A DUAL-FUNCTION ELECTROMAGNETIC DAMPER FOR BRIDGE STAY CABLE VIBRATION MITIGATION AND ENERGY HARVESTING

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ABSTRACT

This paper proposes a dual-function electromagnetic (EM) damper, which simultaneously provides vibration damping and electrical power. A discontinuous conduction mode (DCM) buck-boost converter is utilized as the energy harvesting circuit due to its resistive feature, which enables the optimization of energy harvesting efficiency and vibration damping performance. This paper also presents a numerical study on its application in a full-scale bridge stay cable considering along-wind excitations. The numerical results reveal that the dual-function EM damper achieves a comparable vibration control performance as the optimal viscous damper in a broad wind speed range. Also, average output power of 82.5 mW to 2396.8 mW is harvested with high efficiencies in the wind speed range from 9m/s to 15m/s.

Keywords: EM damper, energy harvesting, buck-boost, wind, buffeting.

1. INTRODUCTION

Vibration-based energy harvesting (or energy scavenging) techniques provide regenerative power that is favorable in many applications. A variety of mechanisms or materials have been explored, including electromagnetic induction, piezoelectricity, electrostatic generation, magnetoelastic effect. Substantial attention has been paid to the development of a sustainable power supply for autonomous wireless sensors based on such techniques (Jung et al., 2011; Casciati and Rossi, 2007).

When extracting vibration energy from a structure, energy harvesting mechanisms produce an intrinsic damping effect on the primary structure (Zhu et al., 2012). Lesieutre et al. (2004), and Liang and Liao(2009) studied the damping as a result of energy harvesting with piezoelectric materials. It naturally inspires energy harvesting directly via vibration damping devices that operate with similar mechanisms. Among the aforementioned mechanisms, electromagnetic induction is a promising one that can well serve vibration control and energy harvesting functions (Shen et al., 2012; Zhu et al., 2012). The merits of a dual-function electromagnetic (EM) damper, termed electromagnetic damping and energy-harvesting (EMDEH) system, includes: 1) it produces greater

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output power compared with micro-scale energy harvesters by absorbing substantial vibration energy from structures; and 2) its electricity conversion avoids common overheating problems associated with conventional fluid dampers.

However, many issues remain unaddressed regarding simultaneous vibration control and energy harvesting in civil structures. These issues include energy harvesting performance in flexible structures with low vibration frequencies, interaction of the dual functions, and optimization of the system given dual objectives. Therefore, this paper investigates the application of the novel EMDEH to real stay cables, a common type of bridge components vulnerable to excessive vibrations under wind excitations. An optimal design approach for EMDEH in consideration of the dual functions is presented, in which a resistance emulation technique is adopted to track the optimal working points of EMDEH. The vibration control and energy harvesting performance of EMDEH are assessed through the numerical study of a full-scale bridge stay cable equipped with EMDEH under actual wind excitation. The vibration reduction, output power and energy harvesting efficiency of EMDEH at full scale are evaluated at different wind speed.

2. SIMULATION DESCRIPTION

2.1. State-space model of stay cable and wind excitation

A full-scale stay cable of the Stonecutters Bridge of Hong Kong is employed as an example for the numerical study. Figure 1 shows the configuration of the stay cable attached with an EMDEH system, which consists of EM damper and energy harvesting circuit. Both ends of the cable are assumed fixed. In the numerical study, the stay cable model is discretized into 100 uniformly spaced segments with 99 internal nodes, as shown in Figure 1. A set of along-wind fluctuating wind forces (as shown in Figure 2), also known as turbulent buffeting force, is applied at all the nodes of the stay cable in the u direction. The dual-function EM damper is installed at the node 98 of the cable, which is located at a distance of x_c=0.05l away from the cable end. Table 1 shows the parameters of the stay cable and wind excitation adopted in this numerical study.

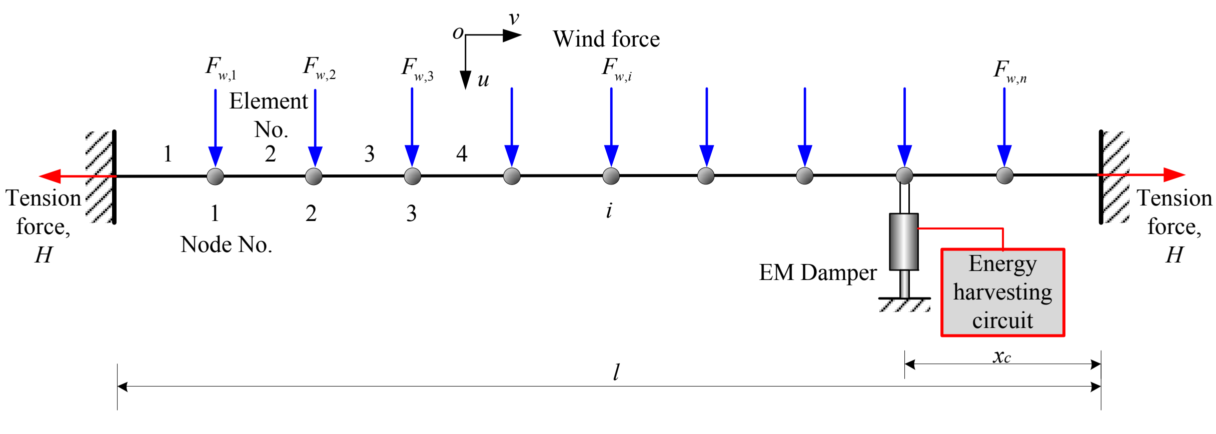


Figure 1: Discretized Model of a stay cable equipped with an EMDEH system.

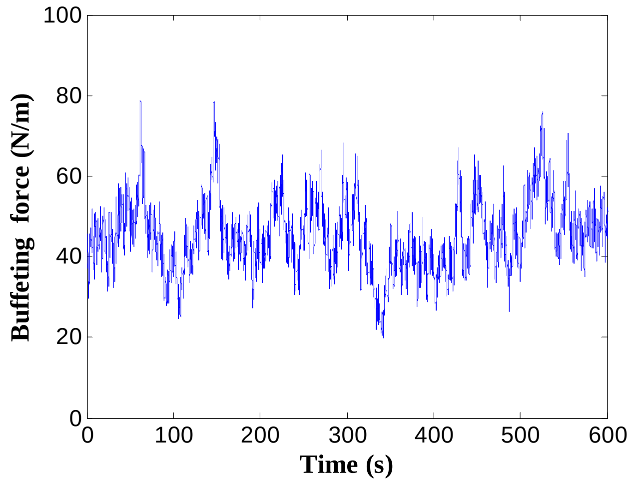


Figure 2: Wind force time histories on element 50 (mean wind speed: 9m/s).

Table 1: Parameters of stay cable and wind excitation

Parameter of stay cable	*value*	Parameter of wind excitation	*value*
Length, l (m)	306.69	Integral length scale, L_u^x	221.4
Outer diameter, D_o (mm)	155	Turbulence intensity, I_u	0.235
Diameter, D_s (mm)	126	Friction velocity, u_* ,(m/s)	0.71
Young's modulus, (MPa)	1.95×10^5	Power law exponent, α	0.29
Axial stiffness, EA, (kN)	2.429×10^6	Low limit frequency, (Hz)	0
Flexural stiffness, EI, (kN-m^2)	5525	Upper limit frequency, (Hz)	8
Mass of per unit length, (kg/m)	98.6	Time step, (sec)	0.0156
Tension force, H, (kN)	5529.6	Duration, (sec)	768
Fundamental frequency, f_{01}, (Hz)	0.391		
Inherent damping ratio, (%)	0.15		

2.2. Design of dual-function EM damper

In this section, the design of dual-function EM damper (EMDEH system) for the stay cable can be divided into two parts, EM damper design and energy harvesting circuit design.

A linear-to-rotary EM damper is employed in this simulation study because the damping density could be significantly increased by gear ratio (n_g). The total damping coefficient of the EM damper is given by

$$C_{total} = C_p + C_{\mathrm{em}} = C_p + \frac{\beta^2 n_g^2 K_{em}^2}{R_{coil} + R_{in}} = C_p + \frac{K_{eq}^2}{R_{coil} + R_{in}} \tag{1}$$

where C_p is the equivalent parasitic damping coefficient, C_{em} is the equivalent EM damping coefficient, variable β relating rotational and linear quantities, K_{em} is the machine constant of the EM damper (N/A) or (V s/rad), R_{coil} is the resistance of the EM damper's coils, R_{in} is the average input resistance of the energy harvesting circuit, $K_{eq}=\beta n_g K_{em}$, is the equivalent machine constant of the linear-to-rotary EM damper, (N/A) or (V s/m).

Considering the optimal damping C_{opt} for cable vibration control of a specific vibration mode (Pacheco et al., 1993), the optimal input resistance is given by

$$R_{\mathrm{in,C}} = \frac{K_{eq}^2}{C_{opt} - C_p} - R_{coil} \tag{2}$$

Resistance emulation technique can be used to achieve the optimal damping for vibration mitigation. On the other hand, the resistance emulation technique is widely adopted to match the optimal load resistance thus track the optimal working points for energy harvesting (Lefeuvre et al., 2007; D'hulst et al., 2010). The determination of optimal resistance for energy harvesting should consider parasitic damping effect (Stephen, 2006; Zhu et al., 2012). Zhu et al (2012) proposed the optimal load resistance of the EMDEH system for achieving maximal energy harvesting efficiency under harmonic vibration condition,

$$R_{\mathrm{in,EH}} = R_{coil}\sqrt{1+\frac{K_{eq}^2}{C_{\mathrm{p}} R_{\mathrm{coil}}}} \Rightarrow \eta_{\max} \tag{3}$$

Due to the low-frequency feature of wind excitation, the first mode of stay cable is usually dominant in the buffeting responses. Therefore, Equation (3) can be applied to calculate the optimal load resistance for energy harvesting in this study.

The discontinue conduction mode (DCM) buck-boost converter shows a constant average input resistance characteristic(Lefeuvre et al., 2007),

$$R_{in} = \frac{2Lf_{sw}}{D_{sw}^2} \tag{4}$$

where L, f_{sw}, D_{sw} is the inductance, the switch frequency, and the duty-cycle of the buck-boost converter, respectively. The energy harvesting circuit mainly consists of a DCM buck-boost converter is shown in Figure 3.

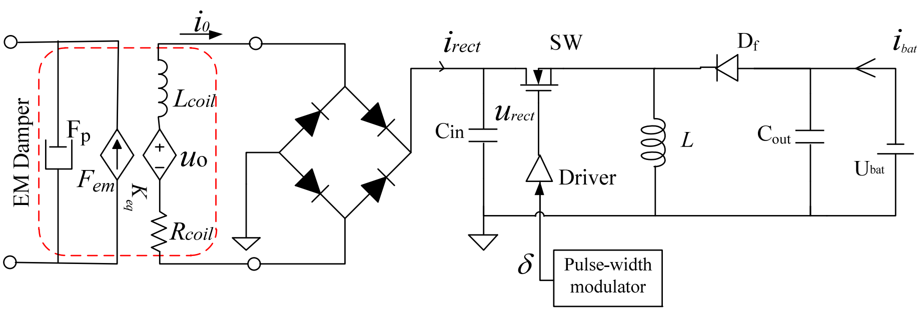


Figure 3: Schematic of energy harvesting circuit.

A rational design for a dual-function EMDEH system should address a dual-objective optimization problem by considering both vibration control and energy harvesting performance. Due to the resistive feature of the DCM buck-boost converter, the average input resistance is the main parameter to be determined. In practice, Equations (2) and (3) can be simultaneously satisfied only if the parameters K_{eq}, C_p and R_{coil} of EM damper are properly determined. However, the selection of EM damper parameters may be subjected to many practical constraints, such as the commercial availability of EM damper. When optimal Equations (2) and (3) cannot be simultaneously satisfied, a trade-off must be made between energy harvesting and vibration control performance in the design of EMDEH.

A rechargeable battery (NiMH, nominal voltage: 2.4 V, capacity: 3 Ah) is selected as the energy storage element, and the fixed duty cycle is set to 0.4. The inductance of the DCM buck-boost converter is determined with Equation (4) at a given switch frequency. The main parameters of EM damper and corresponding circuit are presented in Table 2.

Table 2: Parameters of EM damper and energy harvesting circuit

Parameter	*value*	Parameter	*value*
Machine constant, K_{eq} (N/A, or V.s/m)	1200	R_d of MOSFET, (mΩ)	10
Resistance of damper coils, R_{coil} (Ω)	2	Switch frequency, f_s, (kHz)	20
Average input resistance in DCM, (Ω)	6.72	Duty-cycle of buck-boost, (%)	40
Parasitic damping coefficient, (kN.s/m)	70	Inductance, L (μH)	26.88
Optimal damping, $C_{opt,1}$ (kN.s/m)	236	ESR of inductor, (mΩ)	25
V_f of diode, (V)	0.22	Output Capacitor, C_{out}, (μF)	270
Filter capacitor, C_{in}, (μF)	100	ESR of output capacitor, (mΩ)	10
ESR of filter capacitor, (mΩ)	7	Output voltage of buck-boost, (V)	2.4
R_{on} of MOSFET, (mΩ)	100		

The simulations of a stay cable equipped with the proposed EMDEH system are carried out in MATLAB Simulink toolbox. Figure 4 shows the established Simulink model, consisting of two interacting parts—the state space model of the stay cable and the EMDEH system.

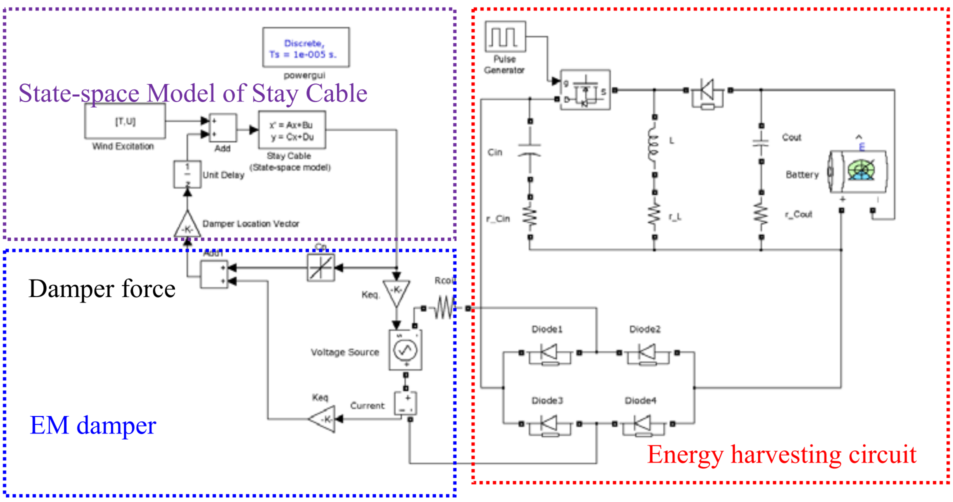


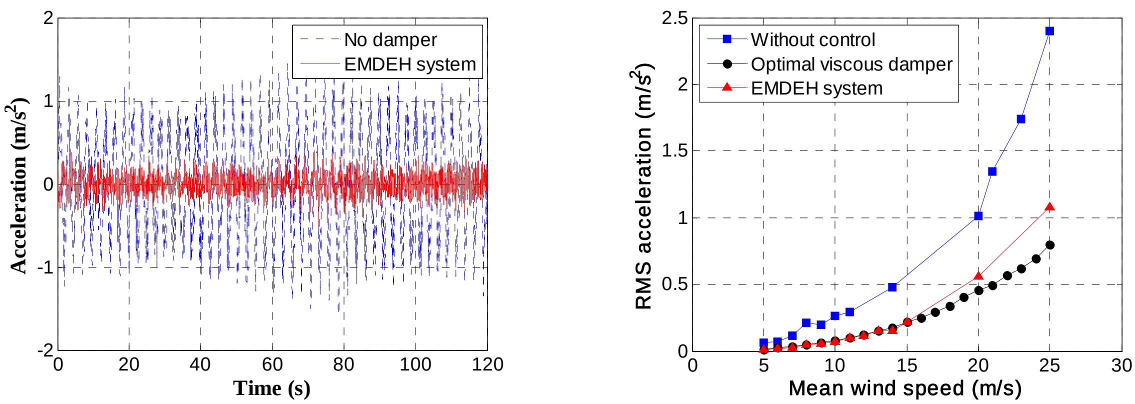
Figure 4: Simulink model of stay cable with EMDEH system.

3. RESULTS AND DISCUSSIONS

This section discusses the simulation results of the stay cable attached to the installed EMDEH at different wind speed with respect to the vibration control and energy harvesting performance.

3.1. Vibration control performance

Figure 5 (a) shows the steady acceleration time histories at a wind speed of 12 m/s, where the EMDEH effectively dampens 89% of the acceleration response. Apparently, the EMDEH can significantly suppress the acceleration amplitudes of wind-induced vibration. Figure 5 (b) summarizes the root-mean-square (RMS) acceleration at different wind speed, in which the viscous damper stands for the optimal passive damping case. The vibration control performance of the proposed EMDEH is comparable to that of the optimal viscous damper at the mean wind speed range from 5m/s to 15m/s. The total damping coefficients of the wind speed range from 5m/s to 8m/s show 10% to 34% diversions from the $C_{opt,1}$ defined by Pacheco et al (1993). This relative small deviation of damping coefficient from the optimal setting may not obviously reduce the vibration mitigation effect. However, severely deviation (70% to 91%) from the optimal damping in the high wind speed cases (20m/s, 25m/s) would cause a slight degradation of vibration control performance compared with the optimal case. Compared with the uncontrolled case, nevertheless, EMDEH can substantially reduce RMS response at the entire wind speed range. A similar observation can be made in the comparison of the peak acceleration responses.



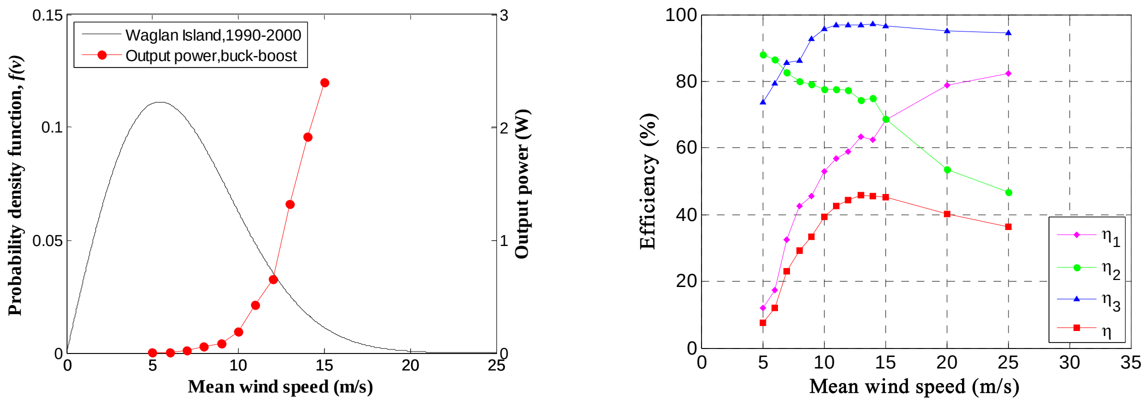
(a) Acceleration of 12m/s case (b) RMS Acceleration under different wind speed

Figure 5: Vibration control performance of EMDEH system.

3.2. Energy harvesting performance

Figure 6 (a) shows the rapid increase of output power with the increasing wind speed, together with the a representative probability density functions of the 10-min mean wind speed distribution in the Hong Kong region. The start-up wind speed for power generation is 5 m/s, which corresponds to the peak of the wind speed distribution curve with an occurrence probability of over 10%. However, the output power at the start-up wind speed is low mainly because of the low vibration amplitude and relatively low efficiency of the buck-boost converter at such low power levels. At the optimal wind speed range (from 9m/s to 15m/s), the output power varies from 82.5 mW to 2396.8 mW.

Figure 6 (b) shows the relationship between energy harvesting efficiencies and mean wind speed. The electromechanical coupling coefficient η_1 depends on the electromagnetic damping coefficient. η_1 is quite low at a low wind speed. When the electromagnetic damping coefficient increases with the increasing wind speed, the electromechanical coupling coefficient η_1 also improves rapidly. The decrease in average input resistance R_{in} caused by the increase in wind speed leads to the reduction of the intermediate energy conversion efficiency η_2. At the optimal wind speed range, the average input resistance of energy harvesting circuit is nearly constant and η_2 is relatively stable. However, the efficiency η_2 drops quickly when wind speed is increased beyond the optimal range. η_3 represents the efficiency of the buck-boost converter, which is relatively low at low wind speed but becomes stable when wind speed exceeds 9 m/s. The overall energy harvesting efficiency η is the product of η_1, η_2 and η_3. η is also low at low wind speed but becomes relatively stable and high when the wind speed ranges from 10 m/s to 20 m/s. It averages 42.3% at the optimal wind speed range. This result indicates that the designed EMDEH can successfully achieve the optimal energy harvesting performance in this case study.



(a) Output power (b) Efficiencies

Figure 6: Energy harvesting performance of EMDEH system under different wind speed.

4. CONCLUSIONS

This paper presents an energy harvesting strategy via an EM damper attached to a bridge stay cable. A dual-function EMDEH system that comprises an EM damper and an energy harvesting circuit is employed to fulfill both vibration control and energy harvesting functions in this application. The resistance emulation technique is employed to track the optimal working points of EMDEH, so a DCM buck-boost converter is utilized. The effectiveness of the proposed EMDEH with regard to vibration control and energy harvesting is evaluated through numerical simulations of a wind-excited full-scale stay cable attached to a properly designed EMDEH. The results show that the novel EMDEH successfully performs the dual functions in its application to stay cables within a specific wind speed range (9m/s to 15m/s). The control effect of EMDEH within this optimal wind speed range is comparable to that of an optimally designed viscous damper for a stay cable. An average energy harvesting efficiency of 42.3% is observed, which is close to the value of theoretical maximum efficiency in this application. The simulations also project output power ranging from 82.5 mW to 2.40 W at the optimal wind speed range, which implies of the proposed EMDEH has a great potential to become a regenerative power source for small electronic devices (e.g. wireless sensors).

5. ACKNOWLEDGMENTS

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