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An active mass damper system for structural control using real-time wireless sensors

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ABSTRACT

In the field of civil engineering, wireless sensor networks are conceived to be deployed in structural monitoring systems. In the structural control applications, the requirement of continuous and real-time sensing represents the main challenge for the wireless sensor network due to the problem of data loss. In this paper, the authors attempt to introduce wireless links and a digital controller into a structural control system for a reduced-scale three-story steel frame mounted on a shaking table. The structural control system mainly consists of four accelerometers, a structural controller, and an active mass damper as actuator. The designed wireless sensors are based on the use of recent low-power System-on-Chip wireless CC1110 transceivers, which integrate an 8051 microcontroller core and are able to operate in most of the license-free ISM (Industrial, Scientific and Medical) frequency bands. The active mass damper is driven by a newly designed digital PID (proportional, integral, and derivative) direct-current motor controller, which is based on the high integration power amplifier LMD18200 and the enhanced 8051 core in CC1110.

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KEY WORDS: structural control; active mass damper; wireless sensor; frequency division multiplexing; PID controller

1. INTRODUCTION

In the last 20 years, many attempts to introduce structural control in civil engineering (which is characterized by systems with large masses) were made [1]. Among others, one of the main inconveniences was associated with the cables connecting the sensor units (necessary to provide the control feedback) to the managing computer (where the sensor signals are processed and elaborated) and the computer to the actuators. These physical connections between parts distantly located across the building are often in conflict with the architectural constraints. Furthermore, their vulnerability to mechanical damage may cause the control system to be put out of service.

Wireless sensor networks could then represent a convenient alternative [2–6]. Nevertheless, they were originally developed without the constraint of real-time transmission. Indeed, the wireless system is designed to store a set of sensor readings and then to send the entire pack to the receiver. Therefore, a modification is required to guarantee the real-time feature of the wireless transmission. The main modification introduced in the solution proposed by the authors consists of adopting a frequency division multiplexing (FDM) technique instead of the most usual time division multiplexing method.

In this paper, an active mass damper (AMD) system, originally conceived in the authors' laboratory for a reduced-scale three-story steel frame, is updated by introducing a wireless sensing system and a digital proportional, integral, and derivative (PID) direct-current (DC) motor controller. The new

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system mainly consists of four wireless accelerometers adopting FDM communication, a structural controller, and an AMD that is based on a DC motor driven by the newly designed PID controller. Laboratory tests are carried out to validate the system.

2. STRUCTURAL CONTROL SYSTEM

The typical active structural control system shown in Figure 1 consists of sensors, which measure the response of the controlled structure; a controller, which processes the data from the sensors according to the associated algorithm and determines the control output signal; and an actuator, which receives the signal from the controller and then generates the control force to be applied to the structure. Therefore, if the controlled structure is regarded as a closed-loop system, the structural control system represents the feedback branch. AMD is a typical active structural control system [7–9].

In the authors' laboratory, the controlled structure is a three-story steel frame of reduced size [10]. It is placed on a shaking table whose motion is used as excitation. The sensors are four uniaxial accelerometers, Kinemetrics FBA-11, installed on each floor of the structure and on the shaking table. The actuator is an AMD mounted at the top of the steel frame. The controller (see Figure 2, excluding the dotted block) is mainly based on the microcontroller C8051F007, which interfaces with four analog-to-digital input channels and two digital-to-analog output channels [6]. Two control algorithms (namely, a linear control and a fuzzy control algorithm) were implemented [6,10]. The firmware has been designed with main focus on easiness of use. The HyperTerminal software is used to access the embedded shell interface exposed by the board through a set of commands.

To introduce wireless data transmission into this structural control system, the original controller needs to be slightly modified. As shown by the dotted block in Figure 2, the wireless transceivers connected to the microcontroller are added via an SPI interface. The wireless transceivers are used to prompt commands to the wireless sensors and to collect the data from them as well. The user can choose to acquire either the wireless or the wired signal input through the computer.

The AMD used in this experiment consists of a uniaxial moving mass. The mass is attached to a cart that is driven by a DC motor through a gear. Control of the position of the moving mass is achieved by a proportional derivative servo controller based on a displacement measurement, which is given by a potentiometer attached to the moving cart.

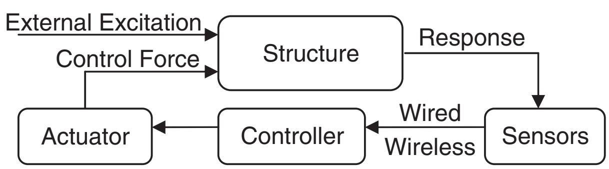

Figure 1. The active structural control system.

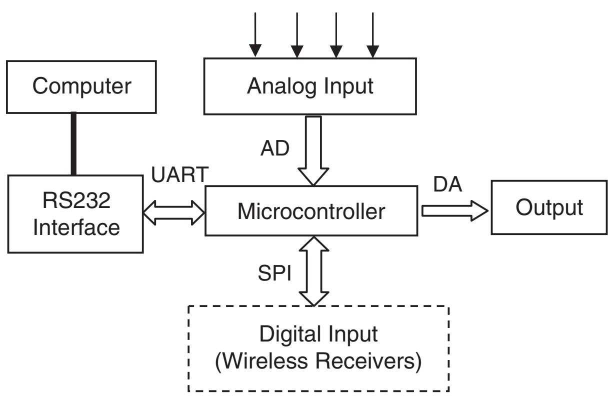

Figure 2. Block diagram of the controller.

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The position servo controller of the DC motor was originally designed and implemented by Quanser Consulting. The authors replaced the old electronics with a new one based on a digital PID control method and a pulse width modulation (PWM) driving scheme. This replacement is accomplished by using the H-Bridge LMD18200T [11], which is more power efficient than a linear amplifier. Compared with the previous motor controller, the new one resulted to be much smaller and more power efficient.

3. WIRELESS SENSING SYSTEM

The wireless sensing system is conceived to replace the cable connection between each of the four sensors and the structural controller, which requires real-time and continuous data acquisition from the sensors. The adoption of a conventional time division multiplexing method encounters the problem of a high transmission delay when many channels are required. This observation led the authors to pursue instead an FDM approach. In the FDM communication, the different signal channels operate on different frequency bands, so that the data transmission can occur simultaneously without conflicts. As shown in Figure 3, each channel of the wireless sensing system is formed by a pair of transceivers, one of which is mounted on the wireless sensing unit (WSU) and the other is connected to the structural controller by the SPI bus. In the SPI bus, the structural controller is the master end and the other transceivers are the slave ends. Only the structural controller can issue communication.

During one cycle of remote data sampling, the controller broadcasts a command to the transceivers, which then send the wireless request to the corresponding WSUs. When the request is received, the WSUs start to perform the AD conversion, and they send the sampled data back to the corresponding base station transceiver. In this manner, the synchronization of the sensing system is guaranteed. To achieve the sampled data, the structural controller communicates with each of the four transceivers in turns during predetermined time intervals. When a data point is lost in the wireless communication, the previous value is repeated.

The WSU [12] associated to each sensor is installed on the structure. It is responsible for powering the sensor, acquiring the structural response data, and sending them to the wireless station. Therefore, it plays the most important role in the wireless sensing system. The block diagram of its hardware at the component level is shown in Figure 4.

Being the WSU initially designed for a tri-axial accelerometer, three input channels are required. The low-power instrument AD620B is used to amplify the signal from a sensor and to change its bias in order to match the input to the analog-to-digital converter ADS8343. Before the conversion, a fourth-order Bessel filter of four channels is applied to perform the anti-aliasing. The ADS8343 has four channels, a resolution of 16 bit, and a maximum sampling rate of up to 100 kHz, which is sufficient for structural monitoring applications. The CC1110 is a System-on-Chip transceiver, which includes not only a wireless transceiver but also an enhanced 8051 microcontroller core, so that no external microcontroller is required.

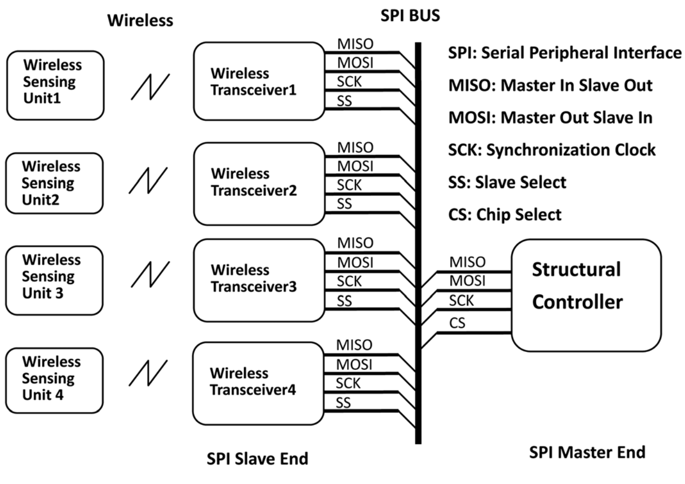

Figure 3. Architecture of the wireless sensing system designed for structural control applications.

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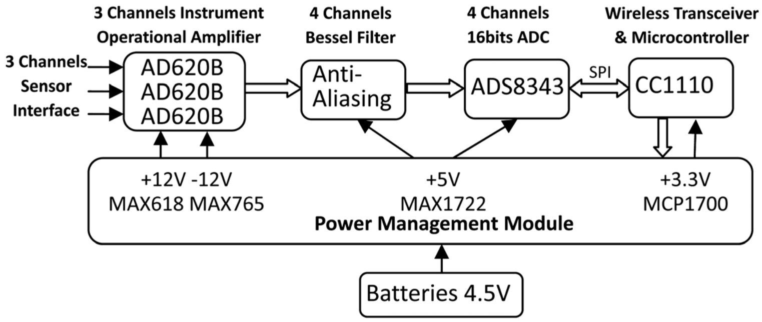

Figure 4. The component-level block diagram of the wireless sensing unit.

To make this platform suitable for both low-power and non-low-power structural monitoring applications involving different types of sensors, a flexible and efficient power management module is designed. It consists of a low-dropout linear regulator, MCP1700, with a quiescent current of 1.6 A, and three switching regulators (namely, MAX618, MAX765, and MAX1722), which feature low quiescent current, highly efficient power conversion, adjustable output voltage, and a medium output power [7].

4. ACTIVE MASS DAMPER

As shown in Figure 5, the AMD used in this experiment consists of a uniaxial moving mass. The mass is attached to a cart, which is driven by a DC motor through a gear. The control of the position of the moving mass is achieved by a newly designed PID controller based on the displacement measurement given by a potentiometer attached to the moving cart. The maximum stroke is ± 15 cm with a nominal maximum acceleration of 5g. The total moving mass is 1.7 kg, making the moving mass approximately 1.2% of the total mass of the structure.

As shown in Figure 6, the motor servo control system consists of a CC1110 processor, which implements a PID algorithm; a digital to analog converter in the form of a PWM, which uses the duty cycle to represent the magnitude of the signal; a power amplifier LMD18200, which is an H bridge for driving the motor; and a position sensor in the form of potentiometer.

The block diagram of the PID algorithm is shown in Figure 7, where $U(k)$ is the error, at step k, between the set point position and the actual position; $Y(k)$ is the output to the PWM; the Z^{-1} operator indicates a single sample time delay; and the saturation represents the input range of the PWM. The optional anti-windup logic is used to stop the integrator when the output is saturated to avoid excessive oscillation.

The processor inside the CC1110 is an enhanced 8051 core capable to operate on a system clock up to a frequency of 26 MHz. Owing to its high speed, the time required to perform one sample time PID

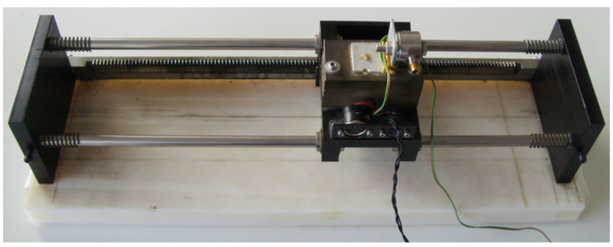

Figure 5. Photo of the active mass damper.

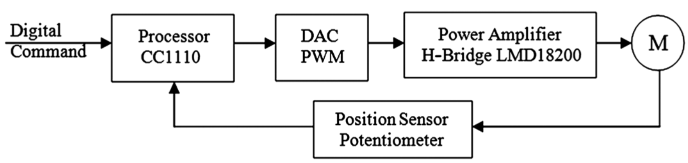

Figure 6. Block diagram of the servo position control system.

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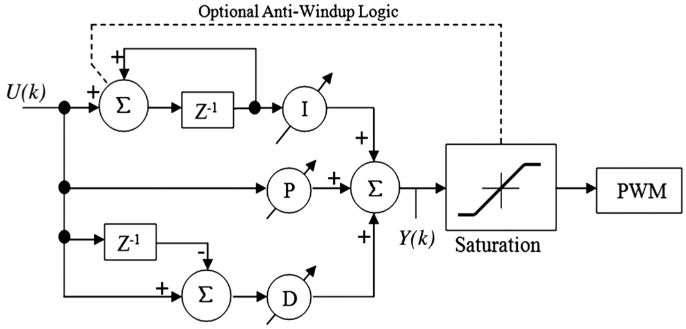

Figure 7. Block diagram of the digital PID algorithm.

calculation is expected to be very small, in the order of magnitude of few hundred microseconds, thus enabling to control at a sample frequency of 1 kHz.

The PWM is supported by the 16-bit 'timer1' of the CC1110. It forms a very power-efficient D/A converter when coupled to a simple switching power stage. The frequency of the clock source of the timer can be up to 26 MHz as well, which means that the resolution is 38 ns. Therefore, it can provide a high-resolution duty cycle even for a short-period PWM signal. In the driving motor application, the frequency of the PWM signal should be close to or greater than the human hearing limit of 20 kHz to avoid audible noise from the motor. When the PWM frequency is fixed to 20 kHz and the 26-MHz timer of the clock source is selected, the resolution of the PWM is still up to 10 bit.

The motor responds to a PWM output stage by time-averaging the duty cycle of the output. Most motors react slowly, having an electrical time constant of 0.5 ms or more and a mechanical time constant of 20.0 ms or more. A 20-kHz PWM output is effectively equivalent to that of a linear amplifier.

The power amplifier after the PWM is implemented by LMD18200 [7], which is a 3-A H-bridge specifically designed for motion control applications. The device is built using a multi-technology process that combines bipolar and CMOS (complementary metal-oxide semiconductor) control circuitry with DMOS (double-diffused metal-oxide semiconductor) power devices on the same monolithic structure. Ideal for driving DC and stepper motors, the LMD18200 accommodates peak output currents up to 6 A. An innovative circuit that facilitates low-loss sensing of the output current has been implemented. As shown in Figure 8, the LMD18200 is highly integrated, and it offers several features that are commonly of interest when designing a motor driver. These features are listed as follows.

(1) It delivers a continuous output of up to 3 A; since the output torsion torque of the DC motor is proportional to the current in the winding, the high current output capability can provide the DC motor with a high-output torsion torque.
(2) It operates at a supply voltage of up to 55 V; when the internal resistance of the DC motor winding is fixed, a high supply voltage can increase the current and the charging speed.

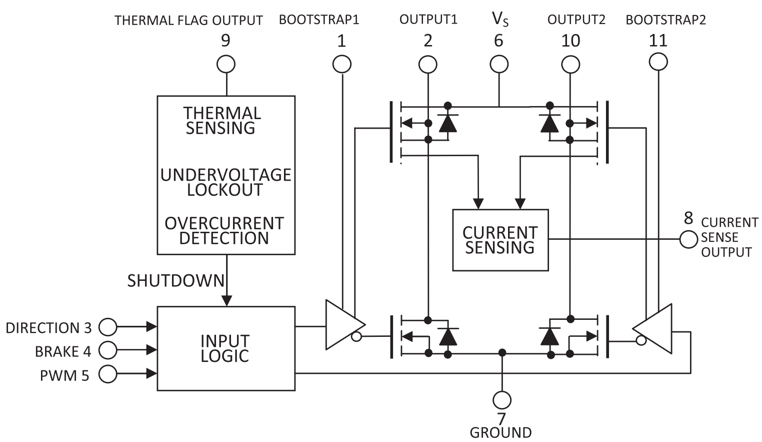

Figure 8. Functional block diagram of LMD18200.

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(3) The resistance, R_{DS}(ON), of the DMOS switch is low, typically 0.3 Ω per switch; the smaller the R_{DS}(ON), the lower the power dissipation of LMD18200.
(4) The control input signals are TTL (transistor–transistor logic) and CMOS compatible, which represent the two typical types of low voltage logic level. The advantage is that, although the power supply of LMD18200 can be up to 55 V, the control input signals can be still of low voltage.
(5) When the upper and lower switches on the same side are turned on at the same time, no ‘shoot-through’ current is generated. Otherwise, if the ‘shoot-through’ current existed, it would be very large (being the R_{DS}(ON) very small) and a high power would be dissipated in the LMD18200, which would lead to a high temperature and might damage the chip.
(6) A thermal warning flag output is detected at 145 °C by the external controller, which then takes preventive actions to protect the chip.
(7) A thermal shutdown (outputs off) occurs at 170 °C; this feature can prevent the LMD18200 from being destroyed due to overheating by automatically switching off the power supply.
(8) The internal clamp diodes are used to form a discharging channel for the motor winding when its power supply is switched off.
(9) A shorted load protection is available. When the load is short-circuited by accident, this feature can prevent the chip from being destroyed by automatically switching off the power supply.

Due to the high integration of LMD18200, the driver module of the motor is simple and small, as shown in Figures 9 and 10. Its interface is also quite simple. There are only three control signal inputs to be interfaced with the controller together with the ground signal, ‘GND’. The other connectors in Figure 10 include ‘PWM’ to control the magnitude of the average driving voltage of the motor, ‘DIR’ to set the polarity of the driving voltage, and ‘BRAKE’ to quickly stop the power supply to the motor in case of an accident. The ‘V + GND’ connector is used to supply power to the module, which can need up to +55 V depending on the requirement of the motor. The ‘OUT1 OUT2’ connector is dedicated to the DC motor.

The whole controller prototype is shown in Figure 11, where, in addition to the driver module, one can also see the CC1110 module mounted on its battery board and a UART (Universal Asynchronous Receiver/Transmitter) to USB (Universal Serial Bus) virtual RS232 module for communication with the configuration software installed on the computer.

To configure through the computer the parameters of the PID controller, the controller is configured as DTE (data terminal equipment), the software HyperTerminal is adopted as the terminal emulation as shown in Figure 12, and the ANSI (American National Standards Institute) emulation is adopted. Some commands useful for the configuration are implemented. For instance, the command ‘pid’ is for viewing the PID parameters; ‘error’ is for viewing the error input, the summation of error and control output of the PID algorithm; ‘kp’, ‘ki’, and ‘kd’ are for setting the value of corresponding parameters, namely, the

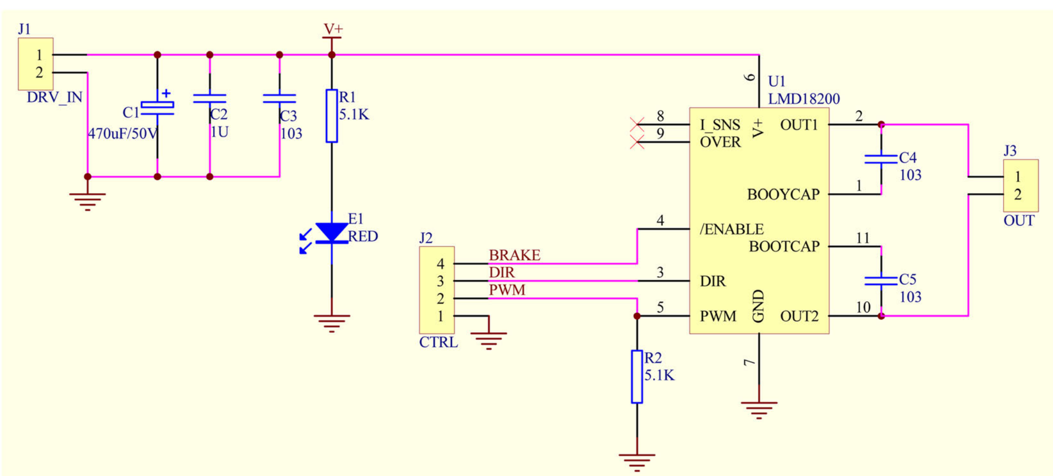

Figure 9. Schematic of the LMD18200 driver module.

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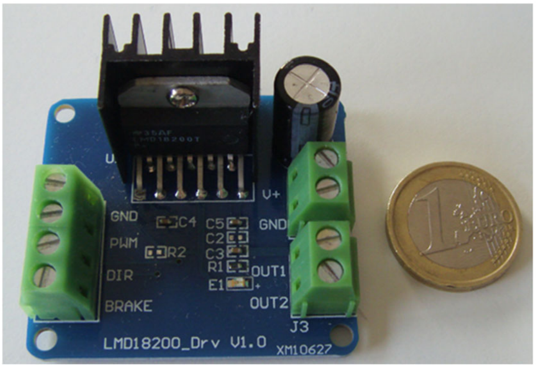

Figure 10. Photo of the LMD18200 driver module.

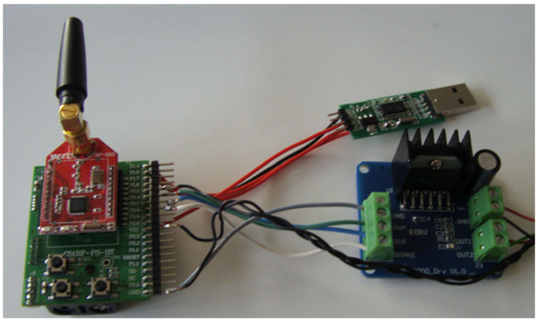

Figure 11. Photo of the whole controller prototype.

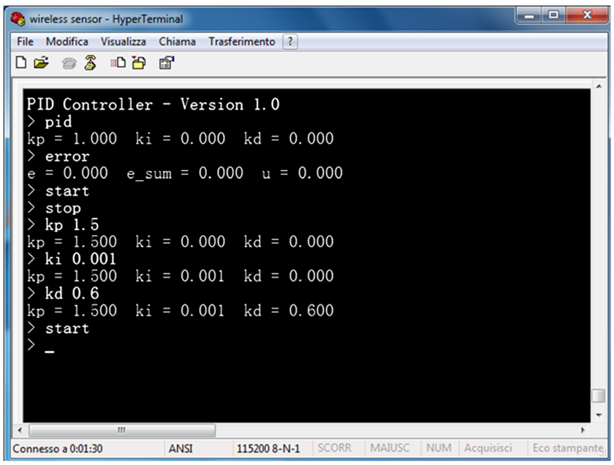

Figure 12. Photo of the configuration interface for the controller.

proportional gain, integral gain, and derivative gain, respectively; ‘start’ and ‘stop’ are for starting and stopping the PID control.

5. EXPERIMENTAL TESTING

As shown in Figure 13, the experimental structure is a three-story steel frame with a total mass of 130 kg. Each floor consists of a $60 \times 30 \times 3$ cm steel plate that weighs 42 kg. The distance between floors is 38 cm, and the total height of the structure is 120 cm. The structure was designed to obtain resonant frequencies in a frequency range of 0–5 Hz. Its configuration can be varied from 3 to 1 degree of freedom

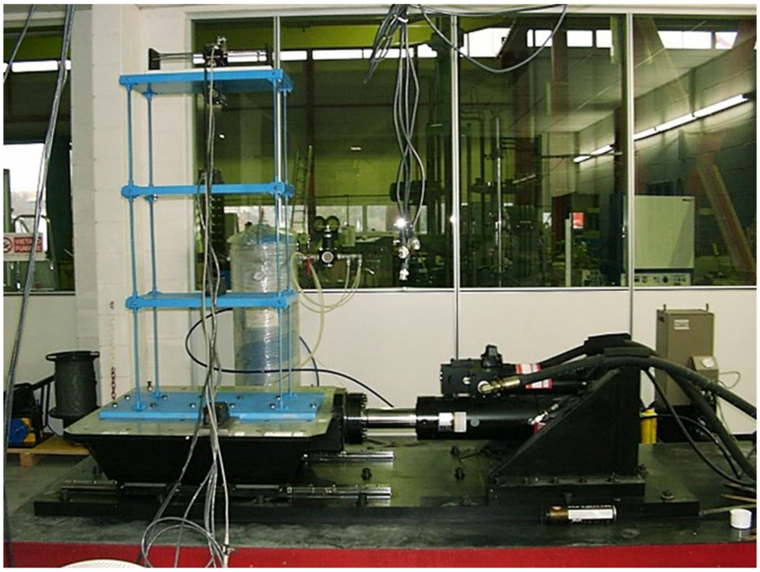

Figure 13. Experimental mock-up: a reduced-scale three-story steel frame, with the AMD mounted on the top and an accelerometer mounted on each floor, is placed on a shaking table activated by an oleo dynamic piston.

by stiffening the structure with braces. The damping ratio of the simulation model of each floor of the uncontrolled frame is 0.002, which is in agreement with the data obtained from the experiment.

In this section, the results from several experiments performed on the three-story frame are discussed to validate the wireless sensing system, the digital PID DC motor controller, and the whole AMD. The excitation of the shaking table is a sinusoidal movement with a frequency of 1.25 Hz and an amplitude of 2 mm. The value of 1.25 Hz is close to the first natural frequency of the frame.

The first goal of the conducted experimental tests consists of validating the data acquisition via wireless sensors. For this purpose, a wired data acquisition device from National Instruments simultaneously acquires the data, which are used as reference. The acceleration data acquired by both approaches are plotted together, and they are partly shown in Figure 14. A good agreement between the data is evident even when considering the records collected at the ground floor where the noise is dominant.

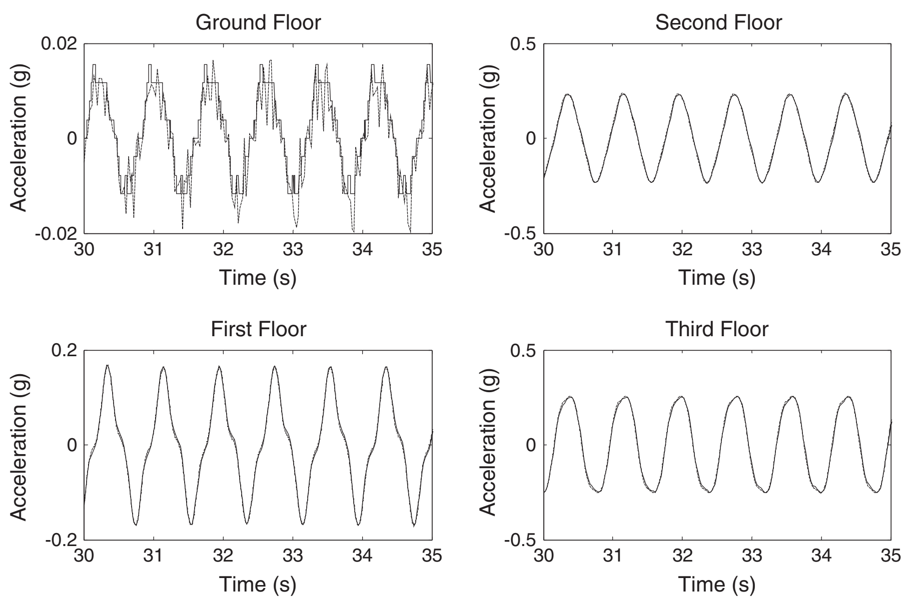

Figure 14. Comparison of the data acquired by wireless sensor and wired data acquisition device. The solid line is the wired data while the dashed line is the wireless data.

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Furthermore, to validate the new system architecture, four experiments are carried out by using different configurations of the control system (wired sensor, old DC motor controller; wired sensor, new DC motor controller; wireless sensor, old DC motor controller; wireless sensor, new DC motor controller). The same excitation (consisting of a 15-Hz white noise segment with a peak amplitude of 9.6 mm) is given by the shaking table during all the tests. The outputs obtained from the controller are consistent, each with the other, as shown in Figure 15.

The final task is to validate the effectiveness of the whole AMD. As for the tests plotted in Figure 14, the excitation is a sinusoidal movement at a frequency of 1.25 Hz, which is close to the first natural frequency of the structure. Therefore, when the excitation starts, the frame without AMD resonates

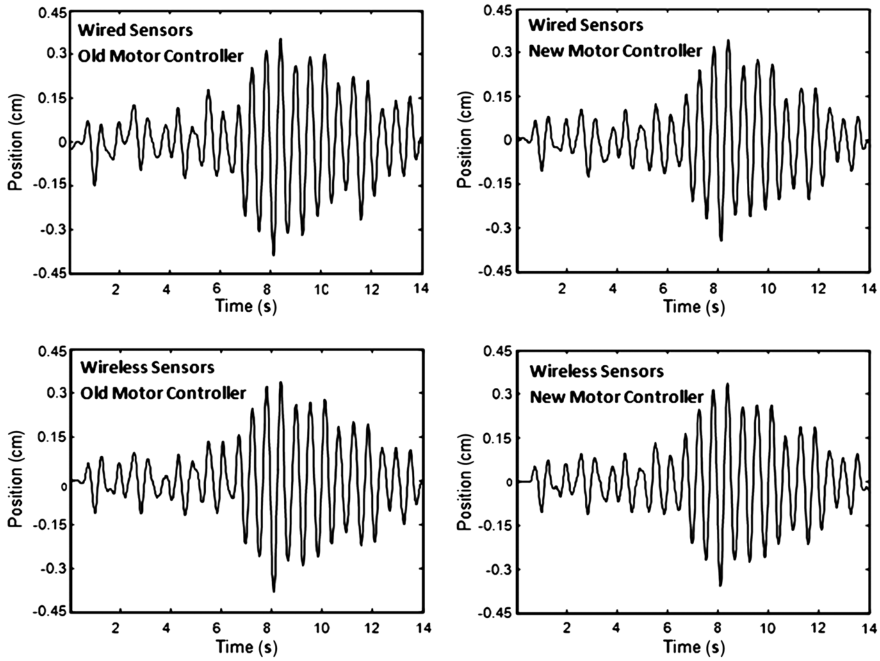

Figure 15. Outputs computed by the structural controller.

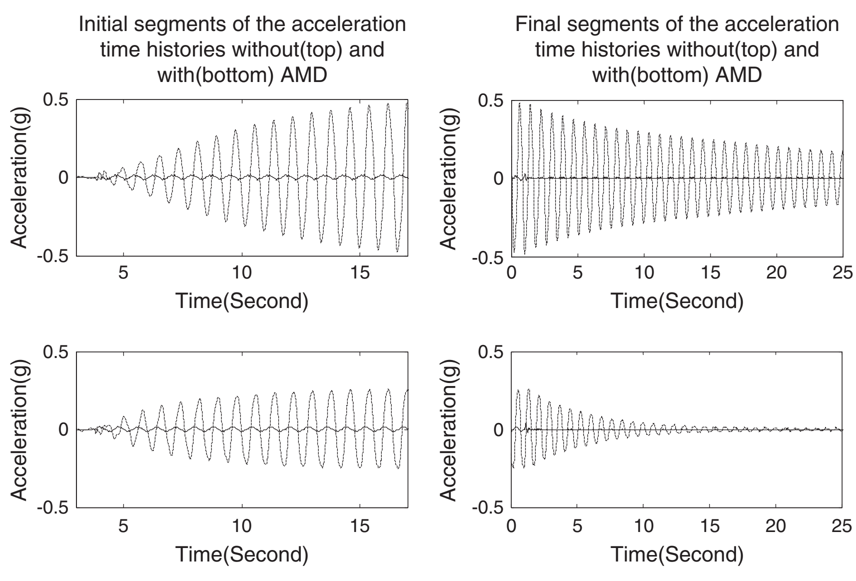

Figure 16. Response comparison of the controlled and uncontrolled frames under the same excitation: initial (right) and final (left) segments of the acceleration time histories, without (top) and with (bottom) AMD. The solid line is the shaking table acceleration, while the dashed line is the top floor acceleration.

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and the amplitude of the top floor acceleration becomes higher and higher, as shown in the top left subplot of Figure 16. To avoid destroying the frame, the excitation is stopped when the amplitude is close to 0.5g. As the excitation ends, the frame response is damped in a very slow manner, as shown in the top right subplot of Figure 16.

The frame with the AMD also resonates when the excitation starts, but the amplitude of the top floor acceleration tends to stabilize at around 0.2g (as shown in the bottom left subplot of Figure 16). When the excitation ends, the frame response is quickly damped (as shown in the bottom right subplot of Figure 16).

6. CONCLUSIONS

In the applications of structural control, continuous and real-time sensing techniques are required. Wireless connections between the sensors and the structural controller are desirable to reduce the high cost and labor-intensive installation and maintenance due to cables.

In the present study, the analog cables are replaced by a customized prototype of a wireless sensing system that is based on the recent single-chip System-on-Chip transceiver CC1110. This solution offers high performance at low cost. The continuous and real-time wireless transmission is achieved by implementing an FDM approach.

To improve the power efficiency and reduce the size, a new digital close loop motor PID position controller is designed. The newly designed PID controller is based on the H-bridge power amplifier LMD18200 and the enhanced 8051 microcontroller core in CC1110. The digital PID algorithm is implemented in the microcontroller core. The feedback signal is the position of the AMD detected by a potentiometer. The PID controller is validated to be effective and efficient in driving the AMD.

The overall system is validated by carrying out some laboratory tests.

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