Wind and Structures, Vol. 7, No. 5 (2004) 293-304
DOI: http://dx.doi.org/10.12989/was.2004.7.5.293

MR damping system for mitigating wind-rain induced vibration on Dongting Lake Cable-Stayed Bridge

Z. Q. Chen†

School of Civil Engineering, Hunan University, Changsha, Hunan 410082, P. R. China

X. Y. Wang‡

Department of Civil and Structural Engineering, Hunan University of Science and Technology, Xiangtan, Hunan 411201, P. R. China

J. M. Ko‡† and Y. Q. Ni‡‡

Faculty of Construction and Land Use, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong

B. F. Spencer‡‡† and G. Yang‡‡‡

Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA

J. H. Hu‡‡‡†

School of Civil Engineering, Hunan University, Changsha, Hunan 410082, P. R. China

(Received November 1, 2003, Accepted July 21, 2004)

Abstract. The Dongting Lake Bridge is a cable-stayed bridge crossing the Dongting Lake where it meets the Yangtze River in southern central China. Several intensive wind-rain induced vibrations had been observed since its open to traffic in 1999. To investigate the possibility of using MR damping systems to reduce cable vibration, a series of field tests were conducted. Based on the promising research results, MR damping system was installed on the longest 156 stay cables of Dongting Lake Bridge in June 2002, making it the worlds first application of MR dampers on cable-stayed bridge to suppress the wind-rain induced cable vibration. As a visible and permanent aspect of the bridge, the MR damping system must be aesthetically pleasing, reliable, durable, easy to maintain, as well as effective in vibration mitigation. Substantial work was done to meet these requirements. This paper describes field tests and the implementation of MR damping systems for cable vibration reduction. Three-years reliable service of this system proves its durability.

Keywords: cable-stayed bridges; stay cable; wind-rain induced vibration; MR dampers; vibration mitigation.

---

† Professor
‡ Associate Professor
‡† Chair Professor and Dean
‡‡ Assistant Professor
‡‡† Nathan M. Newmark Professor
‡‡‡ Research Assistant
‡‡‡† Doctoral Student, Senior Engineer

1. Introduction

Wind-rain induced vibration of stay cables was first observed and reported in 1986, at the Meiko-West Bridge in Japan (Hikami 1988). Since then, the same type of vibration has been found worldwide on cable-stayed bridges, and even on steel arch bridges with vertical steel bars (Ruscheweyh 1995). Of the cable vibration known currently, rain-wind-induced vibration is one of the most dangerous.

Intensive studies have been conducted on mechanisms of rain-wind-induced vibration with wind tunnel test (Hikami 1988, Matsumoto 1995, Verwiebe 1998). Some full-scale measurements of stay cable vibration have been implemented with long-term instrumentation (Main 1999, Chen 2002, Matsumoto 2003) for the clear understand of wind-rain induced vibration. Several approaches to mitigate this vibration are proposed and/or implemented with the aid of secondary cable (Yamaguchi 2003) or high-damping rubber (Nakamura 1998) or viscous dampers (Pacheco 1993, Tabatabai 2000, Krenk 2000, 2001, Main 2002a, 2002b) or dynamic absorbers (Ruscheweyh 1995) or nonlinear dampers (Main and Jones 2002), though each has its limitation. Recently, magneto-rheological (MR) damper has been taken more and more attention for use of suppressing structural vibration (Chen 2002, Johnson 2000, Ko 2002). MR damper will be a good substitution of existing passive damper used to mitigate cable vibration, because its yield force can be changed to a desired value conveniently by adjusting voltage input to MR damper.

The Dongting Lake Bridge (shown in Fig. 1) is a cable-stayed bridge crossing the Dongting Lake where it meets the Yangtze River in southern central China. This bridge is the first three-tower, cable-stayed, pre-stressed concrete bridge in China mainland, with 2 main spans of 310 m and two side spans of 130 m. The bridge deck is 23.4 m wide, consisting of 4 traffic lanes. The bridge weight is supported by 222 stay cables of sizes ranging from 28 to 201 m in length and 99 to 159 mm in diameter. In April, July, and December of each year, the local weather often has heavy rain along with strong wind that can last continuously for more than 36 hours. Right after the bridge was completed in December 1999, rain-wind-induced cable vibration was observed. In several instances, this type of vibration occurred on nearly all the stay cables. Reduction of the cable vibrations of this

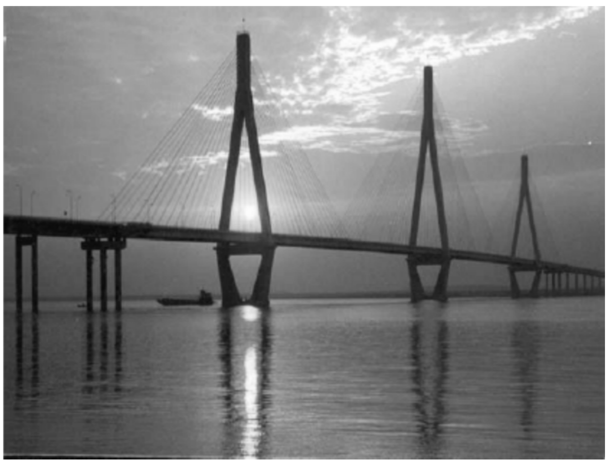

Fig. 1 Dongting Lake Cable-stayed Bridge

bridge, therefore, became a critically important issue, and caused the Bridge Authority to pay close attention to this urgent situation.

To overcome this problem, the Central South University of China and the Hong Kong Polytechnic University conducted a joint research project with the support of Professor Spencer from the University of Illinois at Urbana-Champaign aimed at reducing stay cable vibration using MR dampers. A series of field tests to evaluate the efficiency of mitigating cable vibration with MR dampers are conducted on Dongting Lake Bridge. The test results showed the MR damping system to be a cost-effective approach for suppress the wind-rain induced vibration. Then the MR damper mitigating system was installed on the longest 156 stay cables of the Dongting Lake Bridge, which is thought as the world's first application of MR dampers for mitigation cable vibration in the bridge engineering (Fortner 2003). Since these supplemental damping devices will eventually become permanent aspects of the bridge, many efforts also are focused to its aesthetics and maintainability. This paper reports the situation of field test and practical implement of MR damper on Dongting Lake Bridge. The durability of this system is proved by its reliable service of three years.

2. Evaluation of mitigating efficiency of MR damper

2.1. Test dampers and field test arrangements

RD-1005 MR dampers, manufactured by the Lord Corporation, were chosen to investigate the effectiveness of MR dampers in reducing cable vibration. RD-1005 damper is a compact device suitable for suspension application with 208 mm length and 41.4 mm diameter as shown in Fig. 2. As a magnetic field is applied to the MR fluid inside the monotube housing, the damping characteristics of the fluid increase with practically infinite precision and in under 25-millisecond. The peak to peak damper force can be varied from 0.6 kN to 2.2 kN as the input current varying from 0.0 amp to 1.0 amp. The durability of this damper is guarantied by the fatigue test of 2 million cycles with 13 mm amplitude and 2 Hz frequency.

A series of field measurements and tests were conducted on bridge cables to develop a better

Fig. 2 MR damper of RD 1005

Table 1 Main parameters of selected cables

Cable No.	A10-N	A11-N	A12-N	B15-N
Cable length (m)	107.7	114.7	121.9	142.5
Cable diameter (mm)	119	119	119	134
Mass per unit length (kg/m)	51.8	51.8	51.8	66.8
Elastic modulus (MPa)	200000	200000	200000	200000
Static tension (kN)	31.62	30.95	31.50	36.20
Frequencies of lowest 3 modes (Hz)	1.25	1.11	1.08	0.82
	2.49	2.21	2.14	1.63
	3.71	3.32	3.20	2.45

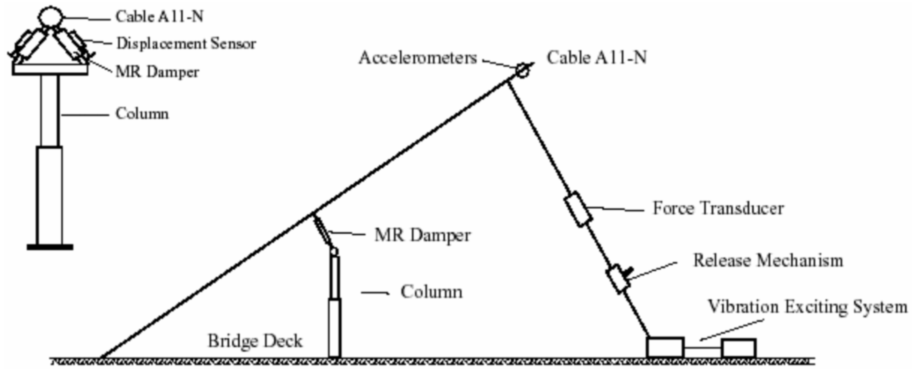

Fig. 3 Schematic of the field test setup for Cable A11-N

understanding of the cables' vibration, and to design an effective vibration mitigation system. Three cables, designated as A10-N, A11-N and A12-N were selected; the dimensions and characteristics of these cables are listed in Table 1. For the sake of comparison, the major parameters of the selected three cables are identical (refer to Table 1). On each of these cables, two piezoelectric accelerometers were permanently installed at location L/6 (L is length of cable) to lower anchorage for long-term monitoring of in-plane and out-of-plane vibration. Two dampers were attached to Cable A11-N at location of 2.5 m height from deck level; but none were attached to Cables A10-N and A12-N for comparison of vibration amplitude during wind-rain induced vibration. The supporting system of the MR dampers, shown in Fig. 3, was designed for test purposes. To evaluate the mitigating effects of MR dampers, the sinusoidal excitation tests under different frequency were carried out. Fig. 3 also shows a vibration exciting system that was utilized to excite the cable at the desired frequencies. Displacement transducers and Load cells are also used to measure the damper stroke and exciting force. All measured signals are recorded with data acquisition system. The equivalent modal damping ratio of cable is employed to evaluate the efficiency of MR dampers. To obtain the cable modal damping, in each field test, the cable was first excited into a steady forced vibration state with a frequency very close to one of its lowest three natural frequencies. This approximate frequency is used because the cable may be damaged if the excitation precisely at its resonant frequency, producing large amplitudes of vibration. The exciting system was then suddenly released from the cable. The cable went into free decay vibration, and the corresponding vibration data was recorded to estimate the modal damping.

2.2. The measured and test results

By means of field test, the first three modal damping ratios of cable A11-N without dampers are 0.164%, 0.196% and 0.141% respectively. According to the previous study (Irwin 1997), to prevent from wind-rain-induced vibration, the Scruton numbers of the cable must be greater than 10:

$$S_c = \frac{m\xi}{\rho D^2} \geq 10 \tag{1}$$

where S_c = the Scruton number, ξ = the modal damping ratio, m = mass per length, ρ = density of air and D = diameter of cable.

For the present cable, the desired damping ratio to avoid wind-rain-induced vibration is more than 0.28%. So the structural damping ratio must be increased in order to prevent the occurrence of wind-rain induced vibration.

A series of tests to estimate modal damping ratios under different input voltage are conducted for cable A11-N. Fig. 4 shows the time history of cable decay vibration with second modal frequency excitation and 0.5 DC voltages input to MR damper (Two test MR dampers are in series connection, and voltage here denotes the single MR damper's one). Due to nonlinear of MR dampers model, different duration of the decay behaves different damping ratio. 20 seconds duration after removing excitation is selected to estimate the equivalent damping ratio for all cases. In additional, it is visible in Fig. 4 that the amplitude of acceleration does not decay smoothly. A band-pass filter is employed to filter components besides modal frequency and then the least-square fitting technique is applied for fitting decay curve, as shown in Fig. 5. With this method, the equivalent modal damping ratio can be estimated.

Fig. 6 shows the plot of the first three equivalent modal damping ratio of cable A11-N versus DC voltages input to MR damper. It is clear in Fig. 6 that the first three modal damping ratios are increased to 0.4% or more after MR dampers are installed, and each of the first three modal damping ratio curves exists a peak, which indicates that there is an optimal voltage for each of the first three modal damping ratios. However, the optimal voltage of each modal damping ratio is not

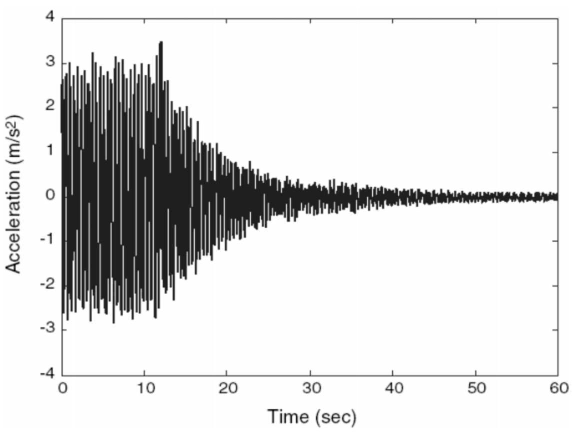

Fig. 4 Decay vibration of Cable A11-N under second modal frequency excitation and 0.5 volts DC input to MR dampers

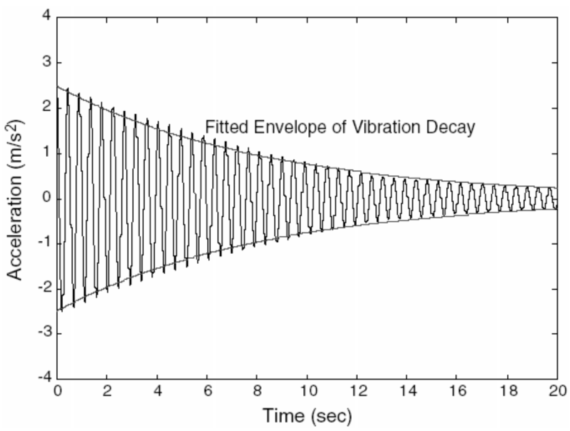

Fig. 5 Filtered time history and fitted envelope of vibration decay

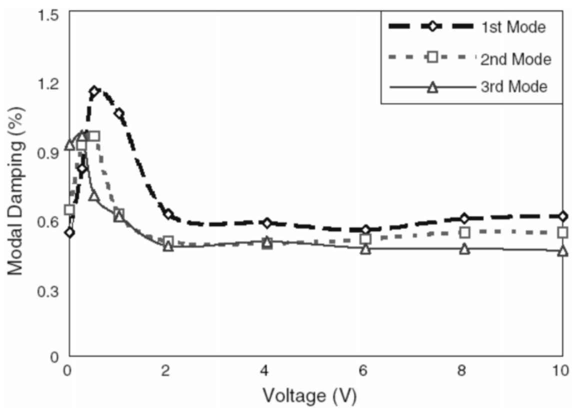

Fig. 6 Modal damping of cable-MR damper system with various DC voltage input

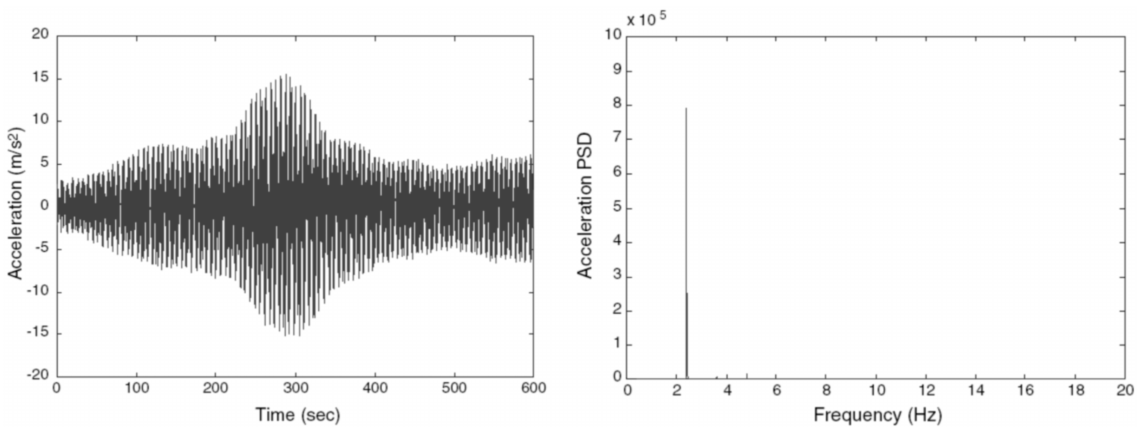

Fig. 7 Time history of in-plane acceleration and PSD of Cable A10-N

same, so each modal damping ratio does not reach maximum under same voltage. Comparing with the case without MR dampers, the first three modal damping ratios of the cable increase 7, 4.88 and 6.81 times on respective optimal voltage after MR dampers are installed. Fig. 6 also shows that the wind-rain induced vibration can be suppressed for cable A11-N though MR dampers are not input with DC voltage (i.e., input voltage is zero).

During the field tests, two events of rain-wind-induced vibration were observed. One event was captured by video camera, and the other one was recorded by both camera and accelerometers. Figs. 7-9 show the time history of in-plane acceleration and power spectrum density (PSD) of respective acceleration of cables A10-N, A12-N and A11-N under the conditions of 10~12 m/s wind speed and middle size raining. Bridge cables without the installation of MR dampers vibrated severely. As shown in Fig. 7, the maximum amplitude of in-plane acceleration of cable A10-N at location L/6 from low anchorage is about 15 m/s^2 and the dominant frequency is 2.43 Hz, which corresponds to the second modal frequency of cable A10-N; and in Fig. 8, the maximum amplitude of in-plane acceleration of cable A12-N at location L/6 from low anchorage is about 8 m/s^2 and the dominant frequency is 3.20 Hz, which is the third modal frequency of cable A12-N. However, the vibration of

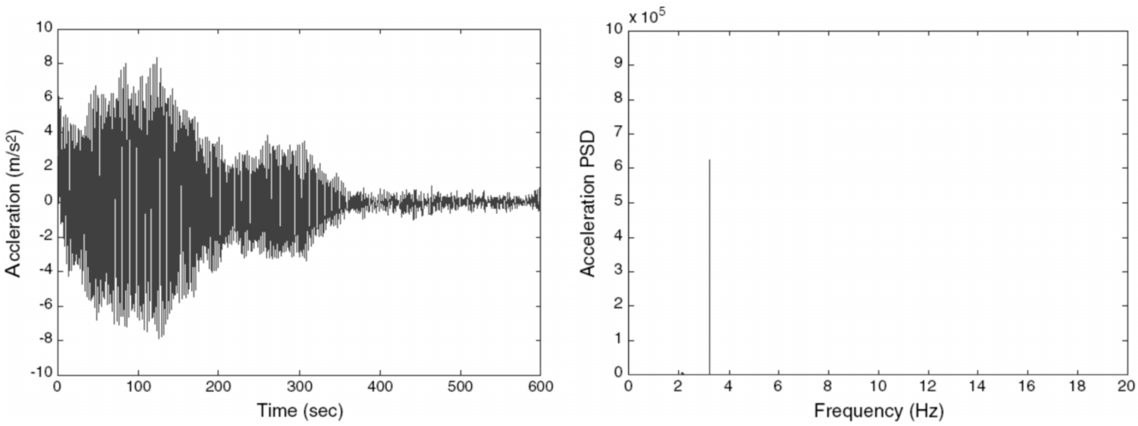

Fig. 8 Time history of in-plane acceleration and PSD of Cable A12-N

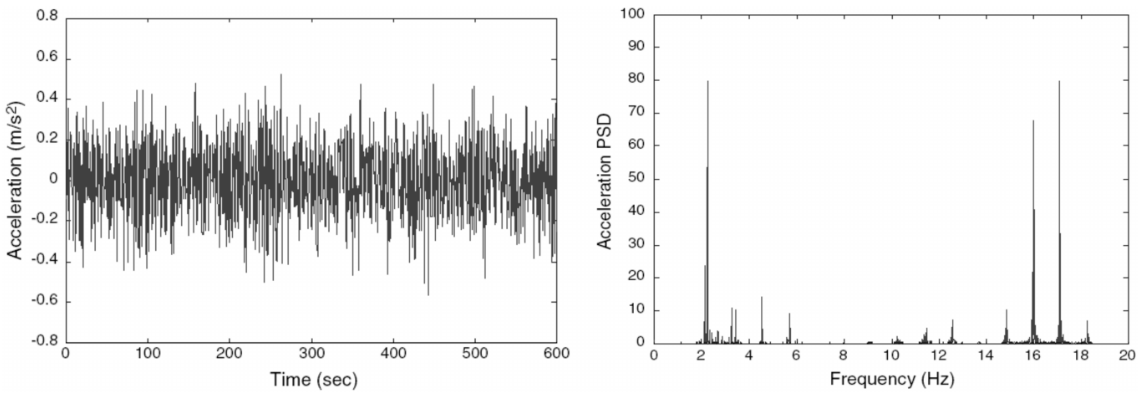

Fig. 9 Time history of in-plane acceleration and PSD of Cable A11-N

cable A11-N installed with MR dampers was very small and had almost no visible movement. From Fig. 9, one can see that the maximum amplitude of in-plane acceleration at location L/6 of cable A11-N with MR dampers (input voltage is zero) is less than 0.4 m/s^2 and the vibration frequency no longer appears as one of the lower modal frequencies. A significant vibration reduction has, therefore, been achieved by using MR dampers.

The acceleration locus of the measured cables is shows in Fig. 10, ordinate denotes in-plane acceleration and abscissa denotes out-of-plane acceleration. From Fig. 10(a),(b), amplitude of in-plane acceleration is always larger than one of out-of-plane and the trace of vibration forms an ellipse. However, to cable A11-N with MR dampers, vibration traces of these cables are no longer elliptical; they become random with very small amplitudes, as shown in Fig. 10(c).

Based on one-year observation and field testing results, the bridge maintenance department made a decision confidently that the MR damping system is chosen to mitigate the cable vibration for the longest 156 stays.

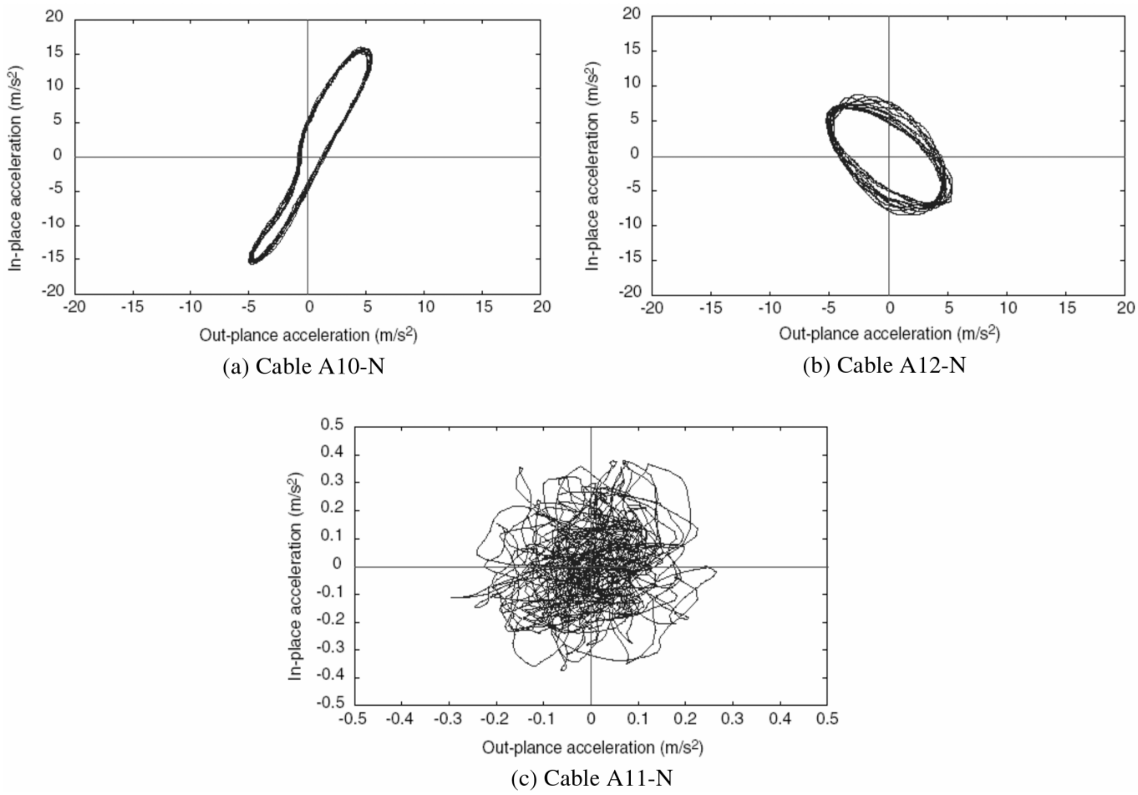

Fig. 10 Locus of acceleration responses

3. Practical design considerations

As a permanent and visible aspect of the bridge, this damping system must be aesthetically pleasing, reliable, durable, and easy to maintain, as well as having efficient vibration mitigation. Substantial work was done to meet these requirements. This section discusses some practical design issues that need to be considered during the design process.

3.1. Attachment height of dampers

Dampers installed on Cable A11-N were 2.5 m above the bridge deck, supported by a strong vertical steel column. Obviously, this column is too high, and it does not meet the aesthetic requirement. Therefore, the column height needs to be reduced. However, as the column height decreases, the position where the MR dampers are connected to the bridge cable is closer to the deck; consequently, the damping force, and its effect on cable vibration, reduces. Thus, a series of tests were conducted to investigate the influences of column height on control effectiveness. The results demonstrated that the column can be as low as 1.5 m, and the MR dampers still will remain effective for vibration control. This configuration was then tested on Cable B15-N, which is the second longest and most heavy cable of the bridge. The results were also very good which indicates that the MR damping system can be effectively used on all stay cables to reduce their wind-rain-

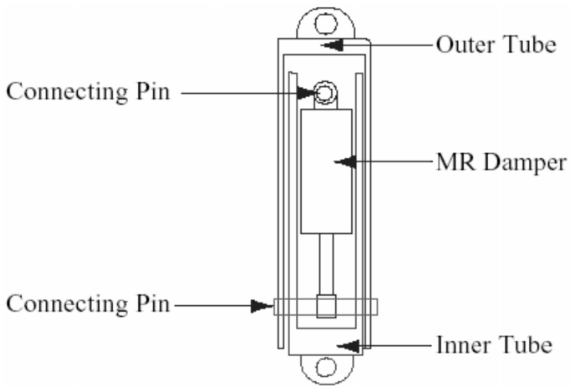

Fig. 11 Diagram of double-tube protection device

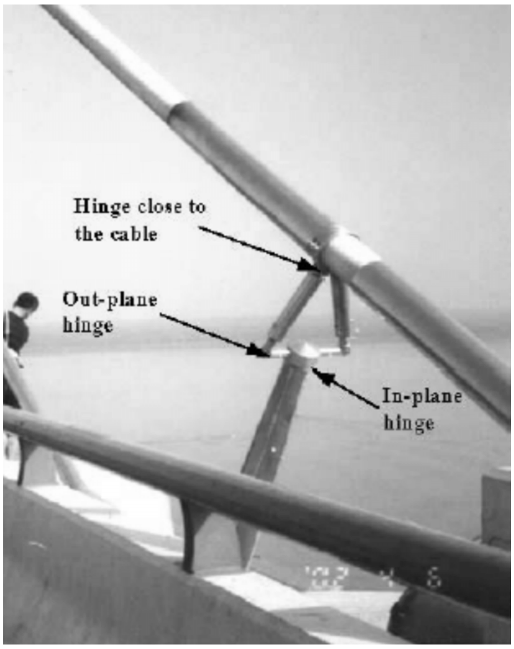

Fig. 12 Hinge arrangements

induced vibration. Based on the foregoing investigation, the overall MR damping system was ready for design.

3.2. Double-tube protection for MR dampers

The Lord RD-1005 MR dampers were originally designed for indoor usage. Therefore, extra protection for outdoor usage was required. Also, the damper rod must be pushed into the middle to get to the initial working position during the installation, and this is not convenient fro field installation. Moreover, it is difficult to maintain a secure connection between the bridge cable, the MR dampers, and the supporting arm. A special double-tube device, shown in Fig. 11, was designed to solve these two problems. The double-tube device contains the damper inside and keeps it away from dust and rain. This device also has the feature that when tubes are pulled from outside, they will push the damper inside.

3.3. Flexible connections

To control the in-plane and out-plane vibration of each cable, two dampers and a short rod form a triangle as shown in Fig. 12. All connection parts are carefully designed to avoid any extra restrictions. For example, two hinges on the cable clamper, which connects the cable and dampers, are placed as close as possible to the cable. Thus, the whole triangle can rotate both in- and out-plane.

Fig. 13 Final installation of MR damper system

3.4. Support arms

The in-situ measurements of rain-wind-induced vibration showed that the amplitude of the MR damper's rod displacement was within 2 mm. This means that when the damper force (less 5 kN for each support arm) is applied, the allowed movement of the support arm along the damper's axle must be less than 0.2 mm to ensure 90% damper efficiency. For a vertical column, it is difficult to achieve a balance between stiffness and aesthetics. However, the inclined arm can easily satisfy these requirements.

The height of the fixing point of dampers on the cable was chosen to be 1.8 m for all cables except the shortest cables. The inclined support arm has a varied T-shape section. The surface of the arms is galvanized in order to fit into the bridge environment as well as for rust protection. The final installation of MR Damper System is shown in Fig. 13.

3.5. Setting and supply of electric current to MR dampers

The field observation shows that the dominate oscillations of the most cables during wind-rain vibration are on 2nd or 3rd models with frequencies less than 3 Hz. Therefore the optical current is chosen to maximize the cable damping of the lowest three modes as shown in Fig. 6. For the higher mode vibration, the MR damping system is effective enough to suppress them. The electrical power line is placed on each cable, and a transformer and A/D rectifier provide the optimal direct current to MR dampers when rain-wind-induced vibration is likely to occur. The whole electric power supply system is carefully protected with tubes and epoxy resin and works reliable. However, a strong suggestion is made to the maintenance department that a through inspection should be done each year before April, the most rainy and windy month at the site.

3.6. Mitigating effects and durability of the overall system

The installation of the entire mitigation system started in April of 2002. In that month, several events of rain-wind weather occurred, the highest wind speed was over 30 m/s. One event occurred when only 16 cables had been retrofitted with MR dampers. The other occurrence was after 80 cables were retrofitted with dampers. The video records of these events showed that all cables installed with MR dampers had very little vibration. Comparing with cables without installation of a damping system, the vibration mitigation effect was very obvious. As more cables were installed with dampers, the vibration of bridge deck also decreased. Since the project was completed, and no visible vibration of cables has been reported.

In May of 2004, after the system served three rainy-windy seasons, the first author's research group in Hunan University organized a through inspection with instruments. Several dampers were randomly took out from the protecting tubes and checked carefully. They look and work as well as new dampers. The electric power supply system is also in good conditions.

4. Conclusions

The installation of MR damping systems on the Dongting Lake Bridge has proved to be an effective and durable cable-vibration control countermeasure by three-years reliable service. The main advantages of MR damping system are:

(1) They can provide large damping forces under small displacement and velocity;

(2) They are effective on cables with different lengths due to their adjustable damping force.

A thorough investigation of the field test and observation, and a thoughtful design of the overall MR damping system are necessary to ensure a good balance between control effectiveness, aesthetics, and maintainability.

Acknowledgements

Supports of the National Natural Science Foundation of China (Project No. 50178103), the Research Grants Council of the Hong Kong Special Administrative Region, China (Project No. PolyU 5051/02E), Transportation Bureau of Hunan Province of China, Administration of the Dongting Lake Bridge, and the Lord Corporation are gratefully acknowledged.

References

Chen, Z.Q., Wang, X.Y., Ni, Y.Q. and Ko, J.M. (2002), "Field measurements on wind-rain-induced vibration of bridge cables with and without MR dampers", *Proc. 3rd Int. Conf. Structural Control*, Como, Italy.

Fortner, B. (2003), "Magnetic fluid dampers motion in civil structures", *Civil Engineering*, January, 40.

Hikami, Y. and Shirashi, N. (1988), "Rain-wind induced vibrations of cables in cable-stayed bridges", *J. Wind Eng. Ind. Aerody.*, **29**, 409-418.

Irwin, P. (1997), "Wind vibrations of cables on cable-stayed bridges", *Proc. Struct Congress*, 383-387.

Johnson, E.A., Baker, G.A., Spencer, B.F. Jr. and Fujino, Y. (2000), "Mitigating stay cable oscillation using semi-active damping", *Smart Structures and Materials 2000: Smart Systems for Bridges, Structures and Highways*, S.C. Liu(ed), SPIE, **3998**, 207-216.

Krenk, S. (2000), "Vibration of a taut cable with an external damper", *J. Appl. Mech., ASME*, **67**, 772-776.

Krenk, S. and Nielsen, S.R.K. (2001), "Vibration of a shallow cable with a viscous damper", *Proc. Royal Society, London*, **A458**, 339-357.

Ko, J.M., Ni, Y.Q., Chen, Z.Q. and Spencer, B.F. Jr. (2002), "Implementation of magneto-rheological dampers to Dongting Lake Bridge for cable vibration mitigation", *Proc. 3rd Int. Conf. Structural Control*, Como, Italy.

Main, J.A. and Jones, N.P. (1999), "Full-scale measurements of cable vibration", *Proc. 10th Int. Conf. Wind Eng.*, 963-970.

Main, J.A. and Jones, N.P. (2002a), "Free vibrations of taut cable with attached damper I: linear viscous damper", *J. Eng. Mech., ASCE*, **128**, 1062-1071.

Main, J.A. and Jones, N.P. (2002b), "Free vibrations of taut cable with attached damper II: nonlinear damper", *J. Eng. Mech., ASCE*, **128**, 1072-1081.

Matsumoto, M., Saitoh, T., Kitazawa, M., Shirato, H. and Nishizaki, T. (1995), "Response characteristics of rain-wind induced vibration of stay-cables of cable-stayed bridges", *J. Wind Eng. Ind. Aerody.*, **57**, 323-333.

Matsumoto, M., Shirato, H., Yagi, T., Goto, M., Sakai, S. and Ohya, J. (2003), "Field observation of the full-scale wind-induced cable vibration", *J. Wind Eng. Ind. Aerody.*, **91**, 1326.

Nakamura, A., Kasuga, A. and Arai, H. (1998), "The effects of mechanical dampers on stay cables with high-damping rubber", *Construction and Building Materials*, **12**, 115-123.

Pacheco, B.M., Fujino, Y. and Sulahk, A. (1993), "Estimation curve for modal damping in stay cables with viscous damper", *J. Struct. Eng., ASCE*, **119**, 1961-1979.

Ruscheweyh, H. and Verwiebe, C. (1995), "Rain-wind-induced vibration of steel bars", *Proc. Int. Symp. on Cable Dynamics*, Liege, Belgium, 469-472.

Tabatabai, H. and Mehrabi, A.B. (2000), "Design of mechanical viscous dampers for stay cables", *J. Bridge Eng., ASCE*, **5**, 114-123.

Verwiebe, C. and Ruscheweyh, H. (1998), "Recent research results concerning the exciting mechanisms of rain-wind-induced vibrations", *J. Wind Eng. Ind. Aerody.*, **74-76**, 1005-1013.

Yamaguchi, H. and Alauddin, M. (2003), "Control of cable vibrations using secondary cable with special reference to nonlinearity and interaction", *Eng. Struct.*, **25**, 801-816.

CC