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REVIEW ARTICLE

Application of Structural Control Systems for the Cables of Cable-Stayed Bridges: State-of-the-Art and State-of-the-Practice

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Abstract

Stay cables are one of the key elements of cable-stayed bridges and are characterized by lightweight, low inherent damping, and high flexibility. They are continuously subjected to small-to-large-amplitude vibrations due to various types of dynamic loads that may, in the long term, cause fatigue and fracture problems for the cable system, and may eventually compromise the safety of cable-stayed bridges. Thus, several countermeasures including surface profiling, cross-ties, and structural vibrational control systems have been used to improve the dynamic performance of stay cables. This article presents a comprehensive state-of-the-art and state-of-the-practice review of structural vibration control systems specifically designed and used for the cables in cable-stayed bridges. Generally, the stay cable dampers are classified as internal and external dampers. Consequently, important aspects of each control strategy are highlighted and various types of devices and their designs are discussed to find the best control solution for suppressing the cable vibrations.

Nomenclature

CEC	Cycle energy control
CFD	Computational fluid dynamics
CVD	Controlled viscous damping
D	Diameter of the cable
DG	Dry galloping
EHC	Energy harvesting circuit
EIMD	Electromagnetic inertial mass damper
EMD	Electromagnetic device
EMDEH	Electromagnetic damper cum energy harvester
EMSD	Electromagnetic shunt damper
EMSD-ID	Electromagnetic shunt damper-inerter damper device
FPB	Friction pendulum bearing
FRP	Fiber-reinforced polymer
HDR	High-damping rubber
ID	Inerter damper
IG	Ice galloping
IMD	Inertial mass damper
IVA	Inerter-based vibration absorber
L	Length of cable
LQG	Linear–quadratic Gaussian
LQR	Linear quadratic regulator
LRB	Laminated rubber bearing
m	Mass
MR	Magneto-rheological
MSM	Mode superposition method
NSD	Negative stiffness damper
PSD	Positive stiffness damper
P-VE	Pseudo-viscoelastic
RWIV	Rain-wind-induced vibration
S_c	Scruton number
SMA	Shape memory alloy
TET	Targeted-energy-transfer
TID	Tuned inerter damper

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TMD	Tuned mass damper
TMD-MR	Tuned mass damper-Magnetorheological
TM-HDR	Tuned mass-high damping rubber
VID	Viscous inerter damper
VIMD	Viscous inertial mass damper
VIV	Vortex-induced vibration
VSD	Viscous-shear damper
WG	Wake galloping
ζ	Damping ratio
ρ	Density of air

1 Introduction

Cable-stayed bridges are one of the most aesthetically appealing and popular bridges worldwide due to their advantages i.e., lightweight, relatively small cross-sections, and high structural efficiency. Meanwhile, the race for achieving a longer span cable-stayed bridge is entering a new era with the Russky Bridge (with a main span of 1104 m) holding the current world record. On the other hand, cable-stayed bridges are characterized by low structural damping, complex dynamic behavior and longer natural time periods [1–3]. Their relatively small section and lighter weight make them susceptible to oscillations under dynamic loadings such as wind, earthquake, pedestrian and traffic loads [4]. Moreover, as the span length of cable-stayed bridges increases, the flexibility of the structure and the length of stay cables also increase, which may result in aerodynamic stability issues.

As shown in Fig. 1, stay cables are generally subjected to direct vibration due to the wind acting along the cable and indirect vibration through cable anchorages at the deck and towers due to wind, traffic, and earthquake loads. Cable vibrations are associated with several problems for the cable-stayed bridges, i.e., (i) comfort reduction for the passing traffic, (ii) resonance, causing the structural damage, (iii) fatigue issues in cables, anchorages, and other components that could reduce their service life, and (iv) potential premature failure of the corrosion protection system. Several cable-stayed bridges such as Puente Real Bridge [5, 6], Saint-Nazaire Bridge 7, Zarate Brazo Largo Bridge [7], Dubrovnik Bridge [8], Kap Shui Mun Bridge [9], Veterans Memorial Bridge [10], Fred Harman Bridge [11], and International Guadiana Bridge [12] have reportedly been damaged due to dynamic loads, as shown in Fig. 2.

A structural control system is defined as a system that reduces vibrational responses of structures due to different types of dynamic loads. Broadly speaking, structural control systems are classified as passive, active, semi-active and hybrid control systems [13]. Passive control systems enhance the dynamic performance of the structure by adding stiffness or damping or a combination of both without a need for a control algorithm or any external source of energy. Active control systems receive the essential dynamic response parameters of the structure under the dynamic loads from the sensors and analyze the data using a predefined algorithm that controls and activates externally powered actuators to counter the external dynamic loads. The active systems need a dedicated and uninterrupted power source for proper operation. Semi-active control systems are similar to active control systems. However, they require a small supply of energy (like a battery), which is advantageous in providing continuous protection of the structures during power failure under extreme external excitations. Hybrid control systems are a combination of passive, active and semi-active control systems in order to improve the performance, efficiency, and stability of the control system. Prior to the date, huge numbers of structural control systems have been proposed and used for civil structures [14–30]. Nonetheless, the structural vibration control system was found to be a promising solution for cable-stayed bridges in order to improve the dynamic response and minimizing vibrations [31–38].

The design service life of cable-stayed bridges is typically over 100-year, owing to their massive construction cost. While engineers are aiming to achieve longer main spans, the key inevitable challenge of cable-stayed bridges remains to be the complex dynamic behavior and cable vibrations due to wind and aerodynamic instabilities. Thus, several countermeasures for suppressing the cable vibrations have been proposed and adopted in practice. Over the past few decades, great progress has been made from theory

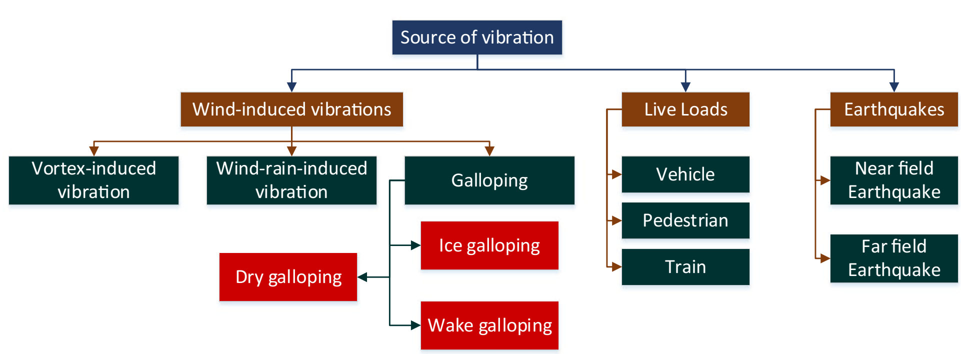


Fig. 1 Different types of dynamic loads in the cable-stayed bridges

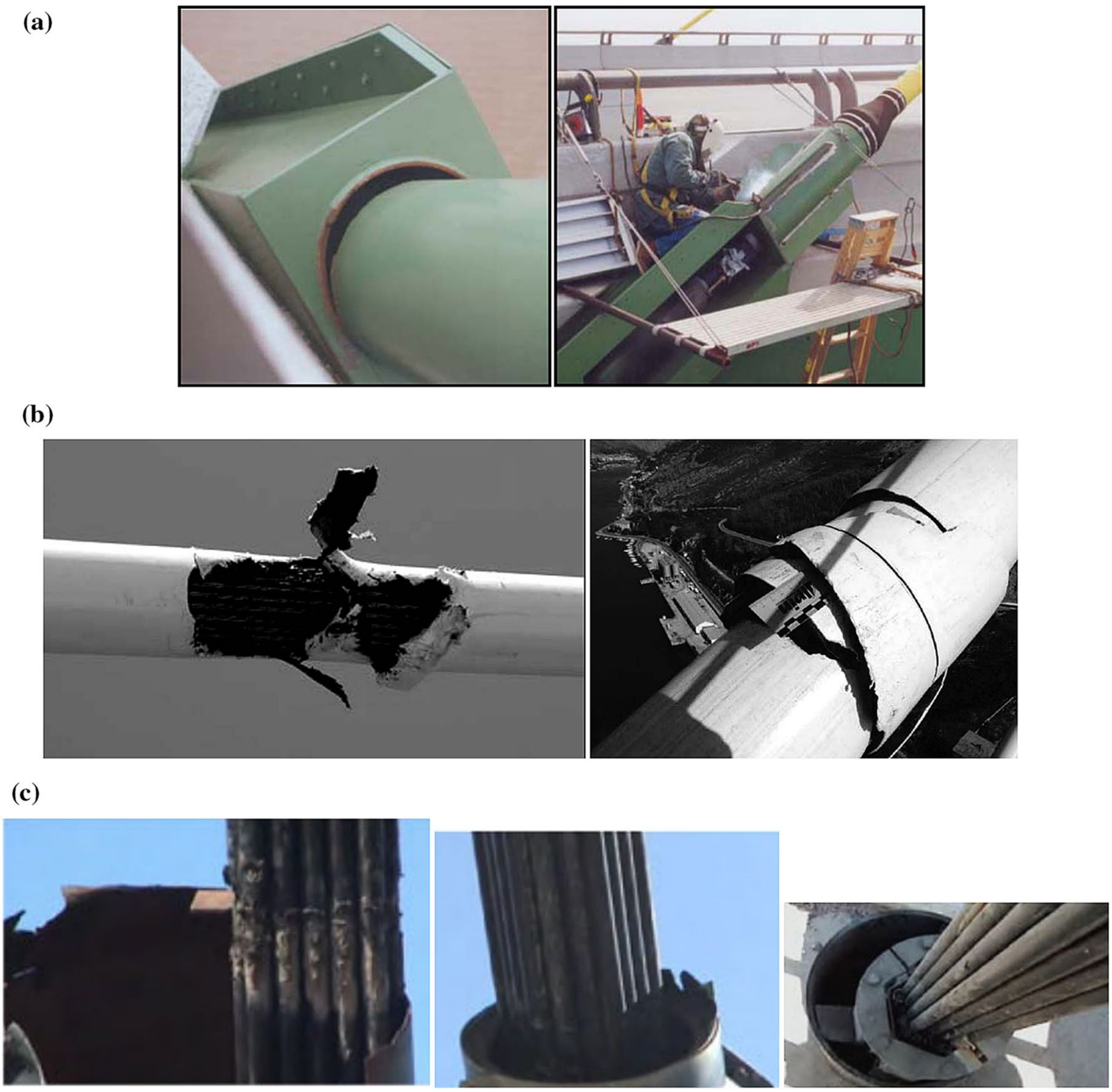


Fig. 2 Damage to the cable system of the cable-stayed bridges due to dynamic loads. **a** Guide pipe fracture failure due to wind and the strengthening it for the Fred Harman Bridge [11] **b** Protective pipe damage of a stay cable of the Dubrovnik bridge due to wind loads [8]. **c** Damage to the cable and anchorage of the International Guadiana Bridge due to cable-deck dynamic interaction and heavy traffic loads [12]

to utilization for the structural control systems specifically designed for stay cables. This paper presents a state-of-the-art and state-of-the-practice review of structural vibration controls used specifically for the cables of the cable-stayed bridges to suppress the cable vibrations due to dynamic loads. In this context, an overview of the vibration problems of stay cable under dynamic loads is provided. Then, various structural control systems for stay cables are classified and systematically reviewed. Subsequently, a summary of stay cable dampers and a list of cable-stayed bridges equipped with stay cable dampers are given. Finally, concluding remarks on suppressing vibrations of cables by means of control systems are given.

2 Vibrations of Stay Cables

As mentioned earlier, stay cables may suffer vibrations due to direct excitation by the wind- or indirectly through the movements of the deck and towers (see Fig. 1). As a direct source of vibration on stay cables, the wind is one of the most challenging aspects of the design of cable-stayed bridges. Figure 3 shows the main vibration phenomena associated with stay cables [7, 39–42]. Various aeroelastic phenomena in cables are motion-induced vibration, vortex-induced vibration (VIV), buffeting, rain-wind-induced vibration (RWIV), wake galloping (WG), dry galloping (DG), ice galloping (IG), aerodynamic

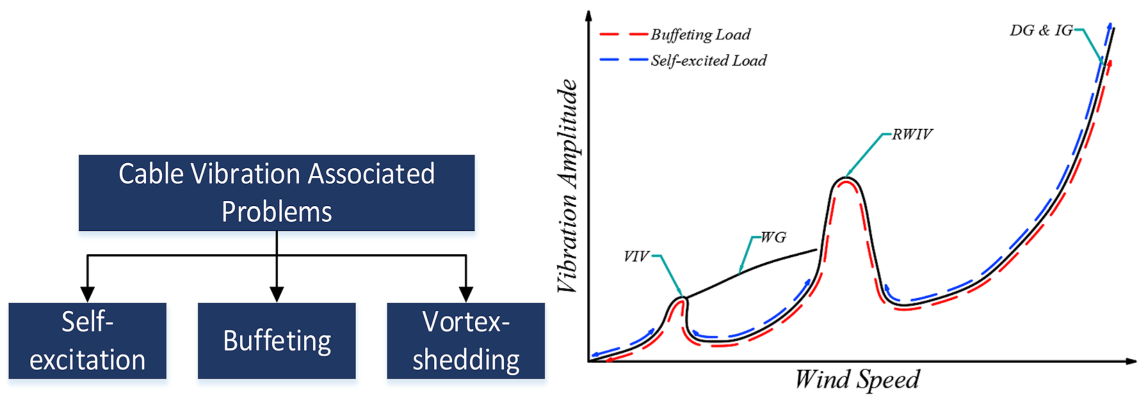


Fig. 3 Cable vibrations phenomena [42, 49]

interference, drag crisis phenomena, etc., [10, 43–49]. It has also been reported that two adjacent cables having alike configurations may experience different vibrational modes during wind-induced vibrations [50]. Meanwhile, the RWIV may cause coupling of in-plane and out-of-plane vibrations of the cables [51]. Indirect excitation or support-induced excitation of the cables is generated by the motion of the girder and pylons through the cables' anchorages or supports [42]. In addition, strong coupling between local and global vibrations may occur when local and global natural frequencies become nearly the same. For example, the cable and anchorage system of a stay cable of the International Guadiana Bridge was damaged due to indirect excitation (heavy traffic loads), as shown in Fig. 2c. This damage reflects the importance of cable-deck dynamic interaction as a combination of the global vibrational mode of the deck and the local vibrational mode of the cables [12]. Therefore, the complex characteristics of the cable-deck interaction significantly affect the performance of stay cable dampers, and it should be considered during the design stage of the stay cable dampers [52].

According to U.S. Federal Highway Administration (FHWA) [46], the maximum allowable amplitude of the cable vibration should be on the order of the cable diameter. In practice, a criterion based on Scruton number (S_c) (also known as Irwin's criterion [53]) is used to evaluate the damping capability of cables. The Scruton number is a non-dimensional number defined as:

$$S_c = \frac{m\zeta}{\rho D^2} \tag{1}$$

where m is mass per length of the cable; ζ is the damping ratio; ρ is the density of air and D is the diameter of the cable. Based on Irwin's criterion, the S_c should be equal to or greater than 10 for smooth circular cable, and for cable with pipe surface treatments, the S_c should be greater than 5 [54]. If a cable does not meet this requirement, additional damping should be provided to control the cable vibrations.

3 Vibrational Control Systems for Stay Cables

A few countermeasures are used to minimize the vibrations of the cables of cable-stayed bridges such as cable surface treatment, using cross-ties and vibrational control systems for stay cables [55]. Cable surface treatment generally reduces the RWIVs [56]. There are several types of surface treatments i.e. helical fillet, rings, and pattern intended [57, 58]. The cross-ties are secondary cables that transversely connect the stay cables together to form cable networks and increase the in-plane stiffness of the cables. Though the cross-ties are found to be effective in reducing the in-plane vibrations of the cables [59] but they are less appealing in terms of aesthetics points of view. The cross-ties create intermediate supports at the stay cables, which cause an increase in the natural frequency of the stay cables for the vertical modes [60, 61]. The cross-ties can also increase the modal damping of the stay cables, however, the damping increment depends on the properties of the cross-ties and their connection with cables [62, 63]. Sometimes, these countermeasures are simultaneously adopted to achieve higher efficiency in minimizing the vibrations of stay cables [64]. For the sake of conciseness, countermeasures other than structural control systems are not further discussed. Stay cable dampers are one of the most notable solutions in controlling the vibrations of stay cables. Generally, stay cable dampers are two types, internal dampers and external dampers. As shown in Fig. 4, stay cable dampers can be installed near the cable anchorage to the deck or, if necessary, at both anchorage ends of the cable (a much less common approach). Moreover, by increasing the damping of cable, stay cables act as tuned mass dampers that may also

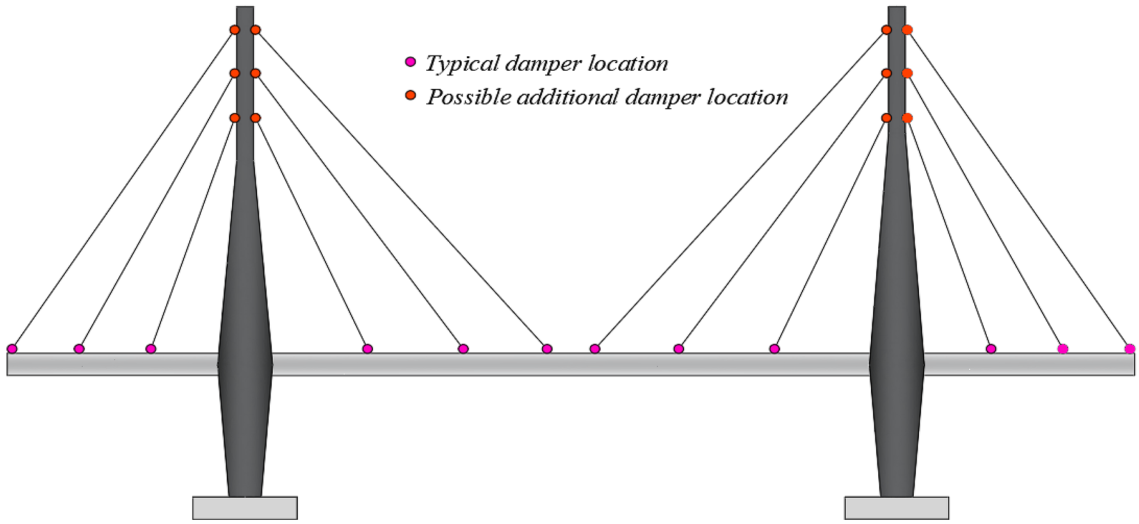


Fig. 4 Installation location of stay cable dampers in the cable-stayed bridges

help in reducing the vibrations of deck or pylons [10, 41]. The research on the importance of stay cable vibrations and its alleviation such as stay cable dampers dates back to the 1980s [65, 66]. The stay cable dampers not only improve the vibrational response of the individual cables but also provides additional damping to the entire bridge, which can also enhance the seismic performance of the bridge [67]. Furthermore, several stay cable and vibration control device manufacturers such as BBR VT International, Freyssinet, Maurer AG, Structural/VSL, etc., have proposed and implemented a variety of stay cable dampers. As a result, a large number of modern cable-stayed bridges are equipped with stay cable dampers worldwide. In the following sections, the two types of stay cable dampers are discussed in detail.

3.1 Internal Dampers

Internal dampers (also called integrated dampers) are placed entirely within the anchor pipe of the stay cables or integrated within the cable system as shown in Fig. 5. As the name indicates, the internal dampers provide a smooth outer shape. Nakamura et al. [68] studied the effect of high-damping rubber (HDR) dampers on the vibrational response of stay cables. The HDR damper was effective in reducing the RWIVs of stay cables. However, the study concluded that for parallel stay cables, the HDR dampers were less effective for wake galloping vibrations.

Hwang et al. [72, 73] proposed to use two types of isolation systems for long stay cable that integrated entirely inside the anchorage system of the cable. The first proposed system consisted of an isolation system namely laminated rubber bearing (LRB) and an internal damper, as shown in Fig. 6a. The second type of isolation system was friction pendulum bearing (FPB) as illustrated in Fig. 6b. The results of the numerical study indicated that the proposed isolation systems outperformed the optimal external passive damper for the stay cable in reducing the wind-associated vibrations of the cables. Although the concept of the proposed isolation systems was numerically analyzed and found to be effective but more detailed studies are needed to address the crucial factors affecting the cable's vibrations for the isolation system of the cables.

Wang and Wu [74] invented the smart damper for reducing the vibrational response of the hybrid fiber-reinforced polymer (FRP) cable. The smart damper consisted of viscoelastic material integrated between two layers of the hybrid cables and had two different configurations as illustrated in Fig. 7. The study concluded that the smart damper having the discontinuous distribution of viscous material provided the same optimal damping for the stay cable and had a better static behavior as compared with the continuous configuration. In addition, the smart damper performance for reducing the out-of-plane vibrations was better than the in-plane vibrations. Furthermore, the result of the numerical study of the proposed smart system was validated with the experimental test results [75] and it was confirmed that with the increase of the vibration amplitude (in-plane and out-of-plane vibrations), the modal damping ratio of the smart damper-cable system also increases.

Egger et al. [76] proposed the multiple-mass-particle impact damper that had a similar configuration as the smart damper. As illustrated in Fig. 8, the multiple-mass-particle impact damper consisted of a stay strand inside a hollow constrainer that was integrated within the cable. The constitutive model of the damper was derived and the proposed impact damper was tested on a real cable through

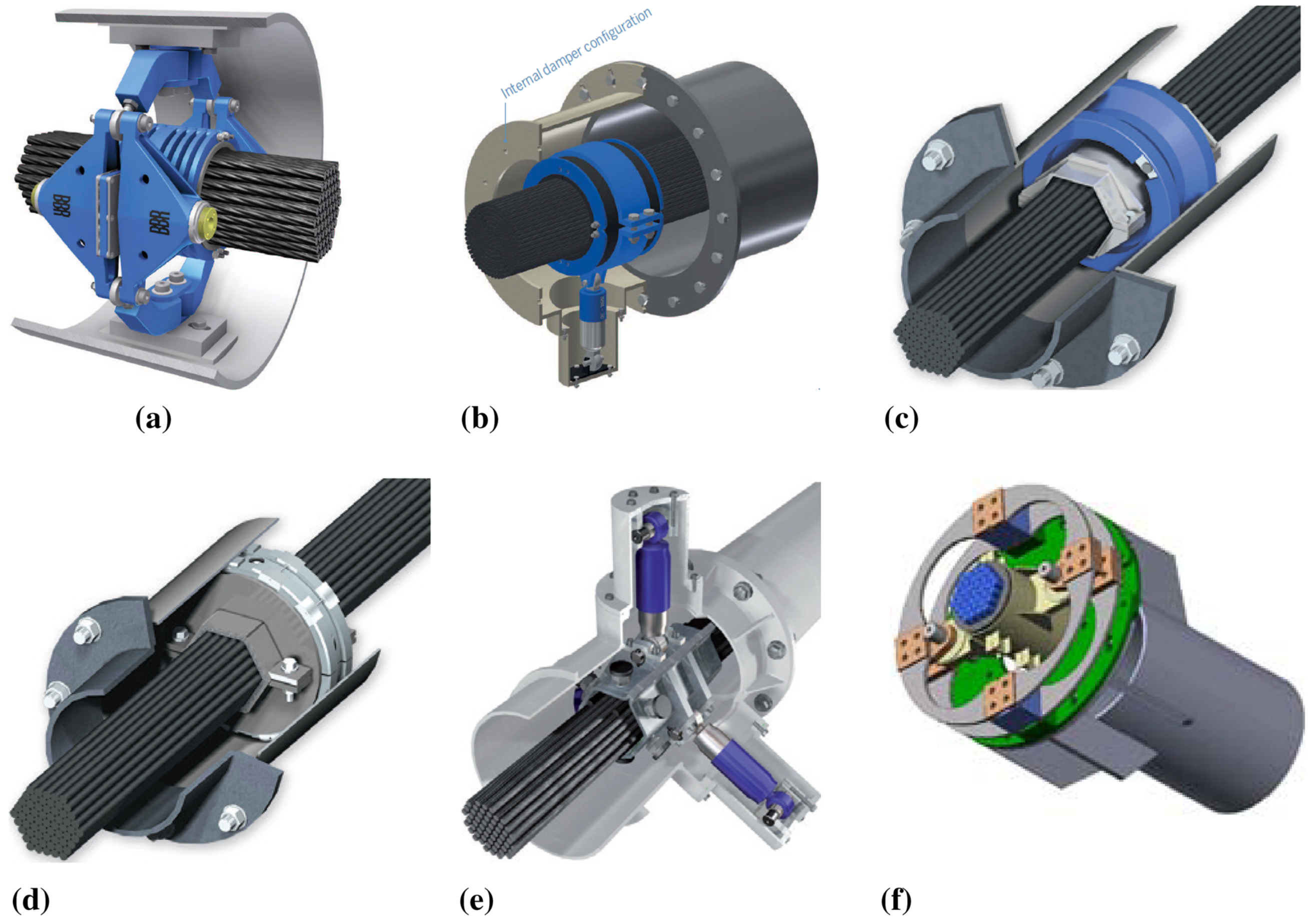


Fig. 5 Some of the most used internal dampers. **a** Square friction damper (courtesy of BBR VT International [69]), **b** Internal viscous damper (courtesy of BBR VT International [69]), **c** Internal elastomeric damper (courtesy of Freyssinet [70]), **d** Internal hydraulic damper (courtesy of Freyssinet [70]), **e** Internal radial damper (courtesy of Freyssinet [70]), **f** Internal friction damper [71]

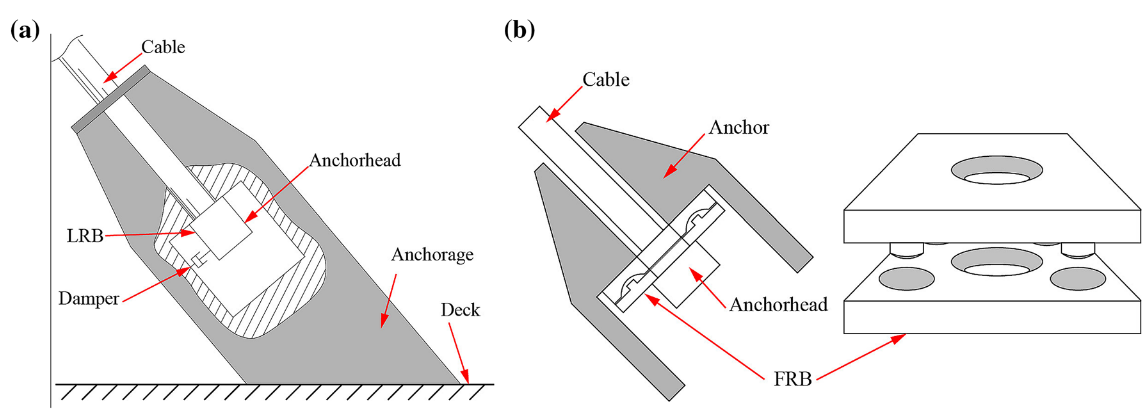


Fig. 6 Detailing of isolation systems proposed for the stay cable. **a** LRB [72] and **b** FPB [73]

an experimental test. The investigation results showed that the multiple-mass-particle impact damper was effectively provided additional damping for a wide range of vibrational modes of the stay cable.

3.2 External Dampers

External dampers are externally mounted to the stay cables as shown in Fig. 9. In practice, external dampers are

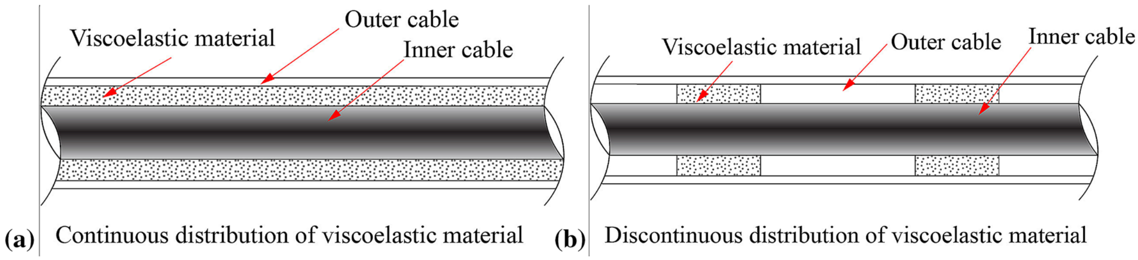


Fig. 7 Smart damper configurations for the hybrid FRP cable [74]

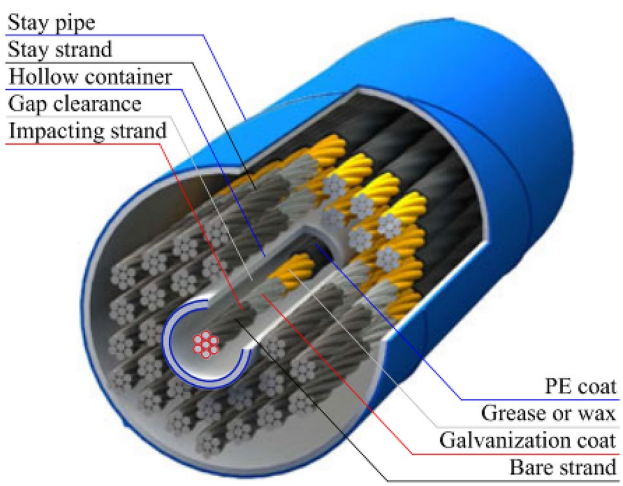


Fig. 8 The 3D view of multiple-mass-particle impact damper in a stay cable [76]

usually placed near to the cable's anchorage for a very long cable, as they are more efficient than the internal dampers. In this regard, Chen and Sun [77] developed an experimental framework for the laboratory scale testing of stay cable with attached dampers such as viscous and magneto-rheological (MR) dampers. The results of the proposed setup framework for the stay cable dampers were comparable with those obtained by the full-scale cable tests.

One of the early investigations on mitigating the stay cable vibrations of cable-stayed bridges due to wind load was done by Wianecki in 1983 [65]. During the construction of the Brotonne cable-stayed bridge, a storm caused the stay cables of the bridge to vibrate up to their third fundamental mode. Consequently, hydraulic dampers (viscous dampers) were installed between the stay cables end and deck to suppress the vertical and horizontal vibrations of the cables. Aerodynamic instabilities with large amplitudes were also observed in the stay cables of the Erasmus Cable-Stayed Bridge shortly after its completion [80]. The initial investigation indicated that RWIVs were the cause of aerodynamic instabilities of the stay cables. Alternatively, the hydraulic damper was proposed and installed to stabilize the stay cables.

Pacheco et al. [81] developed a simple design procedure for designing the external viscous damper for the stay cable. The proposed simplified procedure was based on a universal estimation curve that relates the modal damping ratio of the cable with the cable parameters (length, mass per unit length and fundamental frequency), the mode number, the attached damper, the damper size, and the damper location. The calculated modal damping by this method was found to be high enough to mitigate most of the wind-induced vibrations. Nonetheless, the damper effectiveness may reduce without considering the non-viscous properties of the damper and the sag effect of the cable. Yu and Xu [82, 83] investigated the usage of multi-pairs oil dampers for vibrational control of the stay cables. The design formulation of the damper was based on a hybrid method that considered several parameters including cable inclination angle, cable sag, cable inherent damping, damper stiffness, damper direction, and others [84]. The dynamic in-plane and out-of-plane responses of stay cables subjected to harmonic excitations were determined in frequency domains. It was observed that the modal damping of the first in-plane mode of the long cables with significant sag was much smaller than the other in-plane and out-of-plane modes due to cable-frequency avoidance effects. It was found that the sensitivity analysis should be conducted in order to find the optimum damper properties and position for practical applications. Consequently, it was recommended to use one pair of viscous dampers at each end of stay cables to achieve the required modal damping ratios. Furthermore, Xu et al. [85] validated the theoretical formula of a stay cable with oil damper through free vibration and force vibration tests. Maximum modal damping was achieved based on the optimization of the damper size, which significantly reduced the vibration of the cable.

Tabatabai and Mehrabi [86] developed a complex eigenvalue problem based on the governing differential equation for vibration of the stay cable equipped with a viscous damper that includes the sag extensibility and cable bending stiffness. However, their investigation was limited to the first vibrational mode of the cable and concluding that

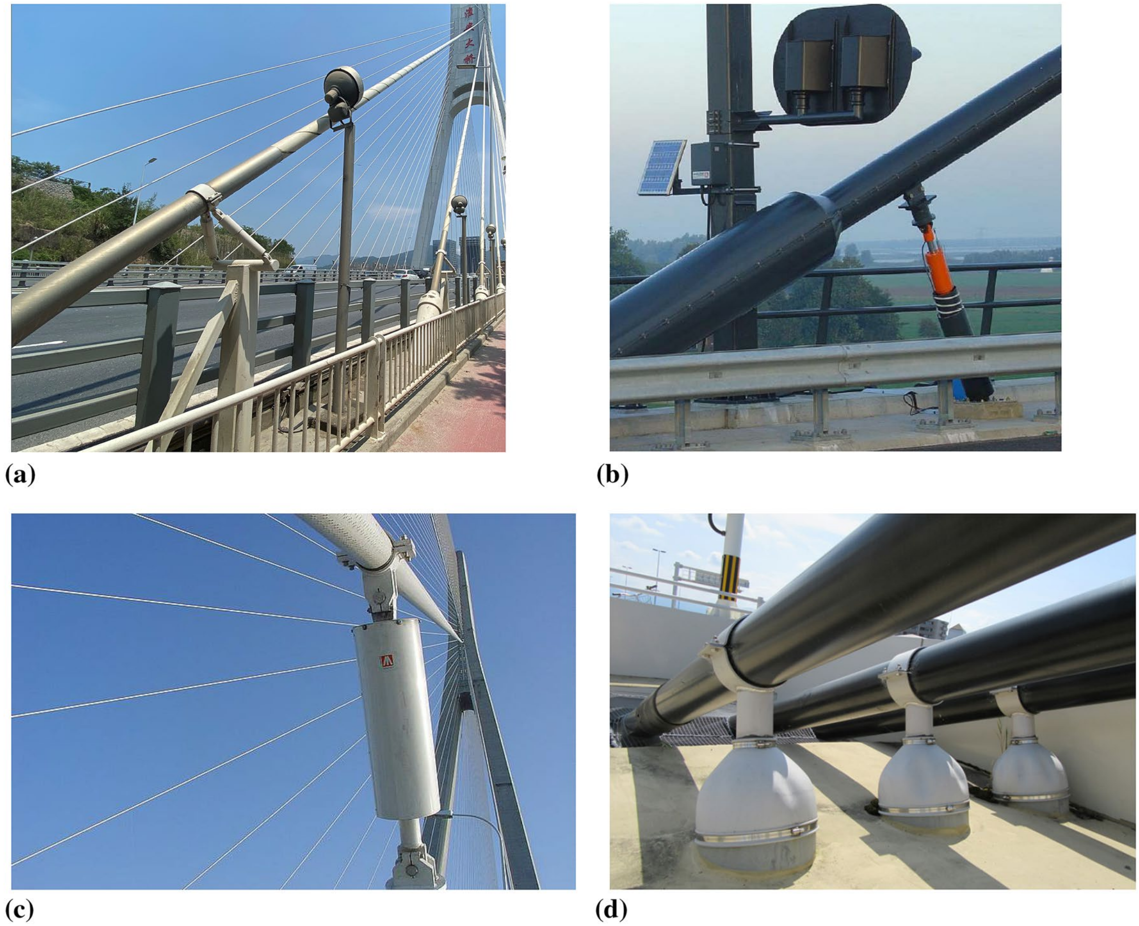


Fig. 9 Some of the most used external dampers. **a** Viscous damper, **b** MR damper (courtesy of Maurer AG [78]), **c** MR damper (courtesy of Maurer AG [78]), **d** HDR damper [79]

viscous dampers not only provide sufficient modal damping for the first mode of the cable but could also improve the modal damping of the higher modes. In addition, the cable sag effect was found to be insignificant on the resulting cable damping ratios, while the bending stiffness had a great influence. To overcome the design limitation of the viscous damper for a single mode of stay cables, Wang et al. [87] proposed an optimal design procedure for the viscous dampers for controlling the multi-mode vibrations of the cable. The design algorithm of the viscous damper was based on the optimal Linear–Quadratic Gaussian (LQG) control theory. Consequently, the results of the numerical analysis showed that the proposed method could effectively provide a high level of damping for the cables over a broad range of vibrational frequencies. Fujino and Hoang [88] derived a formula for designing a viscous damper for the stay cable by assuming a finite support stiffness of the cable. In the design formula, several parameters such as the sag and flexural rigidity of the cable were considered. Weber et al. [89] proposed a design procedure for the linear viscous damper to increase multi-mode damping of the stay cable with the minimum damper distance from the cable support. The proposed design procedure was only dependent on the cable properties (length, mass per unit length, tension force) and the damper position without the need for numerical iterations. Due to the unpredictability of the predominant mode of the stay cables, this method assures the safety of the cables during the large amplitude vibrations. Cheng et al. [90] proposed an energy-based method for evaluating the damping ratio of a cable with an attached viscous damper. The proposed energy-based method had no limitation on the damper location and was found to be advantageous to determine the overall damping of the cable-damper system during the preliminary design stage. Furthermore, Zhou et al. [91] performed a stochastic analysis on the coupling effect of the in-plane and out-of-plane vibrations of stay cable with attached viscous dampers. The results of the parametric study indicated that the in-plane and out-of-plane displacements of the cable-damper system were independent of the loading direction when the viscous coefficient of the damper and the excitation level were constant. However, when the damper size was constant, the in-plane and out-of-plane displacements of the cable-damper system were increasing with the increase of the excitation level. Javanbakht et al. [92] developed a control-oriented model for simulating the dynamic behavior of a stay cable with an attached damper. The proposed model was based on the mode superposition method (MSM) with enhanced shape functions and account different boundary conditions (hinged-hinged and fixed–fixed boundary conditions), bending stiffness and sag effect of the cable. The proposed model required lesser numbers of modes to satisfy the convergence criterion due to the presence of the static correction term. Moreover, the proposed model performed better in terms of the convergence rate and numerical accuracy over the other methods, which shows its potential for control design applications of the stay cable with external dampers. Sun et al. [93] improved the reduced-order model for the stay cable with attached viscous damper. The improved model accounted for the sag-extensibility parameter, which is also known as Irvine parameter that includes the sag and stiffness effects. Numerical studies was performed on cables having different sag-extensibility parameters with one and two viscous dampers having different nonlinearities. The cable vibrational modes that were affected by the sag parameters, only considered for the numerical analysis. The results showed that for the small sag-extensibility parameter, the nonlinear damper had higher modal damping as compared to the linear damper because the nonlinearity induced the energy bleeding effect. Nonetheless, for a certain range of the sag-extensibility parameter, the maximum modal damping ratio of the linear dampers was greater than the nonlinear dampers. When the sag-extensibility parameter was large, the nonlinear and linear damper had almost the same modal damping. Moreover, different damping mechanism was observed for symmetric modes when two similar dampers were symmetrically installed at the cable ends as compared to the summation of the optimal damping obtained by each damper alone. Aforementioned difference was depended on the sag-extensibility of the cable and the nonlinearity of the damper.

Main and Jones [94] performed a field test on linear viscous dampers mounted on stay cables of Fred Hartman Bridge in Houston, USA. The dampers were tuned and optimized for the first vibrational mode of stay cables. The analysis of the field test confirmed the effectiveness of the linear damper on mitigating the stay cable vibrations due to the RWIVs. However, it was highlighted that the linear damper performance was mode-dependent, therefore, it was suggested to use the nonlinear damper for suppressing the stay cable vibrations. In addition, it was pointed out that the damping coefficient of the linear viscous damper should be optimum in order to maximize mitigating the in-plane vibrations of the cable due to RWIV [95]. Furthermore, Main and Jones [96, 97] used an analytical approach based on the complex eigenvalue problem for the free vibration of stay cable with the external linear and nonlinear dampers. The investigation of linear and nonlinear dampers for the stay cables concluded that the nonlinear dampers could achieve optimal performance for a wide range of modes of the cables as compared to linear dampers. A similar conclusion was also obtained from the energy equivalence approach [98] and multi-harmonic balance method [99], the nonlinear dampers are more advantageous in supplying modal damping for a wide range of vibrational modes of the stay cables as compared to linear dampers. Danhui et al. [100] also found that the damping coefficient and cable tension forces have substantial effects on the modal damping of the cable-damper system and these parameters should be used as design variables during the design stages. The advantage of the nonlinear viscous damper over the linear viscous damper is that the nonlinear damper provides the maximum damping at different vibration amplitudes for each vibration mode of the cable while the linear damper can only provide maximum damping for one particular mode of the cable [101]. Unlike the linear dampers, the nonlinear dampers can transfer the induced energy from the lower modes of the cable to higher modes [99]. Due to this unique feature, the nonlinear dampers can be placed closer to the cable anchorage and tuned to the lower vibrational modes of the cables.

Caracoglia and Jones [102] investigated the effectiveness of utilizing two viscous dampers at each end of the cable to suppress the in-plane vibrations of the stay cable. The analytical analysis of the universal estimation curve was extended to a practical universal curve for two viscous dampers attached to a stay cable. When the dampers were spaced closely to each other on the cable, the stiffness of the cable-damper system increased, while the damping ratio decreased. Nonetheless, it was recommended to use the dampers at both ends of the stay cable to have a higher damping level for the system. Hoang and Fujino [103] also studied the combined effect of two viscous dampers attached to a cable. Two cases i.e., (i) one damper at each end of the cable and (ii) two dampers at the same end of the cable were considered for studying the combined effect. It was concluded that the maximum combined damping effect of the two dampers was achieved when they were attached to each end of the cable. When the dampers were located at the same end of the cable, the modal damping was mostly from the outer damper located at a longer distance from the cable end. In other words, utilizing two dampers on the same end of the cable has no advantages over the use of a single damper in increasing the modal damping of the stay cable. Fournier and Cheng [67] studied the effect of damper and support stiffness on the efficiency of the linear viscous damper in suppressing the cable vibrations. The results of the experimental and numerical study revealed that the efficiency of the damper reduced when the damper stiffness increased or the support stiffness decreased. The damper support stiffness had a more profound impact on the efficiency of the damper, and it was suggested to install the damper closer to the mid-span of the cable. Even so, if the damper size exceeds a certain capacity, the damper stiffness and damper support stiffness may have adverse effects on the damper efficiency. Furthermore, in order to have a higher efficiency of the linear viscous damper, it is better to have stiff support and keep the damper stiffness as low as possible. The results of the experimental test also confirmed that the damper stiffness should be minimized to achieve higher modal damping for the cables [101]. Meanwhile, the nonlinear force can dissipate a larger amount of energy for the higher-mode oscillations. Additionally, the rotational restrainer effect has an adverse effect on the damping ratio of the viscous damper attached to the cable [104]. Therefore, the rotational restrainer effect should be accounted for in the design of the damper to supply adequate modal damping to the cable. Nguyen and Macdonald [105] studied the galloping instability effect on a stay cable with two orthogonally attached viscous dampers. It was pointed out the conventional galloping analysis may overestimate the critical wind speed for the galloping effect. Moreover, the complexity of the mode shapes should be accounted for, as it shows the cable instability during the oscillations.

Low frequency and large amplitude oscillations due to RWIVs, severely damaged the guide pipes of the anchorage of a cable of Fred Hartman Bridge (see Fig. 1)[11]. Subsequently, the investigative team recommended implementing the hydraulic dampers as one of the countermeasures to suppress the wind-induced vibrations of the stay cables. Thus, two prototype hydraulic dampers were installed on two stay cables of the bridge. The prototype hydraulic dampers were optimized for damping in the first mode of the cables. After three years of monitoring the prototype dampers, the bridge experienced over 35,000 events of wind-induced vibrations. The results of monitoring confirmed the positive performance of the damper in suppressing the stay cable vibrations. However, the prototype dampers had hydraulic oil leakage, and the out-of-plane vibrations of the stay cable caused damge due to the rotation of the damper at its supports as shown in Fig. 10a. Consequently, the support configurations of the final damper design were changed as shown in Fig. 10b, c to avoid any damage to the dampers

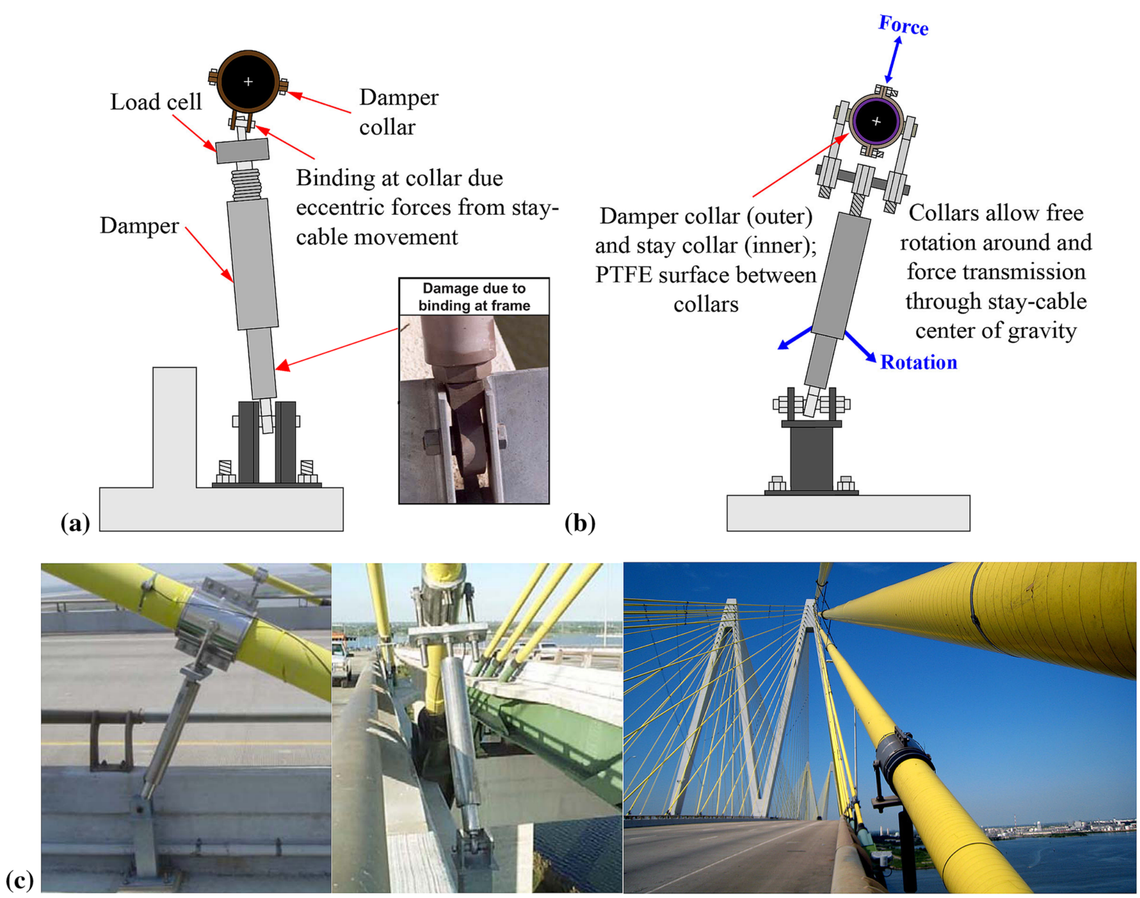


Fig. 10 **a** Damage to the prototype damper due to out-of-plane vibration of the cable, **b** final hydraulic damper design, and **c** hydraulic dampers installed on the stay cables of the Fred Hartman cable-stayed bridge [11]

due to out-of-plane vibrations of the cable. In addition, the modal analysis of the bridge indicated that 95% of the cables had a dominating response greater than the third vibrational mode.

Chen et al. [106] configured lateral and rotational viscous dampers for controlling the cable vibrations. As shown in Fig. 11, the proposed stay cable damper was a combination of a central viscous damper that provides lateral damping and two eccentric viscous dampers providing rotational damping, which were arranged parallelly. The numerical analysis showed that by combining the lateral damper with rotational dampers, the optimal damping of the cable increased up to 30% and 15% as compared with a single lateral damper for the clamped and pinned support configurations, respectively.

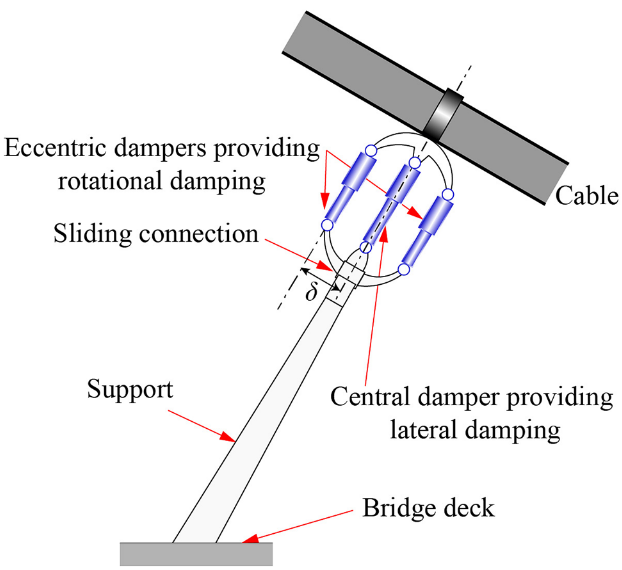


Fig. 11 The schematic view the lateral and rotational dampers installed on a stay cable [106]

Jensen et al. [107] proposed to use a tuned mass damper (TMD) between the closely spaced stay cables of the bridge as shown in Fig. 12a. A band-limited white noise function was used as the excitation input and only the linear behavior of the cables was considered for the numerical study. The results showed that the TMD caused a 14% reduction in the vibrational response of the two closely spaced cables. Hijmissen et al. [108] found that apart from the TMD parameters (the TMD mass, spring, and damping constants), the bending stiffness of the cable with an attached TMD greatly influences the modal damping of the first tuned mode of the cable-damper system, while for the higher modes its effect is insignificant. As illustrated in Fig. 12b, Sun et al. [109] also proposed a similar approach for suppressing adjacent cables' vibrations by using a tuned inerter damper (TID). The approximate solution of the damper was derived for the optimal tuning and damping ratio of the TID. The TID was found to be effective in maximizing the damping ratio of the lower bound of all targeted modes of the cables. On the contrary, the TID had an insignificant damping ratio increase for the in-phase modes of the twin cable system.

Hovenring Bridge (Netherland) is a ring-shaped cable-stayed bridge, designed for bicycles. Wind-induced vibrations were observed on several stay cables of the bridge shortly after its construction in 2011 [110]. An on-site investigation and numerical analysis were conducted to find the modal parameters of the bridge. It was found that the cables were excited due to vortex-induced vibrations, thereafter, a type of TMD called Stockbridge-type damper was installed on the cables as a mitigation measure. The Stockbridge-type damper is a multiple degrees-of-freedom TMD that is usually used for electric power transmission lines. Consequently, the Stockbridge-type dampers were installed on the

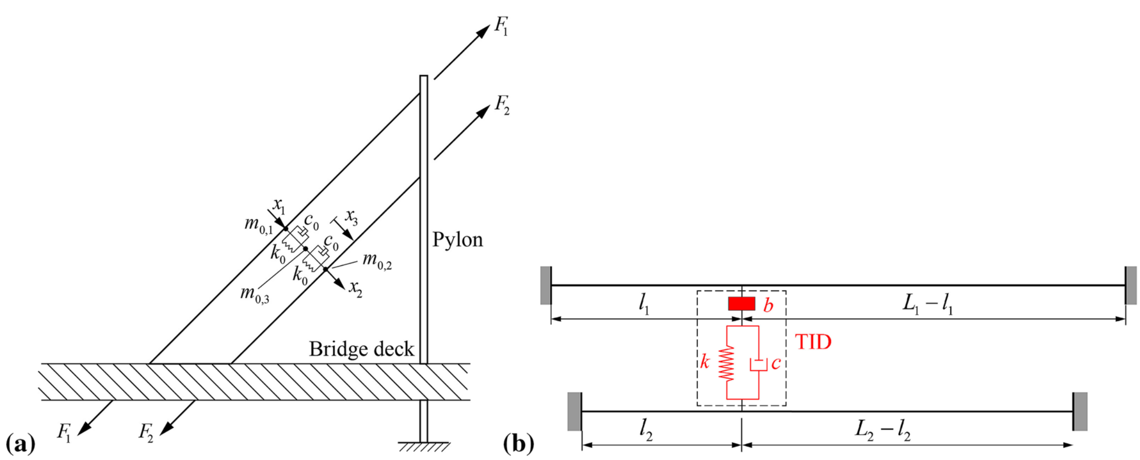


Fig. 12 Analytical models for suppressing the vibrations of the adjacent cables by using **a** TMD [107] and **b** TID [109]

stay cables of the bridge as showing in Fig. 13 and found to be effective in suppressing the cables' vibrations.

Fujino and Hoang [88] derived an approximate formula for the HDR damper externally attached to a stay cable. The damping force of the HDR damper is independent of the frequency due to the hysteretic characteristics of the rubber material. The cable sag and flexural rigidity of the cable were included in the proposed design formula and the support stiffness was assumed to be finite. Cu and Han [111] studied the effect of different parameters of HDR damper including, spring factor, material loss factor, and the damper location on dynamic behaviors of the stay cable. It was suggested that the HDR dampers are more suitable for short stay cables or can be combined with other dampers to have higher efficiency. Le [112] investigated the boundary condition effect on the performance of the HDR damper attached to a cable. The results showed that the efficiency of the HDR damper increases when the rotational restrain of the cable has a finite stiffness. Moreover, the modal damping was found to be independent of the boundary condition and the vibrational modes.

Ni et al. [113] developed a neuro-control algorithm for the semi-active MR damper to control the vibrations of stay cables. The effectiveness of the proposed neural network control methods was tested numerically and experimentally on a scaled cable model with an attached MR damper to its lower anchorage. The study concluded that the proposed control algorithm for the semi-active MR damper could progressively control the vibrational response of the stay cables. Johnson et al. [114] performed a comparative study between the semi-active damper and passive damper for mitigating the vibrations of the stay cables. Several parameters such as cable sag, inclination angle, and longitudinal flexibility of the cables were considered. The results indicated that the

Fig. 13 Stockbridge-type dampers installed on the stay cables of the Hovenring Bridge [110]

semi-active damper was 30–40% more efficient than the passive damper in reducing the vibrational response of the stay cables. Nevertheless, the damping force of the MR damper without current (in the passive mode) increases with the increase of the excitation frequency [115]. The MR damper having a large current could provide a similar damping force for a wide range of frequencies for the stay cables. Weber et al. [116] performed experimental studies to evaluate the effectiveness of the MR damper in reducing the vibrational response of the stay cables. Several constant currents of the MR damper were considered for two different control strategies, namely, maximum damping of one mode and maximum damping of several modes. Results of the tests indicated that although the MR damper reduced the in-plane vibrations of the stay cable, but it was less effective for controlling the out-of-plane vibrations of the cable, especially at higher frequencies. Therefore, it was suggested to tune the MR damper in the damper plane. The optimal current level of the MR damper could provide maximum modal damping to a target mode. However, the damper current had an insignificant effect on the modal damping when the aim was to reduce multi-mode vibration of the cable.

Dongting Lake Bridge experienced severe cable oscillations due to RWIV after the construction [117]. Alternatively, it was suggested to equip the stay cables with semi-active MR dampers. Initially, a couple of semi-active MR dampers were installed on a few cables, and field measurement and real-time monitoring were conducted for 45 days. After confirming the effectiveness of the proposed control system at the end of the test trial, a total 156 of twin-dampers were installed on the stay cables of the Dongting Lake Bridge, as shown in Fig. 14. A decade later after the installation of the MR dampers on the Dongting Lake Bridge, several dampers were randomly selected and their service condition was evaluated [118]. It was found that 80% of the selected dampers could supply a considerable damping force to the cables after 10 years of service. The two most crucial problems associated with the MR dampers were found to be the precipitation of the iron particle and the leakage of the MR fluid. Therefore, it was suggested to increase the durability of the MR dampers and protect them from harsh environments. In addition, it was also recommended to position the piston end in the upward direction to avoid leakage due to gravitational force.

Duan et al. [119] developed a state-derivative feedback control for the semi-active MR damper to suppress the vibration of the stay cables. The flowchart of the proposed semi-active control system is shown in Fig. 15. The cable acceleration was measured by a single accelerometer attached to near the lower end of the cable. The cable was excited by the sweeping sine function and the sinusoidal step relaxation function. With the real-time data collection, the control algorithm was mostly commanded the appropriate dissipative

Fig. 14 Semi-active MR dampers installed on the Dongting Lake Bridge

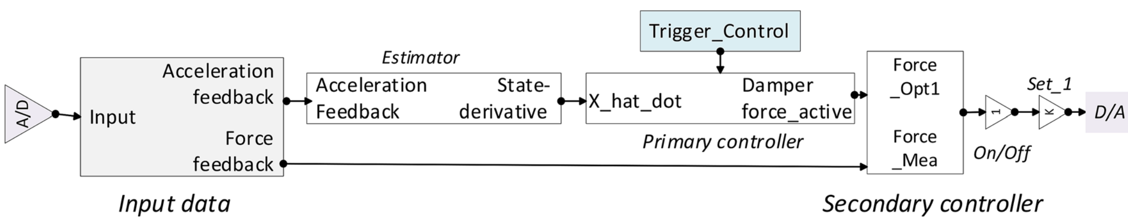


Fig. 15 Semi-active state-derivative control in reciprocal state space framework for the MR damper of a stay cable

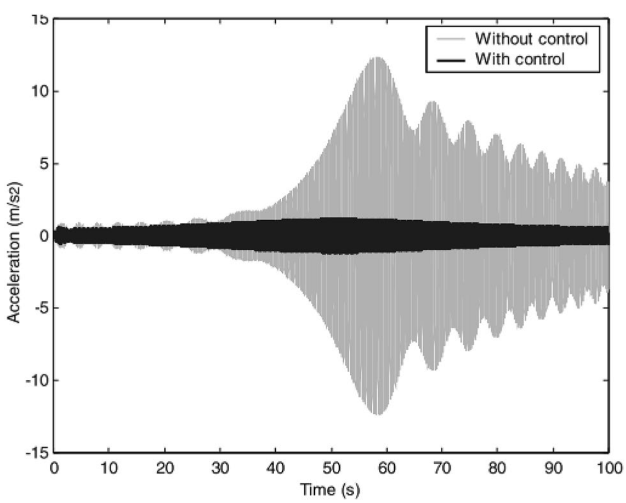


Fig. 16 Stay cable acceleration response with and without a semi-active MR damper under sweeping sine function excitations [119]

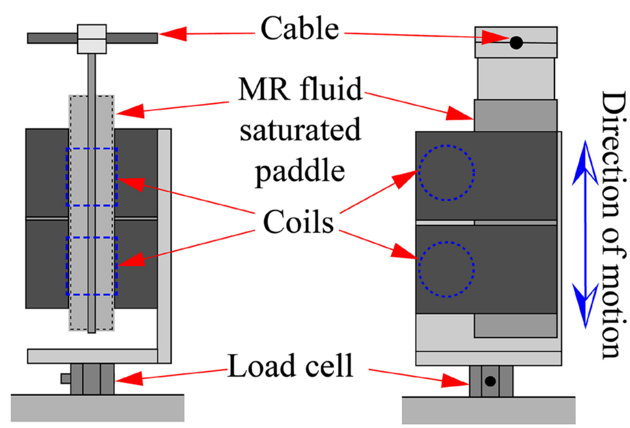


Fig. 17 The MR shear mode damper [120]

force for the MR damper to control the stay cable vibrations (see Fig. 16). In conclusion, high equivalent damping of the stay cable was achieved through the proposed semi-active control system.

Christenson et al. [120] investigated the use of an MR shear mode damper with a clipped optimal H_2/ LQG control method in reducing the vibrational response of the stay cable. As shown in Fig. 17, the MR shear mode damper was made of a foam paddle saturated with MR fluid passing through a pair of parallel steel plates with an attached coil of copper wire at one end of the plates. When the MR fluid-saturated paddle moves in the magnetic field, it generates the damping force. The H_2/LQG control algorithm used the output feedback from the force and displacement sensors to determine the appropriate control force for the damper. The results of the experimental and numerical analyses showed that the semi-active MR shear mode damper reduced the in-plane vibrations of the cable by 50%. Moreover, the semi-active control strategy vibrational response was 20% better than the optimal passive control of the same damper.

Zhou et al. [121] performed a comparative study between the performance of the MR damper and viscous damper for controlling the in-plane and out-of-plane vibrations of a stay cable through three-dimensional finite difference method. When two or more vibration modes of the cable were excited, the MR damper performed better in controlling the cable vibrations as compared to the viscous damper. Otherwise, if only a single mode of the cable was excited and the viscous damper was tuned for that mode, both the dampers had a similar performance. Ying et al. [122] developed a semi-active control method for parametrically excited instability of stay cables based on the linear quadratic regulator (LQR) control method for the MR dampers. The effect of several parameters including the control force bound, time delay, and state observation errors on the instability of the cable were analyzed for controlling the transverse vibrations (out-of-plane vibrations) of the cable. In conclusion, the MR damper with the optimal control configuration was effective in controlling the parametrically excited instability of stay cables, especially for the minimum parameter-excitation amplitude and unstable regions. Johnson et al. [123] showed that the semi-active MR damper locating at 2% length of the cable from the cable end, had a 63% better performance than the optimal viscous damper at the same location. As mentioned earlier, the longer cable is, the higher sensitivity to oscillations during the wind; therefore, the MR dampers (with a similar configuration as shown in Fig. 14) were installed for the longest stay cables of Shandong Binzhou Yellow River Highway Bridge [124]. For this bridge, the semi-active control was developed based on the state feedback of acceleration response from the accelerometers located at several locations of the cable. The optimal damping ratio of the cable with the MR damper having the semi-active control algorithm was substantially higher than the passive MR damper configuration due to the pseudo negative stiffness characteristic of the semi-active control. Li et al. [125] proposed active and semi-active control systems with negative stiffness for vibrational control of the cable. In the numerical analysis, a pseudo-viscoelastic (P-VE) damper was replaced with the active and semi-active control systems because the P-VE damper had similar characteristics and behaviors. The LQR control algorithm was used for the semi-active and active control of the MR dampers. Subsequently, it was concluded that the active and semi-active control system with negative stiffness could provide a larger damping ratio and perform better than the passive dampers in reducing the vibrations of the cable due to enhancement of the cable displacement. The RWIV was observed on the longest stays of the Alamillo cable-stayed bridge [126]. The observed vibration caused discomfort for the passing pedestrians. Several countermeasures were proposed including using MR dampers for the longest cables. The MR dampers were installed at about 3% of the cable length from the cables' anchorage such that they were located below the pedestrian handrail. The field measurement after the installation of the MR dampers concluded that the damper increased the damping of the cables and thereafter no RWIV was observed.

Two control algorithms i.e., modulated homogeneous friction algorithm and the balance logic algorithm were proposed by Zhou et al. [127] for the semi-active control of MR damper attached to a cable. The performance of the semi-active MR damper with these control algorithms was compared to an optimal viscous damper tuned for the first in-plane vibrational mode of the cable. The numerical study indicated that the MR damper with the modulated homogeneous friction control algorithm and the viscous damper almost had a similar performance in reducing the vibrational response of the cable. Meanwhile, in some cases, the balance logic control algorithm outperformed the modulated homogeneous friction control algorithm in mitigating the vibration of the cable with the MR damper. Weber and Distl [128] also developed two control algorithms i.e., cycle energy control (CEC) and controlled viscous damping (CVD) for the semi-active control of MR damper in suppressing the stay cable vibrations. As shown in Fig. 18, the proposed control algorithms were based on the energy-equivalent adaptive cable damping systems for the real-time controlling of the MR dampers. The CVD control algorithm takes the operational temperature of the MR damper into account. The full-scale field testing of the MR dampers with the two proposed control systems on the stay cables of the Sutong Bridge (China) and the Eiland Bridge (Netherlands) confirmed the independency of the cable damping from the amplitudes and frequencies of the vibrations for both algorithms. The CEC and CVD semi-active controls of the MR damper are highly practical as stay cables may vibrate at different amplitudes and frequencies based on the wind condition. The CVD system was also implemented for the stay cables of the Russky Bridge (Russia). The CVD system found to be worthy by computing the actual temperature of the MR damper. This assures the force tracking that is independent of the actual damper temperature, which is very important for bridges with extremely harsh environmental conditions.

Zhao et al. [129] developed a new type of MR damper with a new optimal equivalent control algorithm based on the LQR control algorithm. As Fig. 19 illustrates, the proposed damper consisted of a single rod MR damper having a spring-floating compensation device. In order to evaluate the damper performance in reducing the in-plane vibration of a cable, a numerical analysis was performed on a stay cable

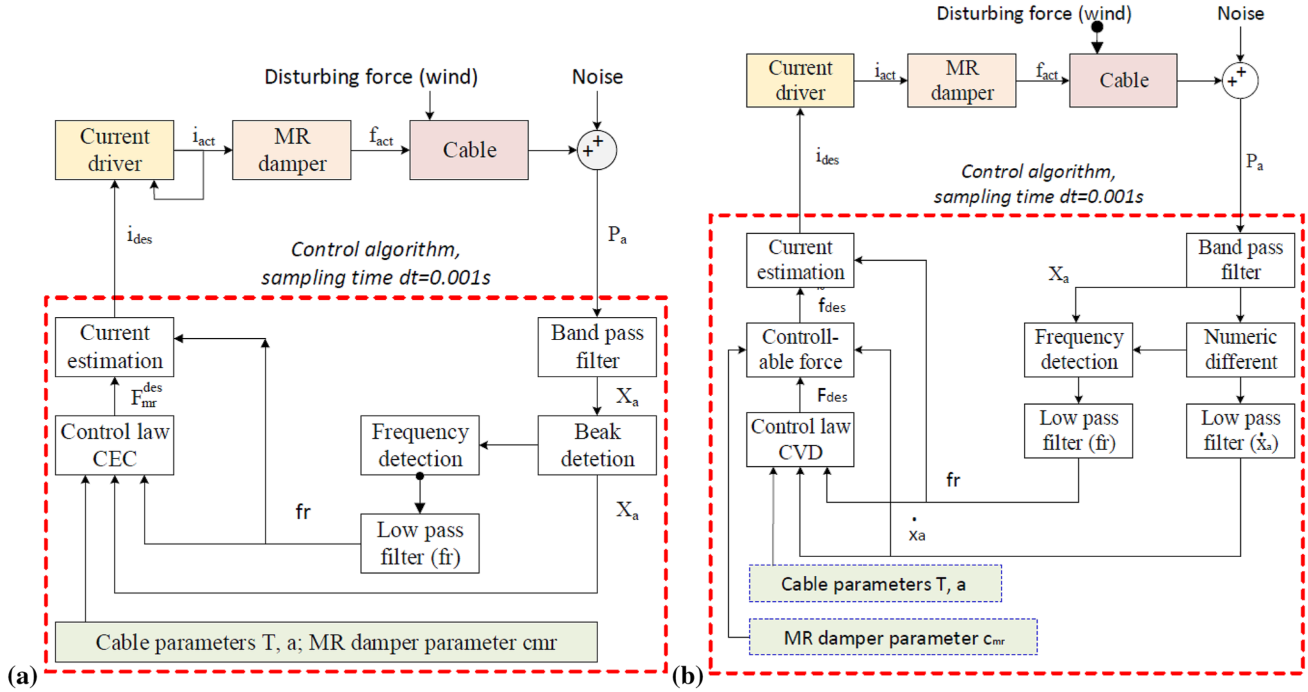
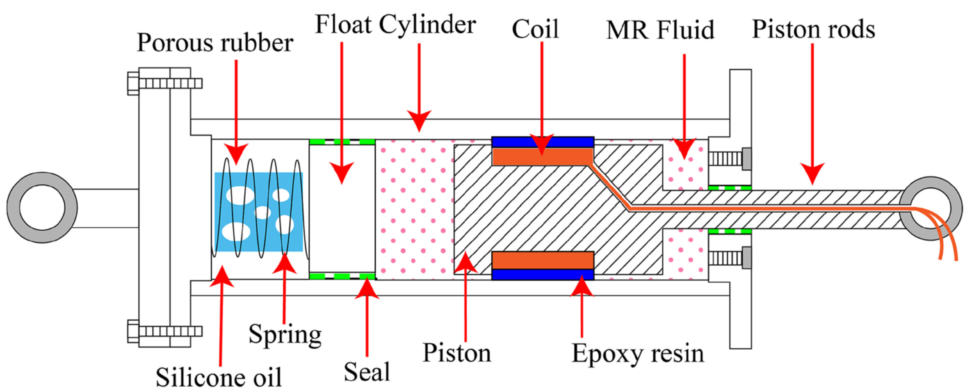


Fig. 18 Control flowchart of the MR damper based on **a** the CEC algorithm and **b** the CVD algorithm [128]

Fig. 19 Schematic detailing of a new MR damper proposed by Zhao et al. [129]



with two semi-active MR dampers. The performance of the semi-active control in reducing the vibrational response of the cable was better than the optimal passive control. Meanwhile, the new optimal equivalent control algorithm with minimum feedbacks requirements had comparable performance to that of the LQR control.

Electromagnetic damper cum energy harvester (EMDEH) was proposed by Shen and Zhu [130] for the application of the stay cable vibrations. The EMDEH was made of an electromagnetic device (EMD) connected to an energy harvesting circuit (EHC). As illustrated in Fig. 20, the application of the EMDEH for a stay cable was numerically studied in the MATLAB/Simulink environment. The EMDEH was found to be efficient in reducing the cable vibrations that was as good as an optimally viscous damper. Moreover, it was also found from the simulation that EMDEH had the capability of regenerating power for small electronic devices such as wireless sensors. Afterward, Cai and Zhu [131] improved the performance of the EMDEH by redesigning the EHC unit. In the redesigned EHC unit, a buck-boost converter having a low-power microcontroller unit was used to regulate the duty cycle based on the feed-forward signal. The improved EMDEH provided stable damping to the cable and comparatively enhanced the cable vibrations.

Lu et al. [132] proposed the viscous inertial mass damper (VIMD) as a negative stiffness device for reducing the stay cable vibrations. As demonstrated in Fig. 21, the VIMD consisted of a viscous damping section and an inertial mass section. The inertial mass section was made of a threaded rod and a ball nut that transfer the

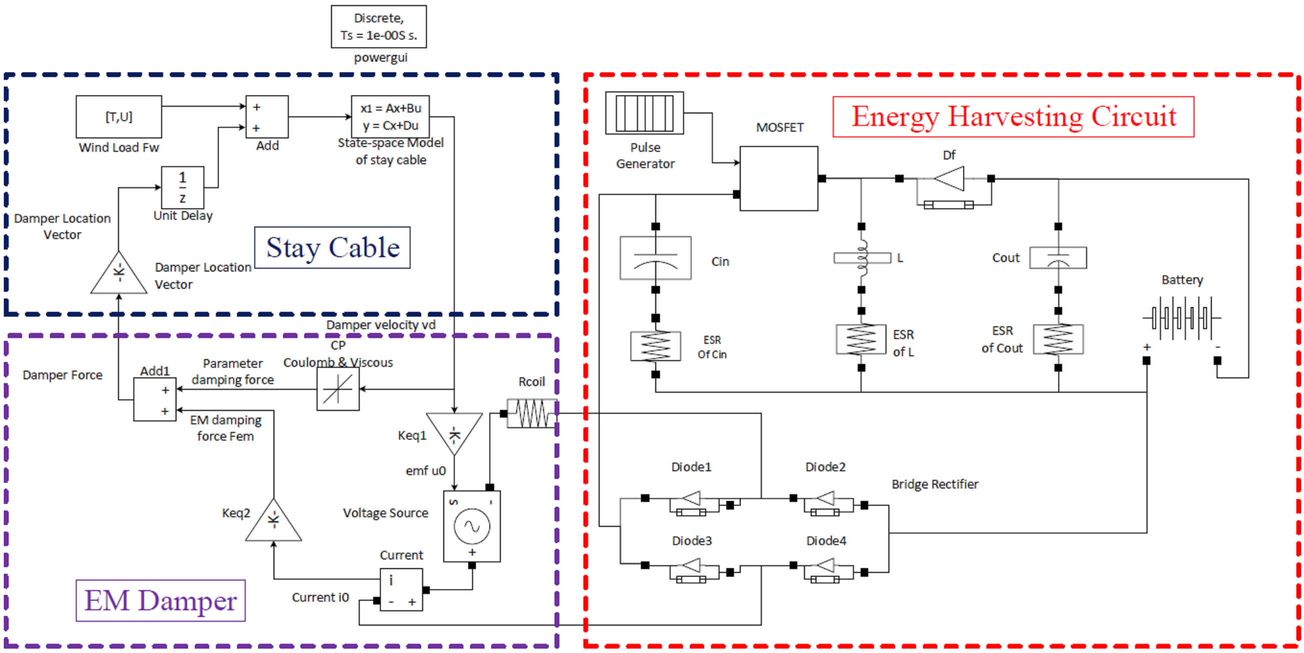


Fig. 20 The model of the stay cable with EMDEH system in MATLAB/Simulink [130]

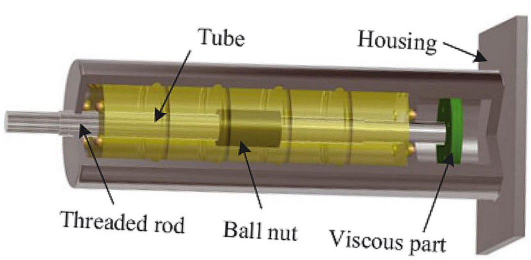


Fig. 21 The detailing of VIMD [132]

linear movement of the threaded rod to rotate the ball nut and the mass tube. As a result, the magnified inertial force was changed to a linear motion. The viscous damping section was made of a piston rod connected to the threaded rod, viscous fluid material and a piston head to produce the damping force. By installing the VIMD at the vicinity of the cable anchorage, the modal damping of the cable was substantially increased for the first four vibrational modes. In addition, the performance of the VIMD in reducing the cable vibration was outperformed the optimal viscous damper. Wang et al. [133] studied the cable sag effect on the performance of an inertial mass damper (IMD) attached to a stay cable. It was found that the IMD was able to alleviate the sag adverse effect on the vibrational response of the stay cable. The sag increased the vibrational frequency of the cable, while it decreased the optimal damping coefficients and the inertial mass of the IMD for the nearly symmetrical vibrational modes. However, the sag had a less significant effect on the asymmetric modes.

Shi et al. [134] investigated the dynamic behavior of a cable with a passive negative stiffness damper (NSD) through analytical and numerical approaches. The NSD was modeled as a combination of a viscous damper with a negative stiffness spring. The results of the analysis showed that with the increase of the negative stiffness of the NSD, its damping ratio also increases. Even though the NSD increased the damping ratio of the cable but it also reduced the stiffness of the cable that may cause instability in the cable system. Therefore, the stiffness of the NSD should be calculated accurately for the stay cable. Lastly, it was found that the NSD was more effective than the conventional viscous dampers in reducing the cable vibrations. Following this, Shi et al. [135] performed an experimental test on a stay cable with a new type of NSD called magnetic NSD to validate the numerical results. As demonstrated in Fig. 22a, the magnetic NSD consisted of a movable magnet placed between two fixed magnets on a shaft, which were covered by a conductive pipe [136]. The experimental results proved that the provided modal damping for the cable by the magnetic NSD was four times higher than the optimal viscous damper. It was also pointed out that the flexural rigidity of stay cables and boundary conditions should be taken into account in order to have an accurate analysis and results. Shi et al. [137] also compared the performance of the passive NSD with the LQR and output feedback active control in suppressing the cable vibrations. The comparative study demonstrated that the NSD could supply a similar high

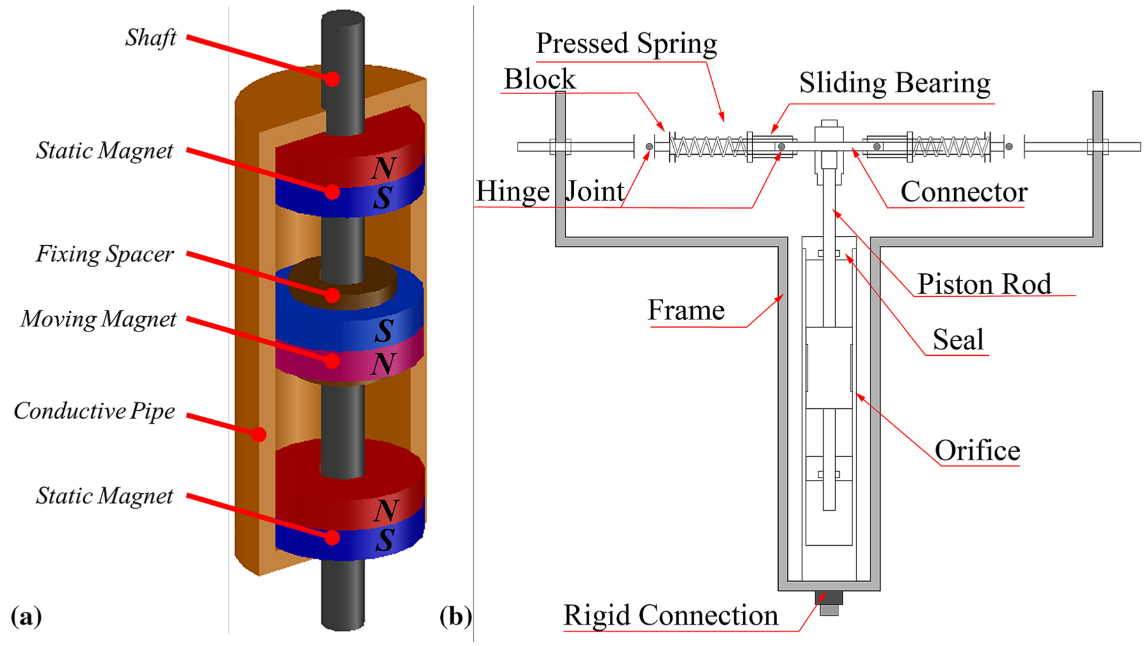


Fig. 22 Details of two types of NSDs proposed by **a** Shi et al. [135] and **b** Zhou and Li [138] for the stay cables

damping level as the LQR active control to the stay cable. In addition, the output feedback control with two feedback variables had comparable performance to that of the NSD. It was concluded that the NSD could provide sufficient damping to the cable as a completely passive control system and may even be more practical as it need not any algorithm or external source of energy. Zhou and Li [138] proposed another type of NSD for mitigating the stay cable vibrations. As shown in Fig. 22b, the NSD consisted of an oil damper and two compressed springs. The NSD characteristics and behaviors were experimentally and numerically studied. The results of the investigation showed that the proposed NSD effectively reduced the single-mode and multi-mode vibrations of the cable and it is more effective in providing modal damping to the cable than the oil damper. Javanbakht et al. [139] research also showed the performance superiority of the passive NSD in reducing the cable oscillations over passive positive stiffness damper (PSD). Similar to other researchers' findings for NSDs, the stability of the system was found to be crucial for the NSD in suppressing the cable vibrations. Therefore, a criterion was defined for determining the stiffness of the NSD based on the length, the bending stiffness and tension force of the cable as well as the support stiffness and the installation location of the damper. A new design procedure aiming to optimize NSD for wind-induced multi-mode vibrational control of the stay cable was proposed by Javanbakht et al. [140]. The proposed NSD optimization approach could effectively reduce a single mode as well as multi-mode vibrations of the stay cable equipped with NSD. Additionally, the performance of the proposed approach found to be much higher than the PSD, zero stiffness damper and even the LQR active control with a similar peak control force at the installation position. Further, Javanbakht et al. [141] showed that the flexible support could increase the damping ratio of the cable-NSD system, leading to reduce the size and negative stiffness of the NSD and eventually minimize the cost and maintenance of the device. Furthermore, Dong and Cheng [142] investigated the effect of the support stiffness on the performance of the cable-NSD system through laboratory experiments. It was found that the impact of the support stiffness on the efficiency of the NSD depends on the stiffness of the NSD. Accordingly, flexible support is beneficial for the cable-NSD system with strong negative damper stiffness, whereas rigid support is more suitable for the cable-NSD system with weak negative damper stiffness.

Chen et al. [143] performed a unified analysis on the NSD and different types of inerter-based vibration absorbers (IVAs) i.e., (i) IMD, (ii) TID, (iii) a viscous damper in parallel with TID, and (iv) a viscous damper in series with an inerter, aiming to reduce the multi-mode vibrations of the stay cable. The analytical study indicated that the NSD enhanced the modal damping of multiple modes of the cable. In addition, the TID had superior efficiency among the other IVAs for controlling the multi-mode vibrations of the stay cable. To attain the best performance, the TID frequency should be tuned to the lowest frequency of the target modes of the cable and have a relatively large inertance. Gao et al. [144] developed an optimum design procedure for the viscous inerter damper (VID) based on output feedback control for mitigation of the multi-mode vibrations of the cable. In this approach, the velocity of the cable at the damper location was used as the feedback input. Higher modal damping for the intermediate modes of the cable was achieved by the proposed method as compared to other methods, while the modal damping of the first and the higher modes of the cable was slightly lesser. Finally, the VID with the proposed method had a substantially better performance than the viscous damper in reducing the multi-mode vibrations of the cable.

Shi and Zhu [145] proposed an inerter damper for the stay cables. The inerter damper was a type of NSD damper with a unique feature. Unlike other typical NSDs, the force of the inerter damper is directly proportional to the accelerations, therefore, its stiffness changes with the vibrational frequency, which eventually avoids any structural instability. The inerter damper added substantial damping to a tuned mode of the cable that was higher than the optimal viscous damper. However, for the rest of the vibrational modes of the cable, the added damping was relatively limited as if the cable was locked at the damper location. In conclusion, the inerter damper could provide the optimal damping for a specific target mode of the stay cable. Li et al. [146] developed another inerter-based damper called electromagnetic inertial mass damper (EIMD), which had negative stiffness. The EIMD primarily consisted of an inerter that provides inertance and an electromagnetic damper provides electromagnetic damping. Figure 23 illustrates the detailing of the EIMD. The numerical model of the cable-EIMD system was developed based on the complex eigenvalue analysis and compared with the experimental results. When the EIMD was installed at 2.5% length of the cable, the first modal damping ratio of the cable was substantially higher than the similar cable with the optimal viscous damper. For the optimal design of EIMD, the inertance and damping coefficient should have optimal values. It was also found that the EIMD is also effective in suppressing the vibration of the higher modes. Li et al. [147] used a combination of electromagnetic shunt damper (EMSD) and inerter damper (ID) to control the vibration of the cables. The direct current was used in the shunt circuit of the EMSD-ID device to control the electromagnetic force generated by the motor. A full-scale experiment showed that the EMSD-ID provided a substantially large modal damping for the fundamental mode of the cable.

Li et al. [148] studied the vibrational response of a stay cable equipped with a single shape memory alloy (SMA) damper. The analytical analysis results indicated that the SMA damper was able to control the vibrations dominated by the first few modes of the cable. It was also found that the optimal location of the SMA damper should be about 0.2% of the cable length in order to suppress the oscillations of the cable over broadband frequency excitations. Zuo et al. [149] proposed a new type of SMA damper for controlling the cable vibrations, as shown in Fig. 24. The damper optimization procedure was also proposed and its performance was compared with an active control system based on the LQR algorithm. Two SMA dampers were located at 0.2% of the cable length from its end to control the in-plane and out-of-plane vibrations. The results of the numerical analysis showed that the optimized SMA dampers had almost similar

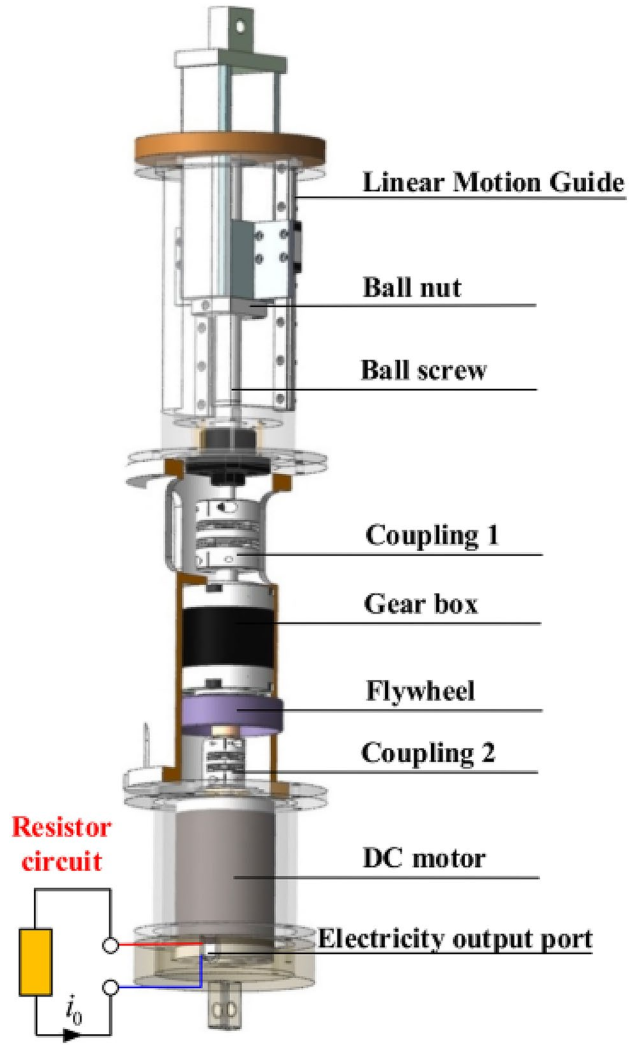


Fig. 23 Detailing of the EIMD [146]

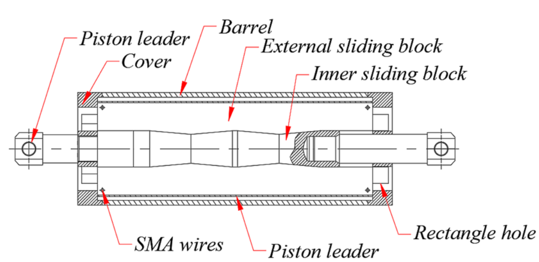


Fig. 24 The SMA damper detailing proposed by Zuo et al. [149]

performance as the active control system. Furthermore, Zou and Li [150] confirmed the effectiveness and application of the same SMA damper on a stay cable of a cable-stayed bridge through numerical and experimental studies. Nevertheless, the SMA damper could effectively reduce cable vibrations at temperatures between −25 and 50 °C [151]. Dieng et al. [152] showed the maximum in-plane displacement reduction can be achieved when the SMA damper is placed nearby the maximum vibration amplitude. However, this location may not be always a practical solution for cables of the cable-stayed bridges. The SMA damper also reduced the oscillation time and vibration amplitude of the cable. Mekki and Auricchio [153] evaluated the performance of the SMA damper in controlling the vibrations of stay cables and comparing it with the TMD performance. It was found that the SMA damper performance depends on the length, cross-sectional area and location of the damper on the stay cable. The comparative study also indicated that the SMA performance was better than an optimal TMD in controlling the harmonic and the high free vibrations of the stay cable. Furthermore, the fatigue life of the SMA damper for a stay cable was found to be 4 million cycles at the strain near 1% [154].

Takano et al. [155] proposed an alternative vibrational countermeasure for the stay cable of the Tsurumi Tsubasa Bridge. As shown in Fig. 25, a combination of an HDR damper and an oil damper (viscous damper) was installed on the stay cables. The vibration test results confirmed the effectiveness of the proposed control system. Furthermore, no wind-induced vibrations have been observed for the stay cables since the installation of the proposed countermeasure. Zhou et al. [156] studied the combined effect of a viscous damper with a spring in reducing the vibration of the cables as an alternative to the cable-cross-tie-damper system. The results indicated that the combination of the damper and spring was effective if both were utilized near the cable anchorage. When the damper and spring were placed at each end of the cable, the effect of the spring on the cable damping was insignificant. For the case where the damper was installed near to cable anchorage and the spring was far from the cable anchorage, the spring considerably changed the maximum damping ratio corresponded to the optimum damper constant. For this case, a specific location of the cable was found for the spring that could effectively add more damping and stiffness to the specific mode of the cable. The fundamental cable frequency increased when the damper and spring were installed in parallel due to the spring stiffness. Another significant effect of adopting spring on the cable was reducing the free length of the cable and alternatively changing the regime of the damper location. Nonetheless, more profound studies should be conducted to conclude the practical application of the damper-spring system in suppressing the cable vibrations. Zhou et al. [157] also investigated the effect of the cross-tie on the damping of a cable-damper system. Two identical parallel cables with attached dampers nearby the cables' anchorage and a cross-tie were considered for the numerical study. It was concluded that when the cross-tie is used with the cable-damper system, its effect should be considered as the cross-tie changes the frequency of the system. Moreover, the cross-tie could substantially increase the damping of the lower vibrational modes of two cables with attached dampers near the anchorage [157, 158]. Ahamd et al. [158, 159] showed that the cross-tie should be placed far away from

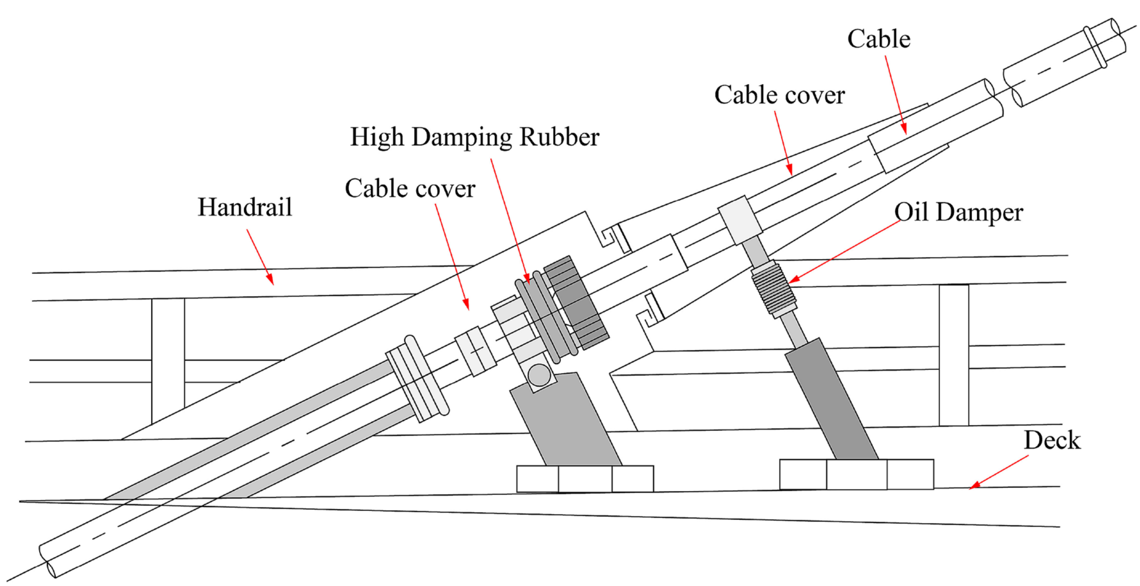


Fig. 25 Schematic detailing of a combined (internal and external dampers) stay cable control system for the Tsurumi Tsubasa Bridge [155]

the dampers in order for the dampers to be more effective in the cable-cross-tie-damper system. Furthermore, it was suggested to increase the cross-tie flexibility to maximize the attainable damping ratio of the cable-cross-tie-damper system. However, this might decrease the in-plane frequency of the system that may cause more localized vibrations within the system. Zhou et al. [160] introduced a concentrated mass to the cable-damper system to improve the efficiency of the viscous damper. The results of the numerical study promoted that combing a mass with the viscous damper-cable system caused the cable to behave as if it was attached to a semi-active damper with negative stiffness properties. The maximum achievable modal damping of the cable-damper-mass system was obtained when the damper and mass were closed to the cable anchorage and the coefficient of the nondimensional mass was lesser than the critical value. It was also noted that the mass location should be designed properly, as the inappropriate installation of the mass may reduce the damping of the damper for some particular vibrational modes of the cable. Zhou et al. [161] examined the effect of connecting two cables by a linear viscous damper as an alternative to the cross-tie. The effect of several parameters for two stay cables having harp arrangement and interconnected with a viscous damper was addressed. The analytical study demonstrated that the interconnected viscous damper considerably increased the multi-mode modal damping of the two neighboring cables and slightly increased their vibrational frequencies. Liu et al. [162] studied the consequence of the integration of the viscoelastic dampers within the cross-ties on reducing the vortex-induced vibration of the stay cables. For this purpose, a wind tunnel test was performed on three stay cables that were interconnected with cross-ties, while viscoelastic dampers were installed within the connection of the cross-ties. The test results proved that the viscoelastic dampers within the cross-ties were able to enhance the stiffness and damping of the cables that eventually reduced the vortex-induced vibration of the stay cables.

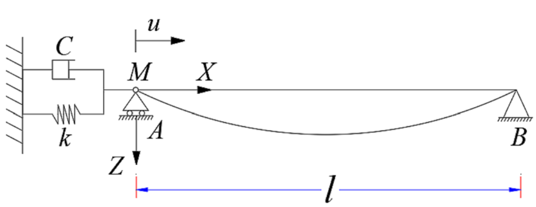


Fig. 26 The spring-damper restraint system for controlling the cable vibration [163]

Jiang et al. [163] proposed a new spring-damper restraining system to be placed at the end of the stay cable. As shown in Fig. 26, the restraining system consisted of a viscous damper and an elastic spring horizontally attached to the end of the movable support of the cable. In other words, the proposed restraining system made one side of the cable movable. Although the results of the numerical and experimental studies showed that the proposed system had an overall 2% damping ratio in the transverse direction and was effective in reducing the in-plane vibrations of the cables, but the performance of the system depends on the cable axial movement at the flexible support. Moreover, the proposed system needs a more thorough investigation to be a practical solution for the mitigation of the cable vibrations, as of some other concerns i.e., out-of-plane vibrations, fatigue, etc., may compromise the performance of the proposed system as well as the safety of the stay cable.

Cai et al. [164, 165] proposed the tuned mass damper-magneto-rheological (TMD-MR) damper to mitigate the stay cable vibrations. As shown in Fig. 27a, the TMD-MR damper consisted of a TMD and an MR damper. The TMD-MR damper can be implemented at any location of the stay cable, which advantageous over other external dampers that have to be installed near the lower end of the cable. Several parameters such as cable inclination, cable geometry-elasticity parameter, damper position, mass ratio, frequency ratio, damper damping ratio, and tuning mode were considered

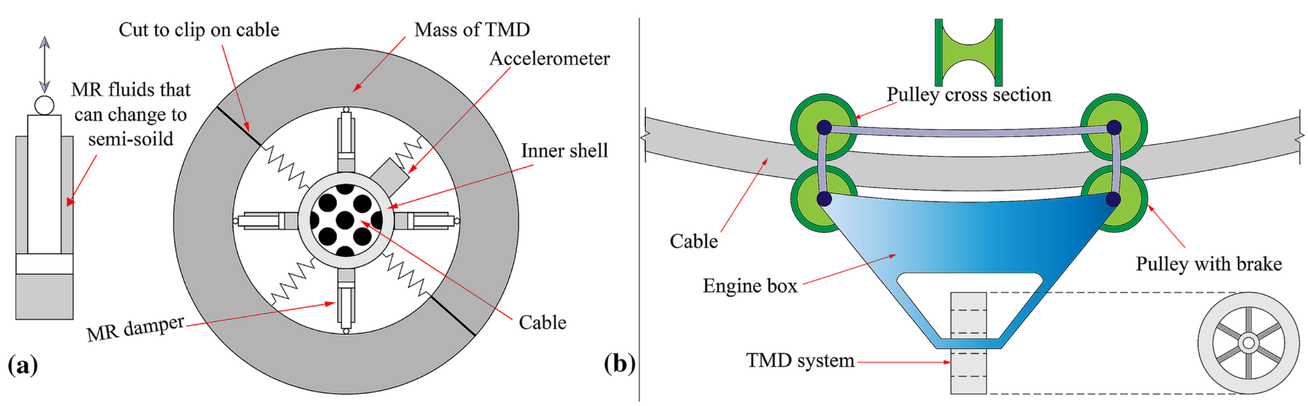


Fig. 27 Detailing of **a** TMD-MR damper [164, 166], and **b** movable TMD-MR damper [167]

for the parametric study. The results of the theoretical study showed that the TMD-MR damper is a promising solution to increase the modal damping of the stay cable. However, the cable-damper system mostly was tuned for a single mode, and multiple TMDs were not recommended as the dominating mode may be unclear for the damper design. In addition, the experimental results showed 20–30% cable vibrations reduction after the implementation of the TMD-MR damper [166]. Besides, when the cable vibrational frequency was not reaching the cable modal frequency, the MR component of the damper was providing additional damping to the stay cable. Finally, it was suggested to set the TMD-MR damper in a passive mode for small vibrations. Salari et al. [167] developed a movable damping system based on the TMD-MR damper. The proposed damper was made of the TMD-MR damper attached to a moving component as illustrated in Fig. 27b. The moving component had an electric engine connected to the pulleys that can move along the cable. A three-dimensional model of a cable with the movable semi-active TMD-MR damper was created and several control strategies, namely, passive-on, continuous sky-hook, on–off sky-hook, and Fuzzy control algorithms were adopted for the control of the cable vibrations. Furthermore, an innovative locating algorithm was used to find the optimal location of the TMD-MR damper along the cable. It was found that the proposed damper had an insignificant influence on the cable tension. Overall, the proposed damper with different semi-active control algorithms reduced the vibrational displacement of the cable, however, the Fuzzy control strategy outperformed the other employed strategies. To overcome the limitations of the viscous damper and TMD in reducing the cable vibrations, Cu and Han [168] proposed a hybrid control system. The proposed hybrid system was a combination of these two dampers. A comparative numerical study was performed between four cable-damper configurations, i) cable with a single viscous damper, ii) cable with two viscous dampers, iii) cable with a TMD, and iv) cable with a TMD and a viscous damper. It was found that the TMD was more effective in reducing the vibration of a single target mode of cable than the viscous damper. Nevertheless, the viscous damper was more effective than the TMD in providing the damping for more target modes of the cable. The combination of the viscous damper and TMD found to be more effective and efficient in reducing the vibrations of the cable as compared with the sole implementation of these dampers. Cu et al. [169] also proposed another hybrid damper called, tuned mass-high damping rubber (TM-HDR) damper for the application of stay cables. As the name indicates, the TM-HDR damper was made of a tuned mass attached to an HDR damper. In other words, the viscous damper and linear spring of TMD were replaced by the HDR damper. When the damper was installed at the center of the cable, it was ineffective for the even modes, even if the damper was tuned for these modes. This was due to the zero displacement characteristics of this location for even modes. It was found that the TM-HDR damper was only effective for a single tuned mode of the cable and its effect for other modes was insignificant.

The adjustable fluid damper with SMA actuators for increasing the damping ratio of the stay cable was proposed by Xu and Zhou [170]. Instead of having a fixed number of orifices in the piston head of the fluid damper, the SMA actuators were installed in the adjustable fluid damper as shown in Fig. 28. By utilizing this configuration, the numbers of orifices were adjusted to control the damper parameters in order to have an optimal design. The advantages of the proposed SMA actuators were i) they act as small mechanical valves to open and close an orifice inside the damper piston, and ii) within a working temperature range the mechanical valves lock at the designed position. The numerical results indicated that the proposed damper provided adequate modal damping for the

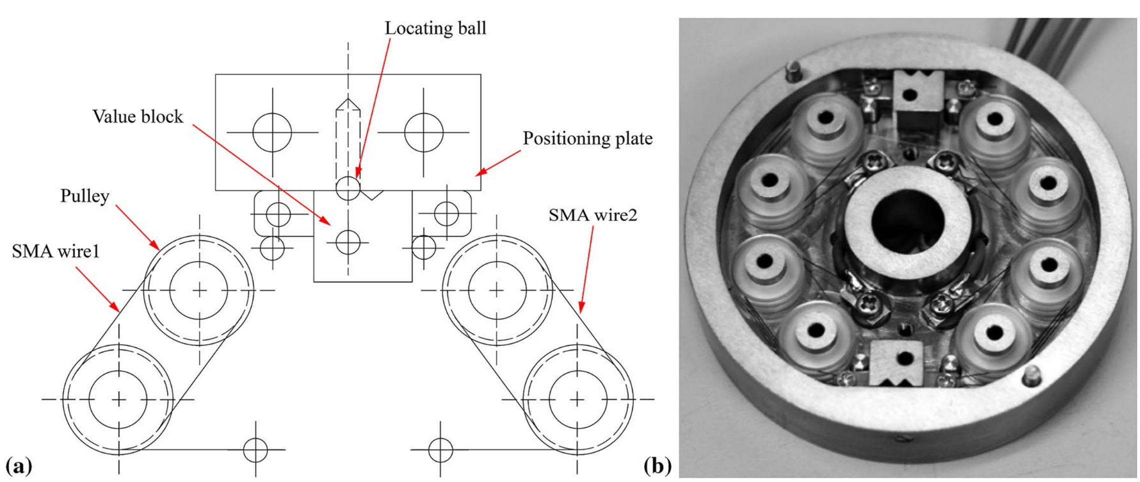


Fig. 28 Piston head of the adjustable fluid damper with SMA actuator, **a** detailing, and **b** prototype [170]

first two modes of the stay cables. Moreover, the results of the case study for the proposed damper in a long-span cable-stayed bridge concluded that the damper location could be very closed to the cable anchorage.

Weber et al. [171] studied the optimal tuning of the Coulomb friction damper (as a semi-active damper) to achieve the maximum damping for the first vibrational mode of the cable. It was shown that the friction damper should be tuned proportionally to cable amplitude at the damper location, which is determined by amplitude feedback in real-time. In addition, it was concluded that this damper should be tuned differently from the linear viscous damper. Izzie et al. [172] investigated the application of the targeted-energy-transfer (TET) device for mitigating the vibrational response of the stay cables. The TET device was a passive control system having linear damping and a cubic elastic restoring effect. The universal design curves for the TET device were proposed and numerically evaluated. It was found the amplitude-dependent damping curve of the TET device was pretty wide and the device could provide high damping to a wide range of the cable frequencies. Besides, though the TET device was placed at a close distance to the anchorage, but it had a satisfactory performance even for a very long stay cable. A piecewise linear absorber for control of the vertical vibrations of the stay cables was proposed by Weiss et al. [173]. The piecewise linear absorber had a nonsmooth restoring forcing function and a mass relatively smaller than the modal mass of the stay cable. When the absorber was tuned for certain initial conditions and oscillation range, the piecewise linear absorber behaved highly nonlinear through the nonlinear interactions and bifurcations of the energies of the absorber with the cable. These nonlinear interactions and bifurcations effectively control the vertical vibrations of the cable under the gravity effects. Chen et al. [174] invented the viscous-shear damper (VSD) for the multi-mode vibrational control of the stay cable. The VSD was made of movable shearing plates that were partially submerged in a viscous medium inside of a casing. The behavior of the VSD was studied experimentally in the laboratory and its analytical formulas were derived. Thereafter, the VSDs were installed on the cables of the Sutong Bridge to evaluate its performance in reducing the cables' vibrations. The results of the study indicated that as the deformation frequency of the damper decreased, the damping coefficient also decreased. Moreover, the VSD effectively provided modal damping for most of the in-plane vibrational modes (within 3 Hz frequency) of the cable, which was significantly higher than an optimal viscous damper.

4 Summary and Practical Examples of the Stay Cable Dampers

Table 1 summarizes the stay cable dampers discussed in Sect. 3. As the table demonstrated much less research has been conducted on internal dampers due to their limitations. On the other hand, the majority of discussed stay cable dampers were external dampers as they can achieve higher efficiency in controlling the cables' vibrations. The viscous damper and MR damper are among the most popular external dampers. The MR damper can work in the passive or semi-active mode, which is one of its main advantages over other stay cable dampers. Since the last decade, a considerable amount of studies on the application of NSDs for the stay cables have been carried out, however, so far no practical implementation of NSDs in the cable-stayed bridges is reported. Lastly, other types of external dampers were found to be promising in reducing the cable's vibrations, nevertheless, their application was limited to the research only.

Table 2 represents a survey of cable-stayed bridges equipped with stay cable dampers around the world. It can also be seen from this table that internal dampers are typically passive devices. The majority of the bridges had been equipped with hydraulic (viscous) dampers as external dampers in the 1980s and 1990s. However, in recent decades with the advancement of technology, the MR damper becomes more popular owing to its better performance in controlling multi-mode vibrations of the cables. Nevertheless, for the short stay cables, the internal dampers are the most common practical option while for the longer stay cables; the external dampers are mostly used due to their higher efficiency. Lastly, the combination of internal and external dampers is rarely used as this configuration has no advantage over using the external damper.

5 Concluding Remarks

This paper reviewed the state-of-the-art and the-state-of-practice of the vibrational control systems used for the stay cables of cable-stayed bridges. The cables of the cable-stayed bridges are continuously subjecting to various types of dynamic loads since the installation of them on the bridge. Excessive cable vibrations not only cause damage to the cable system but also compromise the overall safety of the cable-stayed bridges. The wind is one of the most crucial parameters in the design of cable-stayed bridges and its effect should be studied in order to find effective countermeasures to control unfavorable vibrations. Despite all the advancement of the computational

Table 1 Stay cable dampers summary

No	Device	Abbreviation	Type
1	High-damping rubber [68, 88, 111, 112]	HDR	Internal damper/external damper
2	Laminated rubber bearing [72]	LRB	Internal damper
3	Friction pendulum bearing [73]	FPB	Internal damper
4	Smart damper [74, 75]	–	Internal damper
5	Multiple-mass-particle impact damper [76]	–	Internal damper
6	Viscous damper [11, 65, 67, 80–106, 156–163, 170]	–	Internal damper/external damper
7	Tuned mass damper [107, 108]	TMD	External damper
8	Tuned inerter damper [109]	TID	External damper
9	Stockbridge-type damper [110]	–	External damper
10	Magneto-rheological Damper [77, 113–119, 121–129]	MR	External damper
11	MR shear mode damper [120]	–	External damper
12	Electromagnetic damper cum energy harvester [130, 131]	EMDEH	External damper
13	Viscous inertial mass damper [132]	VIMD	External damper
14	Inertial mass damper [133]	IMD	External damper
15	Negative Stiffness Damper [125, 134–143, 145]	NSD	External damper
16	Viscous inerter damper [144]	VID	External damper
17	Electromagnetic inertial mass damper [146]	EIMD	External damper
18	Electromagnetic shunt damper and inerter damper [147]	EMSD-ID	External damper
19	Shape memory alloy [148–154]	SMA	External damper
20	HDR and viscous damper [155]	–	Combination of internal and external dampers
21	Tuned mass damper-magneto-rheological [164–166]	TMD-MR	External damper
22	Movable TMD-MR damper [167]	–	External damper
23	Viscous damper with TMD [168]	–	External damper
24	Tuned mass-high damping rubber [169]	TM-HDR	External damper
25	Coulomb friction damper [171]	–	External damper
26	Targeted-energy-transfer device [172]	TET	External damper
27	Piecewise linear absorber [173]	–	External damper
28	Viscous-shear damper [174]	VSD	External damper

methods such as nonlinear time-history analysis and computational fluid dynamics (CFD) analysis for studying the wind effects on the cable-stayed bridges, wind-tunnel test with all its setbacks and limitations found to be a more reliable tool for analyzing the aeroelastic instability, especially for long-span bridges [190]. To avoid instabilities, dampers had been used for reducing vibrations of the stay cables since the 1980s. The stay cable dampers are classified as internal and external dampers. Noteworthy that the best location of a damping system for a stay cable is within the cable center [191]; however, it is almost impractical to implement most of the dampers at this location. Therefore, the location of stay cable dampers is typically restricted to the anchorage ends of the cables due to practical and aesthetic reasons. Based on the comprehensive review, the following remarks can be made:

I. *In regards to damper classification* although internal dampers such as elastomeric dampers are among the very first dampers used for the stay cables, yet they are still being adopted in the new bridges especially for short cables owing to their esthetical smooth outer shape. Meanwhile, due to higher efficiency, external dampers like hydraulic damper and MR damper are widely used for relatively long cables.

II. *In regards to the type of popular devices for stay cables*

- The optimal damping ratio of the passive cable dampers (except NSDs) can achieve mostly for one mode of the stay cables, while for the semi-active dampers the optimal damping ratio can be achieved for several modes of the cable through the control algorithm. In light of active and semi-active dampers for the stay cables, accelerometers are the necessary sensors to deliver real-time vibrational data to the control unit and adjust the required damping force of the dampers to suppress the vibrations.

Table 2 Summary of cable-stayed bridges with stay cable dampers

No	Name—Construction year	Overall length (main span) (m)	Country	Control device	Description
1	Brotonne Bridge-1977 [65]	1278.40 (697.5)	France	Hydraulic damper	External damper
2	Rande Bridge-1981 (2015*) [175]	704.58 (400.14)	Spain	Hydraulic damper	External damper
3	Luling Bridge-1983 [176]	678.2 (372.5)	USA	HDR dampers	Internal dampers (at both ends of the cables) installed in 2012
4	Aratsu Bridge-1988 [177]	345 (185)	Japan	Hydraulic dumpers	External damper
5	Alamillo Bridge-1992 [126]	200	Spain	MR damper	External damper
6	Tsurumi Tsubasa Bridge-1994 [155]	1021 (510)	Japan	HDR damper + Hydraulic damper	Combination of Internal and External dampers
7	Puente Real Bridge-1994 [5, 6]	265 (136)	Spain	Friction dampers	Internal damper
8	Fred Hartman Bridge-1995 [11]	754 (381)	USA	Hydraulic damper	External damper
9	Erasmus Bridge-1996 [80]	802 (285)	Netherlands	Hydraulic damper	External damper
10	Kap Shui Mun Bridge-1997 [9]	750 (430)	China	Friction damper	Internal damper
11	Meiko Grand Bridges-1998 [178]	1170 (590)	Japan	HDR damper and Viscous shear-type damper	Internal and External dampers at different cables
12	Vasco Da Gama Bridge-1998 [70]	829 (420)	Portugal	Elastomeric dampers	Internal damper
13	Uddevalla Bridge-2000 [179, 180]	772 (414)	Sweden	Friction damper	Internal damper
14	Dongting Lake Bridge-2000 [117]	880(620)	China	MR dampers	External damper
15	Second Nanjing Bridge-2001 [148]	1238 (628)	China	Elastomeric dampers	Internal damper
16	Dubrovnik Bridge-2002 [8]	518 (304.5)	Croatia	MR dampers	External damper
17	Eilandbrug Kampen Bridge-2003 [78, 128]	412 (150)	Netherlands	MR damper	External damper
18	Leonard P. Zakim Bunker Hill MemorialBridge-2003 [181]	436 (227)	USA	Elastomeric Damper	Internal damper
19	Shangdong Binzhou Yellow RiverHighway Bridge-2004 [124]	768 (600)	China	MR damper	External damper
20	Millau Viaduct Bridge–2004 [70]	2460	France	Elastomeric dampers	Internal damper
21	Veterans Glass City Skyway Bridge–2007 [182]	374	USA	MR damper	External damper
22	Kanchanapisek Bridge-2007 [183]	941 (500)	Thailand	Radial damper	Internal damper
23	Plock Bridge–2007 [70]	615 (375)	Poland	Elastomeric dampers	Internal damper
24	Serebryany Bor Bridge–2007 [70]	1460 (409.5)	Russia	Elastomeric dampers	Internal damper
25	Sutong Bridge–2008 [128, 184, 185]	2088 (1088)	China	Hydraulic damper and MR damper	External damper
26	Megyeri Bridge-2008 [70]	1862 (300)	Hungary	Elastomeric dampers	Internal damper
27	Niederrheinbrücke Bridge–2009 [186]	773 (376)	Germany	Elastomeric dampers	Internal damper
28	Ponte Del Mare-2009 [187]	147.6	Italy	Elastomeric dampers	Internal damper
29	Wuhan Tianxingzhou Changjiang RiverBridge–2009 [188]	1092 (504)	China	Lever mass damper	External damper
30	Christopher S. Bond Bridge-2010 [71]	523	USA	Elastomeric dampers	Internal damper
31	E'dong Yangtze River Bridge-2010 [188]	1486 (936)	China	Viscous-shear damper	External damper
32	Jingyue Changjiang River HighwayBridge–2010 [188]	1444 (816)	China	Lever mass damper	External damper
33	Hovenring Bridge-2011 [110]	72**	Netherlands	TMD	External damper
34	Rao II Bridge–2011 [70]	230 (120)	Vietnam	Elastomeric dampers	Internal damper
35	John James Audubon Bridge-2011 [71]	860 (482)	USA	Friction dampers	Internal damper
36	Awa Shirasagi Ohashi Bridge-2012 [79]	505 (260)	Japan	HDR dampers	External damper

Table 2 (continued)

No	Name—Construction year	Overall length (main span) (m)	Country	Control device	Description
37	Russky Bridge-2012 [128]	1885.53 (1104)	Russia	(i) Hydraulic dampers (ii) MR damper	External dampers (i) for short and (ii) long cables, respectively
38	Xiangshangang Bridge–2012 [188]	1376 (688)	China	Lever mass damper	External damper
39	Second Jiujiang Bridge-2013 [188]	1405 (818)	China	Lever mass damper	External damper
40	Yalu River Bridge–2014 [188]	3026 (636)	China	Lever mass damper	External damper
41	Bouregreg Bridge-2016 [189]	742 (376)	Morocco	(i) Hydraulic dampers and (ii) Radial dampers	Internal damper for (i) short cables and (ii) long cables, respectively

*The bridge was expanded in 2015

** Deck outer diameter of the roundabout flyover

- The viscous damper is one of the most commonly used dampers for the stay cables. The viscous damper can have a linear or a nonlinear property. However, the nonlinear damper has superior performance in dissipating more energy and providing modal damping for multiple modes of the cables. Moreover, the nonlinear damper is more efficient when the damper needs to be installed at a closer distance to the cable anchorage.
- The MR-damper is found to be a very promising solution for vibrational control of the stay cables. The MR damper can provide substantial modal damping to a single-mode or multi-mode of cable. The MR damper is especially effective for long stay cables subjecting to a wide range of vibrational frequencies. Several semi-active control algorithms have been proposed for control of the semi-active MR damper and so far no comparative study has been performed between them, yet their efficiency has been proven in reducing the cable vibrations. Noteworthy, the temperature variation may affect the performance of the MR damper. Therefore, the control algorithm for the semi-active MR damper should account for the operating temperature of the damper, especially for harsh environmental conditions.
- In recent years, the NSD has received great attention in suppressing the cable vibrations. The NSD can supply modal damping to a single-mode or multi-mode of the cable. As a matter of the fact, the NSD as a passive control system can provide comparable modal damping to the cable as the active control system. However, the NSD may cause instability in the cable system; therefore, an accurate calculation of the negative stiffness is the essential key to overcome this drawback.
- The SMA damper can efficiently mitigate the vibrations of the cables over broadband excitations. The SMA damper can work effectively in a very harsh environment (at a temperature between −25 to + 50º C) while its life span is relatively longer than other dampers. However, the SMA dampers are comparatively costlier than other practical dampers.

III. *In regards to damper design for the stay cable:* a number of parameters of the cable including the length, mass per unit length, inclination angle, tension force, sag-extensibility parameter, flexural rigidity, inherent damping, fundamental frequency, and mode number should be considered during the selection and design of the damper. Meanwhile, parameters of the damper i.e., the type, size, stiffness, location, direction, boundary conditions, and other relevant parameters should be used for the design of the damper. In addition, other conditions such as environmental conditions (temperature), support stiffness, and the presence of the cross-ties also should be taken into account for the design of dampers. The connection configuration of the damper with cable is also an important aspect of the external damper. When the damper is designed to suppress the in-plane vibrations of the cable, the support configuration of the damper should allow the out-of-plane rotations to avoid any damage or failure in the damper.

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Data availability All data, models, and code generated or used during the study appear in the submitted article.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

References

1. Shipyards A, Orleans N (1980) Dynamic behaviour of a cable-stayed bridge. Earthq Eng Struct Dyn 8:1–16
2. Abdel-Ghaffar AM, Khalifa MA (1991) Importance of cable vibration in dynamics of cable-stayed bridges. J Eng Mechan 117:2571–2589
3. H. Tabatabai, A. Mehrabi, Evaluations (2000), In: SPIE Proc. Ser., San Antonio, Texas, pp. 836–841
4. Ali HM, Abdel-ghaffar AM (1994) Seismic energy dissipation for cable-stayed bridges using passive devices. Earthq Eng Struct Dyn 23:877–893
5. B. fur Baudynamik (1996), Cable Vibrations, Report no. 1
6. B. fur Baudynamik (1996) Cable Vibrations, Report no. 2
7. Virlogeux M (2005) State-of-the-art in cable vibrations of cable-stayed bridges. Bridg Struct 1:133–168. https://doi.org/10.1080/15732480500301004
8. Savor Z, Radic J, Hrelja G (2006) Cable vibrations at Dubrovnik bridge. Bridg Struct 2:97–106. https://doi.org/10.1080/15732480600855800
9. R. Annan (2006) Friction damper test: report of test achieved with Hong Kong highways authorities on Kap Shui Mun Bridge
10. E. de S. Caetano (2007) Control of Vibrations in Cable-Stayed Bridges
11. Witthoft S, Kesner K, Poston RW (2008) Performance and repair design of stay cables with rain/wind-induced vibrations. J Perform Constr Facil 22:364–372. https://doi.org/10.1061/(asce)0887-3828(2008)22:6(364)
12. Caetano E, Cunha A, Gattulli V, Lepidi M (2008) Cable–deck dynamic interactions at the International Guadiana bridge: on-site measurements and finite element modelling. Struct Control Heal Monit 15:237–264. https://doi.org/10.1002/stc
13. Saaed TE, Nikolakopoulos G, Jonasson J-E, Hedlund H (2013) A state-of-the-art review of structural control systems. J Vib Control 21:919–937. https://doi.org/10.1177/1077546313478294
14. Robinson WH, Tucker AG (1977) A lead-rubber shear damper. Bull New Zeal Natl Soc EarthquakeEngineering 10:151–153
15. A. Javanmardi, Z. Ibrahim, K. Ghaedi, H. Khatibi (2017) Numerical analysis of vertical pipe damper, in: 39th IABSE Symp. Eng. Futur., International Association for Bridge and Structural Engineering, Vancouver, Canada. Vol. 109. No. 13, pp. 2974–2980
16. H Li, L Huo (2010), Advances in structural control in civil engineering in China. Math Probl Eng. https://doi.org/10.1155/2010/936081
17. Fisco NR, Adeli H (2011) Smart structures: part I-Active and semi-active control. Sci Iran 18:275–284. https://doi.org/10.1016/j.scient.2011.05.034
18. Fisco NR, Adeli H (2011) Smart structures: part II-Hybrid control systems and control strategies. Sci Iran 18:285–295. https://doi.org/10.1016/j.scient.2011.05.035
19. Korkmaz S (2011) A review of active structural control: challenges for engineering informatics. Comput Struct 89:2113–2132. https://doi.org/10.1016/j.compstruc.2011.07.010
20. K Ghaedi, Z Ibrahim, H Adeli, A Javanmardi (2017) , Invited review recent developments in vibration control of building and bridge structures, J Vibroengineering, Vol. 19, Issue 5, 2017, p. 3564–3580. https://doi.org/10.21595/jve.2017.18900
21. L Design, B Shrestha, H Hao, K Bi (2016), Devices for protecting bridge superstructure from pounding and unseating damages: an overview, Struct Infrastruct Eng. https://doi.org/10.1080/15732479.2016.117015
22. K Ghaedi, Z Ibrahim, M Jameel, A Javanmardi, H Khatibi (2018) Seismic Response Analysis of Fully Base Isolated Adjacent Buildings with Segregated Foundations, Adv Civ Eng. Vol. 2018, Article ID 4517940, 21 pages. https://www.hindawi.com/journals/ace/aip/4517940/
23. Ghaedi K, Ibrahim Z, Javanmardi A, Rupakhety R (2018) Experimental study of a new bar damper device for vibration control of structures subjected to earthquake loads. J Earthq Eng 00:1–19. https://doi.org/10.1080/13632469.2018.1515796
24. Ghaedi K, Ibrahim Z, Javanmardi A (2018) A new metallic bar damper device for seismic energy dissipation of civil structures. IOP Conf Ser Mater Sci Eng 431:122009. https://doi.org/10.1088/1757-899X/431/12/122009
25. Javanmardi A, Ghaedi K, Ibrahim Z, Huang F, Xu P (2020) Development of a new hexagonal honeycomb steel damper. Arch Civ Mech Eng 9:1–19. https://doi.org/10.1007/s43452-020-00063-9
26. GW Housner, LA Bergman, TK Caughey, AG Chassiakos, RO Claus, SF Masri, RE Skelton, TT Soong, S Member, BF Spencer, JTP Yao (1997) Structural control: past present and future, J Eng Mech. 897–971
27. Soong TT, Spencer BF (2002) Supplemental energy dissipation: state-of-the-art and state-of-the- practice. Eng Struct 24:243–259. https://doi.org/10.1016/S0141-0296(01)00092-X
28. MD Symans, FA Charney, AS Whittaker, MC Constantinou, CA Kircher, MW Johnson, RJ McNamara (2008) Energy dissipation systems for seismic applications: current practice and recent developments, J Struct Eng. 134, 3–21
29. M Gutierrez Soto, H Adeli (2013), Tuned mass dampers. Arch Comput Methods Eng. 20, 419–431. Doi: https://doi.org/10.1007/s11831-013-9091-7
30. A Javanmardi, Z Ibrahim, K Ghaedi, H Benisi Ghadim, MU Hanif (2019), State-of-the-art review of metallic dampers: testing, development and implementation, Arch Comput Methods Eng 27:2, 455–478. https://doi.org/10.1007/s11831-019-09329-9
31. Ali HM, Abdel-ghaffar AM (1995) Seismic passive control of cable-stayed bridges. Shock Vib 2:259–272. https://doi.org/10.1155/1995/918721
32. A. Javanmardi (2019), Seismic behavior investigation of a cable-stayed bridge with hybrid passive control system, University of Malaya
33. A. Javanmardi, K. Ghaedi, Z. Ibrahim, K.U. Muthu (2018), Seismic Pounding Mitigation of an Existing Cable-Stayed Bridge Using Metallic Dampers, in: IABSE Conf. – Eng. Dev. World, International Association for Bridge and Structural Engineering, Kuala Lumpur, Malaysia, pp. 617–623
34. Javanmardi A, Ibrahim Z, Ghaedi K, Khan NB, Ghadim HB (2018) Seismic isolation retrofitting solution for an existing steel cable-stayed bridge. PLoS ONE 13:1–22. https://doi.org/10.1371/journal.pone.0200482
35. Javanmardi A, Ibrahim Z, Ghaedi K, Jameel M, Khatibi H, Suhatril M (2017) Seismic response characteristics of a base isolated cable-stayed bridge under moderate and strong ground motions. Arch Civ Mech Eng 17:419–432. https://doi.org/10.1016/j.acme.2016.12.002

36. Han Q, Wen J, Du X, Zhong Z, Hao H (2018) Simplified seismic resistant design of base isolated single pylon cable-stayed bridge. Bull Earthq Eng 16:5041–5059. https://doi.org/10.1007/s10518-018-0382-0
37. Han Q, Wen J, Du X, Zhong Z, Hao H (2018) Nonlinear seismic response of a base isolated single pylon cable-stayed bridge. Eng Struct 175:806–821. https://doi.org/10.1016/j.engstruct.2018.08.077
38. Q. Han, J. Wen, X. Du (2018) Seismic Mitigation of Single Pylon Cable-Stayed Bridge, in: Eng. Dyn. Vib., CRC Press, pp. 302–335
39. Cheng S, Larose GL, Savage MG, Tanaka H, Irwin PA (2008) Experimental study on the wind-induced vibration of a dry inclined cable-Part I: phenomena. J Wind Eng Ind Aerodyn 96:2231–2253. https://doi.org/10.1016/j.jweia.2008.01.008
40. Cheng S, Irwin PA, Tanaka H (2008) Experimental study on the wind-induced vibration of a dry inclined cable—Part II : proposed mechanisms. J Wind Eng Ind Aerodyn 96:2254–2272. https://doi.org/10.1016/j.jweia.2008.01.007
41. Larsen A, Larose GL (2015) Dynamic wind effects on suspension and cable-stayed bridges. J Sound Vib 334:2–28. https://doi.org/10.1016/j.jsv.2014.06.009
42. Fujino Y, Siringoringo D (2013) Vibration mechanisms and controls of long-span bridges: A review. Struct Eng Int J Int Assoc Bridg Struct Eng 23:248–268. https://doi.org/10.2749/101686613X13439149156886
43. NM Telang, CM Minervino, PG Norton (2000), Retrofit of aerodynamic cable instability on a cable-stayed bridge: case study. Transp Res Rec. Doi: https://doi.org/10.3141/1740-08
44. Phelan RS, Sarkar PP, Mehta KC (2006) Full-scale measurements to investigate rain-wind induced cable-stay vibration and its mitigation. J Bridg Eng 11:293–304. https://doi.org/10.1061/(asce)1084-0702(2006)11:3(293)
45. Ni YQ, Wang XY, Chen ZQ, Ko JM (2007) Field observations of rain-wind-induced cable vibration in cable-stayed dongting lake bridge. J Wind Eng Ind Aerodyn 95:303–328. https://doi.org/10.1016/j.jweia.2006.07.001
46. S. Kumarasena, N.P. Jones, P. Irwin, P. Taylor (2007) Wind induced vibration of stay cables: FHWA-HRT-05–083
47. Taylor IJ, Robertson AC, Wilson SK, Duffy BR, Sullivan JM (2010) New developments in rain-wind-induced vibrations of cables. Proc Inst Civ Eng Struct Build 163:73–86. https://doi.org/10.1680/stbu.2010.163.2.73
48. H. Svensson (2013) Cable-stayed bridges: 40 years of experience worldwide, John Wiley & Sons
49. Jafari M, Hou F, Abdelkefi A (2020) Wind-induced vibration of structural cables. Nonlinear Dyn 100:351–421. https://doi.org/10.1007/s11071-020-05541-6
50. Y.. Ni, Y.F. Duan, Z.Q. Chen, J.M. Ko (2002), Damping identification of MR- damped bridge cables from in situ monitoring under wind-rain-excited conditions, in: L. SC (Ed.), Smart Struct. Mater. 2002 Smart Syst. Bridg. Struct. Highw., Bellingham, pp. 41–51
51. Li S, Chen Z, Wu T, Kareem A (2013) Rain-wind-induced in-plane and out-of-plane vibrations of stay cables. J Eng Mech 139:1688–1698. https://doi.org/10.1061/(asce)em.1943-7889.0000612
52. Liu M-Y, Zuo D, Jones NP (2013) Analytical and numerical study of deck-stay interaction in a cable-stayed bridge in the context of field observations. J Eng Mech 139:1636–1652. https://doi.org/10.1061/(asce)em.1943-7889.0000596
53. P. Irwin (1997) Wind vibrations of cables on cable-stayed bridges, in: Build. to Last Struct. Congr. Proc. 15th Struct. Congr., Reston, VA, pp. 383–387
54. PTI (Post-Tensioning Institute) (2008), Recommendations for Stay-Cable Design, Testing and Installation, Fifith
55. M. De Miranda (2016) Long-span bridges, Elsevier Inc., https://doi.org/10.1016/B978-0-12-800058-8.00015-3.
56. M. Matsumoto, N. Shiraishi, H. Shirato (1992) Rain-wind induced vibration of cables of cable- stayed bridges, J Wind Eng Ind. Aero@namics. 53, 1689–1699
57. Mctavish S, Auteuil AD, Raeesi A (2020) Journal of wind engineering & industrial aerodynamics effect of cable surface characteristics and fl ow turbulence on the aerodynamic behaviour of stay cables in dry conditions. J Wind Eng Ind Aerodyn 207:104414. https://doi.org/10.1016/j.jweia.2020.104414
58. Chang Y, Zhao L, Ge Y (2019) Experimental investigation on mechanism and mitigation of rain–wind-induced vibration of stay cables. J Fluids Struct 88:257–274. https://doi.org/10.1016/j.jfluidstructs.2019.05.012
59. D Zuo, L Caracoglia, NP Jones (2007) Assessment of cross-tie performance in mitigating wind and rain-wind-induced stay cable vibrations, in: 12th Int. Conf Wind Eng, Cairns, Australia. pp. 903–910
60. L. Caracoglia, N.P. Jones, In-plane dynamic behavior of cable networks . Part 1 : formulation and basic solutions, J. Sound Vib. 279, 969–991. https://doi.org/10.1016/j.jsv.2003.11.058.
61. L. Caracoglia, N.P. Jones (2005), In-plane dynamic behavior of cable networks . Part 2 : prototype prediction and validation, J. Sound Vib. 279, 993–1014. https://doi.org/10.1016/j.jsv.2003.11.059
62. Yamaguchi H, Jayawardena L (1992) Analytical estimation of structural damping in cable structures. J Wind Eng Ind Aerodyn 44:1961–1972
63. Yamaguchi H, Nagahawatta HD (1995) Damping effects of cable cross ties in cable-stayed bridges. J Wind Eng Ind Aerodyn 55:35–43
64. Caracoglia L, Zuo D (2009) Effectiveness of cable networks of various configurations in suppressing stay-cable vibration. Eng Struct 31:2851–2864. https://doi.org/10.1016/j.engstruct.2009.07.012
65. J. Wianecki (1983), Cables Wind Excited Vibrations of Cable-Stayed Bridge., Pergamon Press Ltd. https://doi.org/10.1016/b978-1-4832-8367-8.50127-3
66. Asctirafi H, Hirsch GH (1983) Control of wind-induced vibrations of cable-stayed bridges h. J Wind Eng Ind Aerodyn 14:235–246
67. Fournier JA, Cheng S (2014) Impact of damper stiffness and damper support stiffness on the efficiency of a linear viscous damper in controlling stay cable vibrations. J Bridg Eng 19:04013022. https://doi.org/10.1061/(asce)be.1943-5592.0000562
68. Nakamura A, Kasuga A, Arai H (1998) The effects of mechanical dampers on stay cables with high-damping rubber. Constr Build Mater 12:115–123. https://doi.org/10.1016/s0950-0618(97)00013-5
69. BBR VT International Ltd, BBR HiAm CONA Strand stay cable damping systems, (2017) 8. https://www.bbrnetwork.com/
70. S. Freyssinet, Freyssinet HD stay cables, (2016) 12. www.freyssinet.com
71. K. Crouch, D. Dock (2011) Selection factors for cable damping systems, Mod Steel Constr. 40–43
72. Hwang I, Lee JS, Spencer BF (2009) Isolation system for vibration control of stay cables. J Eng Mech 135:62–66. https://doi.org/10.1061/(asce)0733-9399(2009)135:1(62)
73. Hwang I, Lee JS, Lee H (2011) Movable anchorage system with FPB for vibration control of stay cables. KSCE J Civ Eng 15:841–847. https://doi.org/10.1007/s12205-011-0816-6
74. Wang X, Wu Z (2011) Modal damping evaluation of hybrid FRP cable with smart dampers for long-span cable-stayed bridges. Compos Struct 93:1231–1238. https://doi.org/10.1016/j.compstruct.2010.10.018

75. Yang Y, Wang X, Wu Z (2017) Damping behavior of hybrid fiber-reinforced polymer cable with self-damping for long-span bridges. J Bridg Eng 22:05017005. https://doi.org/10.1061/(asce)be.1943-5592.0001058
76. Egger P, Caracoglia L, Kollegger J (2016) Modeling and experimental validation of a multiple-mass-particle impact damper for controlling stay-cable oscillations. Struct Control Heal Monit 23:960–978. https://doi.org/10.1002/stc
77. Chen L, Sun L (2015) Laboratory-scale experimental setup for studying cable dampers. J Eng Mech 141:04014159. https://doi.org/10.1061/(asce)em.1943-7889.0000878
78. S. Maurer (2006), Maurer Cable damper systems, 13. https://www.maurer.eu
79. S Takeichi, Daisuke Saito BEng, K Terada (2018), Low-impact cable system adopted for the Awa Shirasagi Ohashi Bridge, Japan, Bridg Eng. 171, 106–117
80. C Geurts, T Vrouwenvelder, P van Staalduinen, J. Reusink (1998) Numerical modelling of rain-wind-induced vibration: erasmus bridge, Rotterdam, Struct Eng Int. 129–135
81. Pacheco B, Fujino Y, Sulekh A (1993) Estimation curve for modal damping in stay cables with viscous damper. J Struct Eng 119:1961–1979
82. Z Yu, YL Xu, Z Yu (1998) Mitigation of three-dimensional vibration of inclined sag cable using discrete oil dampers—i formulation, J Sound Vib. 214, 659–673
83. YL Xu, Z Yu (1998) Mitigation of three-dimensional vibration of inclined sag cable using discrete oil dampers—ii application, J Sound Vib. 214, 659–673
84. Xu YL, Yu Z, Ko JM (1998) Forced vibration studies of sagged cables with oil damper using a hybrid method. Eng Struct 20:692–705. https://doi.org/10.1016/S0141-0296(97)00100-4
85. Xu YL, Zhan S, Ko JM, Yu Z (2000) Experimental study of vibration mitigation of bridge stay cables. J Struct Eng 4:18–27
86. Tabatabai H, Mehrabi AB (2000) Design of mechanical viscous dampers for stay cables. J Bridg Eng 5:114–123. https://doi.org/10.1061/(ASCE)1084-0702(2000)5
87. Wang XY, Ni YQ, Ko JM, Chen ZQ (2005) Optimal design of viscous dampers for multi-mode vibration control of bridge cables. Eng Struct 27:792–800. https://doi.org/10.1016/j.engstruct.2004.12.013
88. Fujino Y, Hoang N (2008) Design formulas for damping of a stay cable with a damper. J Struct Eng 134:269–278. https://doi.org/10.1061/(asce)0733-9445(2008)134:2(269)
89. Weber F, Feltrin G, Maślanka M, Fobo W, Distl H (2009) Design of viscous dampers targeting multiple cable modes. Eng Struct 31:2797–2800. https://doi.org/10.1016/j.engstruct.2009.06.020
90. Cheng S, Darivandi N, Ghrib F (2010) The design of an optimal viscous damper for a bridge stay cable using energy-based approach. J Sound Vib 329:4689–4704. https://doi.org/10.1016/j.jsv.2010.05.027
91. Zhou Q, Nielsen SRK, Qu W (2010) Stochastic response of an inclined shallow cable with linear viscous dampers under stochastic excitation. J Eng Mech 136:1411–1421. https://doi.org/10.1061/(asce)em.1943-7889.0000188
92. Javanbakht M, Cheng S, Ghrib F (2019) Control-oriented model for the dynamic response of a damped cable. J Sound Vib 442:249–267. https://doi.org/10.1016/j.jsv.2018.10.036
93. Sun L, Xu Y, Chen L (2019) Damping effects of nonlinear dampers on a shallow cable. Eng Struct 196:109305. https://doi.org/10.1016/j.engstruct.2019.109305
94. Main JA, Jones NP (2001) Evaluation of viscous dampers for stay-cable vibration mitigation. J Bridg Eng 6:385–397. https://doi.org/10.1061/(ASCE)1084-0702(2001)6
95. Zhou HJ, Xu YL (2007) Wind–rain-induced vibration and control of stay cables in a cable-stayed bridge. Struct Control Heal Monit. https://doi.org/10.1002/stc
96. JA Main, NP Jones (2002) Free vibrations of taut cable with attached damper ii: nonlinear damper, J Eng Mech. 128, 1062–1071
97. Main JA, Jones NP (2002) Free vibrations of taut cable with attached damper. ii.: nonlinear damper. J Eng Mech. 128:1072–1081
98. Hoang N, Fujino Y (2009) Multi-mode control performance of nonlinear dampers in stay cable vibrations. Struct Control Heal Monit 16:860–868. https://doi.org/10.1002/stc
99. Chen L, Sun L (2017) Steady-state analysis of cable with nonlinear damper via harmonic balance method for maximizing damping. J Struct Eng 143:04016172. https://doi.org/10.1061/(asce)st.1943-541x.0001645
100. Danhui D, Yanyang C, Rong X (2014) Dynamic properties analysis of a stay cable-damper system in consideration of design and construction factors. Earthq Eng Eng Vib 13:317–326. https://doi.org/10.1007/s11803-014-0233-1
101. Zhou H, Sun L, Xing F (2014) Damping of full-scale stay cable with viscous damper: experiment and analysis. Adv Struct Eng 17:265–274. https://doi.org/10.1260/1369-4332.17.2.265
102. Caracoglia L, Jones NP (2007) Damping of taut-cable systems: two dampers on a single stay. J Eng Mech 133:1050–1060. https://doi.org/10.1061/(asce)0733-9399(2007)133:10(1050)
103. Hoang N, Fujino Y (2008) Combined damping effect of two dampers on a stay cable. J Bridg Eng 13:299–303. https://doi.org/10.1061/(asce)1084-0702(2008)13:3(299)
104. Le LX, Katsuchi H, Yamada H (2020) Effect of rotational restraint at damper location on damping of a taut cable with a viscous damper. J Bridg Eng 25:04019139. https://doi.org/10.1061/(asce)be.1943-5592.0001520
105. Nguyen CH, Macdonald JHG (2018) Galloping analysis of a stay cable with an attached viscous damper considering complex modes. J Eng Mech 144:04017175. https://doi.org/10.1061/(asce)em.1943-7889.0001403
106. Chen L, Sun L, Nagarajaiah S (2016) Cable vibration control with both lateral and rotational dampers attached at an intermediate location. J Sound Vib 377:38–57. https://doi.org/10.1016/j.jsv.2016.04.028
107. Jensen CN, Nielsen SRK, Sørensen JD (2002) Optimal damping of stays in cable-stayed bridges for in-plane vibrations. J Sound Vib 256:499–513. https://doi.org/10.1006/jsvi.2002.5002
108. Hijmissen JW, van den Heuvel NW, van Horssen WT (2009) On the effect of the bending stiffness on the damping properties of a tensioned cable with an attached tuned-mass-damper. Eng Struct 31:1276–1285. https://doi.org/10.1016/j.engstruct.2009.02.001
109. Sun L, Hong D, Chen L (2017) Cables interconnected with tuned inerter damper for vibration mitigation. Eng Struct 151:57–67. https://doi.org/10.1016/j.engstruct.2017.08.009
110. Argentini T, Rosa L, Zasso A (2016) Wind-induced vibrations of the stay cables of a roundabout flyover: assessment, repair, and countermeasures. J Perform Constr Facil 30:04016046. https://doi.org/10.1061/(asce)cf.1943-5509.0000897
111. Cu VH, Han B (2015) High-damping rubber damper for taut cable vibration reduction. Aust J Struct Eng 16:1–9. https://doi.org/10.1080/13287982.2015.1092690
112. Le LX, Katsuchi H, Yamada H (2020) Damping of cable with hdr damper accounting for restraint boundary conditions. J Bridg Eng 25:04020105. https://doi.org/10.1061/(asce)be.1943-5592.0001641
113. Ni YQ, Chen Y, Ko JM, Cao DQ (2002) Neuro-control of cable vibration using semi-active magneto-rheological dampers. Eng Struct 24:295–307. https://doi.org/10.1016/S0141-0296(01)00096-7
114. Johnson EA, Christenson RE, Spencer BF (2003) Semiactive damping of cables with sag. Comput Civ Infrastruct Eng 18:132–146. https://doi.org/10.1111/1467-8667.00305

115. Wu WJ, Cai CS (2006) Experimental study of magnetorheological dampers and application to cable vibration control. J Vib Control 12:67–82. https://doi.org/10.1177/1077546306061128
116. Weber F, Feltrin G, Motavalli M (2005) Passive damping of cables with MR dampers. Mater Struct Constr 38:568–577. https://doi.org/10.1617/14313
117. Ko JM, Ni YQ (2003) Structural health monitoring and intelligent vibration control of cable-supported bridges: research and application. KSCE J Civ Eng 7:701–716. https://doi.org/10.1007/bf02829139
118. Wang W, Hua X, Wang X, Wu J, Sun H, Song G (2019) Mechanical behavior of magnetorheological dampers after long-term operation in a cable vibration control system. Struct Control Heal Monit 26:1–19. https://doi.org/10.1002/stc.2280
119. Duan YF, Ni YQ, Ko JM (2005) State-derivative feedback control of cable vibration using semiactive magnetorheological dampers. Comput Civ Infrastruct Eng 20:431–449. https://doi.org/10.1111/j.1467-8667.2005.00396.x
120. RE Christenson, BFS Jr., EA Johnson, Experimental verification of smart cable damping, J Eng. Mech. 132 (2006) 268–278. https://doi.org/10.1061/(ASCE)0733-9399(2006)132
121. Zhou Q, Nielsen SRK, Qu WL (2006) Semi-active control of three-dimensional vibrations of an inclined sag cable with magnetorheological dampers. J Sound Vib 296:1–22. https://doi.org/10.1016/j.jsv.2005.10.028
122. Ying ZG, Ni YQ, Ko JM (2007) Parametrically excited instability analysis of a semi-actively controlled cable. Eng Struct 29:567–575. https://doi.org/10.1016/j.engstruct.2006.05.020
123. Johnson EA, Baker GA, Spencer BF, Fujino Y (2007) Semi-active damping of stay cables. J Eng Mech 133:1–11. https://doi.org/10.1061/(asce)0733-9399(2007)133:1(1)
124. Li H, Liu M, Li J, Guan X, Ou J (2007) Vibration control of stay cables of the shandong binzhou yellow river highway bridge using magnetorheological fluid dampers. J Bridg Eng 12:401–409. https://doi.org/10.1061/(asce)1084-0702(2007)12:4(401)
125. Li H, Liu M, Ou J (2008) Negative stiffness characteristics of active and semi-active control systems for stay cables. Struct Control Heal Monit. https://doi.org/10.1002/stc
126. JR Casas, AC Aparicio (2010), Rain-wind-induced cable vibrations in the Alamillo cable-stayed bridge (Sevilla, Spain). Assessment and remedial action, Struct Infrastruct Eng. 6, 549–556. https://doi.org/10.1080/15732470903068607
127. Zhou Q, Nielsen SRK, Qu WL (2008) Semi-active control of shallow cables with magnetorheological dampers under harmonic axial support motion. J Sound Vib 311:683–706. https://doi.org/10.1016/j.jsv.2007.09.022
128. Weber F, Distl H (2015) Amplitude and frequency independent cable damping of Sutong Bridge and Russky Bridge by magnetorheological dampers. Struct Control Heal Monit. https://doi.org/10.1002/stc
129. Zhao YL, Xu ZD, Wang C (2019) Wind vibration control of stay cables using magnetorheological dampers under optimal equivalent control algorithm. J Sound Vib 443:732–747. https://doi.org/10.1016/j.jsv.2018.12.016
130. Shen W, Zhu S (2015) Harvesting energy via electromagnetic damper: Application to bridge stay cables. J Intell Mater Syst Struct 26:3–19. https://doi.org/10.1177/1045389X13519003
131. Q lin Cai, S Zhu (2019), Enhancing the performance of electromagnetic damper cum energy harvester using microcontroller: concept and experiment validation, Mech Syst Signal Process. https://doi.org/10.1016/j.ymssp.2019.106339
132. Lu L, Duan YF, Spencer BF, Lu X, Zhou Y (2017) Inertial mass damper for mitigating cable vibration. Struct Control Heal Monit 24:1–12. https://doi.org/10.1002/stc.1986
133. Wang ZH, Gao H, Fan BQ, Chen ZQ (2020) Inertial mass damper for vibration control of cable with sag. J Low Freq Noise Vib Act Control 39:749–760. https://doi.org/10.1177/1461348418814967
134. X Shi, S Zhu, J Li, BFS Jr (2016) Dynamic behavior of stay cables with passive negative stiffness dampers, Smart Mater Struct. 25
135. Shi X, Zhu S, Spencer BF (2017) Experimental study on passive negative stiffness damper for cable vibration mitigation. J Eng Mech 143:04017070. https://doi.org/10.1061/(asce)em.1943-7889.0001289
136. Shi X, Zhu S (2015) Magnetic negative stiffness dampers. Smart Mater Struct FAST 24:072002. https://doi.org/10.1088/0964-1726/24/7/072002
137. Shi X, Zhu S, Nagarajaiah S (2017) Performance comparison between passive negative-stiffness dampers and active control in cable vibration mitigation. J Bridg Eng 22:04017054. https://doi.org/10.1061/(asce)be.1943-5592.0001088
138. Zhou P, Li H (2016) Modeling and control performance of a negative stiffness damper for suppressing stay cable vibrations. Struct Control Heal Monit 23:764–782. https://doi.org/10.1002/stc
139. Javanbakht M, Cheng S, Ghrib F (2018) Refined damper design formula for a cable equipped with a positive or negative stiffness damper. Struct Control Heal Monit 25:1–23. https://doi.org/10.1002/stc.2236
140. Javanbakht M, Cheng S, Ghrib F (2020) Multimode vibration control of stay cables using optimized negative stiffness damper. Struct Control Heal Monit 27:1–25. https://doi.org/10.1002/stc.2503
141. Javanbakht M, Cheng S, Ghrib F (2020) Impact of support stiffness on the performance of negative stiffness dampers for vibration control of stay cables. Struct Control Heal Monit 27:4–7. https://doi.org/10.1002/stc.2610
142. Dong Q, Cheng S, Asce M (2021) Impact of damper stiffness and damper support stiffness on the performance of a negative stiffness damper in mitigating cable vibrations. J Bridg Eng 26:1–12. https://doi.org/10.1061/(ASCE)BE.1943-5592.0001683
143. L Chen, S Nagarajaiah, L Sun (2020) A unified analysis of negative stiffness dampers and inerter-based absorbers for multimode cable vibration control, J Sound Vib. https://doi.org/10.1016/j.jsv.2020.115814
144. Gao H, Wang H, Li J, Wang Z, Liang R, Xu Z, Ni Y (2021) Optimum design of viscous inerter damper targeting multi-mode vibration mitigation of stay cables. Eng Struct 226:111375. https://doi.org/10.1016/j.engstruct.2020.111375
145. Shi X, Zhu S (2018) Dynamic characteristics of stay cables with inerter dampers. J Sound Vib 423:287–305. https://doi.org/10.1016/j.jsv.2018.02.042
146. Li Y, Shen W, Zhu H (2019) Vibration mitigation of stay cables using electromagnetic inertial mass dampers: full-scale experiment and analysis. Eng Struct 200:109–693. https://doi.org/10.1016/j.engstruct.2019.109693
147. Li J-Y, Zhu S, Shi X, Shen W (2020) Electromagnetic shunt damper for bridge cable vibration mitigation: full-scale experimental study. J Struct Eng 146:04019175. https://doi.org/10.1061/(asce)st.1943-541x.0002477
148. Li H, Liu M, Ou J (2004) Vibration mitigation of a stay cable with one shape memory alloy damper. Struct Control Heal Monit 11:21–36. https://doi.org/10.1002/stc.29
149. XB Zuo, AQ Li, Wei Sun, XH Sun (2009), Optimal design of shape memory alloy damper for cable vibration control, J Vib Control. 15, 897–921. https://doi.org/10.1177/1077546308094916.
150. Zuo X-B, Li A-Q (2011) Numerical and experimental investigation on cable vibration mitigation using shape memory alloy

damper. Struct Control Heal Monit 18:20–39. https://doi.org/10.1002/stc
151. V. Torra, C. Auguet, A. Isalgue, G. Carreras, P. Terriault, F.C. Lovey, Built in dampers for stayed cables in bridges via SMA. The SMARTeR-ESF project: a mesoscopic and macroscopic experimental analysis with numerical simulations, Eng. Struct. 49 (2013) 43–57. https://doi.org/10.1016/j.engstruct.2012.11.011.
152. Dieng L, Helbert G, Chirani SA, Lecompte T, Pilvin P (2013) Use of shape memory alloys damper device to mitigate vibration amplitudes of bridge cables. Eng Struct 56:1547–1556. https://doi.org/10.1016/j.engstruct.2013.07.018
153. O Ben Mekki, F Auricchio (2011), Performance evaluation of shape-memory-alloy superelastic behavior to control a stay cable in cable-stayed bridges, Int J Non Linear Mech. 46, 470–477. https://doi.org/10.1016/j.ijnonlinmec.2010.12.002
154. Torra V, Isalgue A, Auguet C, Carreras G, Lovey FC, Terriault P (2013) Damping in civil engineering using SMA Part 2–particular properties of NiTi for damping of stayed cables in bridges. Can Metall Q 52:81–89. https://doi.org/10.1179/1879139512Y.0000000036
155. H Takano, M Ogasawara, N Ito, T Shimosato, KT B, T Murakami (1997), Vibrational damper for cables of the Tsurumi Tsubasa Bridge, J Wind Eng Ind Aerodyn. 71, 807–818
156. Zhou H, Sun L, Xing F (2014) Free vibration of taut cable with a damper and a spring. Struct Control Heal Monit. https://doi.org/10.1002/stc
157. Zhou H, Yang X, Sun L, Xing F (2015) Free vibrations of a two-cable network with near-support dampers and a cross-link. Struct Control Heal Monit. https://doi.org/10.1002/stc
158. Ahmad J, Cheng S, Ghrib F (2018) Efficiency of an external damper in two-cable hybrid systems. J Bridg Eng 23:04017138. https://doi.org/10.1061/(asce)be.1943-5592.0001185
159. Ahmad J, Cheng S, Ghrib F (2018) Combined effect of external damper and cross-tie on the modal response of hybrid two-cable networks. J Sound Vib 417:132–148. https://doi.org/10.1016/j.jsv.2017.12.023
160. Zhou H, Huang X, Xiang N, He J, Sun L, Xing F (2018) Free vibration of a taut cable with a damper and a concentrated mass. Struct Control Heal Monit 25:1–21. https://doi.org/10.1002/stc.2251
161. Zhou H, Zhou X, Yao G, Sun L, Xing F (2019) Free vibration of two taut cables interconnected by a damper. Struct Control Heal Monit 26:1–17. https://doi.org/10.1002/stc.2423
162. Liu M, Yang W, Chen W, Xiao H, Li H (2019) Experimental investigation on vortex-induced vibration mitigation of stay cables in long-span bridges equipped with damped crossties. J Aerosp Eng 32:04019072. https://doi.org/10.1061/(asce)as.1943-5525.0001061
163. Jiang J, Li GQ, Lu Y (2013) Vibration control of cables with damped flexible end restraint: theoretical model and experimental verification. J Sound Vib 332:3626–3645. https://doi.org/10.1016/j.jsv.2013.02.001
164. CS Cai, WJ Wu, XM SHI (2006), Cable vibration reduction with a hung-on TMD system, Part I: theoretical study, J Vib Control. 12, 881–899. https://doi.org/10.1177/1077546306065858
165. CS Cai, WJ Wu, XM SHI (2006), Cable vibration reduction with a hung-on TMD system, part II: parametric study, J Vib Control. 12, 881–899. https://doi.org/10.1177/1077546306065858.
166. Cai CS, Wu WJ, Araujo M (2007) Cable vibration control with a TMD-MR damper system: experimental exploration. J Struct Eng 133:629–637. https://doi.org/10.1061/(asce)0733-9445(2007)133:5(629)
167. Salari S, Javadinasab Hormozabad S, Ghorbani-Tanha AK, Rahimian M (2019) Innovative mobile TMD system for semi-active vibration control of inclined sagged cables. KSCE J Civ Eng 23:641–653. https://doi.org/10.1007/s12205-018-0161-0
168. Cu VH, Han B (2015) A stay cable with viscous damper and tuned mass damper. Aust J Struct Eng 16:1–8. https://doi.org/10.1080/13287982.2015.1092693
169. Cu VH, Han B, Pham DH (2017) Tuned mass-high damping rubber damper on a taut cable. KSCE J Civ Eng 21:928–936. https://doi.org/10.1007/s12205-016-0857-y
170. Xu YL, Zhou HJ (2007) Damping cable vibration for a cable-stayed bridge using adjustable fluid dampers. J Sound Vib 306:349–360. https://doi.org/10.1016/j.jsv.2007.05.032
171. Weber F, Høgsberg J, Krenk S (2010) Optimal tuning of amplitude proportional coulomb friction damper for maximum cable damping. J Struct Eng 136:123–134. https://doi.org/10.1061/(asce)0733-9445(2010)136:2(123)
172. Izzi M, Caracoglia L, Noè S (2016) Investigating the use of targeted-energy-transfer devices for stay-cable vibration mitigation. Struct Control Heal Monit 23:315–332. https://doi.org/10.1002/stc
173. Weiss M, Vaurigaud B, Ture Savadkoohi A, Lamarque CH (2018) Control of vertical oscillations of a cable by a piecewise linear absorber. J Sound Vib 435:281–300. https://doi.org/10.1016/j.jsv.2018.07.033
174. Chen L, Di F, Xu Y, Sun L, Xu Y, Wang L (2020) Multimode cable vibration control using a viscous-shear damper: case studies on the Sutong Bridge. Struct Control Heal Monit 27:1–20. https://doi.org/10.1002/stc.2536
175. Bernardo H, Tarquis F, Lucas C, Viartola LM (2019) Rande bridge widening: a 400-m-span cable-stayed bridge expansion. Pract Period Struct Des Constr 24:05019004. https://doi.org/10.1061/(asce)sc.1943-5576.0000439
176. AB Mehrabi (2014) Performance of cable-stayed bridges: evaluation methods , observations , and a rehabilitation case, J Perform Constr Facil. https://doi.org/10.1061/(ASCE)CF.1943-5509.0000715
177. T. Yoshimura, A. Inoue, K. Kaji, M. Savage (1989) A study on the aerodynamic stability of the Aratsu Bridge, in: Proc. Canada-Japan Work. Bridg. Aerodyn.,: pp. 41–50
178. Ito M (1998) The cable-stayed meiko grand bridges, Nagoya. Struct Eng Int 8:168–171. https://doi.org/10.2749/101686698780489180
179. H. Nilsson, C. Hansvold (1999), Uddevalla Bridge, Sweden, Struct Eng Int. 103–105
180. E. Hjorth-Hansen, E. Strømmen, F. Myrvoll, C. Hansvold, R. Ronnebrant (2001) Performance of a friction damping device for the cables on Uddevalla cable-stayed bridge, In: 4th Int Symp Cable Dyn, pp. 179–186.
181. Chandra V, Ricci AL, Donington K (2003) A landmark cable-stayed bridge over the charles river, boston, massachusetts. Transp Res Rec 18:53–68. https://doi.org/10.1680/stco.3.4.203.38961
182. Bonzon WS (2008) The I-280 Veterans' glass city skyway: New landmark cable-stayed bridge, Ohio. Struct Eng Int 18:43–48. https://doi.org/10.2749/101686608783726542
183. Jomvinya K, Vicat E (2009) Kanchanapisek bridge over the chao phraya river, Thailand. Struct Eng Int 19:58–62. https://doi.org/10.2749/101686609787398434
184. You Q, He P, Dong X, Zhang X, Wu S (2008) Sutong bridge - The longest cable-stayed bridge in the world. Struct Eng Int J Int Assoc Bridg Struct Eng 18:390–395. https://doi.org/10.2749/101686608786455298
185. Ge C, Chen A (2019) Vibration characteristics identification of ultra-long cables of a cable-stayed bridge in normal operation based on half-year monitoring data. Struct Infrastruct Eng 15:1567–1582. https://doi.org/10.1080/15732479.2019.1625416

186. Löckmann H, Marzahn GA (2009) Spanning the rhine river with a new cable-stayed bridge. Struct Eng Int 19:271–276. https://doi.org/10.2749/101686609788957748
187. De Miranda M, De Palma A, Zanchettin A (2010) "Ponte del mare": conceptual design and realization of a long span cable-stayed footbridge in Pescara, Italy. Struct Eng Int J Int Assoc Bridg Struct Eng 20:21–25. https://doi.org/10.2749/101686610791555577
188. Wang Z, Wang B, Chai X (2015) Research advancement of damping techniques for stay cables of long-span cable-stayed bridges. Bridg Constr 45:13–19 ((**In Chinese**))
189. Y Wang, Z Gao, Z Zonghui Chen, W Zhao, J Shi, M Liao (2019), The design and construction of cable-stayed bridge over Boure-greg River, Morocco, Bautechnik. 96, 150–159. https://doi.org/10.1002/bate.201800063
190. Fujino Y (2002) Vibration, control and monitoring of long-span bridges-Recent research, developments and practice in Japan. J Constr Steel Res 58:71–97. https://doi.org/10.1016/S0143-974X(01)00049-9
191. Cárdenas RA, Viramontes FJC, González AD, Ruiz GH (2008) Analysis for the optimal location of cable damping systems on stayed bridges. Nonlinear Dyn 52:347–359. https://doi.org/10.1007/s11071-007-9283-5