An Autonomous Wireless Sensing Module for Long-Term Structural Health Monitoring Applications

Nickolai Belov and Ghassan Tchelepi

Green SHM Systems, Los Gatos, CA, 95032, USA
nbelov@greenshmsystems.com

ABSTRACT

Structural health monitoring (SHM) of civil infrastructure is among many areas with a need for low-cost autonomous wireless sensors capable of operating without maintenance for extended periods of time. This paper describes the 3AT-09 wireless sensing module developed by Green SHM Systems. The module incorporates a microcontroller, memory, digital accelerometer, tilt and temperature sensors, and a transceiver. It is powered by a combination of batteries and an energy harvesting device. The module can operate in two modes – active mode and sleep mode. Low power consumption in sleep mode, along with power management capabilities and the use of energy harvesting allows for a very long service life of the module. It is estimated that the module can be self-sufficient for at least 25 years when used as part of a typical SHM application with short active mode sessions. The autonomous wireless sensing module is designed as a platform for long-term monitoring applications. Different sensors and energy harvesting devices can be integrated with the module. Experimental results on the use of sensing modules for vibration monitoring of bridges and tall buildings are provided.*

1 INTRODUCTION

Aging of civil infrastructure is a global multi-trillion dollar problem. Transportation systems (roads, highways, rail systems, ports), utilities (power, communications, water) and public facilities require ever increasing expenditures to maintain their safety, security and integrity (NIST, 2009). Despite large expenditures for upgrades and repair of civil infrastructure there are still thousands of structures that require immediate attention (ASCE 2009). Their use can result in a wide variety of dangerous and/or undesirable events, including catastrophes like the collapse of structures as well as smaller scale failures. In many cases these events are a result from insufficient information about the condition of structures. A lack of predictability of infrastructure failures is one of the major problems that must be addressed.

Aging of civil infrastructure and buildings is a complex process that involves a gradual long-term degradation, wear and can be affected by episodic events like fire, earthquake, flooding, etc. Because the factors affecting the integrity and functionality of engineered structures can not be perfectly predicted, the process of their degradation must be monitored and assessed in some manner. Today the most common form of assessing the condition of a structure is its visual inspection sometimes supplemented with other non-qualitative methods. This approach, however, is limited because it requires personnel-intensive inspections that are, by their nature, subjective, highly variable, and not sufficiently reliable for optimal asset management (Turner-Fairbank, 2001).

Technology that could provide more quantitative data on the integrity and condition of civil infrastructure facilities and buildings – and that can be used in many other areas – does exist. It is based on the use of multi-sensor systems for long-term monitoring of parameters important for the functionality and safety of monitored structures (Fraiser, 2006; Kim, 2007). Collection of measurement data over time, data analysis, use of accumulated historical data for establishing baselines, detection of both long-term trends and short-term changes of monitored parameters can lead to the prevention of catastrophes and much more efficient use of resources.

In order to be widely accepted for monitoring of civil infrastructure facilities this technology has to meet certain requirements, including low cost, long service life without any required maintenance and simple non-invasive installation of multi-sensor systems.

Wireless sensors can provide both simple installation and acceptable cost – primarily due to the low cost of installation. However, energy supply limits the service life of wireless sensors. The best portable batteries available today can power a constantly operating node for only a few days. Battery replacement or other maintenance of wireless sensors may require a service trip to the monitored structure and use of special equipment to reach the locations where the sensors have been installed. The cost of such maintenance can be prohibitively high. Therefore, civil infrastructure monitoring applications require a minimum sensor service life of 10-15 years without maintenance at and the longer – the better.

Service life of wireless sensors can be extended by: (a) adding intelligence to the wireless sensors to allow for switching between an active mode when measurements are made and data is transmitted and an inactive or sleep mode when very little energy is consumed; (b) combining energy harvesting devices with energy storage devices, e.g. batteries or super-capacitors, to power the wireless sensors; (c) adding power management capabilities, including control of battery parameters, to allow for optimum battery use; and (d) providing sufficient mechanical, electrical and environmental protection of all components of the wireless sensors.

Unfortunately, efforts related to combining wireless sensors with energy harvesting devices thus far have not yielded any autonomous wireless sensors capable of operating for 10-15 years and longer, without maintenance. There are several reasons for this. One is related to the small amount of energy produced by the energy harvesting devices and some loss of this energy due to the need for conditioning of the energy harvesting device output voltage to the form suitable for use by the sensor. The other reason stems from insufficient attention being paid long-tem reliability of the energy harvesting devices and the modules themselves in field conditions.

2 WIRELESS SENSING MODULE 3AT-09

Wireless sensing module 3AT-09 (see Fig. 1) has been developed by Green SHM Systems to address the need for wireless sensors with extended service life without any required maintenance.

A block diagram of the module is shown in Figure 2. The wireless sensing module is based on a low-power microcontroller (Controller in Fig. 2), which can operate at different rates with the maximum frequency of about 25 MHz. The microcontroller also has a built-in analog-to-digital converter (ADC) and comparators. An SMBus and SPI™ ports are available for communication with a set of sensors, which is discussed later. The module can be configured with 8 MB or 16 MB of flash memory. Transceiver operating at 2.4 GHz is used to transmit the data to an external data collector. The module is powered by a combination of a primary battery and a secondary or rechargeable battery. The module also contains an energy harvesting device, which transforms the harvested energy into electrical energy and supplies the output voltage to the power management circuit.

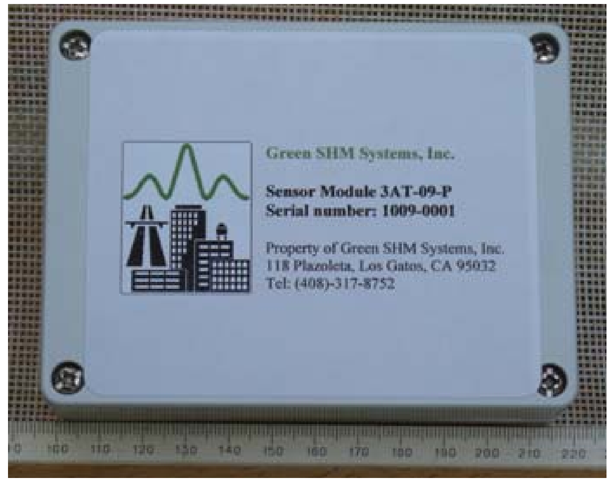

Fig. 1. Wireless Sensing Module 3AT-09

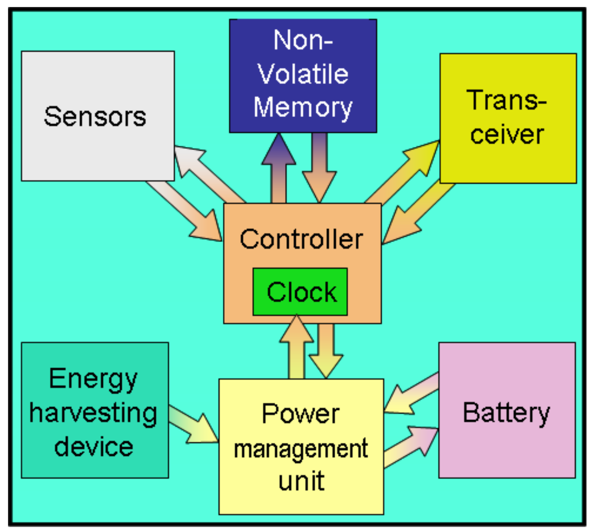

Fig. 2. Block diagram of wireless sensing module 3AT-09

The power management circuit conditions the output voltage of the energy harvesting device and uses the conditioned signal to charge the rechargeable battery.

The autonomous wireless sensing module is designed as a platform for long-term sensing and monitoring applications. It allows for integration with different sensors and energy harvesting devices. The module has an operating temperature range of –40ºC to 55ºC.

2.1 Sensors

The wireless sensing module 3AT-09 has a 3D digital accelerometer, a digital temperature sensor and smart "fuel gauges" which provide vital information about the battery state of charge, remaining capacity and voltage level. The 3D accelerometer is sensitive to gravity and can be used as a sensitive inclinometer as well. All these sensors are located inside the enclosure.

External sensors can also be connected to the sensing module. In particular, up to four vibrating wire strain gauges can be served by the sensing module. The module provides excitation pulses to the vibrating wire, digitizes the output signal and calculates the level of stress. Corrosion sensors and humidity sensors can be added to the module as well.

A digital camera and a microphone can be incorporated into the wireless sensing module. These sensors allow for acquisition of real-time images and sounds, which can be available through the web-based interface.

Other sensors required for specific applications can be integrated with the sensing module as well. If such sensors have analog output then data acquisition hardware might be added to the wireless sensing module.

2.2 Energy Harvesting

Energy harvesting is crucial for ensuring a long service life of the wireless sensing module.

Selection of energy harvesting devices for use with the module depends on the application. In most cases either photovoltaic or piezoelectric energy harvesting devices can be used. Currently, these energy harvesting devices are connected to the module externally. Modules with solar panels located inside the enclosure (the enclosure has a transparent window) and embedded into one of the walls of the enclosure are under development.

Energy harvesting from devices using a vibrating mass is also possible. However, such devices are effective only when the monitored structure experiences either vibrations with frequencies above 30 Hz or high accelerations. Vibration energy harvesting devices can be used in sensing modules for monitoring of rotating structures. For example, wireless sensing modules with a vibration energy harvester located inside the enclosure can be placed on blades of a wind turbine to monitor blade vibrations.

It is desirable to use an energy harvesting device that transfers, on average, more energy to the battery per day or per week than the sum of: (a) the average amount of energy required to support the sensing module for the same period of time and (b) the average amount of energy lost by the battery due to its natural self-discharge and/or loss of capacity over time. However, even smaller amounts of energy generated by the energy harvesting device can dramatically extend the service life of the wireless sensor module.

In order to compensate for the discharge of the secondary battery due to the factors mentioned above, an energy harvesting device should supply the battery with an average current of 1…3 mA (see section 2.7). Many energy harvesting devices that are available today, such as solar cells and some piezoelectric energy harvesters are capable of supplying such currents.

Use of energy harvesting allows for an extended module service life of at least 25 years while allowing measurements to be taken 10-15 minutes every day.

2.3 Wireless Communications

The sensor module transceiver operates in the industrial, scientific and medical (ISM) radio band utilizing the 2.4 GHz frequency. There are two transceiver options, a low-power and a high-power option. The low-power option has a range of about 300 feet. The high-power option incorporates a front end power amplifier which extends the range to about 1500 feet. The sensor module supports both Frequency Hopping Spread Spectrum (FHSS) and a proprietary protocol to communicate with the data collector.

2.4 Clocks

Accurate time measurements and synchronization with other sensing modules can be important in many applications. The 3AT-09 sensing module has an ultra low power real-time clock (RTC) and a high-resolution counter. The RTC is based on a 32.768 kHz watch crystal. It allows for 24 hour independent time-keeping. The RTC provides high accuracy time measurements.

The RTC error is typically below 2 seconds per day in a wide temperature range. When a group of sensing modules is exposed to ambient conditions with a small temperature variation (less than 10ºC) between modules then the expected RTC variation within the group is smaller than 0.5 seconds per day.

The high-resolution counter operates at 25 MHz. It can be used for precise measurements of time intervals.

2.5 Battery Management

A power management unit is used to monitor the battery condition and state of charge. Battery life and, consequently, service life of the wireless sensing module can be extended by maintaining optimum level of battery charge, by minimizing the number of charging cycles, limiting charging current and providing optimum level of operating discharge. These measures lead to a very slow decrease of battery capacity over time.

The user can define both parameters of the battery charging cycle and the set of battery-related parameters reported to the data collector.

Various types of battery chemistries can be integrated into the sensing module and supported by the power management unit (e.g. Li-ion, Ni-Cd and various primary battery types).

2.6 Assembly and Packaging

All electrical components are assembled on one PCB. Electrical connections within the module are made using either soldering or welding. All components and electrical connections are covered by environmentally resistive protective materials to prevent corrosion, oxidation and other environmental degradation.

The wireless sensing module is packaged in an environmentally protected NEMA-4 enclosure rated for both indoors and outdoors applications, which provides sufficient protection from rain, snow, UV radiation, etc.

2.7 Operation and Power Consumption

The microcontroller controls the wireless sensing module by executing a code. The microcontroller receives the measurement data from sensors, transfers the digital measurement data to non-volatile memory and controls data transfer from the memory to transceiver.

The module can operate in two modes – active mode and sleep mode. Operating the wireless sensing unit in active mode is later referred to as a session.

During a session, the sensors make measurements. Measurement data from sensors is acquired either by the microcontroller or by data acquisition hardware (in case of external sensors with analog output). The microcontroller either saves raw data in the non-volatile memory or performs data pre-processing, for example, averaging of consecutive measurements or compensation based on data from sensors of environmental parameters, and then saves the pre-processed data in the non-volatile memory. From time to time the transceiver transfers data from the non-volatile memory to an outside data collector. The data transfer can be done by both direct communication with the data collector or by transferring data through other wireless sensing modules. In active mode, wireless module 3AT-09 consumes about 5 mA of current when measurements are made and up to 110 mA of current when data is transmitted using the high power option. In the sleep mode, the sensors, the non-volatile memory, and the transceiver do not perform any operations, the microcontroller suspends its clock and consumes significantly less power and current than when in active mode. Low-impedance components, for example external sensors, can be disconnected from the power supply in sleep mode. Real-time clock operates directly from the battery output. Current consumption in sleep mode depends on module configuration. Typically sleep mode current is below 50 µA and can be smaller than 15 µA for many configurations.

Switching from sleep mode to active mode is initiated by either internal or external events. Internal events are triggered either by the RTC (scheduled events) or by the power management unit signaling a change in the level of charge of the secondary battery. External events are generated by one of the sensors. For example, the 3D accelerometer can generate a wakeup signal when acceleration exceeds a preset threshold. This feature allows the wireless sensing module to be in a low-power waiting mode ready to register earthquakes.

Switching from active mode to sleep mode happens either after performing all required operations in active mode or at a predetermined time. The latter can happen if one of the operations that normally should be performed in the active mode was not performed despite several attempts. Failure to establish wireless communication can be an example of a situation when switching to sleep mode can be done by a timeout signal in order to keep power consumption under control.

Example. Suppose that wireless sensing module 3AT-09 makes acceleration and stress measurements during a session taking 400 samples per second per axis from 3D accelerometer and 3000 samples per second from vibrating wire strain gauge. Assuming that vibration is measured for 5 minutes and stress – for 3 minutes, one can conclude that about 800K measurements are made during one session. The module can do some data processing. For example, data from vibrating wire strain gauge can be used to detect frequency of wire oscillation and frequency data can be saved at a rate of 100 samples per second. Acceleration data can be averaged in such a way that an average of four consecutive measurements is saved. This also results in saving 100 samples per second per axis. Together with time stamps, temperature measurements, and other system-level data the module will use about 260KB memory to store the data. Time required for data transmission can depend on different factors. Assuming the effective average data transmission rate of 40Kb/s, it is possible to evaluate that the data can be transmitted in about 52 s. Assuming that measurements are done in 8 minutes, that the module uses 3 more minutes for data pre-processing and data transmission takes 1 minute, duration of the session is 12 minutes. If average current consumption in measurement and data processing mode is equal to 5 mA and in data transmission mode it is equal to 110 mA then average current consumption per session can be 13.75 mA.

Three sessions per day with average current consumption of 13.75 mA and sleep current of 50 µA deplete battery by 9.42 mA•hr per day. Battery charging circuit providing an average charging current of 2 mA during 8 hours is enough to fully compensate both this energy loss and energy loss due to self-discharge of the battery.

2.8 Firmware

The wireless sensor module firmware is based on a small footprint Real Time Operating System (RTOS). The firmware implements many tasks, such as boot-loader, data collection, power management, self-diagnostics, house-keeping, synchronization, and communications. The architecture of the firmware guarantees servicing of high-priority events without delay. In order to maintain synchronization of acceleration, stress and sound data among sensing modules it is imperative to record data generated by corresponding sensors without delay. The firmware is designed to be fault tolerant. It utilizes a watchdog timer to allow for recovery from unforeseen conditions that may cause the module to go offline.

3 EXPERIMENTAL RESULTS

Wireless sensing module 3AT-09 was designed targeting long-term structural health monitoring. A batch of sensing modules has been fabricated and tested for short-term vibration monitoring of bridges and tall buildings. Some results of the testing are presented below.

3.1 Vibration Monitoring of Bridges

Wireless sensing modules 3AT-09 have been used for monitoring tests of several bridges in the South Bay area.

Fig. 3 shows vertical acceleration measured at the center of a pedestrian bridge over Highway 280 located in Cupertino, CA. Fig. 4 shows the spectrum of acquired signal for vertical (Z) and transverse (Y) axes of the bridge. Fig. 5 shows vertical acceleration of the light rail bridge at Great Mall station located in Milpitas, CA caused by trains arriving and leaving the station. All measurements were made with a sampling rate of 400 Hz. The graphs presented in Fig. 3 show data after 4-to-1 averaging (equivalent to a sampling rate of 100 Hz). The graphs presented in Fig. 5 show data at an equivalent sampling rate of 50 Hz.

As illustrated by Fig. 3 and Fig, 5, the maximum amplitude of bridge oscillations is often in the range of 10-20 cm/c^2 increasing up to 40 cm/c^2 in some cases. 3D accelerometers used in the sensing modules provide

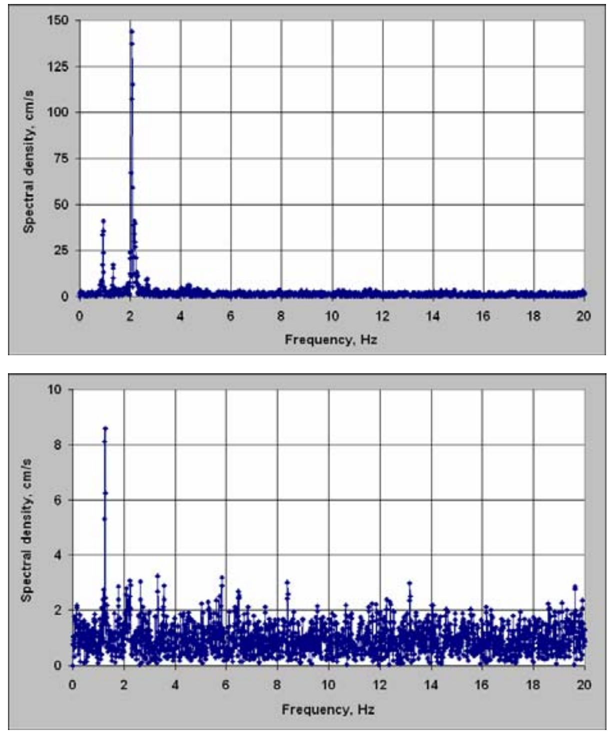

Fig. 4. Frequency spectrum of vibration signals acquired by wireless sensing modules on a pedestrian bridge: vertical vibrations (top), transverse vibrations (bottom).

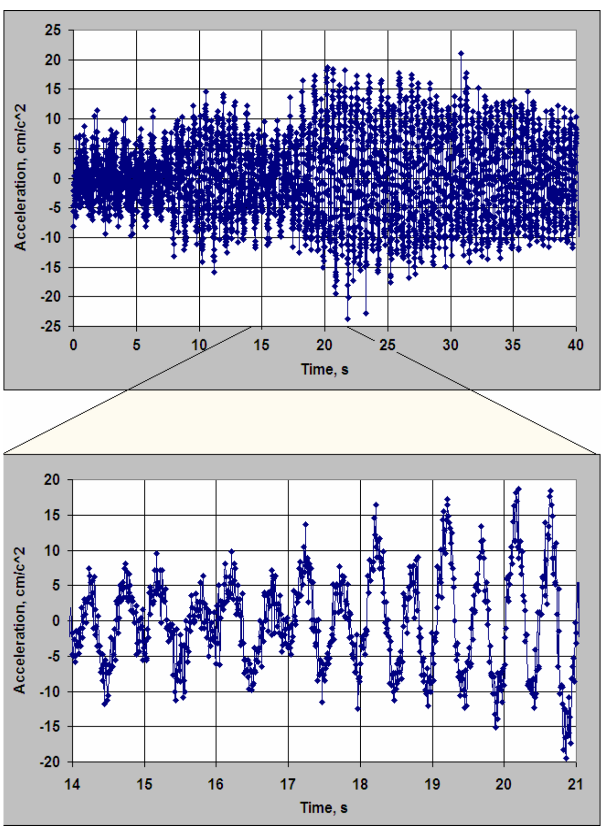

Fig. 3. Vertical vibrations of a pedestrian bridge.

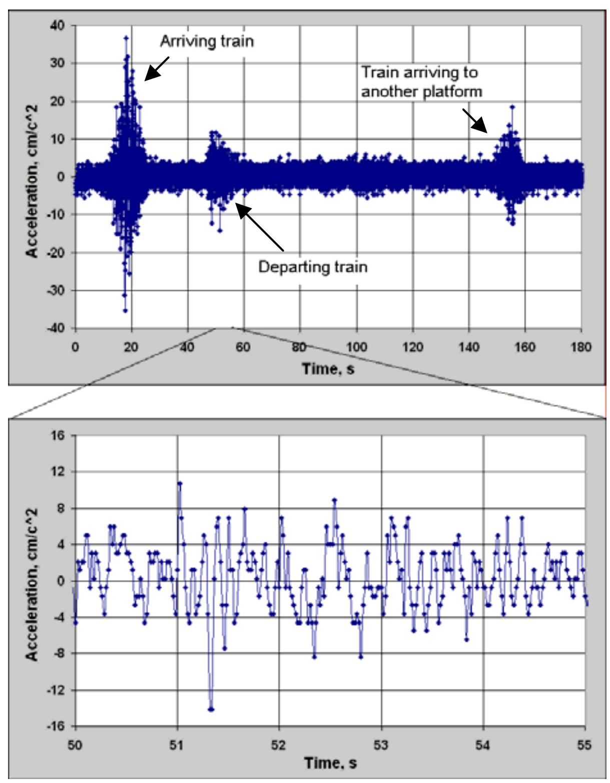

Fig. 5. Vertical vibrations of the light rail bridge (Great Mall station, Milpitas CA). Acceleration spikes have been caused by trains arriving and leaving the station.

high signal quality which allows for reliable detection of main oscillation frequencies of such structures.

Vibration of tall buildings can also be detected by the wireless sensing modules 3AT-09. Peak acceleration experienced by the buildings is typically 3-10 times smaller than that of bridges. Measurements in buildings can be affected by elevators, air conditioning and other equipment that can generate parasitic vibrations. Fig. 6 illustrates acceleration and spectral density data for a tall building. The measurements were made in a 32-story tall building in downtown San Francisco.

3.2 Synchronization of Sensing Modules

Some SHM algorithms require measurements made by a group of sensors to be synchronized. In many cases synchronization accuracy should be about 1 ms or better. For example, high accuracy is needed if vibration data is used to reconstruct oscillation mode shapes.

When operating, a group of wireless sensing modules synchronizes clocks with their data collector clock (master clock). Communication protocol allows for better than 0.2 ms synchronization of all clocks, within a group of wireless modules, with the master clock. This accuracy can be achieved over a wide range of temperatures and periods of time as long as one hour.

Measurement data synchronization may require some data post-processing. Fig. 7 shows an example of measurement data before and after applying a synchronization algorithm.

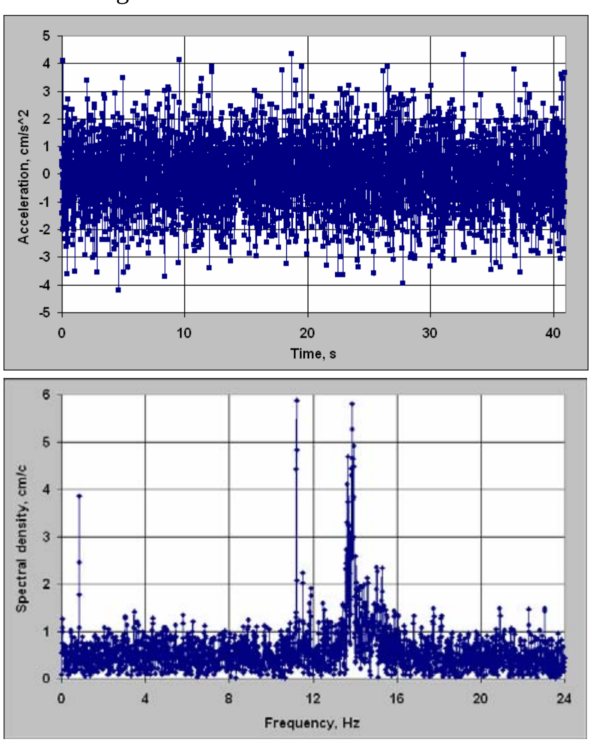

Fig. 6. Lateral vibrations of a tall building in downtown San Francisco. Vibrations at frequencies above 8 Hz can be related to motion of elevators and other equipment.

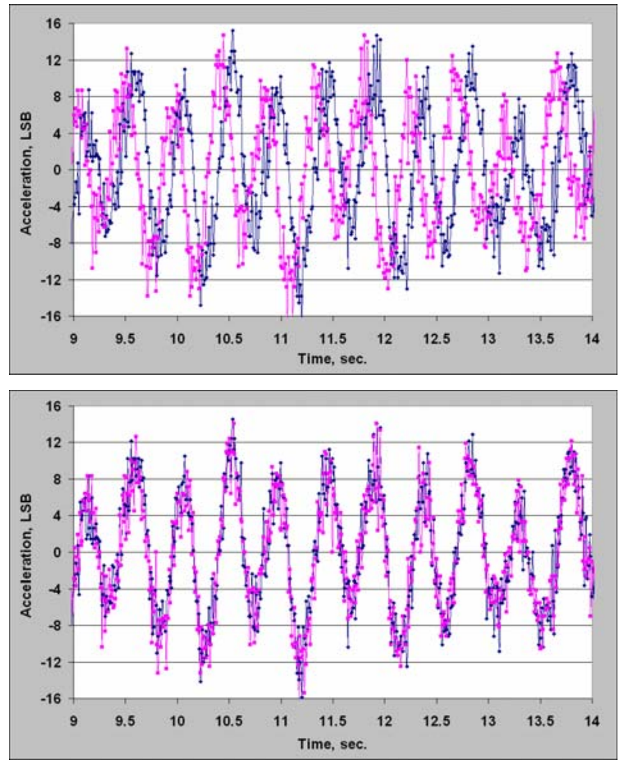

Fig. 7. Effect of time synchronization between two adjacent modules: top – data collected without synchronization; bottom – data collected with synchronization.

4 CONCLUSION

Green SHM Systems has developed the 3AT-09 wireless sensing module capable of operating autonomously for at least 25 years without any required maintenance while making regular measurements (every hour, every day, every week or as required) and delivering measurement data to a data collector through a wireless channel.

Wireless sensing modules with such a long service life have been a missing component required for a wide range of applications, including structural health monitoring of civil and military infrastructure facilities as well as in environmental monitoring, tag-trace-and-locate applications, agricultural and other applications. Experiments show that the wireless sensing modules can provide high quality vibration measurement data from structures such as bridges and buildings.

The developed wireless sensing modules allow for adding different sensors. In particular, Green SHM Systems is working on advanced sensing modules utilizing strain gauges, cameras and microphones.

ACKNOWLEDGMENT

The authors deeply appreciate help provided by Victor Lifton, including valuable recommendations related to selection of batteries for the wireless sensing module.

REFERENCES

(ASCE 2009) *Report card for America's Infrastructure*, American Society of Civil Engineering, 2009. http://www.infrastructurereportcard.org/sites/default/files/ RC2009_full_report.pdf.

(Fraiser, 2006) Fraiser M., Elgamal A. *Video and motion structural monitoring framework*, Proceedings of 4th China-Japan-US Symposium on Structural Control and Monitoring, Oct. 16-17, 2006.

(Kim, 2007) S. Kim, S. Pakzad, D. Culler, J. Demmel, G. Fenves, S. Glaser, M. Turon. *Health Monitoring of Civil Infrastructures Using Wireless Sensor Networks*, in Proceedings of the 6th International Conference on Information Processing in Sensor Networks, Cambridge, MA, 2007

(NIST 2009) *Civil infrastructure. Advanced sensing technologies and advanced repair materials for the infrastructure: water systems, dams, levees, bridges, roads and highways*, white paper, NIST, March 2009.

(Turner-Fairbank 2001) *Reliability of visual bridge inspection*, Turner-Fairbank Highway Research Center, Federal Highway Administration, March 2001. http://www.tfhrc.gov/pubrds/marapr01/bridge. htm.

Nickolai Belov received M.S. in Electrical Engineering in 1981 and Ph.D. in microelectronics in 1989 from Moscow Physics Engineering institute (MPhEI). In 1981-96, he worked at MPhEI as an engineer and research scientist developing MEMS sensors. In 1992-96 he was the head of Sensoelectronic Laboratory. In 1996 he moved to the USA where he participated in multiple MEMS-related projects, including managing the development of MEMS portion of advanced MEMS-based memory device at Nanochip and development of digital 3D accelerometer and finger-controlled 3D force sensor for cell phones and mobile applications at MegaSense. He is the author of more than 40 publications and more than 10 patents in the field of MEMS. His research interest areas include MEMS sensors, multi-sensor systems, energy harvesting and autonomous wireless sensors.

Ghassan Tchelepi received B.S. in Computer Science in 1984 from CSU Chico. He held many engineering management positions at several Silicon Valley startups including TeraStor, Versatile Optical Networks, Areo Data Networks, Nanochip and Green SHM Systems. He has over 25 years of experience developing embedded systems for innovative products in the areas of Near Field recordings, MEMS based probe storage, free space optical switches and low power smart wireless sensors.