ISSN: 2278 – 909X
International Journal of Advanced Research in Electronics and Communication Engineering (IJARECE)
Volume 6, Issue 8, August 2017

MEMS based Wireless Sensor Network for Structural Health Monitoring

Neethu Madhukumar, Dr M R Baiju,

***Abstract*—Wireless sensor network using microelectromechanical systems for evaluating the health conditions of a civil structure after the occurrence of a seismic event is designed. An efficient structural health monitoring system is realized using a 3-axis monitoring platform implemented using 3-dimentional microelectromechanical systems accelerometer at multiple locations within the structure. The sensor nodes record and transmit data when vibration due to seismic events exceeds a predefined threshold value or when instructed by the base station. The entire system is given battery back-up so that the system can operate during emergency power failures and critical data is not lost. The system is designed to operate over the IEEE 802.15.4 baseband. At the base station the data is analyzed and displayed. The results of characterization and the field test are presented.**

Index Terms— ***Microelectromechanical systems (MEMS); structural health monitoring; wireless sensor network***

I. Introduction

Structural Health Monitoring (SHM) using Wireless Sensor Networks (WSN) is becoming a popular field of study [1]-[7]. A typical WSN consists of a sensor, processor, memory, self-power source and a transceiver. It should operate without battery replacement, at least during the operational life time of the civil structure [8]. Installation of SHM increases the safety and serviceability of the structure. However, building owners are still hesitant to install health monitoring system due to high installation and maintenance charges [9]. The installation cost can be considerably reduced by using wireless sensor nodes instead of wired. The cost could further be reduced by the use of low cost sensors which can be mass produced such as MEMS [10]-[13]. MEMS and WSN together form a low cost, high efficient SHM. The work presented in the preceding sections discuss about such a system.

II. WSN Theory of Operation

The WSN are programmed to record and transmit data when the vibration due to a seismic event exceeds a predefined threshold value, which is considered harmful for the building. The algorithm for this is shown in Fig. 1. When such an event occurs, the sensor module wakes up and transmit data to the base station. The node to perform this action can be chosen randomly by the base station. This helps to keep the hardware and software section of all the nodes simple and identical. Since the sensor nodes are WSN, the wakeup call is sent over the radio link. The base station can control any node at any time via the radio link. The entire system works under the master-slave principal, the base station acts as the master and the WSN as slaves. The base station upon receiving the data from a node analyses the data and takes decision on waking up the other nodes. The sensor nodes upon receiving the wakeup call starts transmitting data to the base station. Based on the data received, base station decides the future course of action.

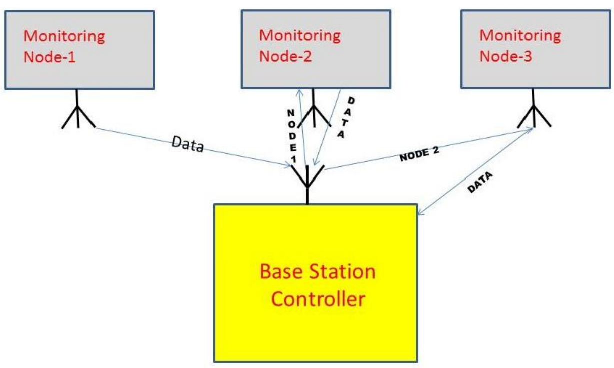

Fig. 1. WSN communication algorithm

III. Architecture of the Proposed System

The system design is shown in Fig.2. The system consists of a 3-dimentional accelerometer, microcontroller board, wireless transceiver and a self-power source. The accelerometer is used in assessing the seismic response of the civil structure. For ideal implementation of SHM system 3-axis monitoring platform at multiple locations within the structures is required. The sensor nodes collect data and transmit to the base station. The base station can either process and store the data or forward the data. The base station is shown in Fig.3. (a)The entire acceleration sensing node is given a battery backup so that they can operate even during probable cases of power failure during seismic events.

Manuscript received July, 2017.
Neethu Madhukumar,*Electronics and Communication, College of Engineering, Trivandrum , Trivandrum ,India ,+91949742880.*
Dr, M R Baiju, *Electronics and Communication ,College of Engineering Trivandrum ,Trivandrum, India,+91446495958 .*

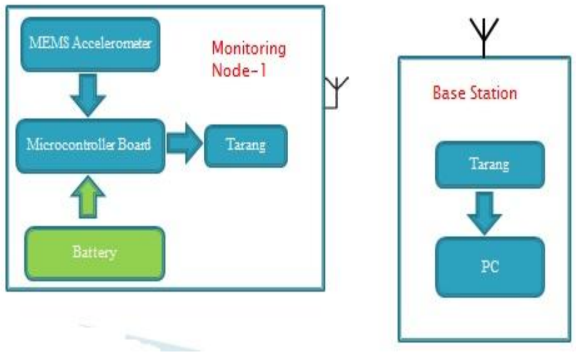

Fig. 2. System Design

It is ideal that the system should operate without battery replacement at least during the operational life time specified for the civil structures. In order to keep it that way the system should consume very little power as possible. It was observed that the sensor nodes consume much less power while in sleep mode compared to measurement mode. Accordingly the sensors were programmed to be in sleep mode during inactive period and switch to measurement mode when vibration exceeds threshold value. The threshold value is predefined and calibrated according to the value that is considered to cause any significant damage to the structure.

IV. IMPLEMENTATION OF THE PROPOSED SYSTEM

The proposed system design is implemented in Open Hardware. The implementation of the system design is shown in Fig. 3.(b) .The design was implemented using the following:

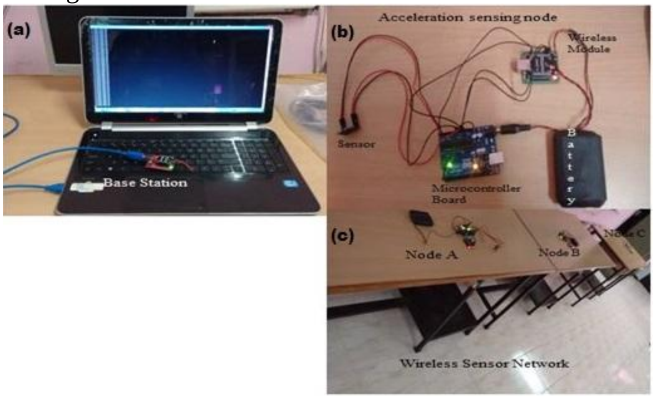

Fig. 3. (a)Base station; (b) System Implementation; (c) Wireless Sensor Nodes

A. *Hardware Requirement*

- Accelerometer: ADXL345 is a MEMS 3-dimentional accelerometer with high resolution (13-bit) measurement up to ±16g, ultralow power consumption. Digital output data is formatted as 16-bit twos complement and is accessible through either a SPI (3-or4-wire) or I^2C digital interface [14].
- Microcontroller board: The Arduino Uno is a microcontroller board based on the ATmega328 [15].
- Wireless transceiver: Tarang modules are designed with low to medium power transmit power and for high reliability wireless networks. The modules operate within ISM 2.4-2.4835GHz frequency band with IEEE 802.15.4 baseband.
- Self-power source: The modules are powered by Lithium ion battery.

B. *Software Requirements*

- ARDUINO 1.6.5,the open-source Arduino Software (IDE) makes it easy to write code and upload it to the board. It runs on Windows, Mac OS X, and Linux. The environment is written in Java and based on processing and other open source software. This software can be used with any Arduino board.
- PuTTy is a free and open-source terminal emulator , serial console and network file transfer application. It supports several network protocols, including SCP , SSH, Telnet, rlogin, and raw socket connection. It can also connect to a serial port(since version 0.59).
- MATLAB is used to obtain real time plots from a serial port.The graph is obtained by accessing serial port data in real time. The COM values and variable values can be changed according to the requirement.

  The laboratory setup of the WSN is shown in Fig. 3.(c). The data obtained from the sensor nodes is analysed and displayed at the base station.

V. DATA ACQUISITION, ANALYSIS AND RESULTS

The accelerometer was designed to operate within ±2g. On triggering the accelerometer using the self-test feature in ADXL345, an electrostatic force is exerted on the mechanical sensor. This electrostatic force moves the mechanical sensing element in the same manner as acceleration . The data thus obtained at each node is observed on the serial monitor of Arduino IDE (Fig. 4.).

The data from the node is sent over radio link to the base station; PuTTy is used to interface the COM port to which the wireless module is connected at the base station(Fig. 5.). Upon analysing the data sent from the selected sensor node and the data obtained at base station it was observed that correct reception was obtained (Fig. 6.). Commands were given from base station to switch to the desired sensor node, it was observed that the switching action was performed with 100% accuracy and the data was obtained at base station with zero time lags.

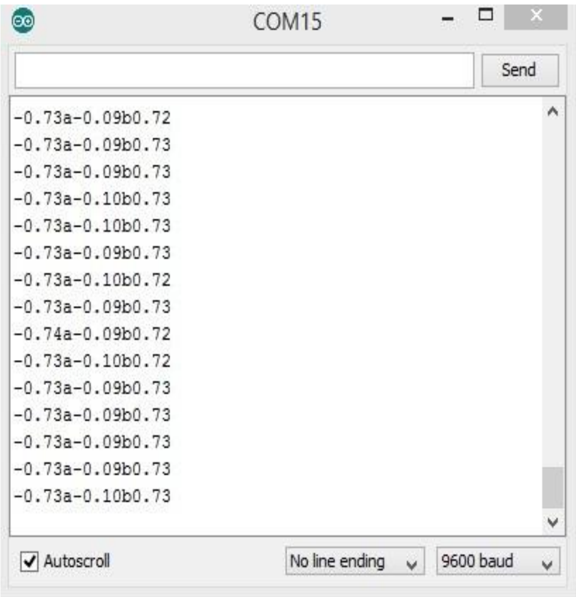

Fig. 4. Acceleration value on serial monitor of Arduino IDE

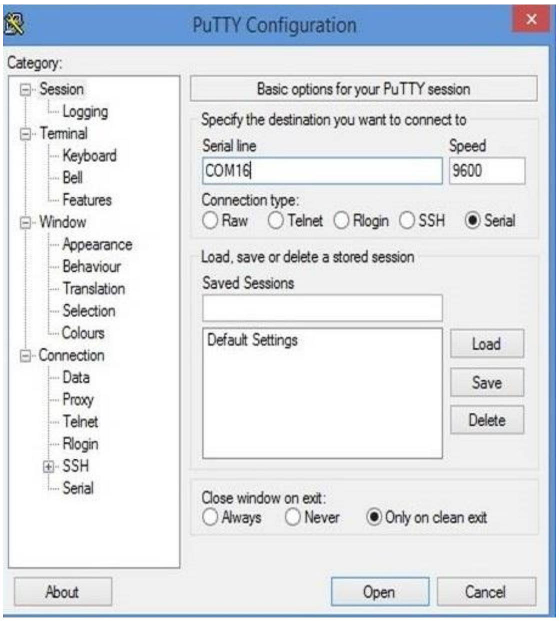

Fig. 5. Selection of COM port using PuTTy at base station

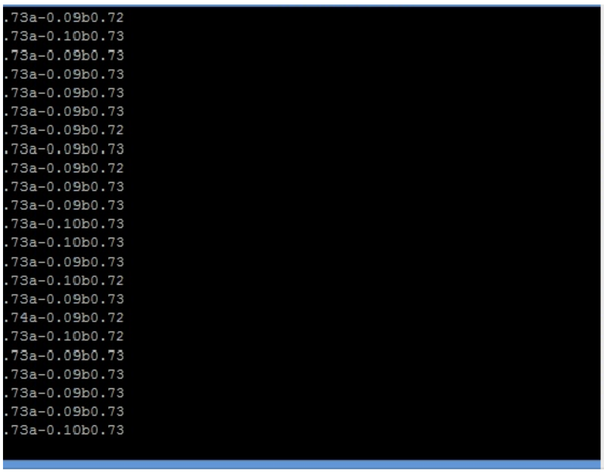

Fig. 6. Acceleration values obtained at base station over wireless link and displayed using PuTTy

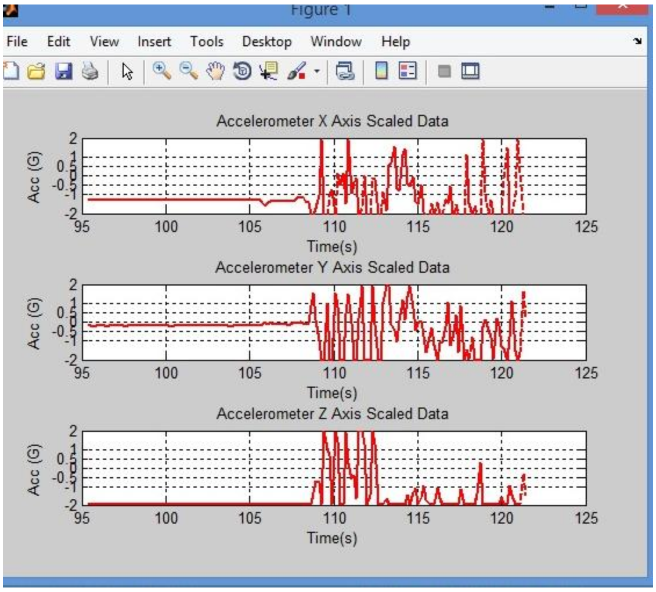

Fig. 7. Real time Plots of vibrational changes in accelerometer obtained at base station over wireless link

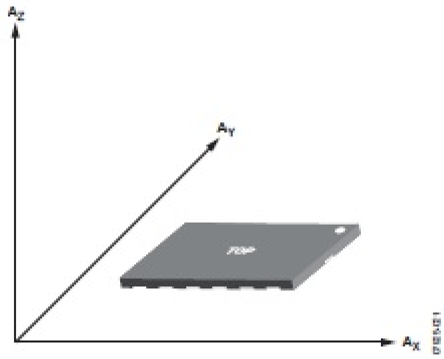

Fig. 8. Accelerometer axes of Acceleration Sensitivity (corresponding output voltage increases when accelerated along the sensitivity axis)

MATLAB was used for better visualisation of the vibration effects on accelerometer. It gives accurate real time plots for different acceleration values. The graph is obtained by accessing serial port data in real time. The change in acceleration in each axis could be clearly observed in the plots obtained. For each change in vibration applied corresponding changes were observed in the real time plots (Fig. 7.). Commands were sent from base station to switch to desired node for graphical analysis of the selected node. The switching action was successfully executed and the plot for the selected node was obtained.

VI. Field Test

In order to verify the feasibility and reliability of the proposed system, the system was tested on idealised models of bridge and building in the Structural Dynamics LAB.

The bridge model consists of two independent spans with a common pier between successive spans. Each span consists of a metallic deck supported by two piers at both ends.

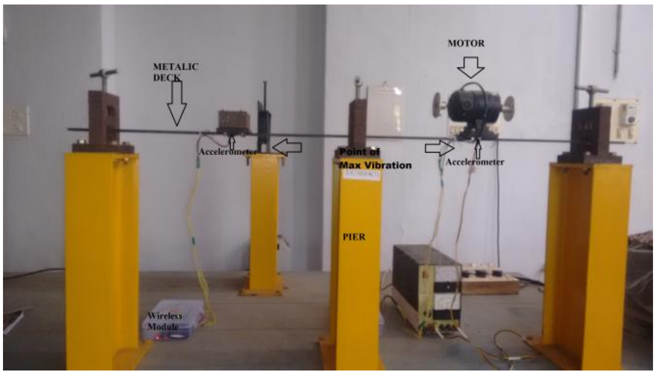

Fig. 9. Field Test 1:Proposed system is tested on a model of a bridge, vibrations are provided on the model using a motor ,the amount of vibration produced by the motor is controlled by a voltage source

The bridge model consist of two independent spans with a common pier between successive spans. Each span consists of a metallic deck supported by two piers at both ends . The model is idealised so that any test valid on this model will be valid on the real bridge. In order to study vibrational effects on the structure ,vibrations were simulated using a motor. The motor was placed on the bridge to provide vibrations along z axis. The motor is controlled using the voltage source connected to the motor. The bridge experiences maximum vibrations at certain points which is marked in Fig.9. The Accelerometers are placed at points were the bridge experiences maximum vibration. In order for the sensornodes to experience vibration at the points on the bridge were maximum vibration is experienced the sensor nodes were placed as shown in Fig.9. The accelerometers were attached to bridge using beewax gum so that it remained intact on the bridge during the application of vibration by the motor.(Fig. 10.).

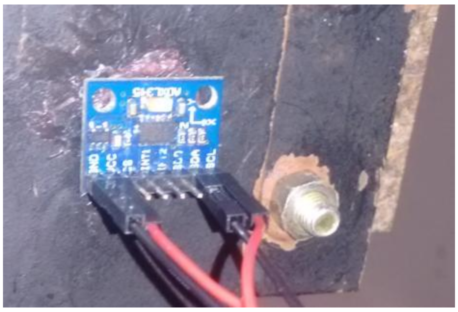

Fig. 10. MEMS Accelerometer fixed using beewax gum on the model of bridge at the point of maximum vibration

For any structure give a force or displacement and then leave the structure freely to vibrate. The frequency at which this structure vibrates is the Natural frequency of the structure. High amplitude vibration is caused when the structure vibrates at the Natural frequency. Under this condition the probability of failure of the structure is more. The earthquake signals are random in nature hence there are chances for the occurrence of
signals that cause the structure to vibrate at its natural frequency. There by increasing the chances of failure. Other than seismic events there are other sources that cause vibration to the structure like the vibration caused by heavy vehicles moving over a bridge, the vibrations experienced by civil structures near road side, the vibration caused to structures in typhoon prone areas, the vibration endured by structures surrounding a construction site due to activities such as piling etc. Hence it is necessary to monitor the vibrations experienced by the civil structures. The motor was used to provide vibrations on the bridge. The voltage source of the motor was adjusted to control the vibrations. The vibration applied on the bridge was slowly increased. The sensor nodes remained in sleep mode when vibrations remained below switched to active mode and started transmitting data to the base station over wireless link. For an increase in vibrations applied corresponding increase in vibrations were obtained at the base station. The data was obtained from sensor nodes to the base station over wireless link with zero time lags.
Figure 11 shows the real time plots of the data obtained at base station. The axis of application of vibration was z axis; corresponding changes were obtained on z-axis at the base station. The x and y axis experiences no vibrations.

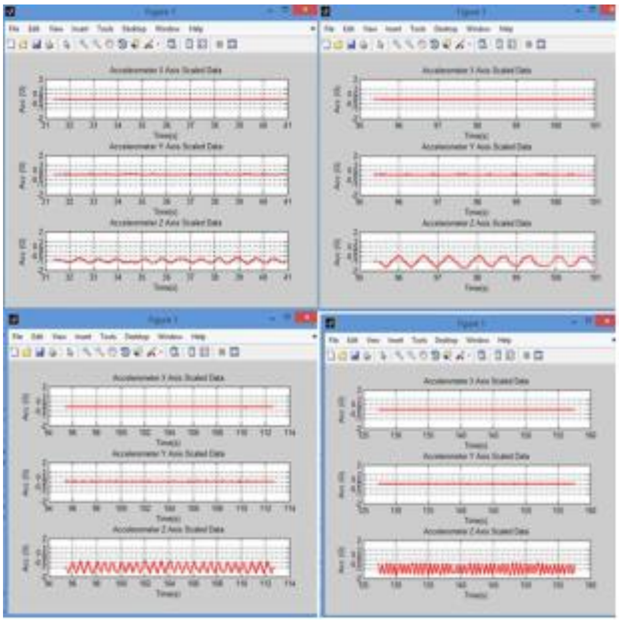

Fig. 11. Data obtained under Field Test 1 at the base station over wireless link when vibrations applied on bridge model is above the pre-set threshold value on the wireless sensor nodes

Another field test was carried out by deploying the sensor nodes on a model of a 3-story building .The 3-story steel frame model was built in 1:3 ratio of an original building, hence any test valid on this structure will be valid on the real structure. It is placed over an horizontal shake table. Also on the horizontal shake table a motor was placed. The vibrations were provided using this motor which is controlled by its voltage source. The model is idealised so that any test valid on this structure will be valid on an original structure. The structure experiences maximum vibrations at certain points which are marked in Figure.12.

ISSN: 2278 – 909X
International Journal of Advanced Research in Electronics and Communication Engineering (IJARECE)
Volume 6, Issue 8, August 2017

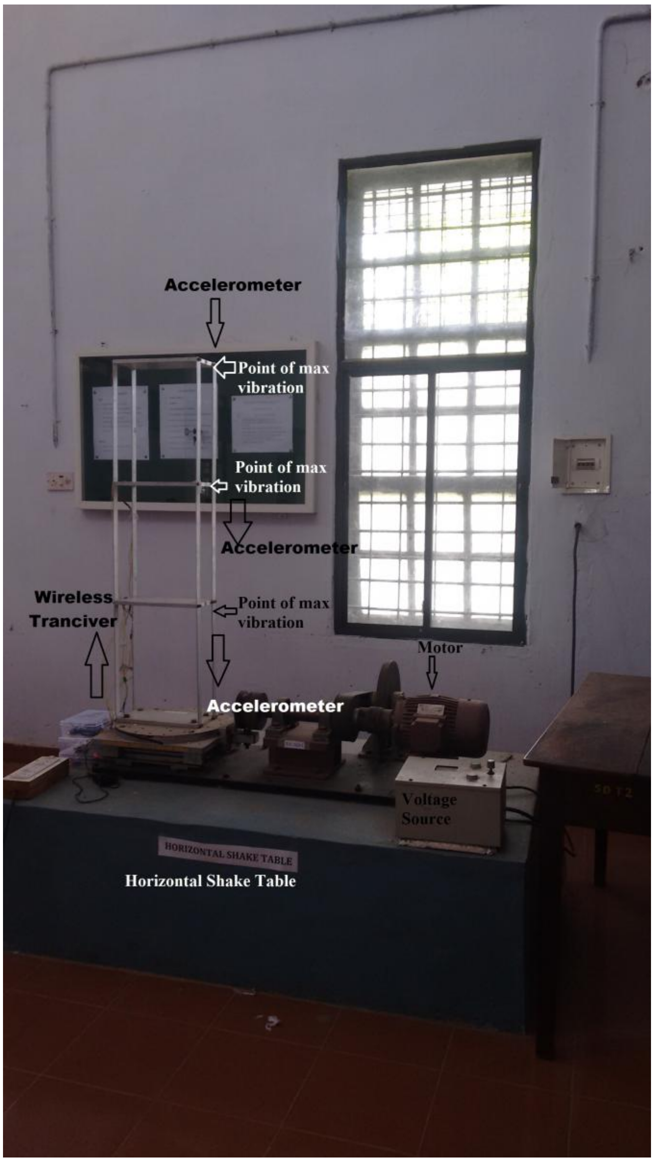

Fig. 12. Field Test 2:The proposed system tested on a steel frame model of a three story building mounted on top of a horizontal shake table for vibrational analysis,the vibrations provided using a motor ,the amount of vibrations produced by the motor is controlled by a voltage source

The sensor nodes were placed on each level of 3-story steel frame building model at the points were the system experiences maximum vibration. The vibrations were provided on the structure using the motor. The amount of vibrations provided by the motor was adjusted using its voltage source. The vibration provided on the structure was slowly increased. When the vibration exceeded the pre-set threshold value of vibration the sensor nodes started transmitting data over wireless link to the base station. The axis of application of vibration by the motor was z-axis but since elongated structure it experiences some vibration in x and y axis also. The wireless sensor nodes remained inactive when the vibrations experienced by the accelerometer was below the pre-set threshold value and when the vibration exceeded the predefined threshold value the sensor nodes stared transmitting data over wireless link to the base station . For changes in vibrations applied corresponding changes were obtained at the base station over wireless link for analysis with zero time lags.

This monitoring system which was designed and implemented helps analyze the vibrations experianced by the civil structure that are considered harmful for the structure by seting the threshold of the sensor nodes in accordance with the design of the civil structure. The monitoring is of paramount importance in the case of earthquake prone area as under such an event the structure may exceed their structural or functional limits which can be visible[16]. They can also suffer enormous damage to their capacity without producing visible signs. Such damage result in life threatening conditions evolving in structure long after damage has occurred . Also structure become incapable of surviving consecutive after shocks which occur within few hours after eath quake and has an intensity of almost 90% of earthquake. As the characterisation and field test results point the monitoring system helps in monitoring vibrations considered harmful for the civil structure. Hence helps give a reliable assessment of the capacity of structure to survive expected after shocks. Thus increases the safety and servicability of the structure.

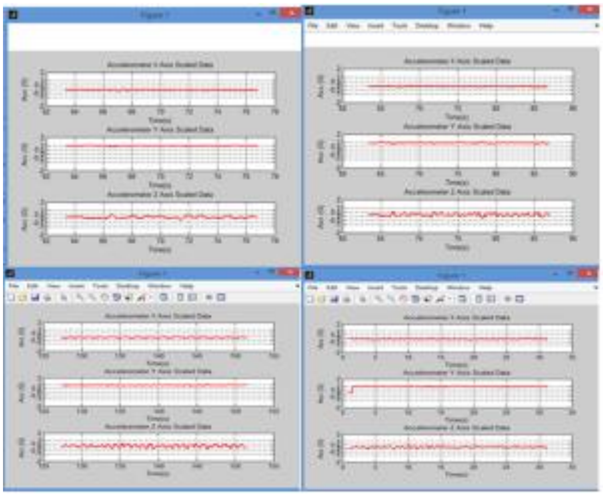

Fig. 13. Data obtained at base station under Field Test 2 over wireless link when vibrations applied on the model of the 3-story building exceeded pre-set threshold value

VII. CONCLUSION

The characterization and field test of the wireless MEMS based structural health monitoring system is proposed. The system is implemented in Open Hardware. The system utilizes the unique features of MEMS sensors for developing low cost, compact and higher accuracy system. Low power consumption and efficient data accusation techniques achieved using the WSN. Battery back-up helps to operate even in emergency power failures during seismic events. The system provides high-quality sensor data at the right time and helps in increasing the safety and serviceability of the Civil Structure.

ACKNOWLEDGMENT

The facilities were provided under NPMaSS programme in National MEMS design LAB, College of Engineering,Trivandrum.

REFERENCES

[1] J. P. Lynch and K. J. Loh, "A summary review of wireless sensors and sensor networks for structural health monitoring," *Shock Vibrat. Dig.*,vol. 38, no. 2, pp. 91–128, 2006.
[2] Sukun Kim; Pakzad, S.; Culler, D.; Demmel, J.; Fenves, G.; Glaser, S.; Turon, M., "Health Monitoring of Civil Infrastructures Using Wireless Sensor Networks," in *Information Processing in Sensor Networks, 2007. IPSN 2007. 6th International Symposium on* , vol., no., pp.254-263, 25-27 April 2007
[3] Ali, N.A.; Drieberg, M.; Sebastian, P., "Deployment of MICAz mote for Wireless Sensor Network applications," in *Computer Applications and Industrial Electronics (ICCAIE), 2011 IEEE International Conference on* , vol., no., pp.303-308, 4-7 Dec. 2011
[4] Werner-Allen, G.; Lorincz, K.; Ruiz, M.; Marcillo, O.; Johnson, J.; Lees, J.; Welsh, M., "Deploying a wireless sensor network on an active volcano," in *Internet Computing, IEEE* , vol.10, no.2, pp.18-25, March-April 2006
[5] Mukhopadhyay, S. C.; Chase, J. G.; Meyendorf, N., "Editorial Special Issue on Sensors Systems for Structural Health Monitoring," in *Sensors Journal, IEEE* , vol.9, no.11, pp.1319-1321, Nov. 2009
[6] Ceriotti, M.; Mottola, L.; Picco, G.P.; Murphy, A.L.; Guna, S.; Corra, M.; Pozzi, M.; Zonta, D.; Zanon, P., "Monitoring heritage buildings with wireless sensor networks: The Torre Aquila deployment," in*Information Processing in Sensor Networks, 2009. IPSN 2009. International Conference on* , vol., no., pp.277-288, 13-16 April 2009
[7] Yizheng Liao; Mollineaux, M.; Hsu, R.; Bartlett, R.; Singla, A.; Raja, A.; Bajwa, R.; Rajagopal, R., "SnowFort: An Open Source Wireless Sensor Network for Data Analytics in Infrastructure and Environmental Monitoring," in *Sensors Journal, IEEE* , vol.14, no.12, pp.4253-4263, Dec. 2014
[8] Tom Torfs, Tom Sterken, Steven Brebels, Juan Santana, Richard van den Hoven,Vincent Spiering, Nicolas Bertsch, Davide Trapani, and Daniele Zonta,"Low Power Wireless Sensor Network for Building Monitoring,"IEEE Journal of Sensors ,vol. 13, no.3, , pp. 909-915 March 2013
[9] M. Pozzi, D. Zonta, W.Wang, and G. Chen, "A framework for evaluating the impact of structural health monitoring on bridge management," in *Proc. 5th Int. Conf. Bridge Maintenance, Safety Manage.*, Philadelphia,PA, Jul. 2010, p. 161.
[10] Varadan K Vijay,"Fabrication Methods and Applications" in *Smart Material System and MEMS:Design and Development Methodologies*. New York :Wiley,2006 ,pp.255-278
[11] Tai-Ran Hsu,"Microsystem Fabrication Processes" in MEMS and MICROSYSTEMS Design, Manufacture And Nanoscale Engineering, 2nd ed.New York:Wiley,2008,pp.271-304
[12] J. Santana, R. van den Hoven, C. van Liempd, M. Colin, N. Saillen, and C. Van Hoof, "A 3-axis accelerometer and strain sensor system for building integrity monitoring," in *Proc. 16th Int. Conf. Solid-State Sensors, Actuat., Microsyst.*, Beijing, China, Jun. 2011, pp. 36–39.
[13] Caimmi, F.; Mariani, S.; De Fazio, M.; Bendiscioli, P., "Investigation of the Effectiveness and Robustness of an MEMS-Based Structural Health Monitoring System for Composite Laminates," in *Sensors Journal, IEEE* , vol.14, no.7, pp.2208-2215, July 2014
[14] Analog Devices High Performance Digital output Vibration Sensor ADXL345 datasheet
[15] ATmega 328 microcontroller data sheet.
[16] A. Amditis, Y. Stratakos, D. Bairaktaris, M. Bimpas, S. Camarinopolos, and S. Frondistou-Yannas, "An overview of MEMSCON project: An intelligent wireless sensor network for after-earthquake evaluation of concrete buildings," in *Proc. 14th Eur. Conf. Earthquake Eng.*, Aug.–Sep. 2010.

Neethu Madhukumar received her B.Tech in Electronics and Communication in 2012 from the University of Kerala, India. She obtained her Masters in Technology from College of Engineering, Trivandrum, in 2015. From January 2014 to December 2014 she was involved in teaching 'Random Processes and Applications" for Bachelours students of College of Engineering Trivandrum as part of Govt. of Kerala project 'Step4U'.

Dr M R Baiju Dr M R baiju received his B.Tech in Electronics and Communication Engineering in 1988 from College of Engineering Trivandrum, India. He obtained his PhD from Indian Institute of Science Bangalore,India, in 2004 in Power Electronics. From 1988 to 1991 he was waorking as Engineer in NTPC Ltd.,Since 1991 he is working in College of Engineering Trivandrum. Currently he is attached to Kerala Public Service Commission as Member.