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Adaptive MR damper cable control system based on piezoelectric power harvesting

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Abstract. To reduce the vibration of cable-stayed bridges, conventional magnetorheological (MR) damper control system (CMRDS), with separate power supply, sensors and controllers, is widely investigated. In this paper, to improve the reliability and performance of the control system, one adaptive MR damper control system (AMRDS) consisting of MR damper and piezoelectric energy harvester (PEH) is proposed. According to piezoelectric effect, PEH can produce energy for powering MR damper. The energy is proportional to the product of the cable displacement and velocity. Due to the damping force changing with the energy, the new system can be adjustable to reduce the cable vibration. Compared with CMRDS, the new system is structurally simplified, replacing external sensor, power supply and controller with PEH. In the paper, taking the N26 cable of Shandong Binzhou Yellow River Bridge as example, the design method for the whole AMRDS is given, and simple formulas for PEH are derived. To verify the effectiveness of the proposed adaptive control system, the performance is compared with active control case and simple Bang-Bang semi-active control case. It is shown that AMRDS is better than simple Bang-Bang semi-active control case, and still needed to be improved in comparison with active control case.

Keywords: cable-stayed bridges; MR damper; energy harvesting; piezoelectric; adaptive control

1. Introduction

Magnetorheological (MR) damper-based control system can gather the robustness of passive control system, low-power requirement and low cost, and the adaptability of active control system. It is promising to mitigate the vibration of the cable induced by wind, rain and other excitations (Jung *et al*. 2008). Recently, different influences on the performance of MR damper-based control system and different strategies have been studied in detail (Jung *et al*. 2008, Maiti and Vijayaraju 2006, Ying *et al*. 2009). MR dampers have been applied to the cable-stayed Dongting Lake Bridge (Wang *et al*. 2002) and Binzhou Yellow River Bridge (Li *et al*. 2005) in China.

In conventional MR damper-based control system (CMRDS), to make full use of the controllable damping characteristics of MR damper and reduce the structural responses, standalone dynamic sensors, power supply and controllers should be provided. For the whole bridge, there are so many cables to control that the control system is too complex. The more cables there are in the bridge, the more dampers, sensors, power supplies and controllers are needed. The control system is so

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complex to install and maintain that it is not easy to ensure the reliability and lower the cost.

To solve the above problems, a smart passive system is proposed which consists of an MR damper and an electromagnetic induction (EMI) system that uses a permanent magnet and a coil (Cho *et al*. 2005, Jung *et al*. 2010, Jung *et al*. 2011). Also a self-powered, self-sensing MR damper is proposed and investigated by Chao Chen and Wei-Hsin Liao (Chen and Liao 2010, Chen and Liao 2011). All these systems significantly alleviate the vibration of stay cable and bring great benefits such as small space, small mass, low cost, high reliabilities, and so on (Chen and Liao 2010, Jung *et al*. 2011). The advances have opened numerous doors for smart or adaptive control systems, which can harvest energy from the vibration for MR damper to reduce the vibration, in engineering applications.

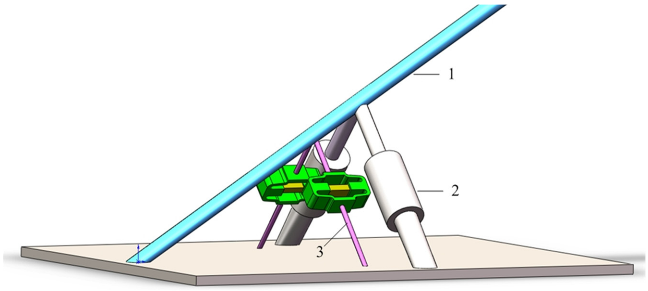
Among the main vibration-to-electric energy conversion mechanisms (piezoelectric, electromagnetic, and electrostatic transductions), piezoelectric transduction has been proved to have larger power densities than the others (Roundy 2003, Feenstra *et al*. 2007, Jeon *et al.* 2008, Cook-Chennault *et al.* 2008, Erturk and Inman 2011). In the last few years, piezoelectric energy harvester (PEH) has been theoretically and experimentally widely investigated. In the field of low-power electronics like MEMS (Micro-electromechanical Systems), new advances have been achieved for vibration-based MEMS piezoelectric harvesters and more attentions have been paid to (Sodano *et al*. 2004). On the contrary, in the field of large-power devices, researchers in Israel developed the piezoelectric technology to generate electricity for the road lamp and the energy is from the vehicles moving on the road. And the problem of vibration-based energy harvesting using piezoelectric transduction for civil infrastructure system applications with a focus on moving load excitations and surface strain fluctuations is formulated. (Erturk and Inman 2011).

In the cable control system, the MR damper requires very low power, about only few watts, to work. The highest efficiency of piezoelectric transduction based on PZT stack can be obtained at 5 Hz, which is much closer to the fundamental frequency of the cable (Goldfarb and Jones 1999). So PZT stack can be used to scavenge energy for powering MR damper in cable control system.

Based on the idea of self-powered adaptive systems, to improve the reliability and performance of the MR damper-based control system, this paper proposes one adaptive control system consisting of MR damper and PEH. Assuming that the wind is vertically applied on the cable in horizontal direction, the proposed system is designed to reduce the wind-induced cable response. According to piezoelectric effect, PEH is used to change mechanical vibration energy of the cable to electrical energy for powering MR damper (Feenstra *et al*. 2007, Jeong *et al*. 2008). The energy is proportional to the product of the cable displacement and velocity induced by the excitation. The larger the product, the larger the power is induced for MR damper. The new system is an adaptive passive control system, with both the simplicity of passive system and adjustability of CMRDS. Through a design for a real cable control system and numerical simulation, the effectiveness of the new system is verified.

2. Adaptive control system

In this paper, an adaptive cable control system is proposed, as shown in Fig. 1. In the control system, two sets of PEH are placed symmetrically on both sides of the cable and in parallel with the damper. For the harvesters, by the elastic rope, one end is connected to the cable, and the other end is connected to the bottom plate which is used to fix MR damper. The elastic rope can only bear tension but not the pressure. On the assumption that the wind is vertically applied on the cable



(1. cable, 2. MR damper, 3. piezoelectric energy harvester (PEH))

Fig. 1 Schematic of an adaptive cable control system

in horizontal direction, when the cable vibrates back and forth, only one harvester will be forced to power both dampers in every 1/4 cycle. The harvester in tension deforms and the deformation is numerically equal to the displacement of damper piston.

For this system, while the cable is moving away from the balance, according to the piezoelectric effect, PEH in tension can transform the energy from cable vibration to electric energy for powering both MR dampers. The larger vibration amplitude may produce the larger energy, and the larger energy cause larger damping force. Then the response of the cable can be reduced by MR damping force. The control strategy achieved by this system is similar to the simple Bang-Bang control strategy.

The system can be designed by the design method similar to CMRDS: first, analyze the cable response under wind excitation without control and with active control to determine the optimal objective control effect and control force of adaptive control system; second, the MR damper parameters can be preliminarily determined; third, according to the properties of the MR damper and existing PZT, obtain the suitable PEH parameters to make the adaptive control system achieve the optimal control effect. The first and second step have been demonstrated in detail in (Li *et al*. 2005). This paper will focus on the third step.

2.1 Equivalent circuit of the whole system

The circuit for the adaptive system can be simplified and regarded as depicted in Fig. 2. In one vibration cycle, two sets of PEH can alternately power the dampers. The circuit design is too complex to analyze in detail in this context. The parameters are temporarily adopted by referring the existing research results.

The power from the piezoelectric element should be rectified, by the circuit (the shady block shown in Fig. 2), to power the dampers. By Kirchhoff's Voltage Laws, the circuit voltage is in balance

$$L\frac{di_R}{dt} + i_R R = V_{cd} \tag{1}$$

where, i_R and V_{cd} are respectively the current and voltage for both damper coils, L and R are respectively the resistant and inductance of both coils.

As the frequency of wind excitation is very low, the inductance is relatively too small and Eq. (1) can be simplified to be

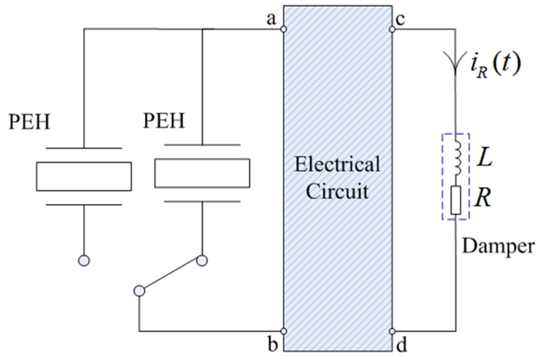


Fig. 2 Equivalent circuit of the whole system

$$i_R R = V_{cd} \tag{2}$$

After the rectification circuit, the real-time power induced by PEH can be directly used for powering dampers, without considering the time-delay of the rectification. The relationship between the power before and after rectification can be expressed by

$$P_{MRD} = i_R^2 R = \phi_r P_{real-time} \tag{3}$$

where, ϕ_r is power conversion efficiency.

It is shown from the existing research that the conversion efficiency can be 25% (Thiam and Pierce 2009). (Chen and Sun 2003) used LDO circuit improve the conversion efficiency to 80%. In this paper, the efficiency is assumed to be 25%.

2.2 PEH parameters

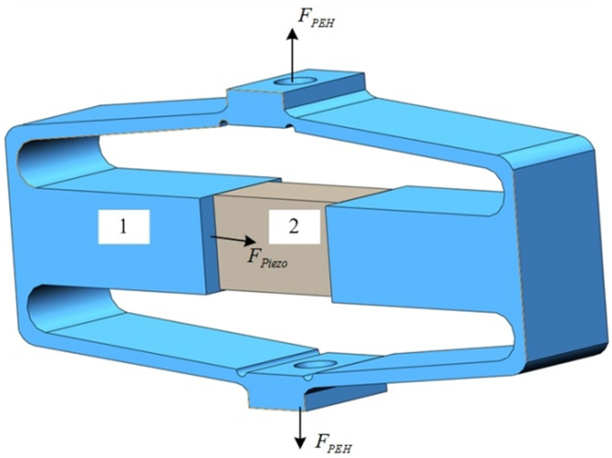
2.2.1 PEH structure

Due to the high power density, PZT stack is used to harvest the vibration energy of the cable. In view of its brittleness, stack cannot bear tension but compression. Referring to Feenstra' studies (Feenstra *et al*. 2007), the structure of PEH can be designated as shown in Fig. 3, which contains an external amplification device and a PZT stack. In this structure, external tension can be amplified and transformed to be compression on the stack. This structure can also conveniently connect the PZT stack and the cable, and solve the stack deformation-limited problem. By the amplification device, smaller tensile force, F_{PEH}, could be amplified and changed into larger compressive force, F_{piezo}, to induce higher voltage or power.

The relationship between the tensile force, F_{PEH}, applied on amplification device and the compressive force, F_{piezo}, applied on PZT stack can be expressed by

$$\phi_F = \frac{F_{piezo}}{F_{PEH}} \tag{4}$$

The relationship between the amplification deformation, y_{PEH}, and the PZT stack deformation, y_{piezo}, can be expressed as



(1. External amplification device; 2. PZT stack)

Fig. 3 The structure of piezoelectric energy harvester (PEH)

$$\phi_s = \frac{y_{piezo}}{y_{PEH}} \tag{5}$$

where ϕ_F and ϕ_s are force amplification coefficient and deformation reduction coefficient, respectively.

2.2.2 The determination of PZT stack parameters

The determination of PZT stack parameters depends on the MR damper parameters, which should be chosen according to the active control method firstly.

(1) The length of stack

To make the design simple, the deformation of PZT stack is assumed to be linear and elastic.

As usual, the damper used in civil engineering needs large piston displacement. Mechanical structures are necessary to match the piston displacement, y_{MRD}, with the deformation of external amplification device, y_{PEH}, and PZT stack, y_{piezo}. And then we got

$$\phi_{MP} y_{MRD} = y_{PEH} \tag{6}$$

ϕ_{MP} is another reduction coefficient for the piston displacement and the external amplification device.

Another preliminary assumption is that PEH can't break down before the damper and the PZT stack can't break down before harvester. Under these circumstances, the maximum deformation of PZT stack, $y_{piezo\max}$, should match with the maximum deformation of amplification device, $y_{PEH\max}$, and the stroke of MR damper, $y_{\max}$, so

$$y_{piezo\max} = \phi_s y_{PEH\max} = \phi_s \phi_{MP} y_{\max} \tag{7}$$

For cable control system, the damper piston displacement is nearly equal to the deformation of amplification and the reduction coefficient, ϕ_{MP}, can be 1.

The ultimate strain of the stack is 1/1000. To ensure the stack safe, the maximum strain should less than or equal to the limit strain (Thiam and Pierce 2009)

$$\frac{\phi_s y_{P\max}}{l} \le \frac{\Delta l_{\max}}{l} \tag{8}$$

Substituting Eq. (7) into Eq. (8), and then

$$l \ge 1000\phi_s\ y_{PEH\max} = 1000\phi_s \phi_{MP} y_{\max} \tag{9}$$

(2) The area of stack

(a) The lower limit

According to the piezoelectric equation, the voltage, V_{ab}, and the energy, W, induced for the stack can be expressed as

$$V_{ab} = \frac{d_{33}F_{prezo}}{C_P^S} \tag{10}$$

$$W = \frac{1}{2}C_P^S V_{ab}^2 = \frac{1}{2}\frac{(d_{33}F_{prezo})^2}{C_P^S} \tag{11}$$

rearranged

$$W = \frac{d_{33}g_{33}Y_{33}^2}{2}\frac{A}{l}(y_{piezo}(t))^2 \tag{12}$$

where, C_P^S, d_{33}, g_{33}, Y_{33}, A and l are the capacitance, piezoelectric strain constant and voltage constant, elastic modulus, the area and the length for PZT stack, respectively. It is known from Eq. (12) that the energy is proportional to the square of stack deformation.

Let

$$K_P = \frac{d_{33}g_{33}Y_{33}^2}{2}\frac{A}{l}$$

Eq. (12) can be simplified as

$$W = K_P(y_{piezo}(t))^2 \tag{13}$$

In the interval [t, $t+\Delta t$], the real-time power induced for stack is

$$P_{real-time} = K_P\frac{(y_{piezo}(t+\Delta t))^2 - (y_{piezo}(t))^2}{\Delta t} \tag{14}$$

If $y_{piezo}(t)$ is differentiable, let Δt approaches to 0, Eq. (14) can be modified as

$$P_{real-time}\big|_{\Delta t \to 0} = 2K_P y_{piezo}(t)\dot{y}_{piezo}(t) \tag{15}$$

where, $y_{piezo}(t)$ and $\dot{y}_{piezo}(t)$ are the stack deformation and deformation rate.

The current in the coils can be derived from Eqs. (3) and (15), and be expressed as

$$i_R = \sqrt{\frac{2\phi_r K_P y_{piezo}(t)\dot{y}_{piezo}(t)}{R}} \tag{16}$$

It is shown that the current is positively proportional to the product of the deformation and deformation rate of PZT stack. It is testified that the current can be induced when cable vibrates away from the balance.

The active control force is applied when the controlled structure is away from the balance; otherwise, the minimum force of MR damper is applied. In the whole control process, the demanding energy W_{xq} should be less than or equal to the energy supplied by the harvester W_{sj}, then

$$W_{xq} \leq W_{sj} \tag{17}$$

$$W_{xq} = \int \frac{u_{xq}^2(t)}{R} dt \tag{18}$$

$$W_{sj} = \int 2\phi_r K_P \phi_s^2 \phi_{MP}^2 y(y)\dot{y}(t)dt \tag{19}$$

where, $u_{xq}(t)$ is the demanding voltage to attain the active control force, $\dot{y}(t)$ and $y(t)$ are the velocity and displacement of the damper piston, respectively.

Substituting Eqs. (5), (15) and (16) into Eqs. (18) and (19), then the lower limit of the area can be got

$$A \geq \frac{l}{d_{33} g_{33} Y_{33}^2} \cdot \frac{1}{\phi_r \phi_s^2 \phi_{MP}^2} \cdot \frac{1}{R} \cdot \frac{\int u_{xq}^2(t)dt}{\int y(t)\dot{y}(t)dt} \tag{20}$$

(b) The upper limit

The damping force of the whole system can be composed of the damping force supplied by harvester, F_{PEH}, and the damping force supplied by MR damper, F_{MRD}.

To ensure the system controllability and the harvester not broken, the ratio of the damping force supplied by harvester to the whole system control force should be small. Assume the ratio of the force of PEH to maximum MR damping force shouldn't exceed $1/k$, we can get

$$F_{PEH} \leq \frac{1}{k} F_{MRD\max} \tag{21}$$

After being rearranged, the upper limit of the area can be got

$$A \leq \frac{1}{k} \frac{\phi_F}{Y_{33} \phi_s \phi_{MP}} \frac{F_{MRD\max}}{y_{\max}} l \tag{22}$$

where, k can be determined referring to the damper design.

3. Analysis and optimization of adaptive control system

3.1 Damper parameters

Without regard to the differences and effectiveness of active control methods, calculate the optimal active control force $u_{\max}$ and expecting optimal control effect by LQR method (Li *et al*. 2005).

Take the N26 cable in Shandong Binzhou Yellow River Bridge as example and the parameters

Table 1 Geometric and material properties of the stay cable model (Li *et al*. 2005)

Length L(m)	Diameter D(m)	Mass of the unit length m (kg/m)	Elastic modulus E_{eq} (10^{11}N/m^2)	Inclination angle (°)	Tension force T(kN)
218.556	0.118	85.496	1.999	24.913	7260

listed in Table 1. The wind is assumed to be applied vertically on the N26 cable in horizontal direction. The bridge is in exposure category B. The design wind speed is 28.7 m/s for the height of 20 m and is 25.687 m/s for the height of 10 m. In a-hundred-year return period basic wind pressure is 0.45 kN/m^2; the ground roughness exponent is 0.16. By using standard DAVENPORT spectral density and random sampling, the standard wind velocity time-history curve is got for the height of 10 m.

According to the simulation under the wind excitation, the damping coefficient and maximum column force of MR damper is respectively: C_d, 22.6153 Ns/m, F_{dymax}, 3799.3 N (Li *et al*. 2005).

The adopted damper can be proportional to the structural and mechanics parameters of the RD-1000 damper produced by LORD company (Spencer *et al*. 1997, Wang *et al*. 2002). The damper's stroke is ±25 mm. The resistance is 4 ohms, and the maximum operating voltage is 5 V. Regulating damper structure parameters, the Bingham model of the adopted damper can be expressed (Wang *et al*. 2002)

$$F_{MRD} = C_d \dot{y} + F(u)\mathrm{sgn}(\dot{y}) + F_0 \tag{23}$$

$$F(u) = 291.6 + 669u + 35.6u^2$$
$$F_{dymax} = 4526.6\ N \quad C_d = 22000\ N \cdot s/m \quad F_0 = -89.2\ N \tag{24}$$

whereas, $\dot{y}$ is the velocity of the piston of MR damper, u is the voltage on the MR damper, $F(u)$ is the adjustable damping force, C_d is coefficient of viscosity, F_0 is friction force.

3.2 PZT stack parameters

Table 2 lists the common properties of PZT materials (Feenstra *et al*. 2007).

Table 3 lists the properties of external amplification structure, which is assumed referring to the previous literature (Feenstra *et al*. 2007).

According to the MR damper parameters chosen in section 3.1, PZT stack parameters can be determined.

Table 2 The properties of PZT materials

Material property	Symbol	Unit	Value
Piezoelectric strain constant	d_{33}	(pC/N)	650
Piezoelectric voltage constant	g_{33}	(m^2/C)	0.1048
Elastic modulus	Y_{33}	(GPa)	44

Table 3 The properties of external amplification structure

Structural parameters	Sign	Value
F_{PEH}/F_{MRmax}	k	5
Force amplification coefficient	ϕ_F	60
Deformation reduction coefficient	ϕ_s	1/80

(1) The length of stack

Substituting the parameters of external amplification structure and the damper stroke into Eq. (9), we can get the range of the stack length

$$l \geq 31.25 \text{ cm}$$

To make the harvester take up as small space as possible, set the length be 32 cm.

(2) The area of stack

The active control force is applied when the controlled structure is away from the balance; otherwise, the minimum force of MR damper is applied. Based on that, in the whole control process, the demanding energy should be less than or equal to the energy supplied by the harvester. Substituting the PZT properties and external amplification structural properties into Eq. (20), the lower limit for the area of stack is determined

$$A \geq 5.2265 \text{ cm}^2$$

To ensure the controllability of the system and ensure the harvester not broken, the ratio of the damping force supplied by harvester to the whole system control force should be small. Substituting properties of external amplification structure and the damper into Eq. (22), the upper limit of the stack area is got

$$A \leq 12.6416 \text{ cm}^2$$

There are three extra conditions to be considered: (1) to ensure the energy generated by the PZT stack to meet the demand of the MR damper; (2) to make the space, taken by PEH, small; (3) the smaller PZT stack, the easier the manufacture process. Based on those conditions, the area and length are respectively chosen as 6 cm^2 (set as 2 cm*3 cm) and 32 cm.

(3) Buckling instability

As a member in compression with two ends fixed, the buckling instability of the stack should be verified. According to the Euler's formula, the destabilizing critical force can be calculated by

$$P_{lj} = \frac{\pi^2 Y_{33} I}{(\mu l)^2} \tag{25}$$

where, μ is length coefficient, 0.5, I is the moment of inertia of stack.

Substituting the area and length of the stack into Eq. (25), the critical force along two axes are obtained to be 763.35 kN and 339.27 kN。

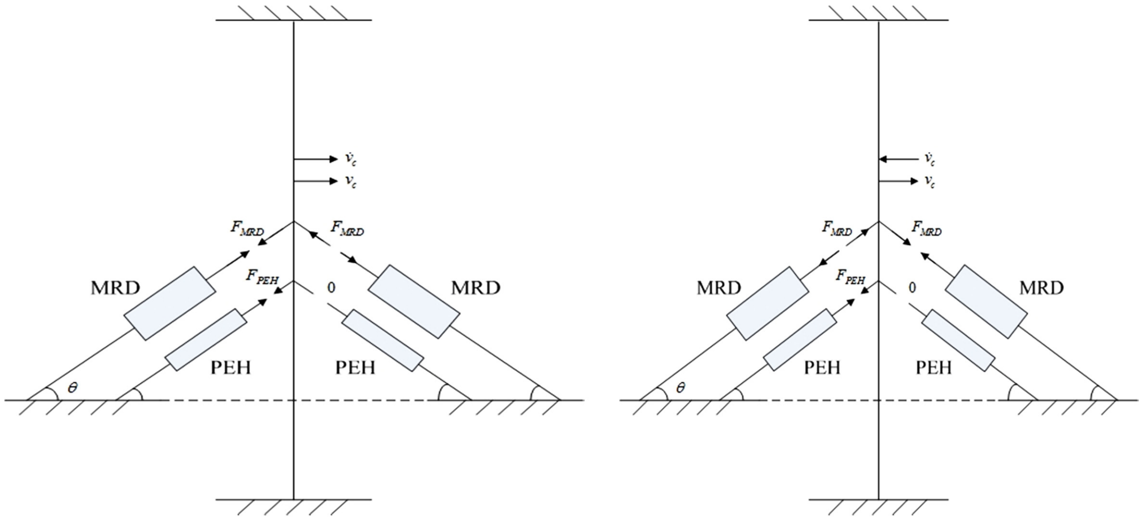
When the stack reaches the maximum elastic deformation, the maximum force is calculated

$$F_{piezo} = Y_{33} \frac{\Delta l_{\max}}{l} A = 52.8kN \leq 339.27kN \tag{26}$$

So, the stack with the area, 6 cm^2 (set as 2 cm*3 cm) and the length, 32 cm, is safe.

3.3 Built-in control strategy

The adaptive control system is one kind of passive control system and has a built-in control strategy.



(a) Away from the balance towards right (b) Back to the balance

Fig. 4 Analysis of force applied to the cable

As shown in Fig. 4(a), when the cable moves away from the balance towards right, left PEH is in tension and produces electric energy for both MR dampers, but no force is applied to right PEH. Meanwhile, the forces of both dampers change with the voltage supplied by the left harvester. During this period, the control force exerted on the cable should consist of two parts: the changing MR damping force and PEH tension force. And the control force can be expressed by

$$F_{sd}(t) = 2F_{MRD}cos\theta + F_{PEH}cos\theta \tag{27}$$

where, F_{MRD} can be expressed by Eq. (23).

As shown in Fig. 4(b), when the cable moves back to the balance, the voltage is still produced by left PEH and no force is applied to right PEH. To ensure the control efficacy, the circuit is cut off. During this period, the control force on the cable remains to be two parts and be expressed by Eq. (27). As the damper is out of power, the column force is minimum value, $F_{dy\min}$. Then F_{MRD} is expressed as

$$F_{MRD} = C_d\,\dot{y} + F_{dy\min}sgn(\dot{y}) \tag{28}$$

Similarly, when the cable moves away from the balance towards left, right PEH is in tension and no force is applied to left PEH. Meanwhile, the forces of both MR dampers change with the voltage supplied by the right harvester. The control force still consists of two parts: the changing MR damping force and PEH tension force. And it can be got by Eqs. (27) and (23). And when the cable moves back to the balance towards right, the voltage is cut off for the dampers. The control force can be got by Eqs. (27) and (28).

On the whole, the built-in control strategy is similar as the simple Bang-Bang control strategy and can be expressed as

$$F_{sd}(t) = \begin{cases} 2(C_d\dot{y}+F(u)sgn(\dot{y})+F_0)cos\theta+F_{PEH}+cos\theta & y\dot{y}>0 \\ 2(C_d\dot{y}+F_{dymin}sgn(\dot{y})+F_0)cos\theta+F_{PEH}+cos\theta & y\dot{y}\le 0 \end{cases} \tag{29}$$

where, F_{dymin} is the minimum column force, F_0 is friction force.

3.4 Control indices

The performance of cable control system can be evaluated by two indexes: the maximum displacement response, v_{cmax}, and standard variation of the displacement response, δ_{dis}^{m}, along the whole cable, expressing as (Li *et al*. 2005)

$$v_{cmax} = \max_{x,t}|v_c(x,t)| \tag{30}$$

$$\delta_{dis}^{m} = \max_{t}\sqrt{\int_0^L v_c(x,t)^2 dx} \tag{31}$$

3.5 Numerical results

To evaluate the performance of the adaptive control system, four cases are simulated here: uncontrolled case, active control case, adaptive control case and semi-active control case. Simple Bang-Bang control strategy and the fundamental damper parameters used in adaptive control case are adopted for semi-active control case.

The responses of cable for four cases under wind excitation are listed in Table 4. It is shown from Table 4 that the vibration responses can be reduced by active control, adaptive control and semi-active control. Compared with uncontrolled case, for the maximum displacement response, the reduction under active control, adaptive control and semi-active control are respectively 60.43%, 43.46%, 28.79%, and for standard variation of the displacement response, the reduction are respectively 61.40%, 45.70%, 32.27%. For the maximum control force, adaptive control case is much closer to active control case and semi-active control case is larger than other cases. In comparison with semi-active control force, adaptive control case is slightly better and is much closer to active control. But compared with the active control, the adaptive control needs to be improved.

Adaptive control system is kind of smart passive control system and is designated to trace and achieve the efficacy of the optimal active control. It is known from Eq. (16) and Fig. 5 that, the voltage generated by PEH is in phase with the product of velocity and displacement of the piston rod or the cable. Then it is inferred that there is phase difference between the adaptive control force and active control force, which can be found from Fig. 6. But it is known from Fig. 7 and Table 4

Table 4 Responses of MR damper system for cables

	Displacement response v_{cmax}	Variation δ_{dis}^{m}	Maximum control force (kN) $F_{sd}(t)$
Uncontrolled	0.3359	3.6567	
Active control	0.1329	1.4115	6.4477
Adaptive control	0.1899	1.9857	5.4304
Semi-active control	0.2392	2.4768	13.635

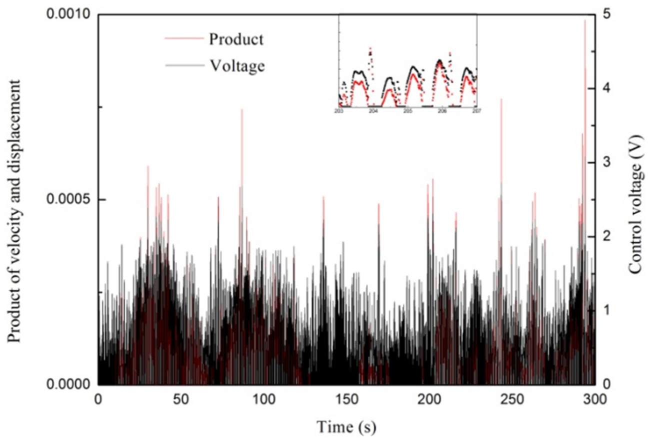


Fig. 5 The comparison of control voltage and the product of velocity and displacement

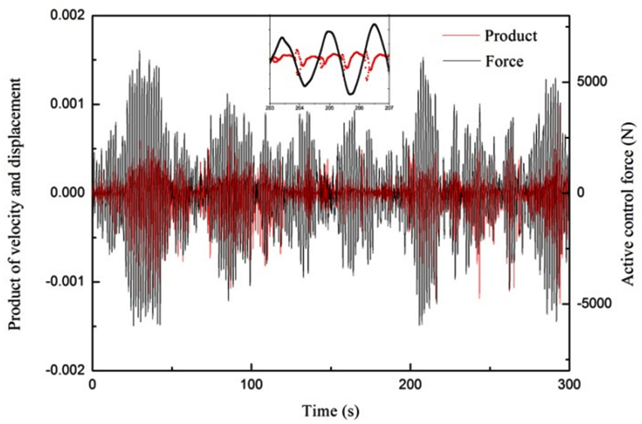


Fig. 6 The comparison of active control force and the product of velocity and displacement

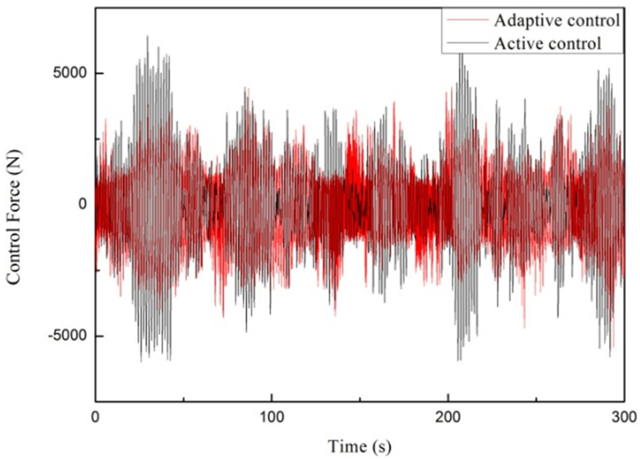


Fig. 7 The comparison of active control force and adaptive control force

that the adaptive control force can mainly trace the active control force and the efficacy of adaptive control is slightly worse than active control case.

It is not sufficient that the PEH parameters are designed only by the conditions proposed in this paper. And it is not appropriate that the voltage is directly applied to the damper. To improve the performance of adaptive control system and obtain a good control efficacy, control circuit should be considered to adjust the voltage to be optimal value with some time-delay.

4. Conclusions

In this paper, an adaptive MR-based cable control system is proposed, including MR damper and piezoelectric energy harvester (PEH) system. Taking the N26 cable of Shandong Binzhou Yellow River Bridge as example, the design method for the whole adaptive control system is given, and simple formulas for the design of PEH are derived. To evaluate the performance of proposed adaptive control system, three control cases such as the active control, adaptive control and the Simple Bang-Bang semi-active control has been simulated. It is shown that the adaptive control system is better than Bang-Bang semi-active control.

The adaptive control system is a pure smart passive control system. The semi-active control system needs a constant input voltage for MR damper and the active control system needs more power. In comparison with active and semi-active control systems, it is an additional advantage of the proposed system that extra power supplies are not required.

Compared with active control system, the proposed system still needs to be improved to achieve better control efficacy in some aspects such as MR damper model, PZT material, stack size, control circuit, and so on. In the future, the sensing function of PEH may be developed for monitoring the cable structure health by adjusting the circuit.

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