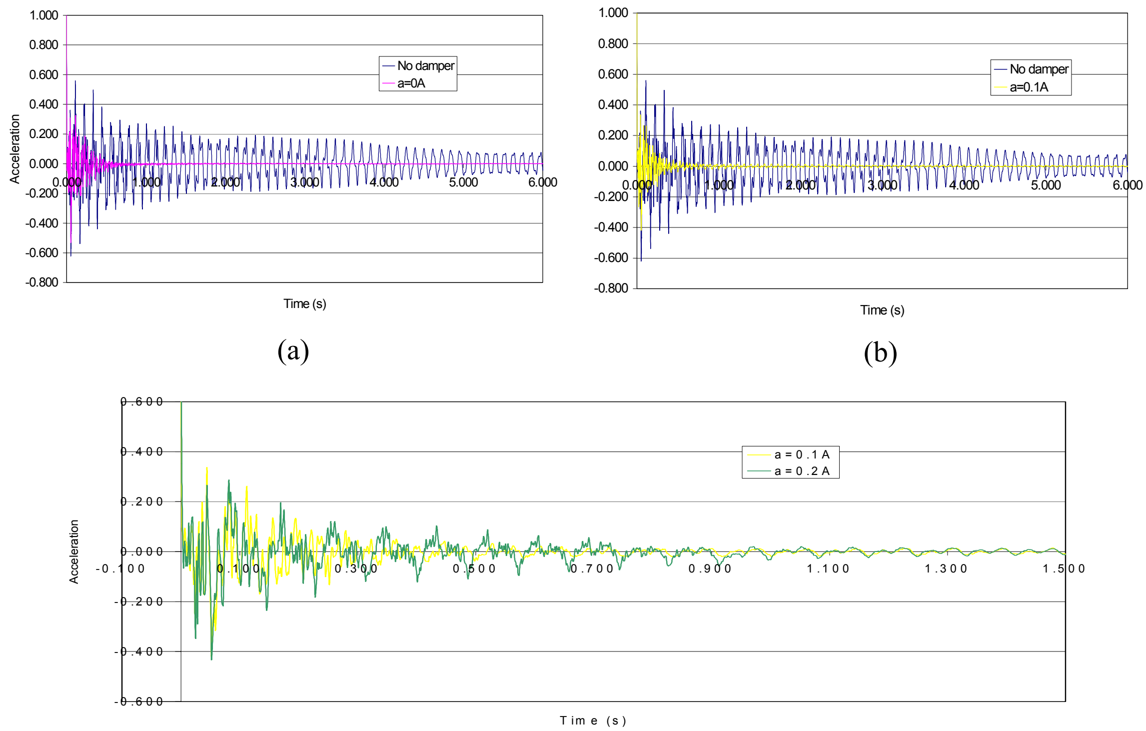


FIG. 4: The Cable Natural frequencies

Free Vibration

A MR damper is connected on point 'B' to reduce the cable vibration. The acceleration time history of point 'D' is plotted in Fig. 5, in which all the data are normalized for the convenience of comparison. It can be observed from Fig. 5(a) that even when there is no current, the damper provides quite efficient damping so that it reduces the cable vibration rapidly. Fig. 5(b) shows when the current reaches 0.1A, the acceleration response is reduced more quickly. Fig. 5(c) shows the acceleration time histories with currents of 0.1A and 0.2A from 0s to 1.5s in details. It reveals an interesting phenomenon that the reduction effect of the MR damper with a current of 0.1A is almost the same as the case of 0.2A after 0.5 second. On one hand, when the measured signal becomes smaller, the relative error due to the noise gets bigger. On the other hand, since the MR damper can be considered as a Bingham element, it needs bigger force to surmount the Coulomb friction to pull and push the damper when the current becomes larger. If the driving force provided by the cable vibration is not enough, the MR damper will work as a fixed support and the damping effect under different currents will not differ much.



(a) (b)

(C)

FIG. 5. ACCELERATION RESPONSE OF CABLE WITH MR DAMPER

Forced Vibration

For the forced vibration, instead of the hanging mass, a shaker working as an excitation source is put on 0.18m away from the low end of the cable. It is 2.3% of the whole cable length.

Fig. 6 shows the acceleration response with 10Hz sine wave external excitation. From this figure, it is observed that the stable vibration of 0.1A case is much less than the one of no damper case. The ratio of the peak value between the case of 0.1A current and no damper is about 14. Also, it can be observed that the time history curve for no damper case is a combination of different frequency components. For the case of 0.1A current, all these frequency components are cut down a lot.

Fig. 7 shows the peak acceleration response of different cases. In Fig. 7(a), the acceleration is normalized with the peak acceleration of no damper case for each frequency. From this figure, the effect of reduction is much better at 9Hz, which should be a resonance frequency for the cable system. When the frequency is away from this resonance frequency, the reduction effect decreases. Fig. 7(b) shows more clearly the existence of the resonance for each current, while the resonance frequency increases with the increase of current. This means the stiffness of the damper becomes bigger so that the natural frequency of the cable-damper system gets larger.

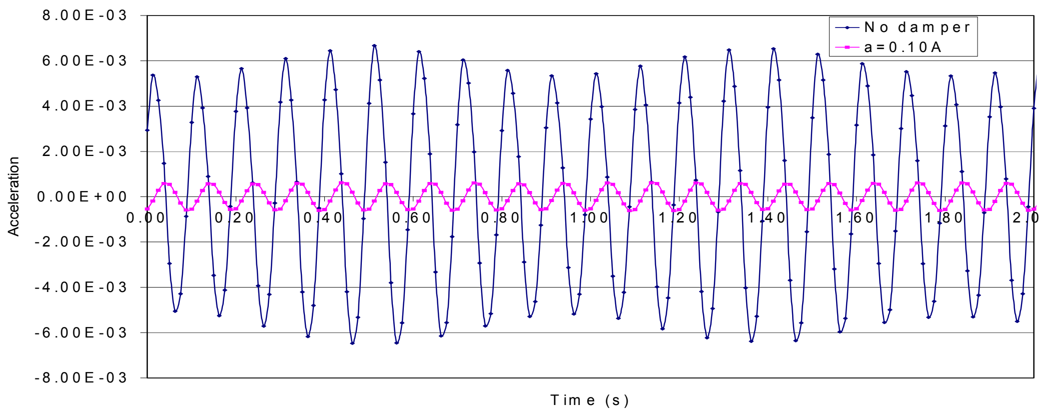
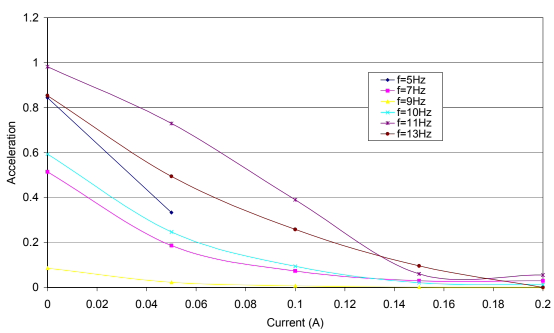
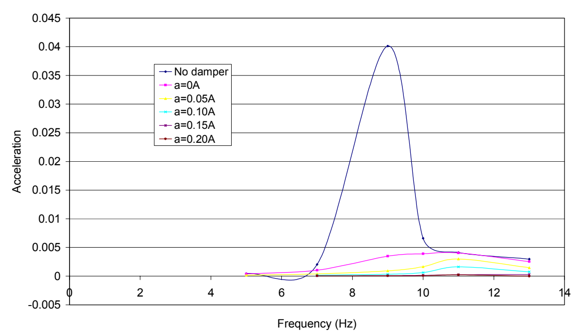


FIG. 6. Cable acceleration response under forced vibration



(a)



(b)

FIG. 7. Peak acceleration response of cable vibration

CONCLUSION

The experiments reported in this paper result in the following conclusions:

(1) MR damper can provide considerable damping force even at passive mode (with zero current) and has a large dynamic range. For the type RD-1097-01 produced by Lord Corporation used in this paper, it has a damping output force of 10N at passive mode and a dynamic range of about 8, under the sine wave loading with a frequency of 1Hz and an amplitude of 10mm.

(2) MR damper can provide almost the same damping force equally for a large range from 0.5Hz to 2.5Hz when the MR damper is turned on electrically. When there is no current in the MR damper, the damping force will increase with the loading frequency.

(3) MR damper is a good choice for adding supplementary damping to reduce the cable vibration. With increased current, the reduction effect will increase. But there exists a saturation current

beyond which the reduction effect will keep the same with increased current.
(4) MR damper can help reduce cable vibration under a variety of excitation frequencies. The reduction effect is extraordinarily good for the resonance case.
(5) With the installation of MR damper, the stiffness of the cable-MR damper system will increase.

This research provides the basis for further development of the MR-damper based TMD system for cable vibration controls, which will be reported in the future.

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