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Energy harvesting and power management of wireless sensors for structural control applications in civil engineering

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Abstract. The authors' research efforts recently led to the development of a customized wireless control unit which receives the real-time feedbacks from the sensors, and elaborates the consequent control signal to drive the actuator(s). The controller is wireless in performing the data transmission task, i.e., it receives the signals from the sensors without the need of installing any analogue cable connection between them, but it is powered by wire. The actuator also needs to be powered by wire. In this framework, the design of a power management unit is of interest only for the wireless sensor stations, and it should be adaptable to different kind of sensor requirements in terms of voltage and power consumption. In the present paper, the power management efficiency is optimized by taking into consideration three different kinds of accelerometers, a load cell, and a non-contact laser displacement sensor. The required voltages are assumed to be provided by a power harvesting solution where the energy is stored into a capacitor.

Keywords: wireless sensor; structural control; power harvesting; power management; frequency division multiplexing

1. Introduction

Structural monitoring finds applications in the management of civil infrastructures (Messervey *et al*. 2011) as well as in the preservation of the monumental cultural heritage (Casciati and Osman 2005, Casciati and Faravelli 2010, Casciati and Al Saleh 2010). Its direct extension to the diagnostics and prognostics comes under the SHM (Structural Health Monitoring) label (Casciati 2008 and 2010). Structural monitoring is also one of the three pillars (monitoring, control law and actuation) of structural control which in civil engineering is characterized by the large masses involved. Structural control systems are conceived to mitigate the response of a structure under external excitations, such as earthquake and wind and many attempts to adopt structural control schemes were made in the last twenty years (Spencer and Nagarajaiah 2003).

In all these situations wireless sensor networks represent a convenient and viable alternative to cabled data transmission (Casciati and Rossi 2004, Lynch *et al*. 2008). Despite several solutions for wireless sensor networks are present in the literature (Lynch 2006, Rice *et al.* 2010, Casciati and

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Chen 2011), the issue of providing energy to the sensor unit without wires is still the bottleneck of the problem.

The authors designed and implemented their own customized solution to address the problem of wireless data transmission from the sensor unit to the storage computer (Casciati and Chen 2011, 2012). In this solution, the recent highly integrated System on Chip (SoC) wireless transceiver, CC1110, from Texas Instrument is adopted. By exploiting the capabilities of its programmable frequency synthesizer and receiver channel filter, the frequency division multiplexing technology, which is selected to support real time communication in multiple channels, can be easily implemented.

In designing the transceiver, special care was devoted to the power management unit, which however still relies on the adoption of batteries. The implementation of capacitors or batteries that can be recharged by an energy harvesting device is regarded as the ultimate goal of the ongoing research (Casciati and Rossi 2007). The design of the power management unit is based on the constraint of compatibility with different types of sensors widely used in civil engineering applications. Namely, the following sensors were taken into consideration:

(1) Kinemetrics FBA 11, which requires a power dual supply of ±12 V. The output signal can range from -2.5 V to +2.5 V.

(2) Kinemetrics three-axial Episensor, FBA ES-T, which requires a low-noise (less than 50 mV of ripple), power dual supply of ±12 V. The output signal can range from -2.5 V to +2.5 V.

(3) Crossbow CXL01LF3, which requires a power supply of +5 V. The output range is from +0.5 V to +4.5 V and it is centered at +2.5 V, which corresponds to 0 g.

(4) FUTEK Load Cells, LTH300 and LTH350, whose maximum excitation voltage is +18 V and the bridge resistance is 700 Ω.

(5) Laser sensor, YT89MGV80, whose power supply requirement ranges from 18 V to 30 V. The output signal range is from 0 V to about +10 V.

2. Power management in the wireless sensing unit

2.1 Overview of the wireless sensing unit

Although there exist some MEMS units which are conceived to transfer the physical variable directly in digitized information, a traditional wired sensor usually consists of a device converting the physical variable into an analog electrical signal, which is then sent to a board where it is sampled

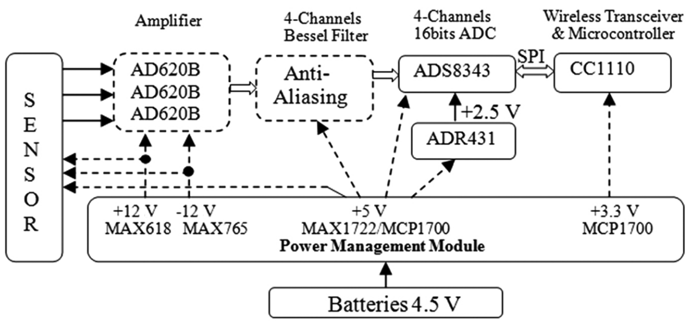

Fig. 1 Block diagram of the wireless sensing unit

and converted into digitized data. Finally, the data are stored in a central computer. The same wire is utilized to provide the power and to transfer the signal.

By contrast, a wireless sensor consists of two parts; namely, a wireless unit and a sensor. The sensor is responsible for converting the physical variable into an analog electrical signal, which is now directly sampled and converted into digital data. The digital data are then sent to the central computer by the wireless radio frequency (RF) unit. As shown in Fig. 1, the unit consists of an amplifier, a filter, an analog to digital converter (ADC), a wireless transceiver, a microcontroller, and a power management module.

The amplifier and the filter are also called the signal conditioning circuits. Although the range of the output signals from the sensors can be wide, the amplitude of the structural response is usually small. Since the resolution of the ADC is fixed, a signal of small amplitude needs to be amplified in order to improve the acquired signal quality before entering the ADC. Therefore, an amplifier is required if high signal quality is stressed. For this purpose, the low power instrument operational amplifier AD620B is herein adopted. Moreover, the frequency of the structural response is usually low in civil engineering so that the high frequency components in the signal can be considered as noise and should be removed by a low-pass filter before entering the ADC. In the proposed design, a fifth-order Bessel filter with a cutoff frequency of 25 Hz to avoid the aliasing is implemented.

After the signal of small amplitude and low frequency has been amplified and filtered, it is sent to the ADS8343 which is a 4-channel, 16-bit sampling analog to digital converter connected to the microcontroller by a synchronous serial interface. Thanks to the adoption of the SoC wireless transceiver CC1110, which already integrates an enhanced 8051 microcontroller core, a further standalone microcontroller is not needed in the wireless unit.

2.2 Power consumption analysis

In order to make the sensing unit as low-power as possible, the low-power feature was considered as a fundamental requirement in the selection of its electronic components. To justify the adoption of the electronic components in Fig. 1, their power consumption is discussed in detail within this Section and it is summarized in Tables 1, 2, and 3. The next Section, instead, is dedicated to the description of the voltage regulators which form the power management module.

The operational amplifier, AD620B, is a low power instrument which requires 1.3 mA as maximum supply current and has a default supply voltage of ±12 V. In Fig. 1 there are three amplifiers so that their total power consumption is about 93.6 mW. The fifth-order Bessel filter uses three quadruple operational amplifiers, TLC2274, whose supply voltage is +5 V and the supply current is about 5 mA. Therefore, their total power consumption is about 75 mW. In Fig. 4, the ADR431 is a voltage reference which requires a current supply of 800 μA without load and a supply voltage of +5 V.

Table 1 Typical power consumption of some electronic components of the wireless sensing unit in Fig. 1

	AD620	TLC2274	ADR431
Supply current	1.3 mA	5 mA	800 μA (No load)
Supply voltage	±12 V	+5 V	+5 V
Power consumption	31.2 mW	25 mW	4 mW
Number	3	3	1
Total consumption		172.6 mW	

Table 2 Power Consumption of the RF SoC transceiver, CC1110, and the ADC converter, ADS8343

	CC1110 (+3.3 V)	ADS8343 (+5 V)
Minimum power consumption	1.65 μW PM2	15 μW Shut down
Maximum power consumption	110 mW AM/Tx/433 MHz/ +10 dBm	8 mW 100 KHz throughout

Table 3 Power consumption of the three sensors

	FBA-11	FBA-EST	CXL01LF3	YT89MGV80 Laser Sensor	LTH300/LTH350 Load Cell
Supply voltage	±12 V	±12 V	+5 V	+18 V (+18 V~+30 V)	+5V (Max: +18 V)
Supply current	2.5 mA	35 mA	12 mA	<80 mA	7.1 mA
Power consumption	60 mW	840 mW	60 mW	<1440 mW	35.5 mW

Hence, its power consumption is about 4 mW. A summary of the power consumption of the discussed electronic components is given in Table 1, whereas Table 2 is dedicated to the requirements SoC transceiver, CC1110, and the ADC converter.

The typical power dissipation of the analog-to-digital converter, ADS8343, is 8 mW at a throughput rate of 100 kHz and a voltage supply of +5 V, but, in the shutdown mode, its power dissipation can be reduced below 15 μW. The low-power, radio-frequency system-on-chip tranceiver, CC1110, features a flexible power management strategy which enables to optimize its power consumption. It can be set in active mode (AM) or in four different power modes which are labeled from PM0 to PM3. In the PM2, the current consumption is only 0.5 μA. The required supply current of the AM depends on the specific configuration. In AM with a low CPU activity, the typical current consumption is 5 mA, when the system clock is set to 26 MHz and no peripheral is running. In AM with the radio in Receiving State (RX, 433 MHz, 250 KHz) the required current supply is 20.5 mA, whereas it increases to 33.3 mA in AM with the radio in Transmitting State (TX, 433MHz, +10dBm).

The power requirement of the five different types of sensors taken into consideration is given in Table 3. It is worth noticing that, although the last two sensors in Table 3 (namely, the laser sensor and the load cells) can operate in a wide range of supply voltage, the minimum supply voltage is chosen in order to reduce the power consumption.

2.3 Power supply requirements

The wireless sensor is designed to be powered by three AA batteries in series which provide a voltage of about 4.5 V. The several components of the wireless sensor need different supply voltages, namely of ±12 V, +5 V and +3.3 V. The power management module is responsible for the conversion and it mainly consists of some voltage regulators. As shown in Fig. 1, the ±12 V supply voltage is for the sensors and their signal amplifiers, the +5 V is for the filter and the ADC, and the +3.3 V is for the RF transceiver.

In order to make the unit suitable to both low-power sensors (CXL01LF3) and non-low-power sensors (FBA-11 and FBA-EST), there are four main aspects to be considered in the design of the power management module:

2.3.1 Highly efficient power conversion

Since the power management module itself will consume some power, a higher conversion efficiency means less wasted power.

2.3.2 Adjustable output voltage

Although the required voltages for the three sensors are determined, in order to make the wireless sensing unit suitable to other sensors, it is better to make the output voltage of the regulators addressed to the sensors adjustable.

2.3.3 Medium output power

Medium output power is required because the wireless sensing unit is also intended for non-low-power sensors. The output voltage of the regulators will not maintain its prefixed value if the required current is too high, so that the output current should be considered as well when selecting the regulators.

2.3.4 Ability to sleep with very little power consumption

In the structural monitoring application, the wireless sensors are not required to acquire data continuously. Since many current sensors are not able to sleep, it is a good method to cut off their power supply when the data acquisition is not required in order to reduce the power consumption as much as possible. Therefore, the power management module should be able to sleep with little power consumption.

2.4 Overall design of the power management unit

According to the above discussed requirements, the power management is designed as shown in Figs. 2 and 3. The power management module consists of an electronic switch (AO3401), a ultralow noise voltage reference (ADP431), and two types of voltage regulators; namely, the low dropout regulator (LDO) MCP1700, and the switching regulators (MAX1722, MAX618 and MAX765).

The batteries directly supply power to the +3.3 V LDO regulator for the SoC RF transceiver CC1110, and supply power to the other regulators through the electronic switch which is controlled by the microcontroller inside CC1110. Therefore, only the power supply of CC1110 is not switchable, since it serves as the controller of the whole unit.

The 5.0 V voltage supply is for the filter and the ADC which are sensitive to noise. Therefore, it

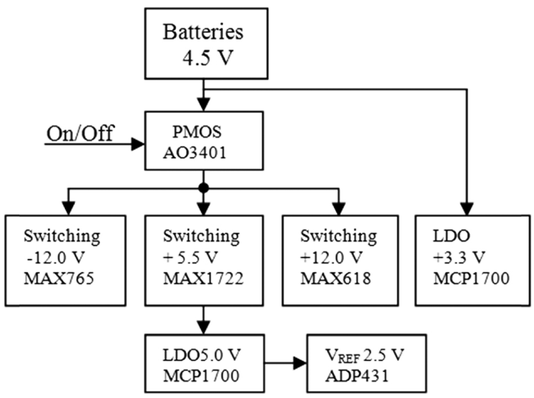

Fig. 2 Block Diagram of the power management unit

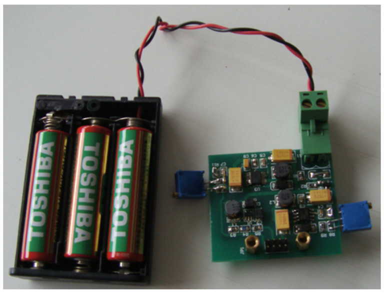

Fig. 3 Prototype of the power management module

is implemented by a switching regulator MAX1722 followed by a second +5.0 V LDO MCP1700 which acts as an active filter to eliminate the noise. In addition, the 5.0 V is used as the power supply of the ultralow noise +2.5 V voltage reference for the ADC.

When the electronic switch is off, in the wireless sensor only the CC1110 is powered. The overall supply current from the batteries consists of the quiescent current of the MCP1700 (only 1.6 μA) and the current drawn by the CC1110 which has four power modes (PM). In PM2, the current supply is only 0.5 μA and the microcontroller can be woken up by the internal timer.

2.5 Voltage regulators

According to the above mentioned aspects, the four key parameters for the selection of voltage regulators of LDO and switching kind are the quiescent current, the conversion efficiency, the output power, and the output adjustability.

2.5.1 Low dropout regulator

A low dropout (LDO) regulator is a direct current (DC), linear voltage regulator which can operate with a very small input-output differential voltage. The efficiency of the LDO regulators depends on both the input-output voltage drop and the quiescent current, I_Q, which is given by the difference between the input and output currents. Since the voltage drop is very small, the I_Q is actually the key parameter that limits the efficiency. Therefore, in the selection of the LDO, the LDO MCP1700 produced by MICROCHIP is chosen because of its low I_Q value (1.6 μA).

In addition to a low I_Q value and a low dropout voltage, another feature of MCP1700 is that the output current can be up to 250 mA. This makes it quite suitable to the envisioned application. Its application circuit is shown in Fig. 4. Only two external capacitors are required.

In the wireless unit, two MCP1700s with output voltage of +3.3 V and +5.0 V are separately adopted. Since they are not intended to supply power to sensors, the output adjustability is not necessary.

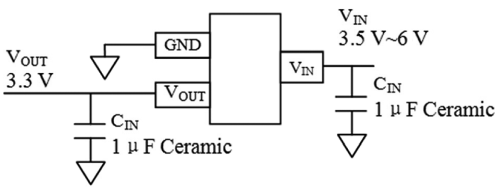

Fig. 4 Typical application circuit of MCP1700

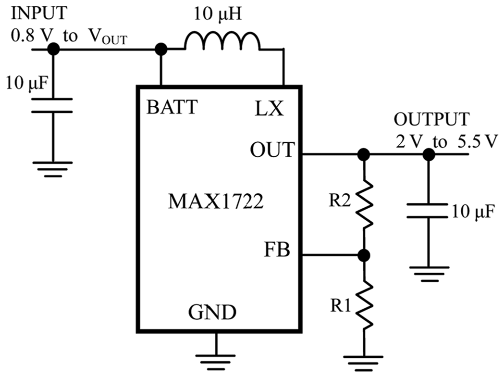

Fig. 5 Adjustable output application circuit of MAX1722

2.5.2 Switching regulators

Compared to the linear regulator, the switching regulator has a much higher efficiency in power conversion, because its pass transistor operates in switching state instead of linear mode. In switching mode, the pass transistor outputs either negligible voltage or negligible current, and therefore it only consumes little power. In linear mode, the pass transistor is subject to the difference between the input and output voltage and the load current, so that the power usually given by the product of the voltage drop by the load current is dissipated in the form of heat. In the wireless unit, three switching regulators which have excellent power efficiency are adopted; namely, MAX1722, MAX618, and MAX715. Their main features are reported in Table 4.

The MAX1722 is a high-efficiency, step-up DC-DC converter which features an extremely low quiescent supply current to ensure the highest possible light-load efficiency. As shown in Fig. 8, its output voltage can be adjusted from 2 V to 5.5 V using the resistors R_1 and R_2. Indeed, it is determined by the following equation

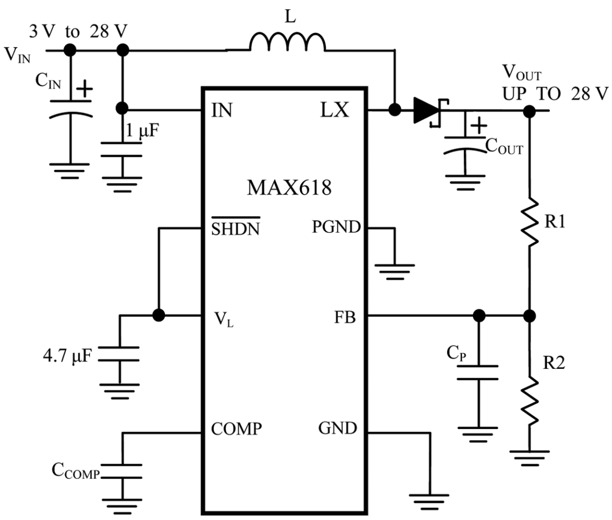

Fig. 6 Adjustable output application circuit of MAX618

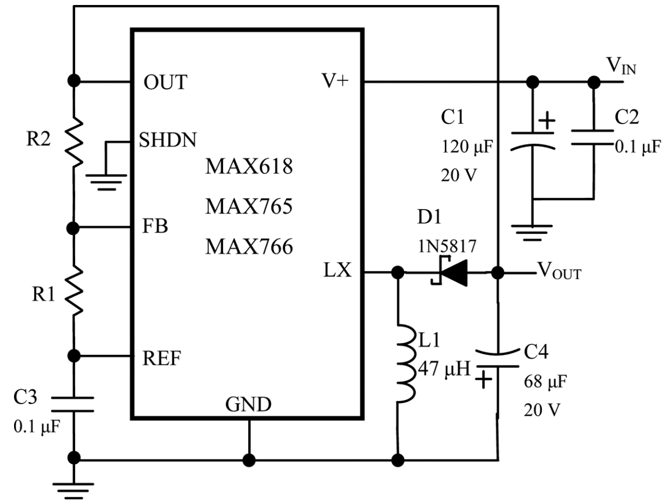

Fig. 7 Adjustable output application circuit of MAX765

Table 4 Features of the power management components

	MAX618	MAX765	MAX1722
Input voltage	+3 V to +28 V	+3 V to +16 V	0.8 V to 5.5 V
Output voltage	Up to +28 V	-1 V to -16 V	2.0 V to 5.5 V
Output current	Up to 500 mA at +12 V	Up to 250 mA	Up to 150 mA
Quiescent current	500 µA	120 µA	1.5 µA
Shutdown current	3 µA	5 µA	N/A
Conversion efficiency	Up to 93%	Around 80%	Up to 90%

$$R_2 = R_1\left(\frac{V_{OUT}}{V_{FB}} - 1\right) \tag{1}$$

where the feedback resistor R_2 should be within the range from 100 KΩ to 1Ω, and the V_{FB} is 1.235 V.

The MAX618 is also a step-up DC-DC converter that generates output voltages up to +28 V and accepts inputs between +3 V and +28 V. As shown in Fig. 9, two external resistors (R_1 and R_2) set the output voltage. First, a value for R_2 between 10 KΩ and 200 KΩ is selected. Then, R_1 is calculated from the following equation

$$R_1 = R_2\left(\frac{V_{OUT}}{V_{FB}} - 1\right) \tag{2}$$

where the V_{FB} is 1.5 V.

The MAX715 is an adjustable, low I_Q, DC-DC inverting switching regulator which can be highly efficient over a wide range of load currents, delivering up to 1.5 W. Its output voltage can be adjusted from -1.0 V to -16 V by using the external resistors R_1 and R_2, configured as shown in Fig. 7. A feedback resistor R_1 of 150 KΩ is recommended. The R_2 is given by the following equation

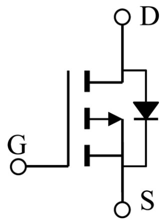

Fig. 8 PMOS AO3401

$$R_2 = R_1 \left| \frac{V_{OUT}}{V_{REF}} \right| \tag{3}$$

where V_{REF} is 1.5 V.

2.6 Electronic switch

The PMOS (P-Channel MOSFET, metal-oxide-semiconductor field-effect transistor) power transistor AO3401 is used as electronic switch which can completely cut off the power supplies of the sensor and some components of the sensing unit in order to minimize the power consumption when the wireless sensor is in sleep mode. The AO3401 scheme is shown in Fig. 8, where *G* is the gate for control, *D* is the drain, and *S* is the source. In a sensing unit, *S* is directly connected to the batteries, *D* is directly connected to the input of the switching regulators, and *G* is connected to the output pin of the SoC RF transceiver CC1110. When *G* is pulled down to 0 V, the channel between *S* and *D* is open. When *G* is pulled up to a voltage close to the one of the batteries, the channel between *S* and *D* is closed.

3. Energy harvesting and storage

In order to demonstrate the concept of energy harvesting and storage in civil engineering, a prototype unit (Casciati and Rossi 2007) is implemented as shown in Figs. 9 and 10. The device is supposed to be connected with a electromagnetic energy harvester, such as a linear motor, a rotary motor *etc*., which is assumed to be driven by the structure vibration and provides electrical energy continuously. Then, the prototype unit can power the aforementioned wireless sensor.

The energy harvester inputs are a high AC/DC voltage and a low DC voltage. The unit outputs a regulated voltage of 3 V through the step-up converter MAX1724.

A super capacitor or a rechargeable battery can be used as the energy storage element. In order to protect the energy storage element from being overcharged and damaged, two Zener diodes (D1 and D2) are used. When the voltage from the energy harvester is higher than the reverse breakdown voltage (which is eqal to 3 V for D1, and 2.4 V for D2), the diode allows a high current to flow, thus limiting the voltage at the reverse breakdown value.

In the prototype unit of Fig. 10, a low power microcontroller is used to manage the power conversion. The microcontroller can enable and disable the charge through the electronic switch S1. It can also monitor the charging voltage and current through its internal ADC.

In the low voltage power management module, the switching frequency of a DC-DC step-up voltage converter is set by the microcontroller so that the output voltage can be controlled. In the

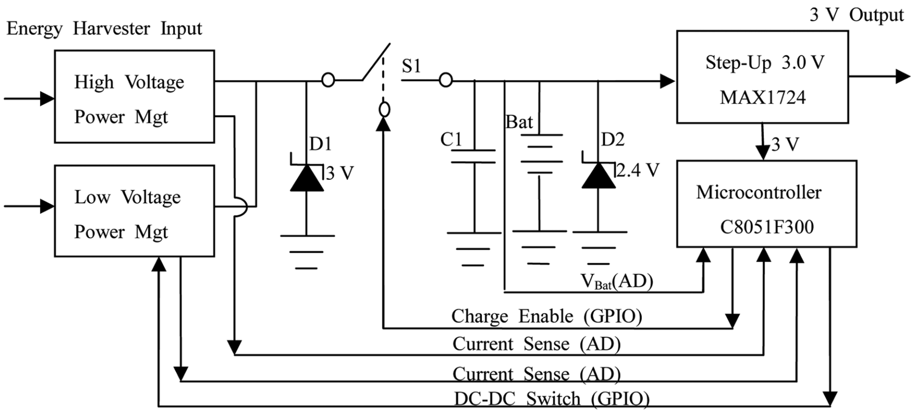

Fig. 9 Functional block diagram of the power harvesting unit (Mgt: management; Bat: battery; AD: analog to digital pin; GPIO: general purpose input and output pin)

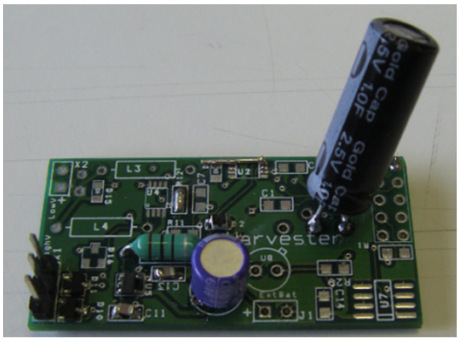

Fig. 10 Prototype of the energy harvesting and storage unit with a 1F super capacitor as energy storage element

high voltage power management module, a full wave rectifier formed by four diodes is adopted. The rectifier can convert an alternating current (AC), which periodically reverses direction, to a direct current (DC) which flows in only one direction. At the output of both the power management modules, a 1 ohms resistor is placed in series. The charging current is indirectly monitored by measuring the voltage of the resistor, being the charging current equal to the current flowing through the resistor.

Based on the above mentioned hardware, the firmware in the microcontroller is able to monitor the charging current and voltage, and hence to estimate the harvested power and energy. Furthermore, by monitoring the voltage of the storage element, the firmware is aware if it is fully charged or not. When the storage element is fully charged, the firmware turns off the switch S1 to disable the charging.

4. Laboratory testing

Some laboratory tests are performed on a reduced scale three-story steel frame mounted on a shaking table (Battaini 1999). A sinusoidal shaking table motion with a frequency of 1.25 Hz and an amplitude of 2 mm is assigned as excitation to the frame. The selected frequency of 1.25 Hz is close to the first natural frequency of the three-story frame. An Active Mass Damper (AMD) is mounted at the top of the steel frame. Two tests are performed using both the wireless sensors and wired sensors. The first test is carried out with the control system activated, and the other one with the AMD held static.

The dotted line is obtained from the wired data, the solid line from the wireless data.

The first goal of the experimental tests consist of validating the data acquisition system via wireless sensors. For this purpose, a wired data acquisition device (DAQ) from National Instrument simultaneously is used as reference for comparison. The acceleration data acquired by both approaches are plotted together and partly shown in Fig. 11, where the good agreement between them is evident even when considering the records collected at the ground floor where the noise is dominant.

The second task is to validate the effectiveness of the control system. As previously mentioned,

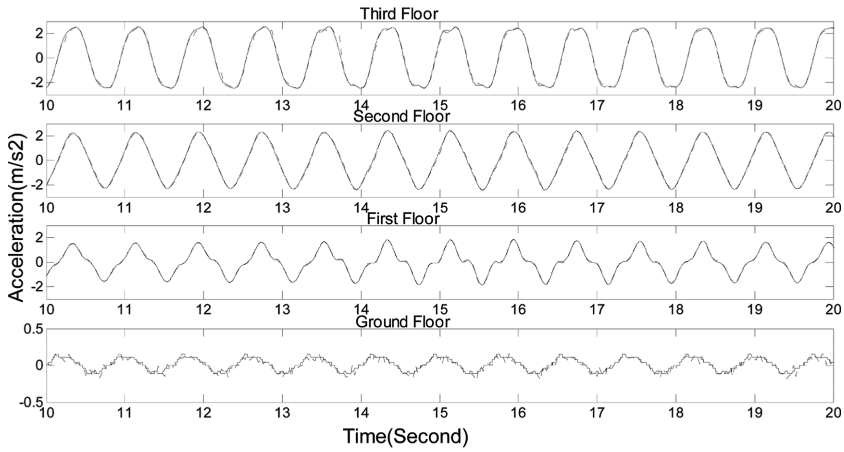

Fig. 11 Comparison of the data acquired by the wireless sensors and the wired data acquisition system

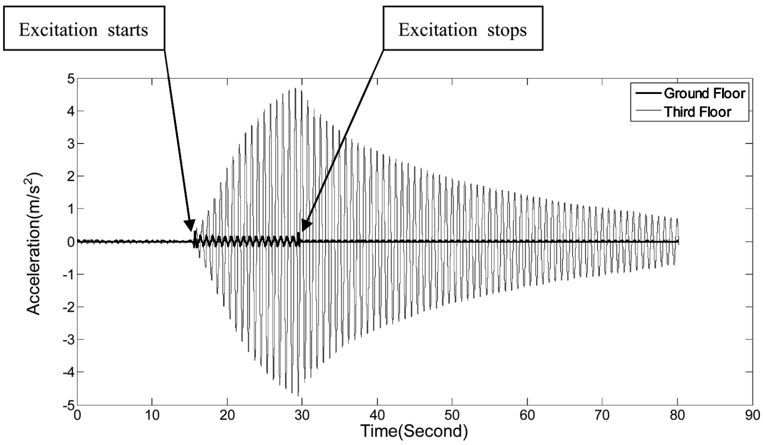

Fig. 12 Records of the acceleration time histories recorded at the ground floor (thick line) and top floor (solid line) of the uncontrolled frame under sinusoidal excitation

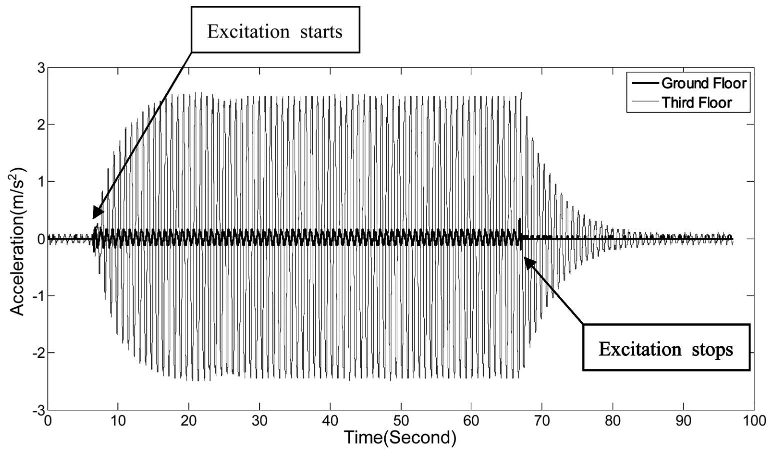

Fig. 13 Records of the acceleration time histories recorded at the ground floor (thick line) and top floor (solid line) of the controlled frame under sinusoidal excitation

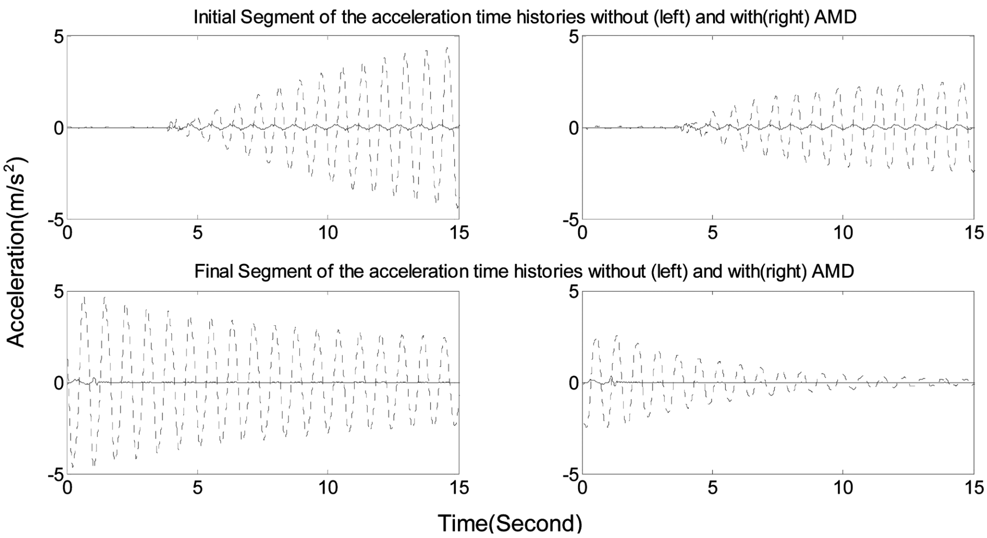

Fig. 14 Comparison between the responses of the controlled and uncontrolled frame under the same excitation: initial (top) and final (bottom) segments of the acceleration time histories, without (left) and with (right) the AMD. The solid line refers to the shaking table acceleration while the dotted line to the top floor acceleration

the excitation is a sinusoidal motion 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 and the amplitude of the top floor acceleration becomes higher and higher, as shown in Fig. 12. In order to avoid destroying the frame, the excitation is stopped when the amplitude is close to 5 m/s^2. As the excitation ends, the frame response is damped in a very slow manner. Instead, the frame with the AMD also resonates when the excitation starts, but the amplitude of the top floor acceleration tends to become stable at around 2.5 m/s^2, as shown in Fig. 13. When the excitation ends, the frame response is quickly damped.

In order to enable a clear comparison between the two responses without and with AMD, the initial segments and the ending segments of the corresponding acceleration time histories are separately plotted and aligned in Fig. 14.

5. Conclusions

A power management board is conceived and implemented in this paper. The low power feature of the wireless sensing unit is guaranteed by the selection of low-power high-efficiency electronic components, such as the low dropout regulator (LDO) and the switching regulators which feature a low quiescent current, a highly efficient power conversion, an adjustable output voltage, and a medium output power. The wireless sensor is able to work with high power efficiency, and to sleep with very little power consumption. The overall duration of the wireless sensor powered by batteries depends on the duty cycle and the capacity of the batteries.

In order to eliminate at least in part the constraint of the batteries, the development of an energy harvesting and storage device is pursued. In particular, a concept prototype based on an electromagnetic device is implemented and first presented in this paper.

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