Monitoring of the seismic activity using high sensitivity MEMS accelerometer

Djordje Klisić, Ilija Radovanović, Nikola Bežanić, Ljubisav Stamenić, Ivan Popović

***Abstract*— MEMS sensors are widely used type of sensors that can be found in many modern gadgets. Affordable price and small dimensions in combination with high sensitivity and precision made them interesting candidates for the wide range applications in various fields. In case of seismology, application of MEMS accelerometer is still in the shadow of the classical accelerometers with the inertial element, although the characteristics of the today MEMS accelerometers can easily match the classical ones. In this paper group of authors decided to test characteristics of the high sensitivity accelerometer and to determine if it is suitable for the applications in seismology. The requirements that sensor had to meet are high sensitivity and noise level below the threshold of human detectable vibrations which is around four degrees of the Mercalli scale or the ground acceleration between 0.015g and 0.04g.**

***Index Terms*—Seismology, MEMS accelerometers, ground acceleration, microcontroller, data acquisition, earthquake detection, seismic waves**

I. INTRODUCTION

Because of their small dimensions, relatively good sensitivity and affordable price, MEMS accelerometers become widely used type of sensors across the variety of different fields in every day applications. The most evident example is consumer electronics, where almost every modern gadget such as mobile phones or tablets cannot be imagined without these sensors for screen rotation or motion detection. Also, these sensors are present in automobile industry where they are used for airbag control, ESP ABS, anti-roll and other applications. Although the main purpose of accelerometers is acceleration measurement, MEMS accelerometers still have to position them in case of geology where classical accelerometers with inertial element are still dominant class of sensors for the measurement of ground acceleration. Even though MEMS accelerometers managed to achieve high level of sensitivity, the main problem why their applications in this field are still limited is the relatively high noise levels. There are several studies examining potential usage of accelerometer network for the ground acceleration measurement and soil imaging that will be able to replace current bulky and expensive versions of geophones. [1-4] Seismological survey of Serbia currently uses combined grid which consist of 24 seismometers stations and 44 accelerometer stations [5], although MEMS accelerometers are still to be introduced to this grid in the future.

For the purpose of this paper, several accelerometers with sensitivity ranging from 1.5g to 6g were tested. Since the accelerometers express the acceleration in m/s^2 or as a percentage of g, it is often unintuitive to understand the results and to compare them with widely accepted representations such as Mercalli or Richter scale. During the late ’90 United States Geological Survey (USGS) devised method that they called ShakeMap which is representation of ground shaking produced by an earthquake. The information it presents is different from the earthquake magnitude and epicenter that are released after an earthquake because ShakeMap focuses on the ground shaking produced by the earthquake, rather than the parameters describing the earthquake source. Also, they devised a scale that describes relation between instrument magnitude, peak velocity, peak acceleration, perceived ground shaking and potential damage to the objects [6-8]

TABLE I
RELATIONS BETWEEN PERCEIVED ACCELERATION, INSTRUMENTAL INTENSITY, PEAK VELOCITY, ACCELERATION AND DAMAGE MADE BY EARTHQUAKE

Instrumental Intensity	Acceleration (g)	Velocity (cm/s)	Perceived Shaking	Potential Damage
I	< 0.0017	< 0.1	Not felt	None
II-III	0.0017 - 0.014	0.1 - 1.1	Weak	None
IV	0.014 - 0.039	1.1 - 3.4	Light	None
V	0.039 - 0.092	3.4 - 8.1	Moderate	Very light
VI	0.092 - 0.18	8.1 - 16	Strong	Light
VII	0.18 - 0.34	16 - 31	Very strong	Moderate
VIII	0.34 - 0.65	31 - 60	Severe	Moderate to heavy
IX	0.65 - 1.24	60 - 116	Violent	Heavy
X+	> 1.24	> 116	Extreme	Very heavy

Idea behind this paper is to create affordable, low power, compact in-house vibration detecting device that will be capable of detecting medium to high natural or manmade vibration intensities. In order to achieve this, MEMS sensor that we used had to fulfill some requirements. According to the scale presented in table I, target sensitivity threshold of the sensor should be 1.4% of g or magnitude four, which is also the threshold of human vibration perception. Even though we

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expected that accelerometers with a greater range will be capable to detect fine vibrations, only the ones with the range below 1.5g and relatively high sensitivity (over 1000mV/g) were capable to do that. The main culprit for inability to detect proper low intensity vibrations was noise. Signal/noise ratio of the MEMS sensors in case of the raw, unfiltered signal was pretty low, especially in case of vibrations that are near the threshold of the human vibration perception. In order to overcome this problem and to improve the sensitivity of the sensor, we investigated which type of filter is most suitable for noise reduction.

II. Materials and Methods

After the thorough testing of the several types of MEMS accelerometers, biaxial ADXL213 has proven to be the most suitable one for the seismic measurements. It has measurement range up to 1.2g while the resolution is 30% of the input voltage as declared by the manufacturer. If the power supply is typical 3.3V input voltage, resolution can theoretically go as high as 1000mV/g which means that sensitivity is 0.001g in ideal situation in case of noise free signal. Accelerometer is capable of measuring dynamic accelerations (vibrations, tremors, quakes) as well as static acceleration such is the gravity. This accelerometer chip comes on a PCB board with defined contacts for easy implementations in development kits. Axes output signals from the accelerometer are analog.

For the data acquisition and processing the most practical choice was to use some of the mbed controllers. In this case, we opted for the LPC1768 model, which is based on a ARM Cortex M3 microprocessor clocked at 96MHz. Microprocessor module is designed as compact 40 pin DIP casing which is easy to connect and use on development kits and protoboards. Module also includes variety of useful interfaces such as USB, SPI, I^2C, CAN, Ethernet and serial ports. Connecting analog outputs from the accelerometer and other components to mbed module is fairly easy by using standard wires and connectors. Also, mbed module has analog input ports that can handle digitalization of the input analog signals. Data acquisition and processing can be set and controlled using online C/C++ compiler which allows OS independent programming. Compiler produces binary file that has to be downloaded to local machine and uploaded to mbed flash memory in order to start the program. Because of all this commodities that mbed module provides and reasonably low price and power consumption, choosing this microcontroller was the logical choice.

Prototype system which consists of the aforementioned accelerometer and mbed microcontroller is devised on

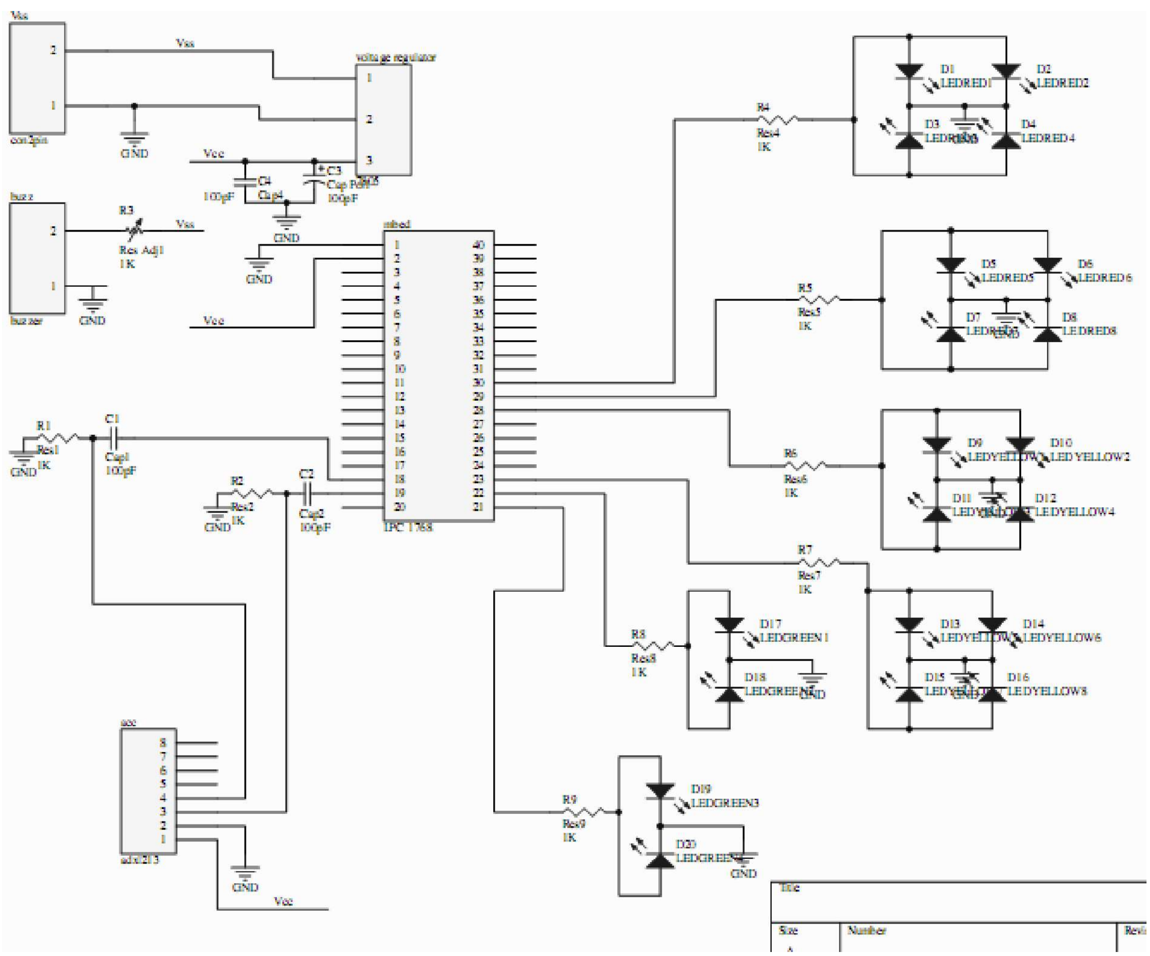

Fig. 1. Electronic schematic of the system. 40 pin mbed microcontroller is positioned in the center. MEMS accelerometer is represented as the 8 pin module in the bottom left part of the schematics, while the LED blocks are positioned to the right. Upper left part is represents the voltage source and vibration generator.

protoboard. Signals are filtered using combination of HP and LP passive RC cutoff filters which are intended to pass only part of the signal frequencies between 1Hz and 250Hz. This frequency range is typical for seismic events [9] Power supply for the system is provided from 9V DC source. Linear voltage regulator L7805 IC made by STMicroelectronics provides 5V voltage supply for the mbed module and MEMS ADXL213 accelerometer. System also includes six blocks of LEDs used to signal and visually represent intensity of the quake. Each block consists of different number of LEDs (two blocks of 1x2 and four of 2x2) and different colors (2x green, 2x yellow, 2x red). Since the system uses low power components predicted autonomy time can reach six to nine months. Electronic schematic of the system are presented on the Fig1.

Even though in ideal case accelerometer sensitivity should be 30% of the input voltage per 1g as declared by the manufacturer it was not the case. Sensitivity testing of the accelerometer x and y axes was performed using testing circle. First position of the accelerometer was when the axes were parallel and oriented as to the gravity and after that it was rotated for 90^0. Preliminary measurement for the both axes showed that measured sensitivity was 780mv/g (Fig 2).

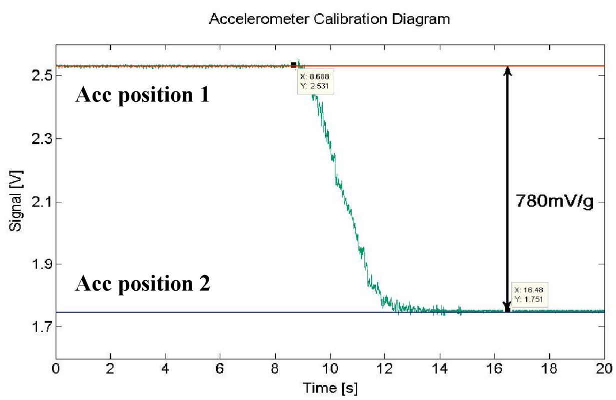

Fig. 2. Calibration measurement for the x-axes in case of ADXL213 accelerometer. First position of the accelerometer was when the x-axes was parallel and oriented as the gravitation force, while the second position was when the system was rotated for 90^0

Using this value, next step was to measure lower boundary of the sensor sensitivity by determining the noise levels. After several consecutive measurements of the accelerometer signal in the isolated environment it was determined that noise level was never greater than 5-6mV (Fig 3a). In order to ensure as much as possible reliability of the vibrations measurement, lower sensitivity threshold of the sensor was set to two times of the noise level or 12mV. When these values are converted to g scale, MEMS senor is capable of detecting vibrations with acceleration of 0.015g which corresponds to the intensity of the magnitude 4 earthquakes which are fairly perceptible by humans. Using values presented in the table 1 thresholds for the each magnitude were implemented in the microcontroller program. Signaling LEDs were capable of signaling six levels of quake intensity which means that first level (magnitude 4) was signaled using first groups of LEDs, while intensities higher than magnitude 9 were signaled using all six groups of LEDs.

Testing of the thresholds was performed by placing system on the iron plate on the flat surface. Peaks of different intestines that are visible on the (Fig 3b) were induced by controlled hitting of the metal plate on the distance of 15cm using flattop rubber hammer.

Since the mbed microcontroller module supports USB communication, it is possible fairly easily to store acquired data from the accelerometer onto the external memory for the further processing and visualization of the results. Acquired data is stored in form of the text file directly on the flash memory of the mbed microcontroller. Besides the programming and uploading of the programs to mbed, PC was used also as tool for visualization of the data and proof of concept for real time acquisition and visualization. In order to see real time data from the microcontroller on the MS Windows platform, it was necessary to install and use some terminal program such as TaraTerm. One of the most useful options of this hybrid terminal software was possibility to output all input data from the sensor directly in the command window. In order to visualize and signal intensity of the quake to the user, aforementioned magnitude thresholds were implemented in the microcontroller program and suitable message with the information about the intensity are displayed in the TaraTerm terminal window.

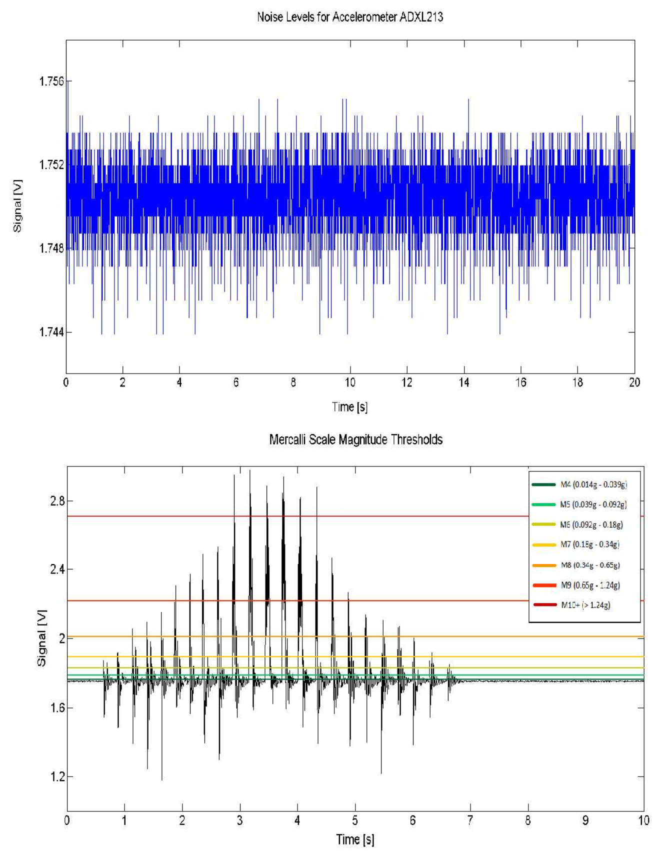

Fig. 3. Noise level of accelerometer signal from one of the axes measured in isolated environment (up) Peak excitations of the surface recorded using the presented system along with thresholds proposed in table 1 (bottom).

III. RESULTS

Since the main purpose of the presented system is vibration detection and intensity scaling, the best way to test its capabilities was to introduce controlled vibration generation to the system. In order to create controlled vibrations, a vibration generator in the form of rotation electromotor was connected to the protoboard near the accelerometer. This electromotor was powered externally using 9V battery voltage supply. Rotation intensity thus vibration generation of the electromotor was controlled using variable resistor (rheostat). Since the electromotor was firmly attached to the protoboard, vibrations were easily transmitted to the accelerometer and also very evident after visualization (Fig4).

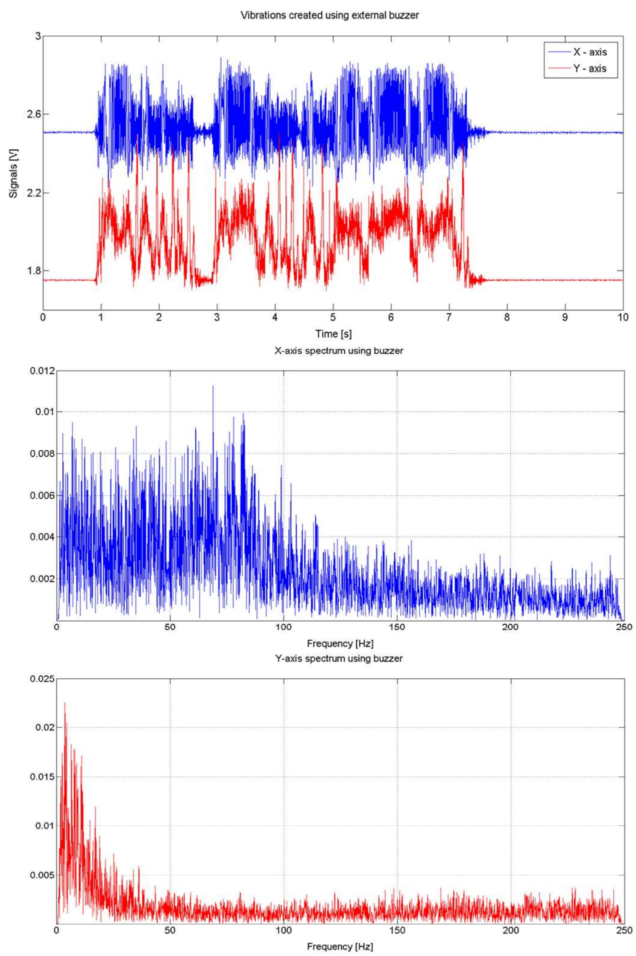

Fig. 4. Signals from accelerometer x and y axes after excitation of the protoboard surface using rotational electromotor as a vibration generator (up). Spectrum of the x and y axes show that sensor has great detection in the range between 1Hz and 250Hz (middle and bottom).

Purpose of this electromotor was to generate high intensity vibrations that can cover desired spectral window between 1 Hz and 250Hz that is characteristic for the earthquake events. Even though vibrations were quite intense, maximum values were controlled to be under the maximal detection threshold of the sensor (1.2g).

Vibrations detection was monitored in two dimensions, x and y axes, because every earthquake wave consists of two types of waves. Those two waves are called P as "primary" and S as "secondary" waves which are propagating in different planes. Primary waves are very high intensity waves that have great propagation velocity and usually are the first one to be detected. Their propagation is longitudinal and resembles propagation of concentric circles on the lake after the rock is thrown [10]. S waves characterize shearing effects and usually are propagating more slowly in comparison to P waves. P and S waves are perpendicular to each other so this is why proper biaxial detection is needed. in order to test the system in real situation a simulation of the high intensity earthquake was performed. System was positioned on the heavy iron plate. This plate on the other hand was positioned on the four springs. Whole construction was then put out of balance first longitudinally allowing the oscillation parallel to the gravity. After few seconds, a lateral component is added by shaking the construction in the direction that is perpendicular to the gravity. Signals of the high intensity earthquake simulation are presented in the Fig5.

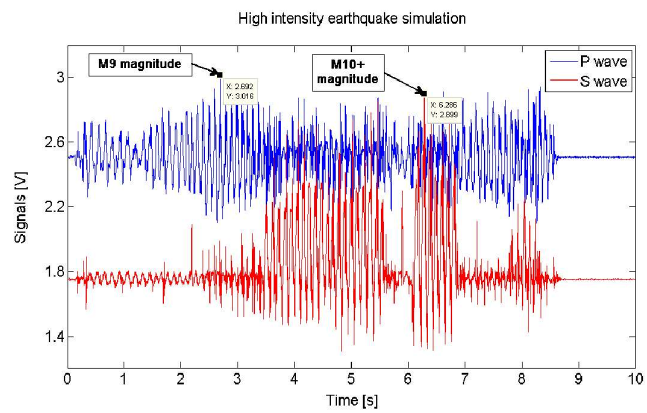

Fig. 5. Simulation of the high intensity earthquake. Signals from the x and y axes of the accelerometer correspond to the P and S wave.

IV. CONCLUSION AND FUTURE WORK

System presented in this paper is just a proof of concept that MEMS accelerometers have achieved certain level of sensitivity which can allow more extensive usage in seismology or mining. Even though signal noise still represents a barrier for the MEMS accelerometers to be used as representing measurement sensors in seismology, simple filtration using passive filters is sufficient to achieve sensitivity levels bordering with human perception. Classic seismometers based on the sensors with inertial element are still going to be only relevant measurement instruments in seismology, but on the other hand in mining and soil studies use of cumbersome geophones is very expensive, since it requires extensive drilling for the good placement of such a device.

Since the aforementioned sensor can precisely measure vibrations that are bordering with the human perception of the earthquake vibrations, it can be used within device that can be used for the in-house vibration detection and recording. Although the presented prototype is bulky and inadequate for commercial applications it can be easily improved and designed as a compact device that has its own signal visualization and data recording capabilities. Next iteration of this device will include LCD screen for the visualization of the signals and displaying the telemetry. Also LAN connectivity would be useful feature easy because it would allow exporting the data in real time to external memory with higher capacity since the mbed internal flash storage is very limited. A backup onsite memory such as high capacity MMC card or USB flash memory should also be integrated.

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