Employing wireless sensing technology in smart structures

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Abstract: Wireless sensors and sensor networks are emerging as a new paradigm for the implementation of cost-effective structural health monitoring (SHM). A significant benefit of wireless technology for this application is that it is much less expensive to install and maintain because few cables are needed. Although wireless technology has been examined for SHM applications, little attention has been paid to the possibility of real-time control applications using wireless technologies. In semi-active control systems that would most likely be powered by a battery, the cost savings are significant in terms of installing and maintaining the wireless network. However, because a power source is nearby, or can be placed nearby, the limitations regarding power are not as severe as in SHM applications. Furthermore, centralized processing of the data is important for high performance control designs making wireless technology beneficial. For such an application the need for real-time measurement at reasonably high sampling rates (relative to the system under control) is paramount. The purpose of this paper is to demonstrate the feasibility of wireless sensing technology in seismic response control.

Key words: MR Dampers, wireless sensors, protective systems, structural control

INTRODUCTION

Research has been conducted for over a decade regarding structural control systems for the purpose of infrastructure protection during natural catastrophes such as earthquakes, hurricanes, and strong winds. Most recently, researchers have studied the use of semi-active control devices such as magnetorheological (MR) dampers. Semi-active controllers cannot input mechanical energy into a controlled system, but are able to adapt to best minimize the affect of such disturbances on a structure.

Wireless sensors and sensor networks are also emerging as a new paradigm for the implementation of cost-effective structural health monitoring (SHM) systems (Spencer 2004). A significant benefit of wireless technology for civil engineering applications is that they are much less expensive to install and maintain because fewer cables are needed. The possibility for dense sensor networks that can process large amounts of data, most likely in a decentralized manner, is promising.

In this field, Lynch (2006) a summary review of the collective experience the structural engineering community has gained from the use of wireless sensors and sensor networks for monitoring structural performance and health. Ruiz-Sandoval et al. (2003, 2004) have reported their experiences using the MICA Mote wireless sensing platform for structural monitoring. Based on extensive experience using the MICA and MICA2 platforms, Spencer (2003) has identified critical hardware issues that must be addressed before the MICA Motes can be used for SHM.

While research has been conducted on the subject of implementing MEMS into *structural health monitoring* systems, this paper proposes to experimentally demonstrate the use of the wireless sensors in *structural control* systems for the purpose of earthquake protection. In semi-active systems that would most likely be powered by a battery, the cost savings in terms of installing and maintaining the wireless network are significant. However, because a power source is nearby, or can be placed nearby, the limitations regarding power are not so severe. Centralized processing of the data is also important for high performance control designs making wireless technology beneficial. For such an application the need for real-time measurement at reasonably high sampling rates (relative to the system under control) is paramount. Although there are numerous advantages, the use of wireless sensors has some limitations in the structural control problem formulation. Data can only be reliably transmitted, at best, around 50 Hz with modern off-the-shelf sensors. Thus, in real-time control, latency in the production of the control signal may become an issue. Occasional data loss is observed as well (Clayton 2006).

The purpose of this paper is to demonstrate the feasibility of wireless sensing technology in seismic response control. A real-time shake table test of a 3-story structure using wireless acceleration sensors was conducted at the Washington University Structural Control and Earthquake Engineering Lab. Experiments are conducted on a lab structure using MR dampers in conjunction with a clipped-optimal controller. The results of a control experiment using the wired accelerometers are compared with those using off-the-shelf wireless accelerometers. A wireless sensor is installed on the second and third floors of the tested structure to measure the acceleration of the floors. The nominal discrete controller design follows the matched pole-zero method to eliminate 'warp' phenomenon due to the low sampling rate of the wireless sensor.

EXPERIMENTAL SETUP

The experimental structure represents a three story building (see Figure 1). The model is made of steel columns and 11.35 kg steel plates. The first and second floor each consist of three plates: one 30.48x50.8x0.95 cm (12x20x3/8 in) plate and two 30.48x38.1x1.27 cm (12x15x1/2 in) plates with a total mass of 34.05 kg. The third floor consists of one 30.48x50.8x0.95 cm (12x20x3/8 in) plate and one 30.48x38.1x1.27 cm (12x15x1/2 in) plate with a total mass of 22.70 kg. These masses were chosen so the building would give natural frequencies within the range of the wireless sensors. Each story is supported by four 3.175x30.48x0.3175 cm (1.25x12x1/8 in) steel columns with fixed connections. The stiffness of each floor is 29,700 N/m. Several experiments have been previously conducted with various configurations of this structure (e.g. Jansen 1999; Yoshida 2003).

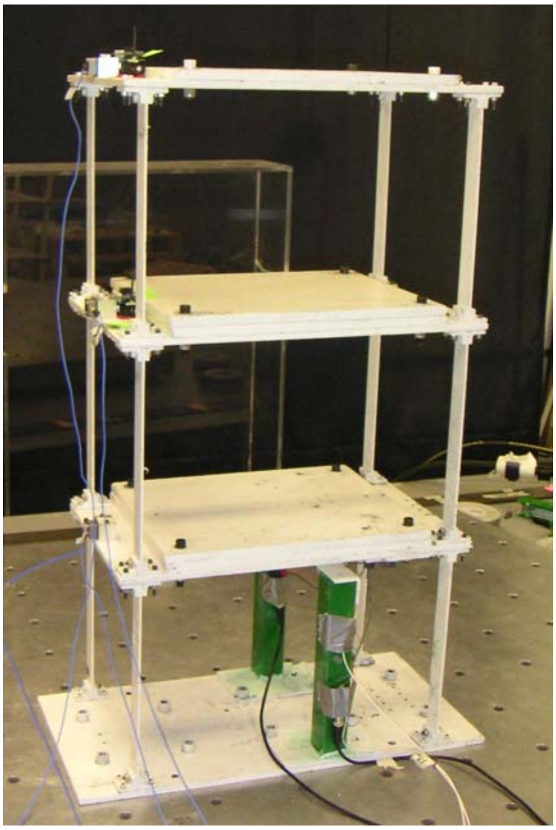

Figure 1 Test Structure.

Two Lord Corporation shear mode MR dampers are used between the ground and the first floor of the structure to provide the control force (see Figure 2). The devices consist of a paddle which slips between two steel plates that are mounted to a coil to generate the magnetic field. The paddle has foam on each side which is saturated with MR fluid (Jansen and Dyke, 2000). Current is supplied to each MR damper by a Lord Corporation Rheonetic Wonder Box Device Controller. As the magnetic field is increased, more force is required to slide the paddle between the plates of the MR device. Two PCB 208B01 force transducers, powered by PCB 484B06 Power Units, are used to measure the force applied to the structure for feedback to the controller.

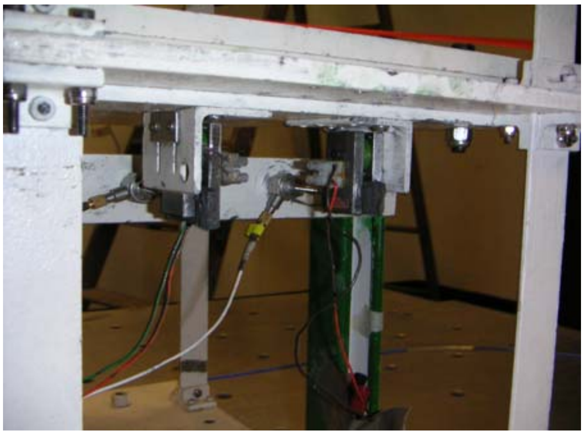

Figure 2 MR Damper Installation.

Wired sensors are used for data acquisition and system evaluation, as well as for the initial tests to confirm the performance of the control system prior to wireless testing. For the wired portion of the experiment, four PCB 370A02 accelerometers are used to measure accelerations of the ground and each floor of the structure. The configuration is shown in Fig. 3a. The data from the accelerometers is amplified by a factor of 10 with a PCB 483B08 Signal Conditioner and then sent to two Siglab 20-42 data acquisition boxes which were used with Matlab to collect the data.

For the wireless studies, two rectangular (2.25x1.25x.25 in) Crossbow Technology, Inc. MicaZ motes, which run on two AA batteries, are used to transmit the acceleration information gathered using the sensor board's ADXL202JE MEMS accelerometers. Each mote integrates a microcontroller, a radio tranceriver, and a sensor board onto one small platform. A mote can communicate with other computers or electronic devices through the radio. Motes can either obtain their power by tapping into a power grid or by running off batteries and can be programmed to be "asleep" when they are not needed thus consuming less power. These motes can be used to gather information including, but not limited to, light, temperature, pressure, strain, and acceleration. These MicaZ motes are programmed to acquire acceleration data over a range of -0.25g to +0.25g corresponding to 40 discrete values of the 10 bit A/D converter on the board. Two Mote*iv* TelosB motes are connected to a computer and used to receive the transmissions from the MicaZ motes.

A digital-to-analog converter was built to facilitate connection of the sensor outputs from the TelosB motes to the DSP-based, real time controller, manufactured by dSpace, Inc. for control action determination. In the real world, an integrated digital receiver and real time controller would be implemented eliminating the need for the D/A converter.

The integration of the wireless sensors led to several challenges. First of all, separate computers had to be used: one for wirelessly receiving the data and another for providing the control signals. Furthermore, an D/A converter had to be built and employed by the system. This resulted in a delay to the wireless data which consequently affected the controller's performance.

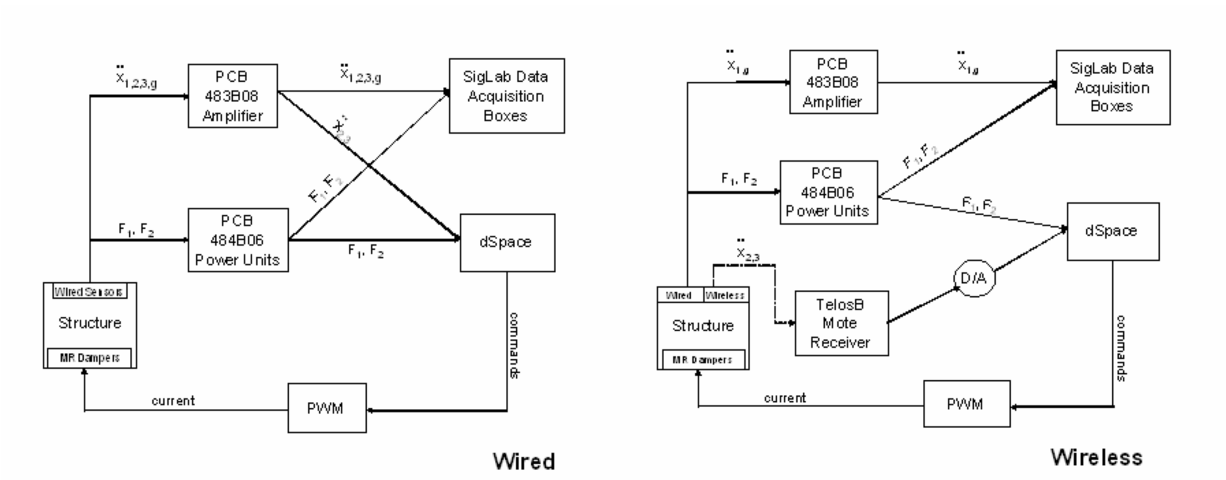

Figure 3 Schematic of the Wired (a) and Wireless (b) Experiments

IDENTIFICATION OF EXPERIMENTAL STRUCTURE

To obtain a mathematical model of the system for control design, transfer functions which mathematically relate the input and output of a system, were obtained experimentally for each floor with respect to the ground excitation and the applied control force. First, a white noise random ground excitation was used to determine the transfer function of each floor. Then, using a PCB 086C03 modally tuned impact hammer to strike the building, the natural frequency due to an applied force was found, again for each floor. The first, second, and third natural frequencies of the building were determined experimentally as 2.28, 6.36, and 8.99 Hz, respectively, with damping ratios of 0.018, 0.010, and 0.010.

Using the identified frequencies and damping ratios, a model of the structure is formed using a control-oriented method based on an analytical model of the structure (Giraldo et al. 2004). The three story lab structure can be represented by the dynamically equivalent three degree-of-freedom system with the equations of motion

$$M\ddot{X}(t) + C\dot{X}(t) + KX(t) = MI\ddot{x}_g(t) + \Lambda u(t) \tag{1}$$

where $X(t)=[x_1, x_2, x_3]^T$; $u(t)$ denotes the control force; $I=[1,1,1]^T$; $\Lambda=[1,0,0]^T$; $M=\mathrm{diag}([m_1, m_2, m_3])$; and

$$C = \begin{bmatrix} c_1+c_2 & -c_2 & 0 \\ -c_2 & c_2+c_3 & -c_3 \\ 0 & -c_3 & c_3 \end{bmatrix};$$

$$K = \begin{bmatrix} k_1+k_2 & -k_2 & 0 \\ -k_2 & k_2+k_3 & -k_3 \\ 0 & -k_3 & k_3 \end{bmatrix}$$

An analytical model is first formed using the theoretical parameters of the structural model based on the mass and dimensions. The stiffness and damping matrices are then adjusted using the method developed by Giraldo et al. (2004) to obtain a more accurate input-output model of the structure. Using the identified natural frequencies and damping ratios of the experimental system, f_e=[2.28 6.36 8.99] Hz, h_e=[0.018 0.010 0.010] and $\Phi = [\phi_1 \quad \phi_2 \quad \ldots \quad \phi_n]$ where ϕ_i are the eigenvectors of $M^{-1}K$ for the analytical model of the structure, the following equations are used to obtain the identified stiffness and damping matrices.

$$K_{id} = M\Phi diag([2\pi f_e]^2)\Phi^T \tag{2}$$

$$C_{id} = M\Phi diag(2h_e[2\pi f_e])\Phi^T \tag{3}$$

CONTROL DESIGN

The principle of the clipped-optimal control algorithm (Dyke et al. 1996) for the MR damper is interpreted as follows: First, a nominal active controller is assumed and designed as the *primary* controller. Then, a *secondary* bang-bang-type controller is designed to drive the MR damper through the command voltage signal to emulate the *primary* controller.

For the design of *primary* controller, Spencer et al. (1994) successfully proposed a H_2/LQG control design for seismic protection. To design the controller, an infinite horizon performance index is chosen to weigh the appropriate structural control parameters, i.e.,

$$J = \lim_{\tau\to\infty} \frac{1}{\tau} \mathrm{E}\left[\int_0^\tau \{y_r^T Q y_r + u^T R u\} dt\right] \tag{4}$$

where $y_r=[d_1\ d_2\ d_3\ a_1\ a_2\ a_3]^T$ is the vector of responses that can be regulated, and d_i and a_i are the relative displacement and absolute acceleration of the i^{th} floor (i=1-3), respectively. Additionally, R is a 1x1 identity matrix (R=1), and Q is the response weighting matrix, given in the form

$$Q = \begin{bmatrix} q_1 I_{3\times3} & 0 \\ 0 & q_2 I_{3\times3} \end{bmatrix} \tag{5}$$

In the experiment, the primary control design is a discrete-time, feedback compensator of the form

$$x^c_{k+1} = f_1(x^c_k, y_{m,k}, f_{m,k}, k) \quad (6)$$

$$u_k = f_2(x^k_c, y_{m,k}, f_{m,k}, k) \quad (7)$$

where x^c_k, $y_{m,k}$, $f_{m,k}$ and u_k are the compensator state vector, the measured acceleration responses, the measured damper force, and the desired control force at time $t=kT$.

The above discrete controller design follows the matched pole-zero method to eliminate 'warp' phenomenon due to the low sampling rate of the wireless sensor, which is 50 Hz.

The purpose of *secondary* controller is to determine the command voltage to make the MR damper force emulate the desired control force. In this paper, a clipped optimal controller is used which follows the bang-bang type control. The voltage applied to the MR damper can be commanded as follows.

$$v_k = V_{\max} \cdot H(\{u_k - f_{m,k-1}\} \cdot f_{m,k-1}) \quad (8)$$

where v_k is the voltage applied at time $t=kT$; $V_{\max}$ is the maximum voltage of the damper; u_k is the desired optimal control force at time $t=kT$; $f_{m,k-1}$ is the measured damper force at time $t=(k-1)T$, respectively, $H(\cdot)$ is the Heaviside step function.

EXPERIMENTAL RESULTS

To validate the controller performance and to provide a basis for comparison, tests were initially performed using wired accelerometers for feedback measurements, in which a random white noise (0-20 Hz) was used for the ground excitation. These tests are referred to herein as the "wired tests." The structure was excited for three minutes at various disturbance amplitudes in passive-off and passive-on states. For the passive-off state, a zero volt signal was sent to the dampers so that the only force they provided was due to the friction of the paddle sliding between the parallel plates. A 4V constant command (corresponding to maximum voltage) was applied to both MR dampers for the passive-on state.

Four different controllers were then applied for evaluation of the semi-active control system. The four controllers are optimally clipped designs that employ different weighting values and responses. Moderately aggressive control designs were used to reduce the impact of modeling errors and latency on the performance of the semiactive system.

The results of the wired tests demonstrated that the semi-active systems performed better than the passive systems (Table 1). The best controller was identified and used for the remainder of the wireless testing. In all subsequent tests, wireless sensors are used for feedback while wired accelerometers are used for data acquisition and control system evaluation. As in the wired experiments, the controlled system was excited for three minutes using a ground acceleration with similar frequency domain characteristics.

Table 1 provides the results from the experiments. Note that moderate performance gains are achieved by the controller. The wireless system is able to achieve reasonable performance in comparison with the wired system. However, a loss in performance is observed due to the D/A converter lags and data quantization with the wireless sensors.

CONCLUSION

The purpose of this experiment has been to demonstrate the use of wireless sensors for structural control applications. The use of wireless sensors as presented in this paper could prove to be a more economical and attractive option than their wired counterparts. To examine their performance for protective systems, a three-story structure was subjected to various amplitudes of random white noise excitations. Several clipped-optimal controllers were designed and tested, and once the best was identified, the experiment was performed using wireless accelerometers. The results were then compared to the results of the wired testing, and the use of the wireless sensors with the controller successfully lessened the motion of the structure only under the high amplitude excitation.

Because this experiment was performed in a laboratory rather than having equipment designed specifically for the application, some steps were taken that would not be necessary in the real world. For instance, an integrated digital receiver and real-time controller would likely be used for real world implementations, whereas in the lab it was necessary to employ a D/A converter and low-pass filter between the sensors and the real-time control hardware. Most likely, the results of the experiment could be improved with the use of more suitable equipment. If the controller could change the digital data into analog data without the use of a separate D/A converter, then the lag in the wireless measurements would not exist, or would at least be insignificant. Also, as advances are made in technology regarding wireless motes and MEMS, the accelerometer boards will operate with higher precision, which will also improve their performances with the controller.

While this research has provided a greater understanding of wireless accelerometers and their use with control systems, many questions remain unanswered. Often, in wireless transmission, some amount of data is lost, but this project did not test the extent of the data loss, nor did it relate the data loss to the performance of the controller. Furthermore, the motes used in this experiment are designed to measure "packets" of data and then transmit several seconds of recorded data at a time; whereas, for the purpose of control, it is best that the motes read and transmit each sample point immediately. In the future, perhaps different communication strategies could be used to repeat this experiment.

In summary, with the current technology and products on the market, wired accelerometers provide the most reliable, accurate results when used with structural control systems; however, wireless accelerometers have the potential to revolutionize the field of structural control as breakthroughs in the field of wireless technology are made.

Table 1 RMS responses of the experimental systems tested.

	Acceleration (cm/s^2) rms			Control Force (N) rms
	First Floor	Second Floor	Third Floor	
Large amplitude random white noise (rms = 292.8 cm/s^2)				
Passive-off	99.1	111.8	141.6	4.6
Passive-on	94.3	99.6	108.4	22.3
Wired Controller	82.8 (0.84/0.88) †	89.4 (0.80/0.90)	113.9 (0.80/1.05)	8.2
Wireless Controller	86.4 (0.87/0.91)	95.7 (0.86/0.96)	108.6 (0.77/1.00)	16.9

† = (% passive off / % passive on)

ACKNOWLEDGEMENTS

Support from the following sources is gratefully acknowledged: NSF Research Experience for Undergraduates at Washington University (EEC-0353718), STARS Program at UMSL funded by Pfizer Inc. and Solutia Inc., Beijing Jiaotong University, and NSF ITR grant CCR-0325529.

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