Smart Structures and Systems, Vol. 7, No. 5 (2011) 379-392
DOI: http://dx.doi.org/10.12989/sss.2011.7.5.379

A multi-functional cable-damper system for vibration mitigation, tension estimation and energy harvesting

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(Received November 2, 2010, Aceepted March 23, 2011)

Abstract. This paper presents a multi-functional system, consisting of a magnetorheological (MR) damper and an electromagnetic induction (EMI) device, and its applications in stay cables. The proposed system is capable of offering multiple functions: (1) mitigating excessive vibrations of cables, (2) estimating cable tension, and (3) harvesting energy for wireless sensors used health monitoring of cable-stayed bridges. In the proposed system, the EMI device, consisting of permanent magnets and a solenoid coil, can converts vibration energy into electrical energy (i.e., induced emf); hence, it acts as an energy harvesting system. Moreover, the cable tension can be estimated by using the emf signals obtained from the EMI device. In addition, the MR damper, whose damping property is controlled by the harvested energy from the EMI device, can effectively reduce excessive cable vibrations. In this study, the multi-functionality of the proposed system is experimentally evaluated by conducting a shaking table test as well as a full-scale stay cable in a laboratory setting. In the shaking table experiment, the energy harvesting capability of the EMI device for wireless sensor nodes is investigated. The performance on the cable tension estimation and the vibration mitigation are evaluated using the full-scale cable test setup. The test results show that the proposed system can sufficiently generate and store the electricity for operating a wireless sensor node twice per day, significantly alleviate vibration of a stay cable (by providing about 20% larger damping compared to the passive optimal case), and estimate the cable tension accurately within a 2.5% error.

Keywords: multi-functionality; stay cable; electromagnetic induction; vibration mitigation; tension estimation; energy harvesting.

1. Introduction

Cable-stayed bridges are composed of one or more of tall towers with steel cables, which support the bridge deck. The stay cables serve as the primary load carrying elements of the bridge, so their structural integrity must be well maintained and monitored. In order to properly secure the integrity of stay cables, their vibration response should be limited within an acceptable level because excessive vibrations of stay cables are directly related to the reduction of the life-span of the bridges and the serviceability deterioration. Moreover, cable tensions should be monitored to check if adequate tension forces are maintained.

Stay cables are susceptible to vibrations induced by external dynamic excitations (such as winds and traffic loadings) because of their flexibility, relatively small mass, and low inherent damping. To

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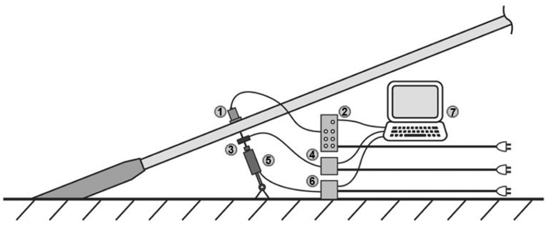
mitigate excessive cable vibrations, many methods have been developed over the past decades (such as, passive control with viscous dampers, active tendon control). In recent years, several researchers have investigated semi-active control systems based on magnetorheological (MR) dampers to suppress cable vibrations (Johnson *et al*. 2000, Ni *et al*. 2002, Jung *et al*. 2008). Fig. 1(a) shows a schematic of the MR damper-based semi-active control system for mitigating cable vibrations.

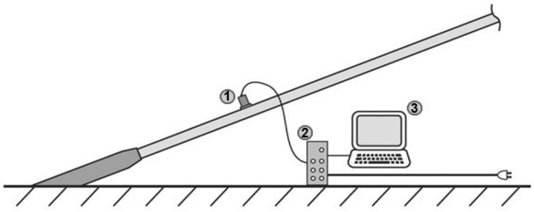
In addition to reducing excessive cable vibrations, keeping the tension force of stay cables within an acceptable range is another important task to secure the integrity of a cable-stayed bridge. This is because small variations in cable tension may cause a dramatic effect on the global response of the other parts of the bridge including the deck and pylon (Casas 1994). Therefore, the measurement of tension force of stay cables in the bridge should be carefully conducted to evaluate degradation or anchorage slippage. There exist several ways to measure the tension force of cables, such as direct methods (Kim and Park 2007) and indirect methods (Zui *et al*. 1996, Russell and Lardner 1998). Among other methods, a vibration method based on acceleration measurements has been most widely used because of the simplicity and cost-effectiveness of the method (see Fig. 1(b)).

Recently, wireless sensor technology has been introduced to the field of stay-cable health monitoring. This technology is considered as an ideal sensing solution for continuously monitoring of stay



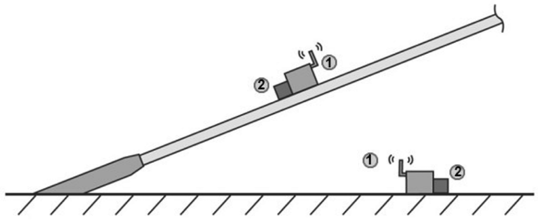
① accelerometer, ② amplifier, ③ load cell, ④ load cell amp., ⑤ MR damper, ⑥ current driver, ⑦ computer

(a) MR damper-based semiactive control system for cable vibration mitigation



① accelerometer, ② amplifier, ③ computer

(b) Tension force estimation



① wireless sensor, ② battery

(c) Wireless sensor nodes for monitoring the state of a bridge

Fig. 1 Several systems for stay cable

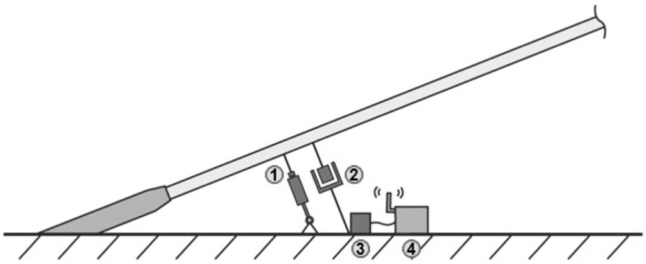
cables as well as bridge deck/towers at relatively low-cost (see Fig. 1(c)). However, for long-term operation of wireless structural health monitoring systems, the power supply issue (i.e., the requirement of periodic battery replacements) should be addressed. To deal with this issue, a few researchers have studied on energy harvesting methods based on solar panels and rechargeable batteries (Jang *et al*. 2010).

As discussed above, stay-cable bridge "service" systems require multiple functionalities in order to secure the integrity of the bridges properly. Hence, an ideal service system for a stay-cable bridge would offer multiple functionalities simultaneously. However, most of the cable vibration researches have only focused on addressing each aspect of the functionalities separately. This is inconvenient and inefficient. Thus, the primary goal of the current study is to develop a simple system which offers all the necessary functions for stay cables. The proposed system consists of an MR damper and an electromagnetic induction (EMI) device. In their earlier studies (Kim *et al*. 2008, Kim *et al*. 2009, Jang *et al*. 2008), the authors investigated an MR damper-based system, employing an electromagnetic induction (EMI) device, with aims to simplify MR damper-based semi-active systems by eliminating external power sources (i.e., batteries) and to reduce vibrations in structural systems. In the MR-damper system, the EMI device, consisting of permanent magnets and coils, was adopted to convert the reciprocating motion of a structure (vibration energy) into useful electric energy based on the Faraday's law of electromagnetic induction. The converted or harvested energy was then used to power the MR damper, changing its damping characteristics. Building on the previous studies, the current work intends to further utilize the MR-EMI system in powering wireless sensors and estimating tension force, developing a simple, yet versatile multi-functional system for cable-stayed bridge structures. The added functionalities of the MR-EMI system attributes to the fact that the converted electrical signal by the EMI device is proposal to the motion of the structures.

In this paper, each capability of the proposed system (e.g., energy harvesting, vibration mitigation, cable tension estimation) is experimentally evaluated by a series of shaking table test and a full-scale stay cable testing in a laboratory setting. In the next section, the proposed multi-functional system is introduced with descriptions of each of the functionalities of the system. Following the description of the proposed system, the experimental setups for a shaking table testing and a full-scale stay cable are described. The paper concludes with the test results and discussion of the findings from the viewpoint of each for the functionality.

2. Proposed multi-functional system

Fig. 2 represents a schematic of the proposed multi-functional system. As depicted in the figure, the proposed system primarily consists of an EMI device and an MR damper. It can be employed to an inclined stay cable as shown in the figure. In the proposed system, an EMI device plays a key role to offer several functionalities, such as the energy harvesting, velocity sensing, and cable tension estimation. The MR damper provides the vibration mitigation functionality, either passively or semi-actively. The electric power harvested from the EMI device can be accumulated in an energy storage unit for powering low-power consumption devices (i.e., wireless sensor nodes). The detailed descriptions of each of the functionality of the proposed system are provided in the subsequent sections.



① MR damper, ② EMI device, ③ energy storage part, ④ wireless sensor

Fig. 2 Multi-functional system based on an MR damper and an EMI device

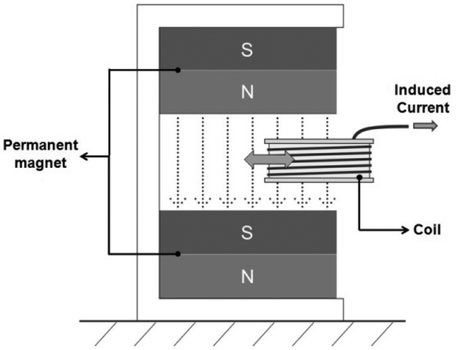


Fig. 3 Illustration of the induction based energy harvesting of the EMI device

2.1 Energy harvesting/storage functionality

An EMI device consists of permanent magnets and coils (see Fig. 3). As the coil moves in and out of the magnetic field, created by the permanent magnets, it generates the electromotive force (*emf*). In other words, the EMI device changes the kinetic energy of the relative movement between magnets and coils to the electric energy (i.e., induced current). Based on the Faraday's law of induction, the induced voltage (or *emf*) in the device is estimated as follows

$$\varepsilon = -N_E\frac{d\Phi_B}{dt} = -N_E B\frac{dA}{dt} = -N_E B\frac{d(wx)}{dt} = -N_E Bw\frac{dx}{dt} = -N_E Bw\dot{x} \quad (1)$$

where ε is the induced electromotive force that has the unit of volt (V), N_E is the number of turns of coils, Φ_B is the magnet flux, B is the magnet field, A is the area of the cross section, w is the coil width, and $\dot{x}$ is the relative velocity between permanent magnets and coils.

There are a couple of options to use the harvested energy from the EMI device for the proposed system. The first option is to directly use it as an input power to operate the MR damper. Thus, the EMI can be used as an alternative power source, eliminating the need of external power sources (i.e., batteries) being used in MR damper systems. The other option is to accumulate it in energy storage (e.g., a rechargeable battery) to power low-power consuming electronic devices and sensors. Fig. 4 shows a block diagram of a simple electric energy storage system for this option. As shown in the figure, the induced current from an EMI device is converted to a DC current through an AC-DC converter (e.g., a diode). A super-capacitor is then used to more efficiently store the generated electric power in a rechargeable battery.

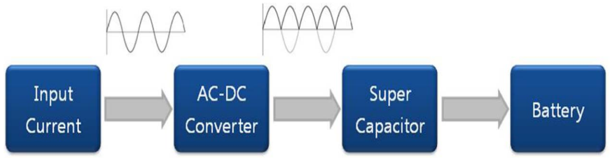
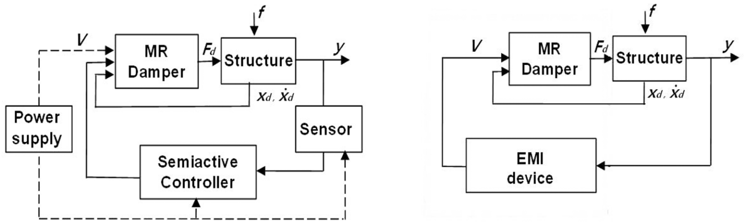


Fig. 4 Block diagram of simple energy storage of the induced current from the EMI device



(a) conventional semiactive control system (b) smart passvie control system using EMI device

Fig. 5 Different vibration control systems based on MR damper

2.2 Vibration mitigation functionality

Fig. 5(a) shows a block diagram for a conventional MR damper-based semiactive control system to mitigate the structural vibrations. As shown in the figure, it requires a controller, a power supply, and sensors to effectively operate the MR damper system. It can be significantly simplified by replacing feedback control and the power supply part with an EMI device as shown in Fig. 5(b). In the MR-EMI system, the input current to an MR damper is varied in line with the magnitude of the cable velocity as in Eq. (1), resulting in more effective vibration mitigation as compared to an equivalent passive system. However, since the proposed system shows the highly nonlinear characteristics, it is difficult to theoretically verify its superiority over other passive devices. Instead, its performance can be validated through numerical simulations and experimental tests (Kim *et al*., 2010, Kim *et al*. 2011). More discussion and test results are provided at section 4.2.

2.3 Cable tension estimation functionality

An accurate measurement or estimation of the tension force of a stay cable in a cable-stayed bridge is very important for overall structural safety. In practice, the cable tension can be calculated from the measured dynamic characteristics of the cables, such as natural frequencies and damping ratios (Kim and Park 2007). Unlike the conventional vibration method, which indirectly estimates the cable tension based on the acceleration responses measured from accelerometers placed on cables, the proposed system can estimate the cable tension based on the induced voltage generated from the EMI device without using additional sensors, such as accelerometers. While a detailed example is presented in a later section (i.e., Section 4.3), Fig. 6 describes a procedure to estimate the tension of the stay cable for the proposed system. As shown in Eq. (1), the induced emf signal from the EMI device is proportional to the velocity of the cable. Taking FFT (fast Fourier transform) of the emf signal provides its power spectral density (PSD). Using the peak-picking method, the natural frequencies of the cable can be extracted from the PSD. The natural frequencies are then substitute in Eq. (2) to calculate the tension of the cable. In the equation, y-intercept, a, is calculated by the linear regression analysis, and then the tension of a stay cable is computed as

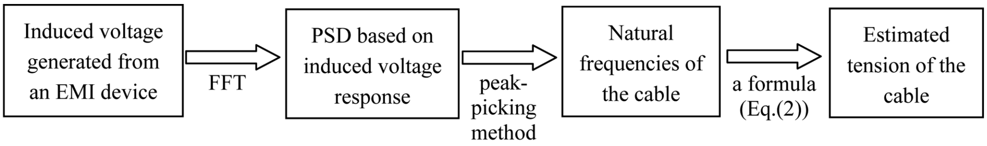


Fig. 6 Procedure to obtain the estimated tension of the cable

$$\left[\frac{f_n(1-\varsigma_n^2)}{n}\right]^2 = \frac{g}{4wl}\left[1+\frac{2\lambda^2}{\pi^4}\frac{[1-(-1)^n]^2}{n^4}\right]T + g\frac{EI\pi^2}{4wl^4}n^2 = a+bn^2 \tag{2}$$

where

$$a = \frac{g}{4wl}\left[1+\frac{2\lambda^2}{\pi^4}\frac{[1-(-1)^n]^2}{n^4}\right]T, \quad b = g\frac{EI\pi^2}{4wl^4} \tag{3, 4}$$

in which, f_n is the nth natural frequency, ς_n is the n^{th} damping ratio, T is the tension, g is the acceleration of gravity, w is the weight per unit length, l is the effective length, λ^2 is the coefficient related with sag, E is the Young's modulus and I is the moment of inertia of the stay cable.

3. Experimental setups

This section describes the proposed multi-functional system, which consists of an electromagnetic induction system (EMI) and an MR damper. It also describes the experimental setup of a shaking table test for validating the energy harvesting capability and a free vibration test setup, which includes a full-scale stay cable.

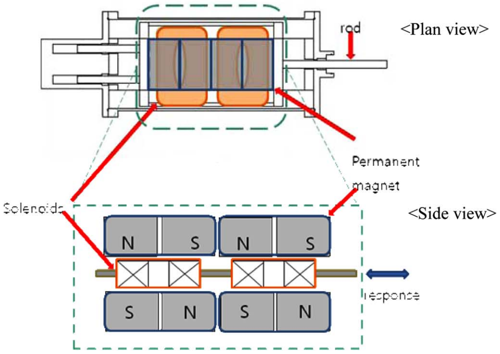
3.1 Proposed MR-EMI system

The two key components (MR damper and EMI device) for the proposed multi-functional system are designed and fabricated for cable vibration control applications by following the sub-optimal design procedure proposed by Lee *et al.* (2008). During the design procedure, the key parameters are the controllable force and dynamic range of an MR damper and the induced current of an EMI device. In the first step, the maximum dynamic range is determined by solving the optimization problem with the pre-specified controllable force at the design velocity. Then, the main design variables related to the configurations of an MR damper and EMI device are found by maximizing the induced current. More detailed design procedure of the proposed system can be found in Lee *et al*. (2008).

The MR damper's maximum damper force level is approximately 2,000 N, and its maximum stroke is 15 mm. In constructing the MR damper, the commercial MR fluid, MRF-336, manufactured by Lord Corporation is used. Further information of the MR damper used in this study can be found in Kim *et al*. (2010).

Fig. 7(a) shows a prototype of the EMI device. As shown in Fig. 7, the cylindrical-shape EMI device is designed using permanent magnets and solenoids. The permanent magnets are sintered neodymium (Nd-Fe-B) and its magnetic flux density is about 0.6 T. For the solenoid, a copper coil

(a) Prototype of the EMI device



(b) Schematics of the EMI device

Fig. 7 EMI device configuration (Kim *et al.* 2009)

with diameter of 0.9 mm is wound 1400 turns. The permanent magnet configuration with alternating poles is adopted to increase induced current. This arrangement doubles the flux density because the magnetic flux of the left part of the magnets is about +0.6T while that of the right part is about -0.6T, while the two sets are connected in series.

3.2 Shake table and cable test setup

To investigate the energy harvesting capability of the EMI device, experimental tests were conducted by using a shaking table, uniaxially driven by a servo-controlled hydraulic actuator. The shaking table has a testing platform of 110 cm by 96 cm, a maximum payload of 600 kg, a maximum acceleration of ±0.4 g and a maximum velocity of 21cm/s. The hydraulic actuator with the maximum dynamic force of 2 tons and the stroke length of ±5 cm can be controlled by a servo-hydraulic controller in a displacement or acceleration feedback mode. Fig. 8 shows the experimental setup for the shaking

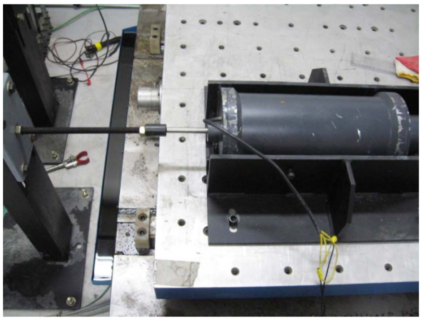


Fig. 8 Shaking table test setup

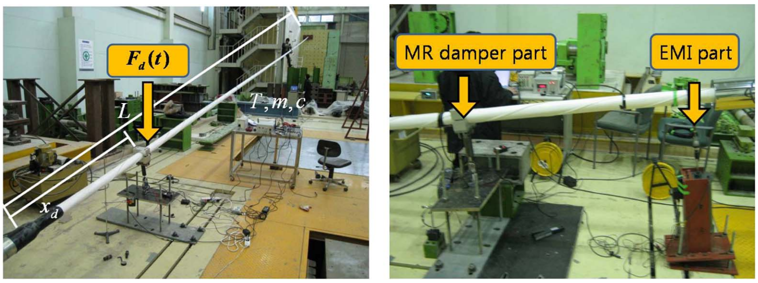


Fig. 9 Experiment setup for stay cable

Table 1 Stay-cable specifications

Parameter	Value
Cable length (L)	44.7 m
Cable mass per unit length (m)	20.3 kg/m
Modulus of Elasticity (E)	200 GPa
Diameter (D)	80 mm
Cable Tension (T)	50 Ton
Inclination Angle (θ)	8.38°

table test.

In order to experimentally evaluate the vibration mitigation and cable tension estimation capability of the proposed system, a series of the experimental tests were performed with a full-scale stay cable as shown in Fig. 9. The MR damper is attached transversely to the cable at 3% of the cable length from the bottom support, and the EMI is placed at 6% of the cable length from the bottom anchor. Table 1 summarizes the properties of the stay cable used in this study.

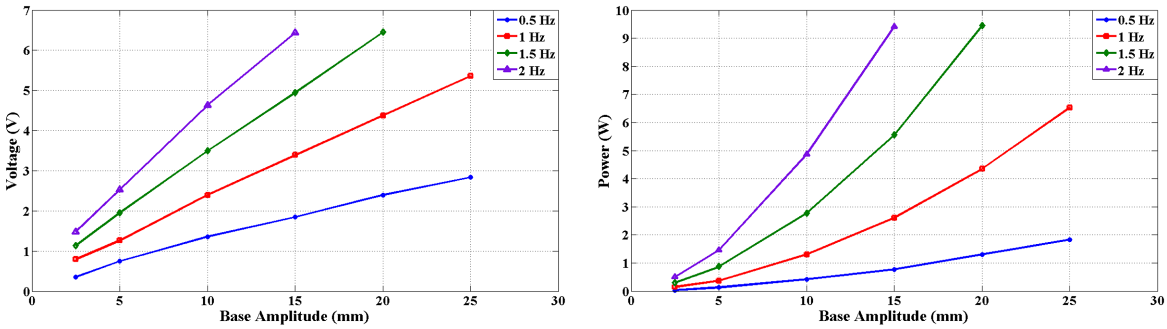
4. Experimental results and discussion

This section presents the experimental test results and discussion. Each of the three functionalities (Energy harvesting/storage, vibration mitigation, and cable tension estimation) of the proposed system is experimentally evaluated.

4.1 Energy harvesting/storage functionality

Fig. 10(a) shows the induced voltage and power by the EMI device with varying harmonic motions of the shake table. The harmonic input frequency was varied from 1 Hz to 2 Hz with an increment of 0.5 Hz, and the input amplitude was varied discretely up to 25 mm. As shown in Fig. 10(a), the induced voltage linearly increased as the base amplitude was increased. It also shows that, for given input amplitude, the induced voltage increases as the loading frequency increases. Fig. 10(b) shows the power generated by the EMI device. For the frequency and amplitude range considered in this study, the maximum power of nearly 10 Watts was produced, indicating that EMI is capable of converting vibration energy into useful electrical energy.

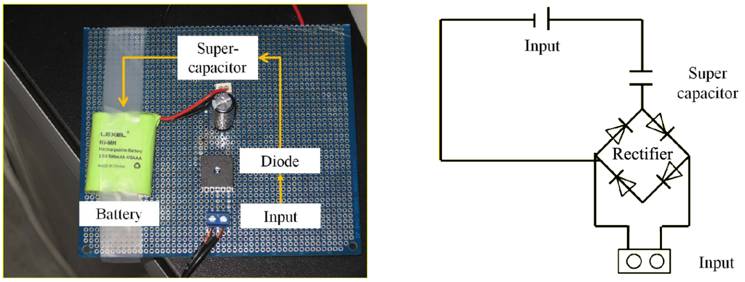
In order to examine the feasibility of harvesting vibration energy from ambient vibrations or



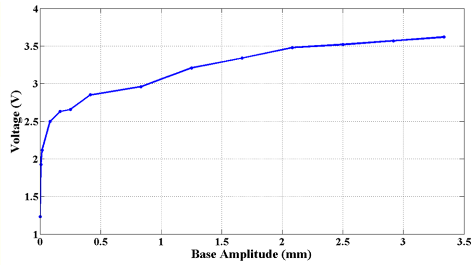
(a) Induced voltage vs. base amplitude

(b) Generated power vs. base amplitude

Fig. 10 Test results of energy harvesting capability



(a) Simple energy storage device



(b) Battery voltage vs. time

Fig. 11 Test results of energy storage device

wind-induced vibrations and storing it in a rechargeable battery for use in a cable system, a simple energy storage device was designed and constructed. The device and its circuit diagram are shown in Fig. 11(a). Using an equivalent wind-induced vibration input, the shake table testing was performed to store the induced voltage in the device. The equivalent wind vibrations were created based on the acceleration data measured from an in-service cable-stayed bridge under the average wind velocity of about 5 m/s. From the measured data, it was observed that the main exciting frequency was about 8.0 Hz. The magnitude of the input excitation in the test was scaled up by 6 times to amplify the relative motion of the EMI device. In practice, the amplification of small magnitudes of vibrations can be easily realized by incorporating a toggle linkage. Fig. 11(b) shows the amount of charged voltage in the battery as a function of time. The voltage increases from the discharged state at 1.3 V to the fully charged level at 3.6 V. The battery was charged over 50% in less than one hour and it was fully charged in about 3 hours. The results demonstrate that the EMI device attached to a stay cable under moderate wind loads can generate and store electricity.

Table 2 Estimated daily power consumption of Imote2 (Park *et al*. 2010)

Mode	Current(mA)	Power(mW)[1)]	Duration[2)]	Power consumption (mWh)
Wake-up	48	216	30[3)] sec (× n times)	1.8 (× n times)
Sensing[4)]	169	760.5	49.6 sec (× n times)	10.48 (× n times)
Data processing	80	360	9.6 sec (× n times)	0.96 (× n times)
Data transfer	55	247.5	30.8 sec (× n times)	2.12 (× n times)
Sleep	0.1	0.45	24 hour - (120 sec × n times)	10.8 - 0.015× n times
Total				10.8 + 15.34 × n times

1) Nominal input voltage for Imote2: 4.5VDC
2) n-times measurement per day
3) Wake-up time for one sensor node. It increases little as the network size increases
4) The SHM-A board was used for acceleration sensing with Imote2

As an application of the harvested energy from the EMI device for cable systems, this study investigated to see if the energy is sufficient to power wireless sensors. To this end, this study considered the power consumption of Imote2, which is a wireless sensor platform being used for long-span bridges for structural health monitoring (Park *et al*. 2010). Table 2 shows power consumptions of an Imote2 unit in a different mode of operation. Based on the formula of the total daily power consumption in the table, an Imote2 sensor node requires 26.14 mWh of power for one time of sensing per day. Similarly, a total power of 41.48 mWh is needed in the case of sensing twice per day.

From the shaking test results, the total harvested energy stored in the rechargeable battery is 1,800 mWh (i.e., 3.6V × 500 mAh). Approximately 25% of the energy may be lost during the boosting process of the voltage from 3.6 V to 4.2 V, which is a nominal operating voltage for Imote2 sensor nodes. Hence, the remaining power, around 1,340 mWh, is available for operating Imote2 sensor nodes. To be on a conservative side, assuming that about 90% of this remaining power can be consumed for powering Imote2 sensor nodes, the total power to be used for Imote2 sensor nodes is about 1,200 mWh. Assuming taking measurements twice a day, which is typical for structural health monitoring using wireless sensor nodes in bridges, this amount of power would be sufficient to operate an Imote2 sensor for nearly one month. Thus, the energy harvesting/storage capability of the proposed system can be utilized as a power source for wireless sensor nodes.

4.2 Vibration mitigation performance

In this study, a series of free vibration testing were conducted to evaluate the vibration mitigation capability the proposed system. From the free vibration testing, the first modal damping ratio of the cable is determined, and the damping ratio is used as a measure of vibration mitigation of the cable. In order to compare the relative performance of the proposed system, three cases are considered: (1) uncontrolled, (2) passive optimal, (3) proposed system (smart passive control). The uncontrolled case indicates that no damper or control system is attached to the cable. Thus, the cable vibration is reduced solely by its inherent damping. Under the passive optimal case, the MR damper of the proposed system provided damping to the system (i.e., the cable), and it is operated in a passive mode (a constant current is supplied to the damper and the EMI device is detached in this case). After conducting a series of passive control testing, the MR damper with a 2 V input is determined as the passive optimal case because it reduced the cable vibration most. For the proposed system,

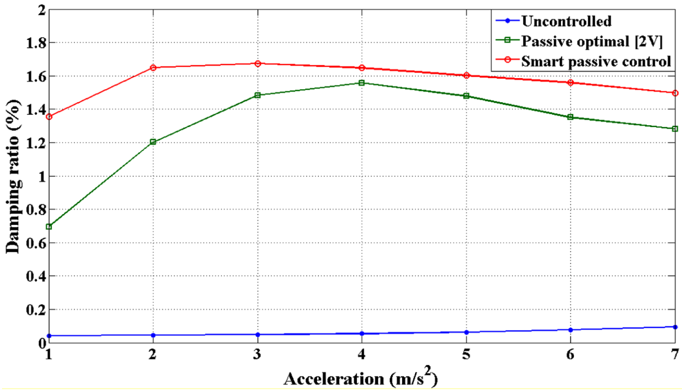


Fig. 12 Damping ratios vs. amplitude of acceleration in each control case

Table 3 RMS acceleration response in each control case

Control strategy	Uncontrolled case	Passive optimal (2V) case	Proposed system
RMS acceleration(m/sec^2)	2.5408	1.3153	1.2476

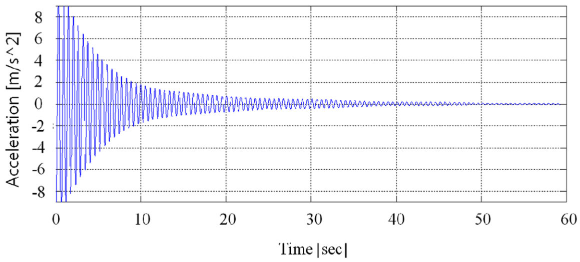
the MR damper is operated based on the induced voltage signal by the EMI device; hence, it is named as the smart passive control case in this study.

Fig. 12 shows the damping ratio changes for three different cases. As shown in the figure, the damping ratios of the passive and proposed cases are larger than those of the uncontrolled, indicating that they outperform the uncontrolled in reducing free vibration of the cable. Moreover, the proposed system has larger damping ratio than the passive optimal case over the all amplitude range. Also, the proposed system shows the relatively stable performance with respect to the acceleration level, while the performance of the passive case is dependent on the acceleration amplitude. In a sense, therefore, the proposed system is more robust than the passive case, because the variation of its damping ratio is smaller than that of the passive optimal case with respect to changes in acceleration levels. Overall, the proposed system outperforms the other two cases.

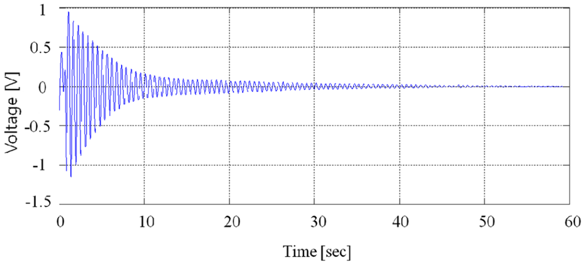
To further compare the performance of each case, the RMS acceleration responses measured at the mid-point of the stay cable are summarized in Table 3. As the table shows, the RMS responses of the proposed system and the passive control case are much smaller than that of the uncontrolled case. As compared to the passive optimal case, the RMS value of the proposed system is also smaller, indicating that the proposed system outperformed the passive optimal in reducing the RMS vibrations of the cable. Based on these test results, therefore, the proposed system can effectively reduce the vibration of a stay cable.

4.3 Cable tension estimation

In order to experimentally validate the tension estimating capability of the proposed system, the additional experiments were performed with the full-scale cable test setup. A conventional method used to estimate cable tensions based on the acceleration measurements. However, for the proposed system, the induced voltage of the EMI device can be used for estimating the tension of a stay cable. This is because the induced voltage is proportional to the velocity of the cable, so the induced signal can used to relate the dynamic characteristics of the cable.

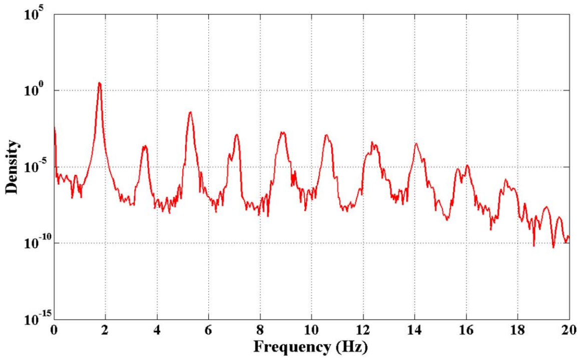


(a) acceleration

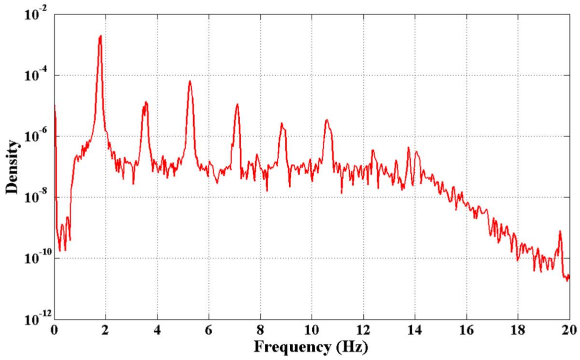


(b) induced voltage

Fig. 13 Time history responses of acceleration and induced voltage (Jung *et al*. 2009)



(a) PSD from the measured acceleration



(b) PSD from the induced voltage generated in EMI device

Fig. 14 Estimated power spectrum densities

Fig. 13 compares free vibration responses of the acceleration and the induced voltage. By using these free vibration responses, the natural frequencies of a stay cable might be extracted. As seen form the figures, two dynamic responses show similar trends even though the physical quantities (units) measured are different.

Fig. 14 shows the power spectrum densities (PSDs) extracted from the measured dynamic responses in Fig. 13 after filtering to eliminate high frequency noise (over 15 Hz). As seen from the figures, the shape of the PSD from the accelerations (Fig. 14(a)) is slightly different from that of the induced voltage PSD (Fig. 14(b)), particularly, in the high frequency range. However, the frequencies where the peak values occur are very similar between the two PSDs. The peak frequencies represent the natural frequencies of the stay cable. By using the peak-picking method, the natural frequencies of the cable are extracted for both PSDs as shown in Table 4. The table shows that the natural frequencies from the induced voltage are nearly same as those from the acceleration within 3% error.

After obtaining the natural frequencies of the stay cable, its tension force can be estimated by using a formula as in Eq. (2). Table 5 shows the actual tension of the cable and the estimated tension forces based on the induced voltage from the EMI device. There is only 2.45% error between the

Table 4 Estimated natural frequencies of cable

Mode number	1st	2nd	3rd	4th	5th	6th
Acceleration	1.7578	3.5596	5.3174	7.1191	8.8330	10.5908
Induced voltage	1.8018	3.5596	5.2734	7.0752	8.8330	10.5908

Table 5 Comparison of cable tension force

	Actual tension	Estimated tension	Error
Value	510 kN	522.5 kN	2.45 %

actual and estimated cable tensions. Thus, the proposed system is capable of estimating the cable tension using the EMI signals, eliminating the need of additional sensors or vibration testing.

5. Conclusions

This paper proposed a multi-functional system based on an EMI device and an MR damper. It can be used to secure the structural integrity of cables by mitigating excessive vibrations, estimating cable tension continuously with self-powering capability. Furthermore, the system is capable of harvest vibration energy to power wireless sensor nodes. To validate its multi-functionality, a thorough experimental investigation on each capability of the proposed system (e.g., energy harvesting, cable tension estimation, vibration control) was carried out. By conducting the shaking table test, the energy harvesting capability of the EMI device was validated. In addition, the vibration mitigation and cable tension estimation capabilities of the multi-functional system were experimentally verified by carrying out the free vibration test using a full-scale stay cable. The test results show that the proposed system can sufficiently generate and store the electricity for wireless sensor nodes, reduce vibration of a stay cable, and estimate the cable tension. Therefore, the proposed multi-functional system based on an MR damper and an EMI device could be used in cable-stayed bridges for multiple purposes.

Acknowledgments

This research was partially supported by supported by a grant (07High Tech A01) from High tech Urban Development Program funded by Ministry of Land, Transportation and Maritime Affairs of Korean government, and the Smart Infra-Structure Technology Center (SISTeC) funded by Ministry of Education, Science and Technology of Korean government.

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