Design of Piezoresistive MEMS-Based Accelerometer for Integration with Wireless Sensing Unit for Structural Monitoring

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Abstract: The use of advanced embedded system technologies such as microelectromechanical system (MEMS) sensors and wireless communications hold great promise for measuring the response of civil structures to ambient and external disturbances. In this paper, the design of a high-performance, planar piezoresistive MEMS accelerometer is discussed in detail. The piezoresistive accelerometer possesses superior performance characteristics including low noise densities when measuring local structural responses characterized by high-frequency content. A low-cost wireless sensing unit, designed for automated structural monitoring, is utilized to record and wirelessly transmit measurements obtained by the piezoresistive accelerometer. To validate the performance of the wireless monitoring system including the interfaced piezoresistive accelerometer, a five degrees-of-freedom laboratory test structure is utilized.

Introduction

The field of structural engineering can gain great benefit by embracing new technologies being developed in related fields such as microelectromechanical system (MEMS) sensors and wireless communications. One area where advanced technology can have an immediate impact is in improving the current state-of-practice of structural monitoring systems. The importance of structural monitoring is growing due to the recognition that monitoring is an effective vehicle for advancing the understanding of civil structures and their response to external loads. For example, research directed toward developing performance-based earthquake engineering design criteria can benefit from wide-spread use of monitoring systems because they provide empirical data for the validation of structural and statistical models. Structural monitoring systems are also required for the acquisition of real-time response time histories that are used by structural health monitoring algorithms to rapidly identify potential damage in a structural system.

To date, few structures have been instrumented with structural monitoring systems. Historically, critical structures located in zones of high seismic activity have justified installation. The lack of widespread adoption can be attributed in part to the high costs of current commercial monitoring systems. With commercial monitoring systems employing wires for the transfer of measurements to a centralized data server, the capital and installation costs of the systems can be high. The Tsing Ma Suspension Bridge in Hong Kong serves as a recent example (Ni et al. 2001). The bridge was instrumented in 1997 with a wired-based monitoring system of over 350 sensors; the system cost is estimated to have been over $8 million (Farrar 2001). A significant contributor to costs are expensive installations that can represent up to 25% of the total system cost. In addition, installations can be a challenging undertaking, with potentially over 75% of the installation time attributed to the installation of system wires (Straser and Kiremidjian 1998). Commercial monitoring systems make extensive use of force-balance accelerometers that have been specially designed for installation in civil structures. With broad dynamic ranges, they represent an accurate method of measuring both ambient and forced structural responses. However, the cost of individual force balance accelerometers can be high, with uniaxial versions costing over $1,000 each (Celebi 2001).

The high costs associated with commercial monitoring systems can be eradicated through the adoption of new and revolutionary technologies from related engineering fields. For example, the adoption of MEMS sensors could reduce overall system costs. Various MEMS-based accelerometers are commercially available that can serve as accurate substitutes for traditional force-balance accelerometers at substantially reduced costs. Accelerometers fabricated by a MEMS process are mechanically similar to traditional accelerometers but only fabricated on a micrometer scale. An additional advantage of MEMS sensors is their ability to monolithically fabricate signal conditioning circuitry on the same die, resulting in improved sensor performance and reduced sensor costs (Judy 2001).

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The application of advanced embedded system technologies to the design of current monitoring systems can drastically reduce system costs, simplify installations, and enhance system functionality. The use of wireless communications for the transfer of measurement data to a wireless sensing network can eliminate the need for cables, thereby reducing costs associated with system installation and maintenance. An additional advantage is the flexibility in the design of the sensor network, with peer-to-peer communication possible between sensing nodes. The use of wireless communications in the design of structural monitoring systems was first introduced by Straser and Kiremidjian (1998). The functionality of structural monitoring systems can be increased by directly integrating computational power with system sensors. This enabling innovation allows monitoring systems to directly interrogate measurement time histories to accomplish computational tasks associated with damage detection and system identification. Research has begun to explore embedding computational methods associated with system identification and damage detection within wireless sensors designed with microcontrollers (Lynch et al. 2002).

The design and fabrication of a high-performance, piezoresistive MEMS-based accelerometer intended for application in civil structures is explored. After successfully fabricating the piezoresistive accelerometers, the performance of the accelerometer is assessed. For validation purposes, the accelerometers are interfaced to wireless sensing units designed for structural monitoring applications (Lynch 2002). The wireless monitoring system, with the piezoresistive accelerometer interfaced, is instrumented on a laboratory test structure to record forced vibrations induced by a shaking table to which the structure is mounted.

MEMS-Based Accelerometers

The field of MEMS accelerometers can be segregated into two dominant microsystem architectures: capacitive and piezoresistive. Although both types of accelerometers employ internal proof masses that are excited by acceleration, the architectural differences are in the transduction mechanism used to correlate the movement of the internal proof mass to acceleration. Capacitive accelerometers employ a differential capacitor whose balance is disrupted by the movement of the proof mass. Piezoresistive accelerometers generally rely on strain induced within a flexural element that attaches the proof mass to the sensor housing for identification of the mass movement. Capacitive-based MEMS accelerometers, such as the ADXL iMEMS series (Analog Devices, Norwood, Mass.) have enjoyed more commercial success than piezoresistive designs. This is a direct result of piezoresistive accelerometers having not been capable of keeping pace with the reduced fabrication costs associated with capacitive architectures (Maluf 2000). Problems associated with temperature coefficients and drift properties of piezoresistive materials have necessitated careful packaging and compensation circuitry that have added to piezoresistive accelerometer costs.

Advances made in MEMS fabrication processes require a revisit to the piezoresistive accelerometer. With new processes available and old processes improved, a low-cost, high-performance piezoresistive accelerometer is now possible. In particular, deep reactive ion etching (DRIE) fabrication techniques could be used in the fabrication of MEMS accelerometers. The low-noise property of piezoresistive accelerometers at high frequencies, compared to those of capacitive accelerometers, is additional motivation for a renewed interest in the piezoresistive

accelerometer. Although many methods can be employed for the identification of damage in structures, the success of these methods is limited to cases where damage is severe enough to result in significant changes in the global modes of response of the structural system (Doebling et al. 1996). Most recently, researchers have explored the use of high-frequency local response measurements of structural components to identify the onset of damage (Park et al. 2000). As a result, the success of these techniques will necessitate accelerometers that exhibit superior performance in the high-frequency bands of interest. With excellent noise properties at high frequencies, the piezoresistive accelerometer can be applied to this emerging class of damage detection problems.

Design of Piezoresistive Accelerometer

The use of piezoresistive materials in the design of MEMS-based accelerometers was first proposed by Roylance and Angell (1979). Their design calls for a proof mass attached to a silicon housing through a short flexural element. The implantation of a piezoresistive material on the upper surface of the flexural element was used for measuring out-of-plane acceleration of the proof mass. The strain experienced by a piezoresistive material causes a position change of its internal atoms, resulting in the change of its electrical resistance (Senturia 2001). By completing a Wheatstone bridge around the piezoresistors of the accelerometer, a linear relationship between acceleration and voltage can be derived.

A new approach to the design of piezoresistive accelerometers is explored. Departing from the Roylance design, a lateral in-plane accelerometer that can exploit the use of DRIE fabrication techniques is examined (Partridge et al. 2000). The design of the planar accelerometer is straightforward. A pie-shaped proof mass, as shown in Fig. 1(a), is attached to the sensor housing through a slender cantilevering element. Acceleration in the plane of the sensor will cause deflections in the proof mass and flexural element. Implanted in the walls of the cantilevering element is a piezoresistive material that will change resistance with strain. The flexural element is designed to concentrate strain in the vicinity of the piezoresistive implant. The housing surrounding the proof mass is instrumental in providing a lateral stop on the mass movement, thereby setting the maximum measurable acceleration (range). This housing is advantageous because it prevents deflections that would result in nonlinear flexural responses in addition to protecting the accelerometer from shock (exceedingly high accelerations such as those above 1,000 g).

The physical dimensions of the accelerometer, illustrated in Fig. 1(b), can be varied to deliver ideal performance specifications for a particular application. To maximize sensor sensitivity (voltage per unit acceleration), the flexural width w is minimized while the radial length r of the proof mass is maximized. The bandwidth of the accelerometer is determined from the length of the flexure l, with shorter flexural elements increasing the lateral resonant frequency of the sensor. Because out-of-plane vibrations of the proof mass are undesirable, the thickness t of the flexural element is chosen to satisfy a 4 to 10 ratio between flexural thickness and width. In the process of fabricating piezoresistive accelerometers, different dimensions for the flexural element and proof mass are selected. The final element dimensions and anticipated performance specifications of the piezoresistive accelerometer are documented in Table 1.

Deep reactive ion etching and oblique ion implantation fabrication processes are two enabling MEMS fabrication technologies
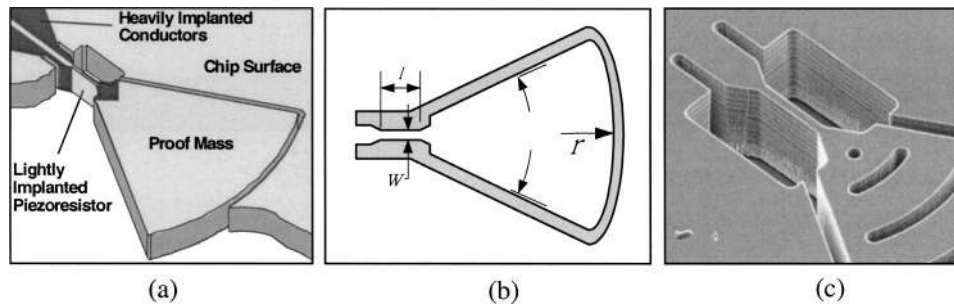
Fig. 1. (a) Design illustration; (b) physical dimensions and; (c) SEM image of planar piezoresistive accelerometer

chosen for the planar piezoresistive accelerometer. The fabrication of the accelerometer begins with the creation of a bonded etched silicon on insulator (BESOI) substrate created by the oxidation and bonding of standard wafer surfaces. An additional layer of low-temperature oxide (LTO) is grown on the top surface of the substrate in a pattern corresponding to the dimensions of the flexural and proof mass elements. To precisely remove silicon exposed by the pattern in the LTO layer, DRIE is used to remove substrate material until the internal oxide layer of the substrate is reached. With the sides of the flexural element exposed, oblique ion implantation is used to deposit a thin layer of boron within the sides of the flexural element. One side is implanted with a moderate amount of boron to form a 4 kΩ piezoresistor. A greater amount of boron is implanted on the opposite side of the flexural element to yield a conduction return path of 200 Ω. Upon completion of implantation, the LTO layer is removed, and a thin layer of oxide is grown. Oxidation of silicon renders silicon surfaces chemically and electronically stable (Lyshevski 2002). The backside of the substrate is marked and DRIE etched to release the proof mass and flexural elements of the accelerometer from the substrate. The sensor die is cut from the substrate and placed in a ceramic package for sealing. Fig. 1(c) is a scanning electron microscope image of the completed piezoresistive accelerometer.

The output of the accelerometer is a differential voltage signal linearly proportional to acceleration. To provide an easy interface to low-cost microcontrollers, a differential voltage amplifier is used to convert the differential voltage to a single voltage signal with amplification. Unlike some commercially produced accelerometers, an antialias filter is not provided on-chip in the prototype accelerometer, necessitating a four-pole Butterworth antialias filter to condition the accelerometer's output before interfacing to a data acquisition system.

Wireless Structural Monitoring

With industry interest in structural monitoring growing, low-cost alternatives to current monitoring system designs should be ex-

plored for development. Advanced technologies from the field of embedded systems, particularly wireless communications and low-power microcontrollers, can be adopted for use in structural monitoring systems. An additional incentive is derived from the price and functional synergies that exist between low-cost MEMS-based sensors and embedded system technologies. To demonstrate the performance of the piezoresistive accelerometer, a wireless monitoring system constructed from embedded system technologies is employed for logging the measurements derived from piezoresistive accelerometers. The wireless monitoring system proposed is built from modular wireless sensing units to which different sensors are interfaced. Computational power and wireless communications are included with each unit for local interrogation of measurement data and for a means of reliably communicating measurement data to the global sensing network. In the proposed wireless structural monitoring system, the wireless sensing units would be installed throughout a civil structure, as shown in Fig. 2.

The design of the wireless sensing unit illustrated in Fig. 3 can be divided into three functional categories: the sensing interface, the computational core, and wireless communications. The sensing interface is responsible for the interfacing of multiple sensing transducers (accelerometers, strain gauges, and linear displacement transducers serve as nonexclusive examples) that will measure various components of the structural response to ambient and forced vibrations. A sensing interface that can accommodate multiple channels and different modes of operation is designed. At the core of the sensing interface subsystem is the Texas Instruments ADS7821 single-channel analog-to-digital (A/D) converter. The analog-to-digital conversion resolution is 16-bits, and sampling rates as high as 100 kHz can be attained. Two additional sensing channels are provided that accept duty cycle modulated outputs from a wide class of digital sensors. Many commercial MEMS-based accelerometers, including the ADXL family from Analog

Table 1. Accelerometer Dimensions and Anticipated Performance Characteristics

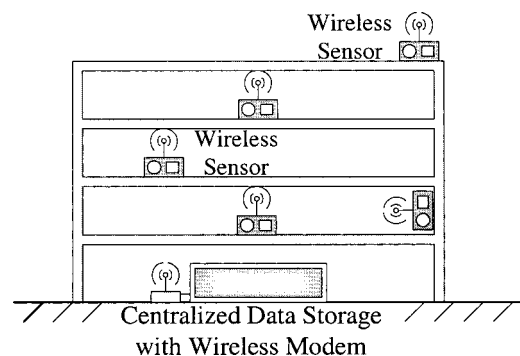| Accelerometer property	Theoretical
Flexural length, l	30 μm
Flexural width, w	5 μm
Thickness, t	30 μm
Proof mass radius, r	1 mm
Proof mass angle, ϕ	60°
Range	10 g
Bandwidth	1.6 kHz

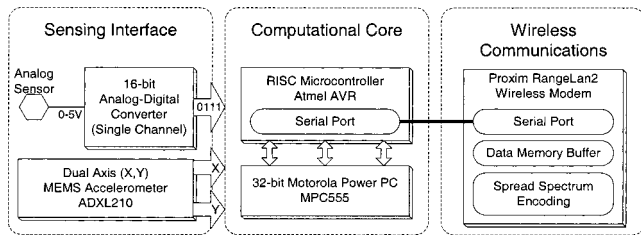**Fig. 2.** Proposed wireless structural monitoring system

Fig. 3. Overview of hardware design of proposed wireless sensing unit

Devices, provide duty cycle modulated outputs with resolutions of 14-bits. In total, three sensing channels are provided.

The computational core of the wireless sensing unit controls the operation of the entire wireless sensing unit. To acquire sensor measurements, the core initializes the sensing interface by establishing a desired data acquisition sampling rate. After initialization, the core triggers the sensor interface to collect measurements that are then read by the core and stored in on-board memory. After time-history data have been stored, the core is free to execute computational tasks such as filtering or interrogation of the data. The core can also choose to communicate the data through the wireless modem to the entire network of wireless sensing units in the structure. Chosen is a two processor core design comprised of a low-power, 8-bit microcontroller for simple unit operation and a powerful 32-bit microcontroller dedicated to performing data interrogation tasks. The 8-bit Atmel AT90S8515 AVR microcontroller (San Jose, Calif.) is selected for its rich set of hardware features, low cost and efficient power consumption characteristics. For the execution of computationally demanding data interrogation algorithms, the 32-bit Motorola MPC555 PowerPC microcontroller (Schaumburg, Ill.) is selected. With 448 KB of flash ROM and 26 KB of RAM, sufficient on-board memory is provided to serve as storage of measurement data. Special data registers are provided by the MPC555 to perform rapid floating-point calculations in hardware. The rationale of a two processor core design is to provide a low-power core. The 8-bit microcontroller is limited in its computational resources and, therefore, only used for the operation of the sensing unit. Because the 32-bit microcontroller requires more power, it is not turned on until data interrogation tasks are required. After the tasks have been completed, the processor is once again turned off.

By ensuring overall low system costs and modular installation features, wireless communication is an important ingredient in the sensing unit design. The Proxim RangeLAN2 radio modem (Sunnyvale, Calif.) is chosen to serve as the wireless communication technology of the wireless sensing unit. Operating on the 2.4 GHz unregulated FCC industrial, scientific, and medical (ISM) band, data rates of 1.6 MB can be attained with communication ranges of up to 350 m in unobstructed open space. Within structures constructed from heavy construction materials (e.g., concrete), communication ranges are reduced (Davidson and Hill 1997). The range of the RangeLAN2 can be reduced to 170 m inside structures. Frequency-hopping spread spectrum (FHSS) techniques ensure a reliable means of communication that is immune to narrow-band interference.

The wireless sensing unit shown in Fig. 4 is assembled into a compact package for deployment. The form factor of the wireless sensing unit, when completely assembled, measures 10 by 10 by 4 cm. A two-layer printed circuit board is designed to house integrated circuit parts, including the two microcontrollers, the
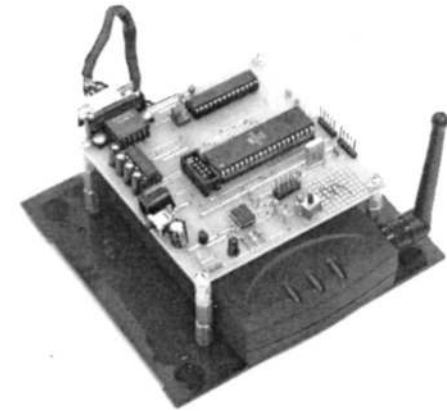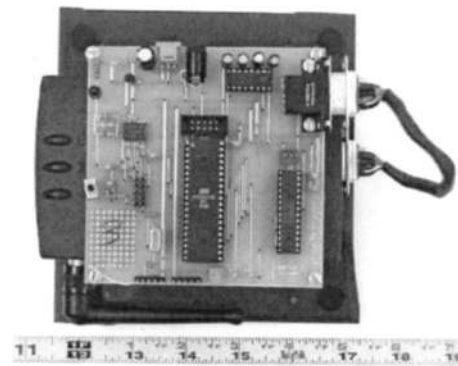

Fig. 4. Fully assembled wireless sensing unit ready for deployment

analog-to-digital converter, and all support electronics. Careful attention is paid during the design of the circuit to prevent the injection of electrical noise that can result from a poor circuit board layout (Ginsberg 1990). The RangeLAN2 radio modem is kept in its original packaging and is not included in the printed circuit board design. The total cost of the academic prototype is under $500, but commercial production can substantially reduce its current cost.

Piezoresistive Accelerometer Validation

The performance of the piezoresistive accelerometer is experimentally characterized. Prior to interfacing to the wireless sensing unit, the fabricated accelerometers are tested in the laboratory setting. In particular, the sensitivity, resolution, bandwidth, and range are quantified, as summarized in Table 2. Because the performance of the piezoresistive accelerometer will be compared to that of the Analog Devices ADXL210 accelerometer in the next set of validation tests, the ADXL210 properties have also been listed. The ADXL210 accelerometer is a capacitive MEMS accelerometer with an identical range ($10\,g$) as the piezoresistive accelerometer. The bandwidth of the piezoresistive accelerometer is experimentally measured to be 680 Hz. The sensitivity of the piezoresistive accelerometer is determined to be $1.25\,mV/g$, which is low compared to the ADXL210. An amplifier is required prior to interfacing the piezoresistive accelerometer to a data acquisition system to ensure a larger sensitivity.

The resolution of the sensor is the lowest measurement possible before noise dominates the sensor output. The resolution of the piezoresistive accelerometer measured at 100 Hz is very low,

Table 2. Experimentally Characterized Piezoresistive Accelerometer Performance Compared to Analog Devices ADXL210

Accelerometer property	Piezoresistive	ADXL210
Range	10 g	10 g
Resonance (bandwidth)	680 Hz	Variable (10 kHz$_{max}$)
Sensitivity	1.25 mV/g	100 mV/g
Resolution at 100 Hz	0.02 mg	0.5 mg

indicating the lack of noise in the accelerometer design. In comparison, the noise of the ADXL210 is 25 times greater. The resolution of the piezoresistive sensor varies as a function of frequency, with noise attributed to two noise sources. The first source, termed Johnson noise, represents random noise derived from the thermal properties of a resistor (Senturia 2001). Johnson noise is constant over all frequencies and is theoretically estimated to be 7 nV for the piezoresistors implanted in the accelerometer's flexural element (Partridge et al. 2000). The second noise source, termed Hooge noise, is inversely proportional to frequency. Hooge noise is a natural property of all resistors and dominates over Johnson noise at lower frequencies. It is theoretically determined that Hooge noise is equal to Johnson noise at approximately 40 Hz. Both Johnson and Hooge noise levels represent asymptotes for the accelerometer noise. The noise of the piezoresistive accelerometer measured at 100 Hz is 250 nV, a noise level nearly 30 times larger than that theoretically determined but still well below that of the ADXL. Improvements in fabrication can drive the noise levels of the current piezoresistive accelerometer closer to the theoretical Johnson and Hooge asymptotes. Fig. 5 clearly shows the frequency dependence of noise in the current piezoresistive accelerometer, with theoretical noise asymptotes also shown. To illustrate low noise levels of the piezoresistive accelerometer at high frequencies, the piezoresistive and capacitive accelerometers are used to track a 0.2 g sinusoid signal driven at 400 Hz. The results of this experiment are presented in Fig. 6.

System Validation

To validate the performance of the wireless sensing unit with the piezoresistive and ADXL210 accelerometers interfaced, a five degrees-of-freedom test structure mounted to an 11-kip shaking
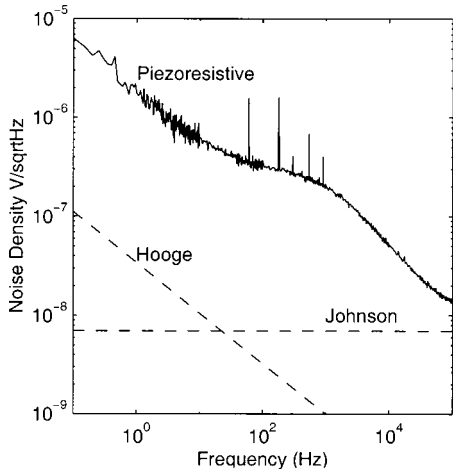

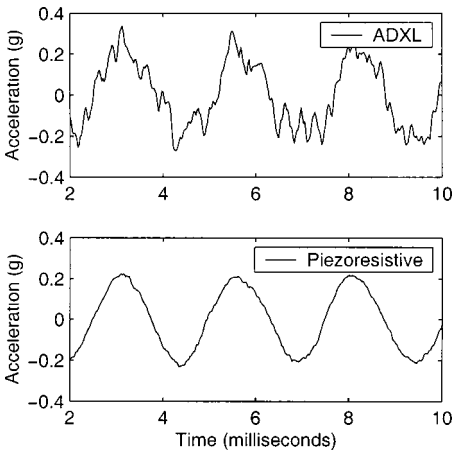**Fig. 5.** Noise spectral density of piezoresistive accelerometer

Fig. 6. ADXL and piezoresistive accelerometers tracking sinusoidal excitation (0.2 g 400 Hz signal)

table is utilized. The test structure is constructed from aluminum and designed to act as an ideal lumped mass shear structure. Five rigid aluminum plates weighing over 7 kg are attached to four slender columns approximately 0.6 by 1.3 cm in a cross-sectional area. The two accelerometers are fastened to the top story of the structure to measure their absolute acceleration response. The wireless sensing unit is attached to the fourth story as shown in Fig. 7. A small wire is used to connect the accelerometers to the wireless sensing unit's analog-to-digital converter.

First, from log decrement calculations of the structure's free vibration response, structural damping is estimated to be 0.5% of critical damping. Next, a sweep sine signal of constant displacement amplitude (0.2 cm) and linearly varying frequency (0.25 to 3 Hz over 60 s) is applied by the shaking table. During the excitation, the absolute acceleration response at the top story is recorded by the wireless sensing unit at a sampling rate of 30 Hz. Fig. 8 presents the measured absolute acceleration response of the structure as measured by the two accelerometers and the theoretical response determined from an analytical model of the structure. The measured absolute acceleration response is in good agreement with that obtained for the theoretical model. Perhaps not visually discernible from the measured response, the ADXL210 appears to exhibit less noise compared to the piezoresistive accelerometer at low frequencies of response. This fact
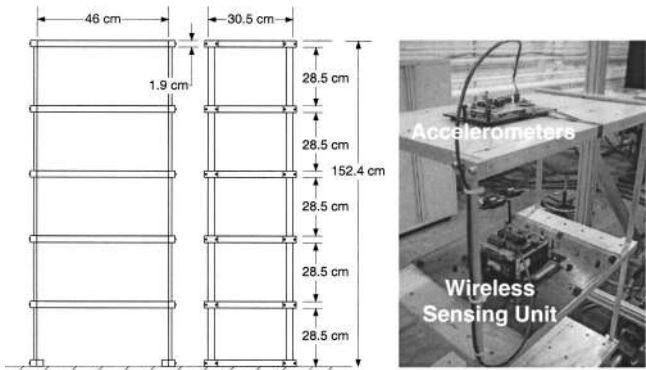

Fig. 7. Laboratory validation of MEMS-based accelerometers interfaced to wireless sensing unit
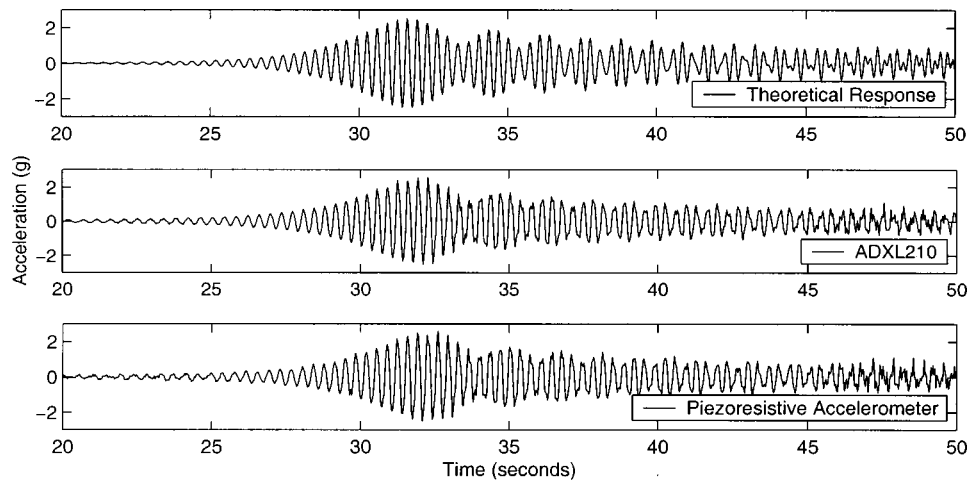
Fig. 8. Time-history response of test structure to sweep excitation

will become self-evident when comparing the frequency response of the system based on the measurements derived from the two accelerometers.

The frequency response function of the recorded time history is calculated by the wireless sensing unit using an embedded fast Fourier transform (FFT) algorithm. The FFT is performed on 1,024 consecutive time points of the response from 10 to 44 s. For smoothing of the frequency response functions, the FFT is repeated 10 times with the derived frequency response functions averaged. The first three modes of response of the test structure can be visually identified from the response functions of Fig. 9. The first three modes are identified at 2.87, 8.59, and 13.54 Hz. The identified modal frequencies are within 3% of those analytically calculated from the theoretical model at 2.96, 8.71, and 13.70 Hz. When comparing the two frequency response functions, the piezoresistive accelerometer is noisier, with increased scatter in the low magnitudes of the response function. This noise is a direct result of the Hooge noise that dominates the piezoresistive accelerometer output at low frequencies (<40 Hz). However, the noise present in the piezoresistive accelerometer is acceptable, particularly for high amplitude response measurements, with the modes of response of the test structure easily identified by the derived frequency response function.
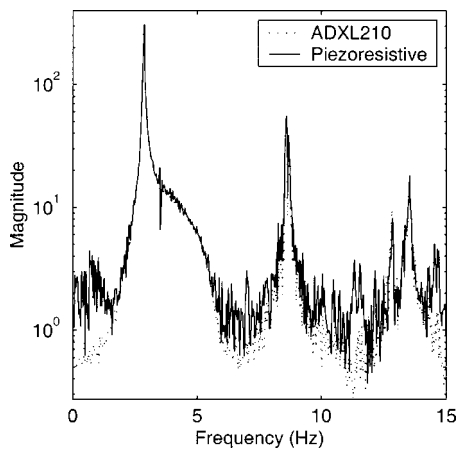

Fig. 9. Smoothed frequency response function derived from sweep forcing function

Conclusions

The design of a novel piezoresistive accelerometer, capable of an application for measuring the response of civil structures, has been presented. Advanced microsystem fabrication methods, including DRIE and oblique ion implantation, have rendered the design of a low-cost piezoresistive accelerometer possible. The performance of the piezoresistive accelerometer was validated in a series of experiments. Performance characteristics such as sensitivity, range, bandwidth, and resolution were characterized. In comparison to capacitive accelerometers commercially available, the piezoresistive accelerometer was superior, particularly when measuring responses defined by significant high-frequency content. The noise inherent in the design of the accelerometer can be driven closer to their asymptotic limits with improvements in the fabrication process. The high-frequency superiority of the piezoresistive accelerometer makes it a potential candidate for use in structural health monitoring systems employing damage detection methods that rely on local structural responses.

The design of a wireless structural monitoring system was also explored. The wireless monitoring system is built from wireless sensing units that embody the integration of the most advanced technologies of the embedded system market to deliver a low-cost, low-power system. The piezoresistive accelerometer is interfaced to a wireless sensing unit for structural response monitoring. A simple five degrees-of-freedom test structure is employed with the accelerometers mounted to the top-most story for measuring its absolute acceleration response. The ADXL210 capacitive MEMS accelerometer is installed adjacent to the piezoresistive accelerometer for performance comparison purposes. A sweep sinusoidal signal is used to excite the lower modes of the structure with the structural response recorded by the accelerometers and wireless sensing unit. The time-history responses are in good agreement with those predicted by a theoretical model of the structure. By calculating the frequency response function of the system, it is observed that the piezoresistive accelerometer exhibits more noise than the capacitive accelerometer. Nevertheless, the noise level does not prevent the identification of structural modal properties. Efforts are underway to improve current fabrication methods in order to reduce noise to levels theoretically predicted by Hooge and Johnson noise models.

Acknowledgments

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