Effectiveness of In-Service Dampers over Long-Term Operation for Cable Vibration Suppression: A Study Based on Field Testing

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Abstract. In order to explore the operation mechanism of dampers used on super long-span bridges, the characteristics of dampers in long-term operation are studied through field tests. Firstly, viscous damper and liquid leakage MR damper are selected to test the influence of fluid connecting rod on its damping force; Then, wireless and wired sensors are used to collect the acceleration response of cables with viscous dampers and MR dampers. Finally, the vibration characteristics of the cable are analyzed, and the control performance of the selected damper is evaluated. The results show that the high-order multi-modal vibration of the cable will occur in the range of 2-6Hz whether the damper is installed or not. In addition, fluid leakage may reduce the additional modal damping ratio achieved by MR damper.

Keywords. cable-stayed bridges; cable vibrations; field tests; dampers; long-term operation; control performance

1. Introduction

As important parts of cable-stayed bridges, stay cables often suffer from undesired vibrations induced external loads. Making the condition worse, the inherent damping of these stay cables is usually extremely low, which is insufficient to suppress the amplitudes of the unwanted vibrations and cause further damages, such as accelerating cable fatigue, destroying anti-corrosion system and frightening the pedestrians at their presence.

To mitigate these vibrations, various countermeasures have been proposed, among which the viscous dampers have firstly been applied widely in practice due to their low cost and simple configuration. Pacheco et al [1] developed an estimation curve to determine the location and parameter for viscous dampers in stay cables while Krenk [2] presented an accurate asymptotic approximation of the damping ratio for the lower modes of stay cables. Main and Jones [3] evaluated the control performance of viscous dampers on Fred Hartman Bridge.

With the ability to provide more damping for stay cables, semi-active magnetorheological (MR) dampers appeared as an attractive alternative of the passive viscous dampers. Chen et al [4] firstly utilized the MR dampers to mitigate the cable vibration induced by wind-rain on Dongting Lake cable-stayed bridge. Christenson et al [5] and Johnson et al [6] carried out experimental and numerical studies, which showed the higher control performance achieved by the MR damper. Li et al [7] explored the MR damper on Shandong Binzhou Yellow River Highway Bridge, in which the negative stiffness behavior in the semi-active damping force is observed. After that, the negative stiffness characteristics were analyzed.
theoretically to reveal the control mechanism of the semi-active MR dampers [8], which resulted in an extensive attempt to develop passive negative stiffness dampers for stay cables [9-13].

Until now, more than a decade has passed since the first application of viscous and MR dampers on stay cables. The current status of these dampers and whether they still work as originally designed turn out to be a new significant concern. Ataei et al [14] evaluated the viscous dampers used for the seismic control of Beijing Yintai Center. With the viscous fluid leaking, the viscous dampers would restore the damping force through a delay that might dramatically decrease the control performance under seismic excitations. Furthermore, a design procedure based on corrected response spectrums was proposed, in which the possible fluid leak of viscous dampers was considered [15]. For the MR dampers, Caterino et al [16] assessed the effectiveness of a MR damper from 2008 to 2013 under a condition of absolute inactivity. Wang et al [17] tested the long-term mechanical behavior of 30 MR dampers, which had been in service over ten years for cable vibration control on Dongting Lake Bridge. As shown in the results, six of them failed to provide sufficient damping while the rest dampers generated less damping force, with 32.4% and 29.8% reduction of the equivalent damping coefficient and the damping force amplitude compared with the new ones, respectively. The above studies mainly focused on the degradation of the damping force achieved by the dampers that had experienced a long time. Few in-situ assessments have been conducted to investigate the control performance of these dampers over long-term operation.

In this paper, the in-situ effectiveness of viscous and MR dampers, which have been in service for cable vibration control on one real cable-stayed bridge over about ten years, is investigated based on field tests. Firstly, the current status of these dampers is evaluated based on a series of visual inspections. Four viscous dampers and three MR dampers with various degrees of leakage, are then chosen as classical cases for further field testing. A measurement system based on various sensors is established and the testing procedure is presented. After that, the field tests are carried out for viscous and MR dampers, respectively, followed by a detailed analysis to assess the effectiveness of these dampers in controlling cable vibrations. Finally, conclusions drawn from the above results are addressed.

2. Preliminary assessment of cable vibration system

2.1 Preliminary assessment based on visual inspection

For the real cable-stayed bridge, 272 cables are used to bear the deck, in which the longest one is 577 m. To control unwanted vibrations, 152 viscous dampers and 48 MR dampers have been attached near the support with a height of 3.5 m.

A systematic visual inspection was firstly carried out to evaluate the current status of these in-service dampers, which have been working continuously about ten years for cable vibration control. Imperfect conditions that might reduce control performance were observed. For example, various degrees of corrosion and fluid leakage occurred on some viscous dampers as depicted in Figure 1. Here, the definitions of the condition, such as light, medium and severe, are just relative and qualitative. Besides the corrosion and fluid leakage, the failure of power supply was also found for the MR dampers.
Figure 1. Typical imperfections for the in-service viscous dampers: corrosion on the piston and leakage of the fluid

The overall situation of the in-service dampers is presented in Table 1. There are 152 viscous dampers in total and 144, up to 95% of them, have corrosion on their piston rods. In contrast, 24% of the viscous dampers suffer from the leakage problem. For the MR dampers, the situation seems more serious. About half of the MR dampers have corrosion on the piston rods and 34 MR dampers, which mean the percentage is over 70%, are working with various degrees of fluid leakage.

| Type   | Total | Corrosion Number | Leakage Number |
|--------|-------|------------------|----------------|
| Viscous| 152   | 144              | 36             |
| MR     | 48    | 25               | 34             |

2.2. Hysteretic loops of the dampers with fluid leakage

A viscous damper with fluid leakage on the bridge is chosen to demonstrate the effect of the fluid linkage on its damping force via laboratory tests. Figure 2 shows the hysteretic loops of this viscous damper under 0.2, 0.4 and 0.8Hz with the displacement amplitude of 4.8mm. Being different from the typical ones, all the force-displacement curves with fluid leakage have an abnormal slip of 3.7mm in the second and fourth quadrants.

Figure 2. Hysteretic loops of the viscous damper with fluid leakage

Figure 3 gives an example of the MR damper with fluid leakage. When the current is zero, only a small amount of slip could be found. When the current are 1A, 2A and 3A, the hysteretic loops of the MR damper slide about 10.3mm in the second and fourth quadrants.
Figure 3. Hysteretic loops of the MR damper with fluid leakage

3. Field testing setup

As shown in the above assessment, many dampers are under operation with imperfect conditions. The hysteretic loops of the dampers with fluid leakage have a significant slip, which would have a direct influence on their control performance. However, these results obtained through visual inspection and laboratory tests are generally qualitative and not enough for evaluating these dampers exactly over long operation. Therefore, a field testing is designed to acquire cable vibration responses for analyzing the in-situ effectiveness of the dampers quantitatively. Taking the practical feasibility into account, four stay cables with viscous dampers and three stay cables with MR dampers are chosen as typical cases for further short-term monitoring. Table 2 lists the selected stay cables with more details, including the leakage condition and monitoring date.

| Type | Cable No. | Leakage Condition |
|------|-----------|-------------------|
| Viscous | NA18U | No |
| | NA21U | Medium |
| | NA22U | No |
| | NJ22U | No |
| MR | NA30U | Light |
| | NA34U | Medium |
| | NJ32U | Severe |

For each selected cable, both wireless and wired sensors, as demonstrated in Figure 4, are explored to collect its field vibration response. At an attitude of 15m above the deck, two wireless accelerometers are installed in and out of the cable gravity plane, respectively. Another wireless accelerometer locates near the anchorage of the cable to measure the vertical vibration of the deck. One wired accelerometer is installed at the same position as the third wireless accelerometer for time synchronization of the wired and wireless data. One LVDT is attached in parallel to the piston rod to obtain the displacement response of the damper. During the monitoring, the damper is first removed and then re-connected to the cable.
4. Evaluation of the in-service dampers for cable vibration control

4.1. Vibration characteristics of the cables without dampers

A representative segment of measured in-plane acceleration for the cable NA18U when the damper is removed and the corresponding power spectral density (PSD) are presented in Figure 5. High frequency components, for example, the vibrations from 2.5Hz to 5.1Hz, are very significant, which mean the cable vibrates in its 7th to 14th modes. For other cables without control, the similar high frequency components can also be found. So, under natural conditions, the cables often vibrate in their high order multi-modes.

![Figure 5. One segment of in-plane acceleration for the cable NA18U without control](image_url)
Taking the high-order multi-modal vibrations into consideration, the first ten modal frequencies and inherent damping ratios, which form the baselines for evaluating the control performance of dampers, are estimated for the cables by the following process. As a first step, the modal frequencies are obtained by picking up the peak values in the PSD. Then, the stochastic subspace identification (SSI) method [18, 19] driven by the measured data is employed to identify the inherent damping ratios under the assumption of regarding the wind load as a white noise excitation. According to the available data, four values of each mode for the cables disconnected with viscous dampers and three values of each mode for the cables disconnected with MR dampers are obtained. Figure 6 plots the identified inherent modal damping ratios and their mean values for the seven selected cables. In general, the inherent modal damping ratios decrease with the mode number. For the four cables with viscous dampers, the first modal damping ratio is about 0.70% while the tenth modal damping ratio declined to 0.05%. The first modal damping ratios for the cables with MR dampers are 0.30%, 0.43%, 0.58%, respectively, which are smaller due to the increasing of the cable length. For the high modes, the modal damping ratios also decline quickly less than 0.1% for the tenth mode.

**Figure 6. Inherent modal damping ratios for the selected cables**

### 4.2. Vibration characteristics with attached dampers

In fact, the viscous or MR dampers are always connected to the cables on the bridge site. So, it is of greater importance to understand the vibration characteristics for the cables when the dampers are attached. Another representative record of in-plane acceleration and the corresponding PSD for the cable NA18U are illustrated in Figure 7. Similar to the uncontrolled situation, high order multi-modal vibrations, especially the frequency components around 4.1Hz, are remarkable for the cable.
To further investigate the vibration characteristics of the cables with dampers, Figure 8 presents the contour of the PSDs in the time-frequency domain, which are calculated using twenty consecutive one-minute segments of in-plane accelerations. As can be seen clearly, for cable NA21U, the dominant vibrational frequencies of the cables change with the time. For the cable NA34U, the MR damper is under passive off condition. Similarly, the main vibrational modes vary with the time in the range of 2-6Hz. Other cables have the same vibration characteristics.

4.3. Evaluation of the in-service dampers
Figure 9. 20-minutes acceleration RMS responses of the stay cables with viscous dampers

First, the viscous dampers are assessed using the 20-minutes RMS responses of the stay cables. As shown in Figure 9, the horizontal axis is the out-of-plane acceleration while the vertical axis is the in-plane acceleration. In general, the in-plane acceleration of all the cables is always less than five times of the out-of-plane acceleration, whether the viscous damper is installed or not. For the cables NA18U and NJ22U, the in-plane acceleration RMS responses without control are about 0.5m/s² and 1.5m/s², respectively. Under controlled conditions, the in-plane acceleration RMS responses reduced remarkably to 0.2m/s² and the out-of-plane acceleration RMS responses declined to about 0.1m/s².

For different conditions, the external excitations are not the same, especially the wind varying with the time. Thus, the RMS of acceleration is not enough to demonstrate the control performance. With the damper connected, the modal damping ratios of the cables are estimated using the SSI method. Subtracting the corresponding inherent damping ratios, the additional modal damping ratios are achieved as drawn in Figure 10. For the first mode, the additional modal damping ratios achieved by the viscous dampers are 0.52%, 0.59%, 0.74% and 0.36%, respectively. With the mode number increasing, the additional modal damping ratios decline slowly to less than 0.3% for the high modes of the four cables.

Figure 10. Additional modal damping ratios achieved by the viscous dampers

It’s worth noting that the damper on the cable NA21U has medium leakage while other three have no visible leakage. This leakage has little impact on the low modes while slightly reduces the realized additional modal damping ratios for the high modes, for example, from the 5th to 10th modes.

In a word, the additional damping ratios provided by the viscous dampers decrease with the mode numbers. On the cable NA21U, the medium leakage slightly affects the performance of the viscous damper for high modes.
The modal damping ratios added by the MR dampers are plotted in Figure 11. Three identified values and the corresponding mean value are included. About 0.4% damping ratio is provided for the first mode of the cable NA30U. As the mode number increases, the additional modal damping ratios decrease in general, though some fluctuations can be observed. As pointed out above, the leakage situations for the MR dampers on NA30U, NA34U and NJ32U are light, medium and severe, respectively. Coinciding with this trend, the additional modal damping ratios for every mode of the three cables decline generally with a few exceptions.

5. Conclusions

The effectiveness of the viscous and MR dampers over long-term operation for cable vibration control is investigated in this paper. A series of visual inspections were performed firstly to evaluate the current condition of the dampers used on one real cable-stayed bridge. Hysteretic loops of the dampers with fluid leakage are presented. Then, a measurement system was established to test the selected cables and dampers. The vibration characteristics of the cables are analyzed using the measured acceleration responses. Additional modal damping ratios provided by the dampers were identified and the effect of various degrees of leakage was discussed. According to the results in the present study, the following conclusions could be addressed:

High order multi-modal vibrations always occur to the cables regardless of the dampers are attached or not. The main vibrational modes of the cables lie in the range of 2-6 Hz.

The effectiveness of the viscous dampers depends on the vibration characteristics of the cables. In special, the high frequency components in the displacement response would make the viscous dampers lose their efficiency.

The fluid leakage has an obvious impact on the control performance of the MR dampers. The more serious the leakage is, the less the additional modal damping ratio is.

It should be noted that the fluid leakage has a significant influence on the hysteretic loops of the dampers. As a future study, the mechanical model of the dampers with fluid leakage will be established and their control performance will be analyzed numerically to provide more exact guidance for the maintenance and repairing of the dampers on long-span cable-stayed bridges.

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