Smart Structures and Systems, *Vol. 23, No. 6 (2019) 695-702*
DOI: https://doi.org/10.12989/sss.2019.23.6.695

Integrated cable vibration control system using Arduino

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(Received August 3, 2017, Revised October 19, 2017, Accepted January 18, 2019)

Abstract. The number of cable-stayed bridges has been increasing worldwide, causing issues in maintaining the structural safety and integrity of bridges. The stay cable, one of the most critical members in cable-stayed bridges, is vulnerable to wind-induced vibrations owing to its inherent low damping capacity. Thus, vibration mitigation of stay cables has been an important issue both in academia and practice. While a semi-active control scheme shows effective vibration reduction compared to a passive control scheme, real-world applications are quite limited because it requires complicated equipment, including for data acquisition, and power supply. This study aims to develop an Arduino-based integrated cable vibration control system implementing a semi-active control algorithm. The integrated control system is built on the low-cost, low-power Arduino platform, embedding a semi-active control algorithm. A MEMS accelerometer is installed in the platform to conduct a state feedback for the semi-active control. The Linear Quadratic Gaussian control is applied to estimate a cable state and obtain a control gain, and the clipped optimal algorithm is implemented to control the damping device. This study selects the magneto-rheological damper as a semi-active damping device, controlled by the proposed control system. The developed integrated system is applied to a laboratory size cable with a series of experimental studies for identifying the effect of the system on cable vibration reduction. The semi-active control embedded in the integrated system is compared with free and passive mode cases and is shown to reduce the vibration of stay-cables effectively.

Keywords: stay-cable bridge; vibration control; control algorithm; Arduino; magneto-rheological (MR) damper

1. Introduction

As the number of constructed stay-cable bridges with long-spans is increasing worldwide, maintaining constructed bridges is becoming an important issue to maintain the serviceability and safety of bridge structures. Since the first observation of wind-rain induced vibration on stay-cables in 1986 at the Meiko-West Bridge in Japan, a similar type of cable vibration has been observed in bridges worldwide, and has been one of the factors responsible for the unsafety of bridges (Chen *et al.* 2004, Maślanka *et al.* 2007). The stay-cable, one of the most significant members in a cable-stayed bridge, is a vital component that influences the safety and integrity of a bridge owing to its high vulnerability to large amplitude vibrations. The vibration caused by wind, rain, vortex, and deck-cable interactions has a negative effect on the safety of a stay-cable, creating large oscillations in the cable (Fujino *et al.* 2012). Because of the large flexibility, relatively small mass, and low damping inherent in a cable, the stay-cable has insufficient capacity itself to reduce the vibration (Johnson *et al.* 2003, Duan *et al.* 2005, Maślanka *et al.* 2007). If the cable is continuously exposed to vibrations, the lifespan of both the cable and the between the cable and the bridge deck and towers reduces owing to stresses and fatigue, threatening the bridge's safety and serviceability, as well as the level of safety the public who utilize the bridge feel (Watson and Stafford 1988, Johnson *et al.* 2003).

The passive control has been utilized as an effective and practical tool for vibration reduction; it is implemented by attaching viscous dampers transversely on the cable to improve cable damping (Li *et al.* 2007, Maślanka *et al.* 2007). Many bridges in the world have utilized the viscous passive damper on the cable to reduce vibration, including the Brotonne Bridge in France (1983), the Sunshine Skyway Bridge in Florida (1988), and the Aratsu Bridge in Japan (1989). The use of this scheme in long-span bridges, however, has revealed that, despite its effectiveness, it has installation challenges. Owing to aesthetic and practical reasons, the damper location is restricted to a location close to the cable anchor, within 5% (Johnson *et al.* 2000, Li *et al.* 2007). For a bridge having a short cable, the passive damper can provide sufficient damping by being installed at feasible location, whereas for a long-stay bridge having a cable that is over 1,000 m, the passive damper alone has difficulty in meeting the control requirement of the cable because of insufficient damping to eliminate the vibration (Johnson *et al.* 2003, Li *et al.* 2007, Huang *et al.* 2012).

The semi-active control as an alternative to passive control has received considerable attention as a new solution for vibration reduction of long stay-cables (Li *et al.* 2007, Huang *et al.* 2012). With a semi-active control, the magnetorheological (MR) damper has become a promising

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http://www.techno-press.com/journals/sss&subpage=7
ISSN: 1738-1584 (Print), 1738-1991 (Online)

semi-active damping device in civil engineering, especially in the cable-stayed bridge for vibration reduction (Duan *et al.* 2005, Wu and Cai 2006, Maślanka *et al.* 2007, Huang *et al.* 2012). Compared to the passive control with viscous damper, the semi-active MR damper has outstanding features for cable vibration reduction (Duan *et al.* 2006, Huang *et al.* 2012, Sun *et al.* 2017). Owing to the advantages of the semi-active MR damper, theoretical studies have been conducted to implement the MR damper in cable vibration control (Liu *et al.* 2006, Wu and Cai 2006). Wu and Cai (2006) conducted a performance test of the MR damper with different frequencies, temperatures, and input currents, and identified the effectiveness of the passive mode MR damper on cable vibration reduction based on the test using scaled laboratory cable. Li *et al.* (2006) installed the combined stay cable/MR damper system and conducted a series of tests to identify the efficiency of the MR damper on cable vibration control under sinusoidal excitation with the first two modal resonant frequencies. The experiments were carried out with different control strategies, passive-off (without input current), passive-on (with maximum input current), and semi-active control (based on state feedback of response), and the MR damper with semi-active control indicated better control efficacy than the passive mode. Because the stay-cable has low damping, Zhou and Sun (2013) conducted free vibration damping tests on a full-scale cable, attaching a pair of MR dampers to the cable to examine the effect of the MR damper on the cable damping. Compared to the free cable without the MR damper, the free cable with the MR damper experienced increased cable damping event though there was no applied voltage. When the passive-on voltage was transmitted to the MR damper, the damping of the cable was greatly increased. The MR damper was applied not only in theoretical studies, but also to real stay-cables of a bridge. The first application of MR damper to a real stay-cable was carried out in 2002 on the Dongting Lake Bridge in China (Chen *et al.* 2004). Since then, the MR damper has been applied to the Eiland Bridge in Netherlands (Weber *et al.* 2005), Third Qiantang River Bridge (Wu *et al.* 2004), and Bingzhou Yellow River Highway Bridge in China (Li *et al.* 2007).

Although the MR damper is known to be an effective damping device for semi-active control, many theoretical and experimental studies have used the MR damper in a passive mode without embedding a semi-active control algorithm (Chen *et al.* 2004, Wu *et al.* 2004, Weber *et al.* 2005, Wu and Cai 2006, Li *et al.* 2007, Zhou and Sun 2013). Without consideration of the state feedback of the cable response, unique cable dynamics are neglected, and it is difficult to fully maximize the efficiency of the MR damper. Even though the MR damper is used with semi-active control, this control system cannot be easily applied in the real-world owing to equipment requirements, including data acquisition system, a damping device, several cables, and a power supply device. In a recent study, Sun *et al.* (2015) developed a structural vibration control system using the Arduino platform, a low-cost, low-power platform, in which a semi-active control algorithm has been embedded. However, this Arduino-based control system was implemented on a 3-storey shear building, and few studies regarding the implementation of the Arduino-based control system on stay-cable have been reported.

The purpose of this study is to develop an integrated cable vibration control system based on the Arduino platform in which has been embedded a semi-active control algorithm. As an open source technology, the Arduino platform is a single board system, performing both data acquisition and processing functions, with a low-price and low-power consumption. A low-cost, low-power consumptions MEMS accelerometer is built on the Arduino platform to implement a state feedback of cable acceleration for the semi-active control. This study selects the magneto-rheological (MR) damper as a semi-active damping device, controlled by a semi-active control algorithm with clipped-optimal controller embedded in the Arduino platform. To identify the performance of the developed integrated control system, this study installs a cable for a laboratory experiment and conducts a series of test to estimate fundamental natural frequency and tension of a cable. A series of experimental studies are carried out to examine the efficiency of the proposed control system based on semi-active control on cable vibration reduction by comparing with passive mode control.

2. Theoretical background

2.1 Cable dynamics

The cable dynamics are derived from the motion of a taut string with assumptions of small sag and high tension-to-weight ratios in the cable (Irvine 1981). A combined cable/damper system is indicated in Fig. 1, where a damper is located x_d from the anchorage of the cable. The length of the cable is denoted as L, and m, c, and T are the mass per unit length, viscous damping per unit length, and cable tension, respectively. For a small deflection of the cable, the transverse cable motion with a damper can be represented as the following partial differential equation (Johnson *et al.* 2007, Li *et al.* 2007).

$$m\ddot{v}(x,t) - Tv''(x,t) + c\dot{v}(x,t) = f(x,t) + F_d(t)\delta(x - x_d) \quad (1)$$

where $F_d(t)$ is the transverse damping force from the MR damper at location $x=x_d$; $v(x,t)$ is the transverse displacement of the cable; $\ddot{v}(x,t)$ and $\dot{v}(x,t)$ are the corresponding acceleration and velocity, respectively; $v''(x,t)$ is the second derivative with respect to x; $f(x,t)$ is the distributed load along the cable; and $\delta(x-x_d)$ is the Dirac-delta function. The corresponding boundary conditions for cable motion are $v(0,t)=v(L,t)=0$ for all t.

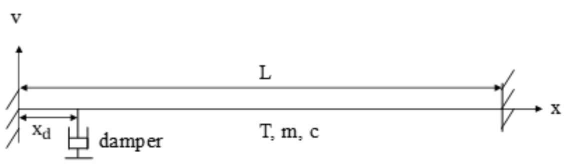

Fig. 1 Combined cable/damper system without sag

The motion of the cable in matrix form is derived by substituting the assumed excitation and approximated transverse deflection into the equation describing the cable's motion and integrating over the length of the cable.

$$M\ddot{q} + C\dot{q} + Kq = f + \phi(x_d)F_d(t) \tag{2}$$

where the mass matrix $M=[m_{ij}]$; damping matrix $C=[c_{ij}]$; stiffness matrix $K=[k_{ij}]$; generalized displacement vector $q=[q_{ii}]$; excitation matrix $f=[f_1\, f_2 \ldots f_m]^T$; shape function $\phi = [\phi_1(x_d),\ \phi_2(x_d)\ \cdots\ \phi_m(x_d)]^T$ at damping location; and mode number m. Each matrix is explained in previous studies (Johnson *et al.* 2007, Li *et al.* 2007).

The state-space form of cable dynamics can be formulated as follows

$$\begin{aligned} \dot{X} &= AX + Bf_c + Gf \\ Y &= CX + Df_c + Hf + v \end{aligned} \tag{3}$$

where $X= [q^T\ \ \dot{q}^T]^T$ is the system state, $Y= [v(x_d,t)\ \ \ddot{v}(x_d,t)]^T+v$ is a vector including displacement and acceleration at damper location, v is a vector of sensor noise, and

$$A=\begin{bmatrix} 0 & I \\ -M^{-1}K & -M^{-1}C \end{bmatrix} \qquad B=\begin{bmatrix} 0 \\ M^{-1}\phi \end{bmatrix}$$
$$C=\begin{bmatrix} \phi^T & 0 \\ -\phi^T M^{-1}K & -\phi^T M^{-1}C \end{bmatrix} \qquad D=\begin{bmatrix} 0 \\ \phi^T M^{-1}\phi \end{bmatrix} \tag{4}$$
$$G=\begin{bmatrix} 0 \\ M^{-1} \end{bmatrix} \qquad H=\begin{bmatrix} 0 \\ \phi^T M^{-1} \end{bmatrix}$$

2.2 Cable control

The semi-active control is selected as the control scheme in this study. While many controllers are known to be used for semi-active control (Aly 2013), the clipped-optimal controller based on state feedback of acceleration for semi-active control is selected because this controller is known to be suitable for the MR damper (Dyke *et al.* 1996). To make the MR damper generate the desired damping force, the clipped-optimal controller determines the appropriate command input voltage applied to the current driver for the MR damper.

The desired control force f_c is provided based on the Linear Quadratic Gaussian (LQG) control. The control of cable vibration is treated as an optimization problem, and the LQG control is used to solve this problem. A quadratic cost function is defined based on LQR theory as follows.

$$J_t = \int_0^\infty [X(t)^T QX(t) + Rf_c^2(t)]dt \tag{5}$$

where Q is a state weight matrix, R is a weight factor for control, X(t) is a system state, and f_c is the desired control force.

The desired control force is determined by minimizing a quadratic cost function based on the constraints imposed by the state-space matrix of cable dynamics as follows.

$$f_c = -K\hat{X}(t) \tag{6}$$

where K is the control gain, satisfying the algebraic Riccati equation, and $\hat{X}(t)$ is an estimated system state X(t), calculated by the Kalman filter based on the measured cable displacement at the location of the damper.

The command input voltage is determined by the relationship between damping force generated by the MR damper and the desired optimal control force. When the magnitude of damping force is smaller than that of the desired control force with the same sign, the command voltage is increased to the maximum level in order to match the damping force with the desired control force by increasing the damping force of the damper. If the damping force is the same with the desired control force, the command voltage remains constant. Otherwise the command voltage is set to zero. The clipped-optimal algorithm can be summarized in a simple equation as follows.

$$v = V_{max} H\{(f_c - F_d)F_d\} \tag{7}$$

where v is the command voltage to the current driver, V_{max} is the maximum voltage saturating magnetic field in the MR damper, f_c is the desired optimal control force, F_d is the damping force generated by the MR damper, and H(.)is the Heaviside step function.

3. Design of the Integrated cable vibration control system

This study develops an integrated cable vibration control system (Fig. 2) that performs two main functions, sensing the cable response and controlling the damping device. As a low-cost and low-power single microcontroller board, the Arduino Due is selected as a platform for the integrated vibration sensing and control system. The Arduino Due is the first Arduino product based on the 32-bit ARM core microcontroller, meeting the needs for vibration sensing and control in this study. This board has 54 digital input/output pins, 12 analog inputs, 84 MHz clock, a USB OTG capable connection, two DAC, and a 3.3 V operating voltage. For programming Arduino, an interface named the 'Integrated Development Environment (IDE)' is provided, which is capable of writing, debugging, and uploading code based on C and C++ to the board.

As the component for sensing the cable response, this study selects a tri-axial accelerometer ADXL 335 based on the MEMS accelerometer. The ADXL 335 is small and low-cost; moreover, it has a low-power consumption (350 μA), minimum measurement range of ±3g in tri-axis, and 270 mV/g of sensitivity. The sampling rate of this accelerometer ranges from 0.5 Hz to 1,600 Hz for the X and Y axes, and from 0.5 Hz to 550 Hz for the Z axis.

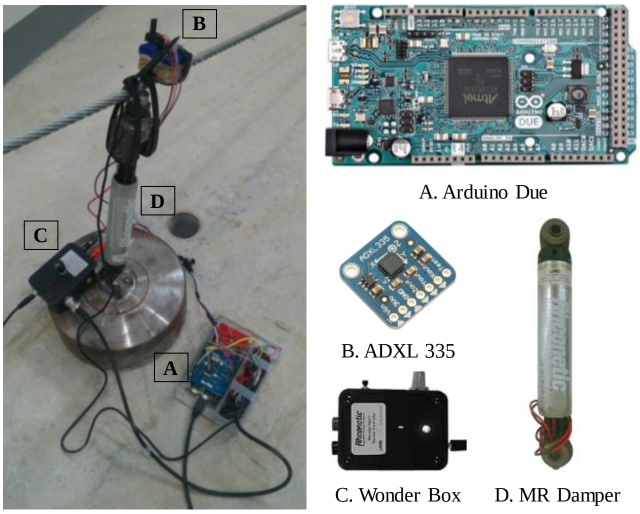

Fig. 2 Integrated control system with semi-active damping device

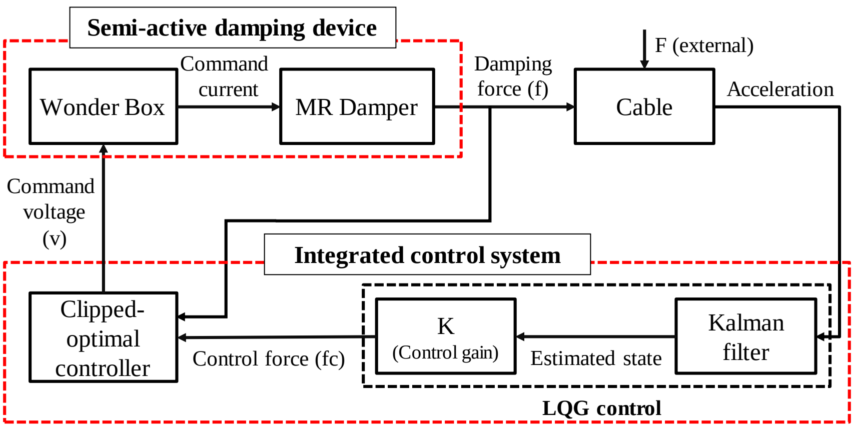

Fig. 3 Block diagram of the control process

The semi-active control algorithm is implemented on the Arduino Due through the IDE interface. For semi-active control, the LQG control algorithm is first programmed to estimate the system state using the measured cable response and provide control gain used to calculate the control force. While 20 shape functions are known to be effective for determining the control force of a cable (Johnson *et al.* 2007), cable dynamics in this study are constructed using one shape function, focusing on reducing the first mode of vibration because of the limited performance of the Arduino board.

The cable's tension is also measured to construct cable dynamics using vibration-based methods, finding the linear relationship between natural frequencies and cable tension proposed by Shimada (1994). Because of limited operating speed, the sampling rate of the Arduino board is set to 20 Hz as a maximum speed when the semi-active control is embedded. To control the MR damper's performance, clipped-optimal controller is implemented on the Arduino board to determine the command input voltage to the MR damper.

As a damping device for semi-active control, the MR damper, RD-1097-01 model, produced by Lord Corporation is selected. This model is designed to generate 100 N as its maximum damping force under 1 A of current and 51 mm/s of piston velocity. Under the passive-off mode, the damping force is less than 9 N at a piston velocity 200 mm/s. This damper has a stroke from –25 mm to 25 mm, and a response time that is less than 25 ms (response speed = 40 Hz) under a step change of the current from 0 A to 1 A for 51 mm/s piston velocity (Maślanka *et al.* 2007). Details of damper characteristics in terms of displacement, loading velocity, and input current can be found in Wu and Cai (2006). As the MR damper is controlled by the current signal, this study uses the Wonder Box to convert the command voltage produced by the semi-active control to current.

The procedure for cable vibration control is summarized in Fig. 3. At the damper location, acceleration sensed by the low-cost MEMS accelerometer is measured. This is the first cable response that is measured. The measured cable response is transmitted to the Arduino Due and used to

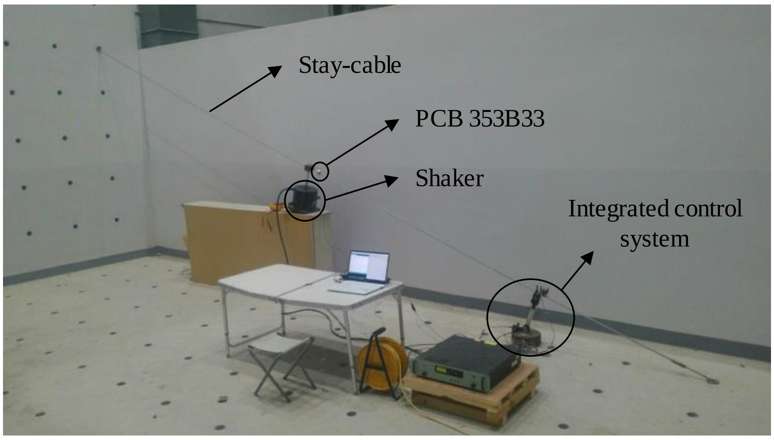

Fig. 4 Experimental setup for cable vibration control

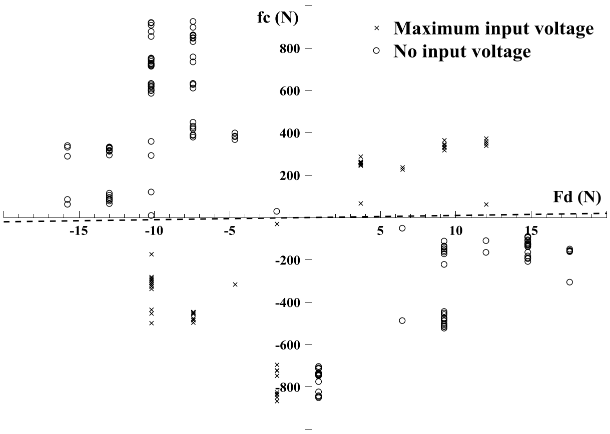

Fig. 5 Spatial distribution of control voltage depending on optimal control force and damping force (the dashed line represents $f_c = F_d$)

Table 1 Properties of the model cable

Length (m)	Inclined angle (°)	Tension (N)	Mass (kg/m)	Diameter (mm)	Break load (Ton)	Cable type	Natural frequency (Hz)		
							First	Second	Third
6.95	43	379.2	0.314	10	5.46	IWRC	2.5	5.0	7.5

calculate the desired control force through LQG control. The command voltage is generated by the clipped-optimal algorithm based on the relationship between control force and damping force measured by a load cell at the damper location. The control voltage is converted to current, and this current is applied to the MR damper to control cable vibration.

4. Experiment

4.1 Experimental setup

In this study, a cable/MR damper system for a laboratory experiment is developed to examine the effectiveness of the proposed system on cable vibration reduction (Fig. 4). The geometric and mechanical properties of the cable are indicated in Table 1. The MR damper is located 15% of the total length of the cable from the lower anchorage. An exciter (B&K Exciter 4808) is installed in the mid-span of the cable to impose in-plane sinusoidal excitation to the cable in a perpendicular direction. To measure the cable response, an accelerometer (PCB 353B33, 101.9 mv/g) is installed in the middle span of the cable. The force of the MR damper is measured by a load cell located in between the MR damper and the cable. The cable tension is fixed at 379.2 N, and its value is estimated by the vibration-based methods proposed by Shimada (1994).

4.2 Test of the integrated control system

A series of experiments to validate the performance of the proposed system were conducted with the following

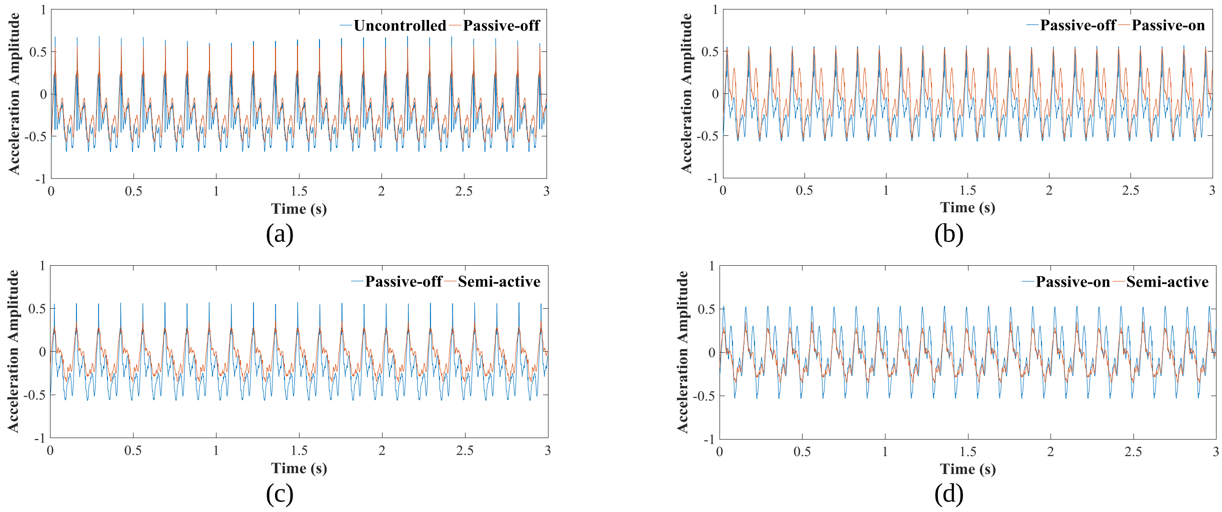

Fig. 6 Time histories of the acceleration response of the cable: (a) uncontrolled and passive-off; (b) passive-off and passive-on; (c) passive-off and semi-active; and (d) passive-on and semi-active

four control schemes: (1) without the MR damper (namely, “uncontrolled”), (2) with the MR damper having no applied current (namely, “passive-off” control), (3) with the MR damper having constant applied current (namely, “passive-on” control), and (4) with the MR damper having an inconstant current controlled by the semi-active control algorithm. The four tests were carried out with the same excitation condition under a constant amplitude and the third natural frequency (7.5 Hz). The exciter was not able to induce sufficient vibration in the first and second natural modes of the cables, whereas the third mode could be excited.

Before conducting a series of test, the performance of the system was evaluated. In particular, the system’s stability, time delay, and command signal were investigated. First, as the response speed of the MR damper (40 Hz) is higher than that of the developed control system (20 Hz), the damper can be controlled by the system with sufficient time to be saturated, showing the same result in the experiment. Therefore, developed control system could provide control voltage to the damper stably. Second, the existence of the time delay when the Arduino-based control system is operating was investigated. The time delay was not identified in the Arduino platform because the integrated control system was designed to have a maximum sampling rate of 20 Hz, running the semi-active control fully. Third, a signal of the control voltage was examined to verify whether the MR damper is well controlled or not based on a clipped optimal algorithm. The spatial distribution of control voltage is indicated in Fig. 5 for the first ten seconds operation time with a relationship between the optimal control force and damping force. This study confirmed that the MR damper is correctly controlled by the Arduino-based integrated control system satisfying the clipped optimal algorithm.

Fig. 6 represents the time histories of cable accelerations with the four different control schemes, when the driving frequency of the exciter is 7.5 Hz. The obtained acceleration responses showed that all the MR dampers with passive-off, passive-on, and semi-active control reduced the cable vibration compared the uncontrolled case. Supporting the result from Fig. 6, Table 2 shows that all passive-off, passive-on, and semi-active control schemes reduce the level of maximum acceleration compared with the uncontrolled case. Note that whereas the standard deviation of the passive-on control is larger than that of the uncontrolled case, the passive-on scheme has a lower maximum acceleration. Both passive-off and semi-active control showed lower variation in acceleration than the uncontrolled case.

This study calculated the power spectral density of cable accelerations to show a dominant mode vibration and to identify the effect of semi-active control on vibration reduction (Fig. 7), as can be seen in Zhou *et al.* (2017). Two effective control schemes, showing large vibration reduction, were chosen to compare the power spectral density of a cable response each other. Both control schemes indicated the same dominant excitation frequency (7.5 Hz). Compared to a passive-on control, a semi-active control showed more energy reduction in the excitation frequency, indicating a good performance in vibration reduction.

Table 2 Experimental results of the cable vibration control with/without control

Cases	Standard Deviation	Maximum acceleration (m/s^2)	Control efficacy (%)
Uncontrolled	0.2440	0.6834	-
Passive-off	0.2306	0.5682	16.86
Passive-on	0.2645	0.5336	21.02
Semi-active	0.1731	0.3513	48.60

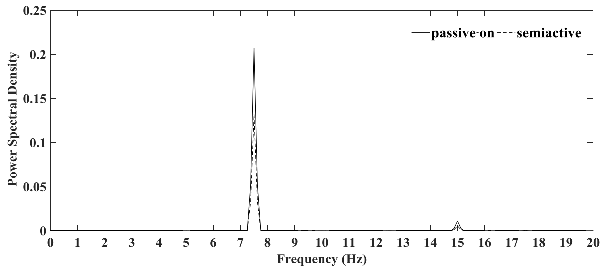

Fig. 7 Power spectral density of cable accelerations from passive-on and semi-active control

The following conclusions can be drawn from the results in Figs. 6 and 7, and Table 2. First, semi-active control most effectively reduced the cable vibration in terms of acceleration compared with passive-off and passive-on control. The cable response by semi-active control exhibits less vibration than other controls, and the control efficacy also supported the finding that semi-active control can reduce the maximum acceleration about 2.5 times more than passive-off and passive-on control. Second, both passive-on and passive-off control could reduce the cable response while showing a similar vibration reduction.

To apply the developed control system to real-world applications, it is important to identify the appropriate capacity of a power source that provides the operating power for the integrated control system. Measuring the power consumption of this system is needed to design the appropriate power source. Arduino Due, which is a platform for this system, has two components, a micro-controller and power regulator, which consume power. During normal operation, the Arduino Due micro-controller (SAM3X, 84 MHz) uses 75 mA/h, and the power regulator consumes 10 mA/h. Under the input voltage with 9 V, it is concluded that the integrated control system consumes 0.765 W/h and 18.36 W/d.

5. Conclusions

The objective of this study was to develop an integrated cable vibration control system, embedding a semi-active control. The integrated system was constructed based on the Arduino Due platform, which known to be low-cost and have a low-power consumption. This system was designed to function in two ways, i.e., sensing the cable response and controlling the MR damper to reduce cable vibration. A low-cost, low-power MEMS accelerometer was employed to sense the cable vibration, and a semi-active control algorithm was implemented in this system to reduce cable vibration. For controlling the damping device, this study implemented the clipped-optimal controller known be effective for performing semi-active control. An experimental test was carried out using a stay-cable installed for the laboratory experiment to identify the utility of the proposed system on vibration reduction and the effectiveness of semi-active control compared with passive control.

In conclusion, the results of this study have indicated that the developed integrated cable vibration control system can reduce the vibrations of stay-cables with low operating power effectively. Even though both passive and semi-active control showed vibration reduction of stay-cable, this study found that semi-active control is more appropriate for this control system, showing a larger decrease in vibration amplitude. The efficacy of semi-active control corresponds well with that found in earlier studies regarding vibration reduction of stay-cables (Duan *et al.* 2006, Huang *et al.* 2012). Several performance tests were conducted to examine the problem in stability, time delay, and signal generation of the integrated control system, and were satisfied without any problem. This work contributes to not only existing knowledge of semi-active control performance by providing experimental results, but also is a new pioneering study reporting an implementation of the integrated control system based on a low-power, low-cost Arduino platform for cable vibration control.

However, several limitations to this study need to be acknowledged. First, the developed integrated control system is designed to consider only the excitation frequency (7.5 Hz) of the cable because of a hardware limitation of the Arduino platform. With a low sampling rate of 20 Hz, this system is limited to mainly reducing the energy in the single mode (7.5 Hz) of the vibration caused by the exciter. Further study is needed to consider more modes of cable vibration to improve the vibration reduction capability. Second, the scope of this study is limited to the application of the integrated control system to a laboratory-size cable. Further work needs to be done to verify the performance of the control system by applying this system to a real bridge structure. Third, the proposed system needs additional equipment, including a power supply and wire, making its installation more complicated and economically inefficient. To apply this system to a real constructed stay-cable, further study is recommended to make a wireless-based integrated control system and generate the power needed to operate the control system using natural energy such as solar power.

Acknowledgments

The research described in this paper was financially supported by a grant (16CTAP-C097436-02) from Infrastructure and Transportation Technology Promotion Research Program funded by Ministry of Land, Infrastructure and Transport of Korea government.

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