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Low Cost MEMS accelerograph: structure, operation and application to seismology

Ramadan Madi Ali Bakir[1], M.S.M. Elksasy[2], Mahmoud Sami Salam[1], Mohamed Sabry Saraya[2], Mohamed M. Abdelsalam[2]

[1]*National Research Institute of Astronomy and Geophysics (NRIAG), seismology department*.

[2]*computers Engineering and Control System Dep., Faculty of Engineering, Mansoura University*

Correspondence: Ramadan Madi Ali Bakir; el-equaz (9521); Tel: +201009277899; Email: ahr_bakir@yahoo.com

ABSTRACT

Micro Elector Mechanical Systems (MEMS) sensors enable a wide range of different applications in many fields: among others, in the last decade the use of MEMS accelerometers for seismology-related applications has grown exponentially. In this paper, we do a comprehensive review of MEMS accelerometers: Operating Principle, technical specifications, types, performance, Comparison with Geophone. We introduce the applications within seismology and earth sciences related disciplines. We introduce how to use MEMS accelerometer and geophone to build a low Coast earthquake monitoring unit. Moreover, we will discuss the performance of MEMS accelerometer, geophone by conducting a practical experiment to measure one of the explosions that occur near the city of Helwan, Cairo, Egypt.

Keywords: *MEMS, geophone, Earthquake monitoring, amplitude and phase response, MPU6050, Raspberry-pi*

1. Introduction

The technical advancements throughout the 20th century made it possible to realize increasingly reliable and sensitive seismometers thus that today, from a scientific point of view, accuracy is crucial: the greater is the quality of the observation, the more reliable will be the knowledge of the earthquake-related phenomena [1]. Traditional sensors based on a spring-mass principle have heavy proof masses making them bulky and difficult to transport and manage. The application of MEMS to seismology is very recent: in the book “Instrumentation in Earthquake Seismology” [2] edited in 2004, the MEMS were not even mentioned. The second edition [3], introduced a comprehensive section on micro machined devices. MEMS a platform technology to create small electrical devices in the order of micrometers to millimeters in size, MEMS a system capable of getting information from the external environment converting the measured physical quantities into electrical impulses. MEMS are fabricated directly upon a silicon substrate and can reach the dimension of a few microns. The term “MEMS” in academic literature appears since the mid-1980s [4], they are today used in a multitude of fields and are ideal for large-scale and large-volume applications (e.g., monitoring of machines and vehicles, navigation systems, etc.) [5-8], in this paper, we discuss MEMS accelerometer. MEMS accelerometers are used in shake prevention of a camera, a game controller and the air bag of a car. Because of its small size and light weight, MEMS sensor element can save the weight and power consumption of a measuring instruments [9]. Moreover, since the single crystal silicon used in MEMS is a stable substance, a MEMS product is excellent in long-term endurance. A MEMS sensor has small distortion in phase spectrum and linear response in amplitude spectrum. These are desired characteristics for measuring ground motion. MEMS accelerometers can be classified according to the physical effect used in the sensing mechanism: capacitive, piezo resistive, piezoelectric, electrochemical, optical, thermal, etc. Each method has its own advantages and disadvantages. For example, piezoelectric accelerometers are not suitable for static acceleration, while the capacitive ones are generally more performing and reliable.

This review aims to provide the state-of-the-art of the use of MEMS in the broad field of seismology, we describe the functioning principles of the capacitive MEMS which are the most suitable for applications within the sensing and the frequency ranges of seismological interest. We introduce the basics of the capacitive devices, technical specifications, performance, Comparison with Geophone. By the end of the review we introduce low Cost accelerograph device developed by the authors based on MEMS accelerometers.

2. Material and methods

2.1. ACCELEROMETERS OPERATING PRINCIPLE

2.1.1. A. Accelerometer model:

An accelerometer can be modeled as a second order spring-mass-damper system Fig.1. When an acceleration (a) is applied to proof mass (m) suspended by springs with a spring constant (k), and having a damping (b), then the force ($Fapplied$) acting on the proof mass is given by:

$$F_{applied} = ma_{applied} \tag{1}$$

The force exerted by springs and damping in the system can be defined as:

$$F_{spring} = kx \tag{2}$$

$$F_{damping} = b\dot{x} \tag{3}$$

Applying Newton's second law which states that the algebraic sum of all the forces equals the inertial force of the proof mass, we get:

$$F_{applied} - F_{spring} - F_{damping} = m\ddot{x} \tag{4}$$

$$m\ddot{x} + b\dot{x} + kx = F_{applied} = ma_{applied} \tag{5}$$

The transfer function H(s) of the system is given by:

$$ms^2x(s) + bsx(s) + kx(s) = F(s) = ma(s) \tag{6}$$

$$s^2x(s) + \frac{b}{m}sx(s) + \frac{k}{m}x(s) = \frac{F(s)}{m} = a(s) \tag{7}$$

$$H(s) = \frac{x(s)}{a(s)} = \frac{1}{s^2+\frac{b}{m}s+\frac{k}{m}} = \frac{1}{s^2+\frac{\omega_0}{Q}s+{\omega_0}^2} \tag{8}$$

ω_0 is the resonance frequency and Q is the quality factor, Accelerometers work in the low frequency domain (ω << ω0) with their mechanical sensitivity calculated by setting s = 0 in the transfer function $H(s)$ to get:

$$\frac{x}{a} \sim \frac{m}{k} = \frac{1}{{\omega_0}^2} \tag{9}$$

In order to have a large sensing bandwidth, we need a high resonant frequency which can be achieved by reducing the size of the proof $mass$ and increasing the stiffness of the springs. However, this reduces the sensitivity of the device. Therefore, there is a tradeoff between the sensitivity and bandwidth.

2.1.2. Specifications of Accelerometers:

MEMS accelerometers are used for various kinds of applications and therefore their specifications are application dependent [11-12]. For example, in seismic measurements, accelerometers with an operation range greater than ±0.1 g, frequency range of 0–1 Hz, and resolution less than 1 µg are required. On the other hand, in shock or impact sensing, they require a range of 10,000 g, a resolution less than 1 g, and a bandwidth of 50 kHz. In this section, we give a brief overview of the specifications of an accelerometer and the design parameters on which they depend. Accelerometers are typically characterized by their sensitivity, frequency response, resolution, nonlinearity, range, cross-axis sensitivity, and shock resistance.

- **Sensitivity:** The sensitivity of an accelerometer is defined as the output voltage signal generated per unit input acceleration in 'g'. It is sometimes referred to as scale factor and denoted by 'S'. The general units are mV/g. For a triaxial accelerometer, the axial sensitivities are independent along the X, Y and Z axes are denoted by XS, YS and ZS.

$$X_s = \frac{Output\ Voltage\ generated\ (mV)}{input\ acceleration\ along\ X-axis\ (g)} \tag{10}$$

$$Y_s = \frac{Output\ Voltage\ generated\ (mV)}{input\ acceleration\ along\ Y-axis\ (g)} \tag{11}$$

$$Z_s = \frac{Output\ Voltage\ generated\ (mV)}{input\ acceleration\ along\ Z-axis\ (g)} \tag{12}$$

- **Cross-Axis Sensitivity:** Cross-axis sensitivity is the output voltage generated due to an acceleration orthogonal to a sensitive axis. Cross-axis sensitivity is generally expressed in percentage of the sensitivity i.e., ratio of the measured voltage in the cross-axis direction to the measured voltage in the sensing axis. For a tri-axial accelerometer, each axis has two cross-axis sensitivities. For example, in the case of X-direction sensing axis, there is cross-axis sensitivity due to Y-axis acceleration (Xs) AY and Z-axis acceleration (Xs) AZ.

$$(Xs)_{AY} = \frac{Output\ Voltage\ generated\ (mV)}{input\ acceleration\ along\ Y-axis\ (g)} \tag{13}$$

$$(Xs)_{AZ} = \frac{Output\ Voltage\ generated\ (mV)}{input\ acceleration\ along\ Z{-}axis\ (g)} \qquad (14)$$

A three-axis single proof-mass accelerometer can move freely in the three directions and the proof-mass displacement is directly proportional to the output voltage. It is therefore prone to high cross-axis sensitivity. On the other hand, a single-axis accelerometer has high stiffness in the cross direction and thus has very low cross-axis sensitivity. Therefore, the monolithic integration of multiple proof masses has a similar advantage.

- **Dynamic Range and Nonlinearity:** The dynamic range of the accelerometer is the maximum dynamic acceleration that can be measured accurately. It is given in '±g'. The output response of an ideal accelerometer is linear with the input acceleration. The nonlinearity of the accelerometer, therefore, measures the deviation in the output signal with respect to the ideal linear sensitivity behavior. It is expressed in terms of full-scale range as

$$\%Non\ linearity = \frac{Maximum\ deviation\ (g)}{Full\ scale\ range\ (g)} \times 100 \qquad (14)$$

- Frequency Response and the Bandwidth: The frequency response gives the dependence of accelerometer sensitivity on frequency. It also gives the amplitude and phase responses of the accelerometer [13]. The sensitivity of an accelerometer remains constant below the resonant frequency. The range of frequencies in which the sensitivity remains constant within a tolerance band of ±3 dB is the 3 dB bandwidth of the accelerometer.

2.1.3. Types of Accelerometers

Depending on the transduction mechanism employed to convert the proof-mass displacement due to acceleration into a measurable signal, accelerometers can be classified as Piezo resistive [14], Piezoelectric [15], capacitive, resonant [16], optical [17], thermal [18], and tunneling [19]. The advantages and disadvantages of these transductions are explained in Fig.2. we will only discuss MEMS accelerometers parameter and specifications. In capacitive accelerometers, the displacement in the proof mass due to acceleration is converted to a proportional capacitance change, which is later converted and amplified into a voltage signal. There are rotor electrode plates attached to the proof mass and stator electrode plates attached to the substrate. The design of a capacitive accelerometer is accomplished so as to have a simultaneous capacitance increase and decrease with the same acceleration with differential sensing traditionally used for quantifying the acceleration. Differential sensing increases the sensitivity by a factor of 2.

2.2. MEMS accelerometer operation principles

Different types of MEMS accelerometers based on different working principles such as piezo resistive, capacitive and piezoelectric have been reported. However, the capacitive and piezo resistive types are widely considered by researchers, both the 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. On the other hand, piezo resistive 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. The authors of this paper have reported the operation principles of capacitive accelerometer that satisfy the requirements of for ground motion monitoring and earthquake sensing.

2.2.1. *MEMS structure.*

The capacitive MEMS transducers can be classified into two types according to the different designs of their geometry [20]: variable gap and variable area transducers Fig.3. The first type is characterized by fixed area and variable gap between the capacitors. The second type is characterized by fixed gap and variable area. Capacitive based MEMS accelerometers, such as MPU6050 series [21] from InvenSense Inc. use a comb finger type differential capacitive MEMS structure as shown in Fig.4-A. Have enjoyed more commercial success [22] however, these commercial sensors are designed for general purpose applications and therefore the bandwidth is larger. Hence such sensors are designed to have a large natural frequency which needs larger stiffness constant (k) and smaller proof mass (m). So the present day MEMS accelerometers largely depend on the signal conditioning electronic circuits for achieving larger sensitivity [23]. The proof mass together with movable fingers moves along and against the forced direction as shown in Fig.4-B while the fixed combs remain stationary [22]. This movement changes the air gap (d0) between the fixed fingers and the movable fingers thus changing the capacitances C1 and C2 as depicted in Fig.4-B. The overlap area remains constant. This change in capacitances can be measured and calibrated with the applied external acceleration. The movable fingers constitute the differential capacitance pair C1 and C2 with left and right comb fingers as shown in Fig.4-B.

2.2.2. Characteristics of Capacitive MEMS Accelerometers to Seismology.

The available MEMS accelerometers have different technical specifications. The exact requirements depend on the specific application and the following parameter should be considered:

1. the noise output spectral density should have a flat response to the acceleration and be in the order of $10^5 to\ 10^{-7} m.s^{-2}/\sqrt{Hz}$;
2. the sensitivity, defined as the ratio between the physical input and the electrical output, should be in the order of $10^2\ mV.m^{-1}.s^2$;
3. The detectable amplitude range should be in the order of $\pm 2 \times 10^0\ to\ \pm 2 \times 10^1\ m.s^{-2}$; however, it ultimately depends on the aims of the application.
4. the bandwidth should overlap, even partially, with the range between $10^{-2}\ and\ 10^2\ HZ$;
5. the resolution, defined as the least detectable acceleration, should be in the order of $10^{-2} - 10^{-3} m.s^2$.

The Power Spectral Density (PSD) of a noise as shown in Fig.5. for the commercial MEMS accelerometer employed for an urban seismic network [25] and for the best MEMS available today. Even the poorer ones are able to detect peaks of acceleration for local earthquakes.

2.3. MEMS accelerometer Verses conventional geophone

A MEMS accelerometer has some significant advantages over conventional geophones: light-weight and compactness. Therefore, a small and light 3-C sensor using MEMS accelerometers is more easily assembled than conventional geophones. An existing 3-C geophone is heavy and large, causing low productivity in the field. As a MEMS accelerometer can be incorporated with a tilt sensor, horizontal setting does not have to be so stringent.

One of the most important advantages of a MEMS accelerometer is that it has linear frequency response from DC to about 500Hz Fig.6. This broadband capability offers dramatic improvement in measuring ground motion at lower frequency band. In seismic reflection surveys, data in low frequency band contain important information such as shear waves and reflection waves returning from deep layer boundaries. In earthquake seismology, low-frequency (long-period) data are important for characterizing ground motion to reveal the mechanism of the earthquake, as the low frequency component is sometimes dominant in earthquake, especially when the source is far away. Stability of MEMS accelerometer is important for long term monitoring, too. MEMS accelerometer has some disadvantages: it requires a power supply; and gravitational acceleration has to be calibrated.

2.4. Application of Capacitive MEMS Accelerometers to Seismology

The following wide areas of application can be distinguished: (i) earthquake observation and seismological study, (ii) seismic surveys and imaging, and (iii) vibration monitoring of structures and structural assessment.

2.4.1. earthquake observation and seismological study

In the last decade, MEMS accelerometers have been more and more exploited for a new generation of seismic monitoring network. The implementation of high-density, real-time, and low-cost networks was also encouraged. The MEMS-based seismic stations can also be installed in relatively noisy sites such as urban areas or even inside buildings, over time, some of MEMS developed until they become well-established structures extending both at urban scale and country scale. Some of the most relevant cases of earthquake observation networks based on MEMS sensors. Among the first, a network of 25 MEMS accelerometers managed by the Idaho National Engineering and Environmental Laboratory [28], the Quake-Catcher Network (QCN) managed by the University of Stanford [29,30], a project from the Japan Meteorological Agency [31], and the Community Seismic Network (CSN) developed by the California Institute of Technology [32]. The use of MEMS-based networks for more specific seismological applications (i.e., localization, magnitude estimation, etc.) is conversely not really robust at present, mainly because the data accuracy requested for such tasks is certainly higher. In fact, rougher information about the arrivals or about the amplitude of seismic waves would result in relevant uncertainties in the estimation of the location of a given earthquake or into a weak assessment of its energy release (i.e., earthquake magnitude) although some results are encouraging [33-35]. However, MEMS stations could contribute for temporary network tightening in case of seismic crisis when a fast monitoring enhancement around the epicentral area is desirable, also with the help of local citizens [34]. Moreover, in the cases when a certain degree of redundancy is required (e.g., diversification of the instruments or of the transmission protocols), then a mixed traditional-MEMS network could represent a proper solution in terms of cost–benefit ratio [37].

2.4.2. Seismic Surveys and Imaging

Another field of application of MEMS accelerometers is the seismic surveying and imaging both for deep (i.e., oil and gas exploration) and shallow (e.g., near surface geophysics) investigation; fundamentally. the MEMS sensors might be preferable because of their reduced dimension and weight, being easier to handle, and also better in the long-term endurance [38], Considering the spectrum of the seismic noise, MEMS accelerometers give better results at the higher frequency, while the traditional geophones are still better in the lower frequency range (below 1 Hz). In this field, either the commercial products, or specifically designed devices can be used. Moreover, the use of MEMSs can indirectly improve the quality of the seismic imaging: a huge array of sensors (hundreds to thousands) can be deployed at the same time with contained cost and acceptable quality, resulting in high-resolution geophysical models.

2.4.3. Vibration Monitoring and Damage Assessment of Structures

The Structural Health Monitoring (SHM) is a fundamental tool to integrate and support conservation strategies of infrastructures and to preserve their strategic function (i.e., security, management, organization). Buildings and any infrastructure in general, are built to stand for ordinary and extreme events. The stress factors acting on the structures can be due to natural or anthropogenic factors: seismic events, atmospheric agents (wind, thermal cycles), vibration due to traffic flow, and applied loads. They all contribute to lower the resistance properties (corrosion, alteration, etc.). Several recent projects encompass the realization of prototypes of MEMS-based (mainly accelerometers and gyroscopes) monitoring station specifically designed for SHM: they are based on the measure of the structural vibration, from which structural health and post-event (e.g., earthquake) damage can be diagnosed [39][40]. Other studies also investigated the possibility to use the MEMS accelerometers integrated within the smartphones to develop citizen-engaging networks for SHM, like the ones created for earthquake observation and EEW [41][42][43].

3. **Results**.

PRO-MATE developed with high-resolution and low coast that uses low-power high-performance ARM processing system, a Linux operating system to create low power data acquisition and processing system, and an embedded Tri-axial accelerometer. With the ability to transfer, the seismic processing data products above a certain seismic threshold and device operation status to a Things Board IOT cloud server. Seismic data products include STA/LTA auto picking; PGA; PGV. With PRO-MATE Low cost, low power consumption, small size, and processing ability, we can deploy it in a seismic intensity rapid reporting or earthquake early warning network. It can also be used to monitor landslides, and the structural integrity of buildings and bridges, additionally; there may be many other uses for seismology, engineering and Earth sciences, such as array seismology or ray tracing. PRO-MATE belongs to smart devices category, which in turn can participate in smart cities, where they provide intelligent services to monitor high-rise buildings and the various activities that occur around them, such as wind activities, and constructions activities. PRO-MATE is the first Egyptian ground-motion accelerograph unit designed in National Research Institute of Astronomy and Geophysics (NRIAG). PRO-MATE designed to meet our different needs at NRIAG as we can add and modify in the core program and algorithms of unit according to the needs of network operators. We believe that this unit considered as a start for NRIAG to move forward manufacturing and implementation of products of this type, which gives us a research benefits. This unit used in the various research applications carried out by researchers at NRIAG and can be used as a low-coast product and available to all authorities and individuals in the Egyptian society.

PRO-MATE accelerograph, was designed using 3-axis MEMS digital accelerometer as seismic sensor, low power 32-bit embedded processing board (raspberry pi model 4B) with wireless and wired communication and Linux operating system as a processing and control unit, interface board, Global Positioning System (Gps) board, and power management board Fig.7. The acceleration data from sensor board extracted by the processing unit via I2C port, data processed then stored onto large-capacity SD card memory and processing parameters broadcasted onto data acquisition center via communication port. The stored measurement data can be accessed either by reading the SD card with a computer or via a browser-based graphical user interface (GUI). This small digital accelerograph, that integrates sensor, data acquisition, data storage, and data processing and transmission, consumes less power and is more affordable to install and maintain traditional seismometer stations. The GUI also allows PRO-MATE control including initiating measurements and specifying measurement parameters. A rechargeable lithium-ion (Li-Ion) battery powers the system. System status and acceleration waveform monitored through LCD and indication LEDs on the top of device indicating operational parameters of the system. The GPS board corrects digitizer clock, system time correction, and location of the device. The wired IP internet Communications allows the system to communicate with the data acquisition through broadcasted data messages; the board allows users remotely access the device through http, Ssh programs. The power management board provides the system with different types of power. The sensor circuit needs 3.5 volts, while we need 14.7 volts to charge the standby lithium battery and 5V for the Raspberry pi and Gps boards. Interface board physically interconnects all boards together. The digital MEMS accelerometer provides integrated a 3-axis accelerometer with an onboard Digital Motion Processor (DMP). The board features a user-programmable accelerometer full-scale range of ±2g, ±4g, ±8g, and ±16g. Sensitivity scale factor dependent on selected full-scale range, 16384 LSB/g for ±2g, 8192 LSB/g for ±4g, 4096 LSB/g for ±8g, 2048 LSB/g for ±16g. It also features three 16-bit sigma-delta analog-to-digital converters (ADCs) for digitizing the accelerometer outputs. An on-chip 1024 Byte FIFO buffer helps lower system power consumption by allowing the system processor to read the sensor data in bursts and then enter a low-power mode as the DMP collects more data. Communication with all registers of the device performed using either I2C at 400 kHz [54]. In order to test the recording capability of the PRO-MATE accelerograph, a Minimate data acquisition system with geophone of 4.5 HZ was used as reference sensor [55]. Reading from both devices was compared for PROMATE validation. The two devices were installed as shown in Fig.8 for a period of three hours to record one of the explosions (blast-mate) that occur near the city of Helwan – Cairo governorate. Data were collected from both devices and data analysis was performed as shown in Fig.9.

a hammer shoot of 5 m away from the two sensors. Geophone and accelerometer instrument response has been removed signal and the geophone signal has been differentiated, acceleration of both devices was plotted. Accelerometer signal is noisier than the geophone, but polarities and amplitudes are very similar, at least in the early part of the wave train. All recordings with the Minimate sensor and PRO-MATE were done at 1 kHz sampling frequency. In Fig.10 we show a representative example of a simultaneous recording with the two sensors. The two sensors captured blast from mining site during, Fig.11 shows comparisons between the Minimate sensors and PRO-MATE accelerometer. We see that the amplitudes are generally the same, but the zoom in of the first part of the arriving wave shows that there is a shift in the arrival time on the two instruments, on the order of 0.01 s. it may be related to the timing problem with the digitizer. All in all, our field tests indicate that the instrument response information of the PROMATE system is sufficiently well known and that the system produces data which corresponds to that from one of our Minimate systems. We also conclude that the accelerometer systems are significantly noisier than the geophone systems.

4. Conclusion

In this review, we provided the state-of-the-art of the role of capacitive MEMS in seismology and related disciplines. MEMS are small, low power, durable, and, above all, cheap devices enabling a wide range of applications in terms of scale and variety of recorded signals. MEMS sensors were revealed to be very important for the most recent developments in seismology-related disciplines. They enabled the implementation of several systems that otherwise would have been just impossible to realize, mainly because of the huge costs. In fact, high density seismic networks or high detail structural monitoring were only rarely encountered in the past. In the most recent years, MEMS-based applications have been greatly emerging, especially those devoted to earthquake early warning systems and earthquake intensity mapping. Despite the progress reached in the last decade, the performance of MEMS sensors is still not comparable to the traditional devices. The self-noise of the MEMS accelerometer will be likely reduced in the next generations of sensor, so that also part of the seismic background noise could be assessed. Another disadvantage is the relatively poor response at low frequencies; this is the reason that MEMS sensors are especially suitable for strong-motion seismology these days. However, the most recent developments are promising and, likely; in the very next future the sensors offering good performances at lower frequency will broaden the range of application.

5. Tables and graphs

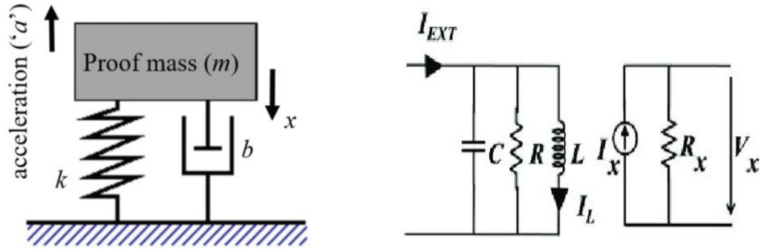

Fig.1. mechanical and electrical model of accelerometer, K spring stiffness constant, b damper constant, and m proof mass [10].

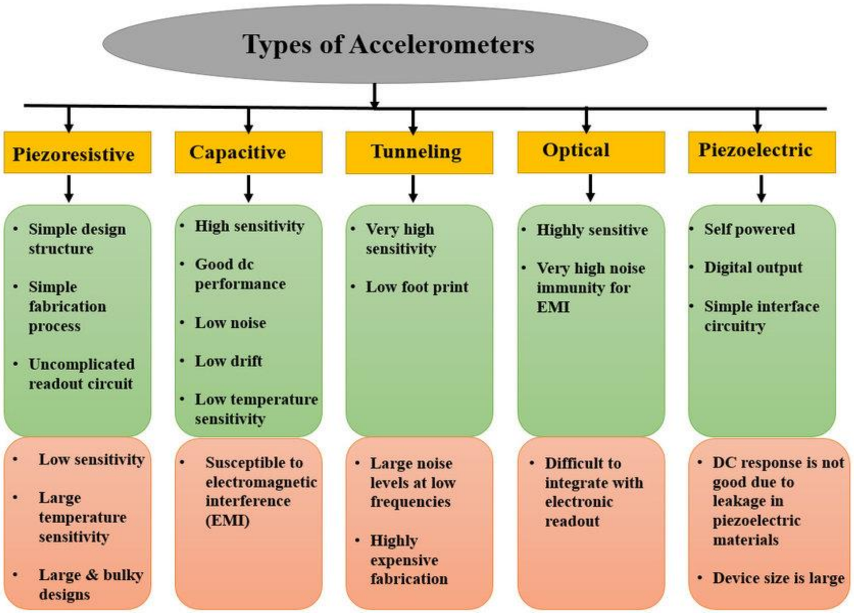

Fig.2. advantages and disadvantages of various transduction schemes

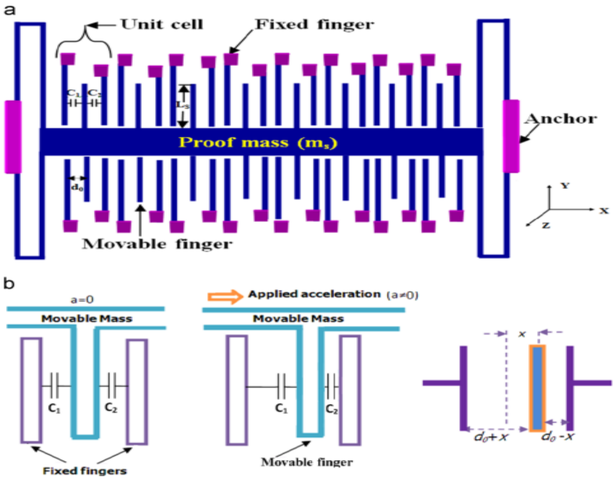

Fig.3. (Left): variable-gap capacitor with parallel electrodes of fixed area; if the gap x(t) remains small with respect to all areal dimensions, the fringing fields can be neglected. (Right): variable-area capacitor; the air gap is fixed and the area is variable with respect to one degree of freedom. If the gap is small with respect to areal dimensions, fringing can be neglected

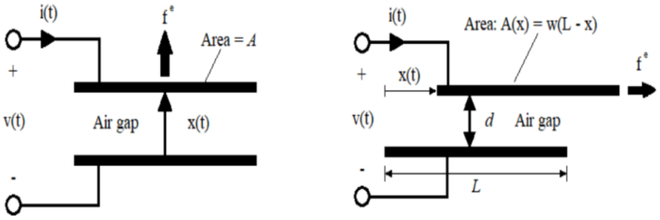

Fig.4. (a) Structure of MEMS capacitive accelerometer and (b) single unit of differential capacitance in the comb [24]

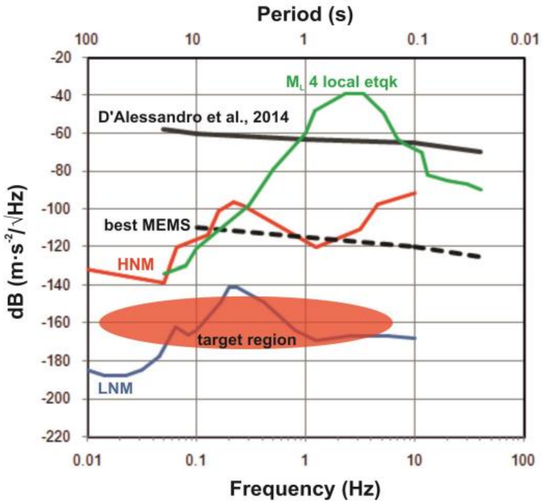

Fig.5. Comparison of the Power Spectral Density (PSD) for some MEMS sensors compared with the seismic noise models (red and blue lines [26]), and with a spectra response of a local earthquake (green line). The red area indicates the target zone desirable for the next generation of MEMS sensors. Figure from [27]

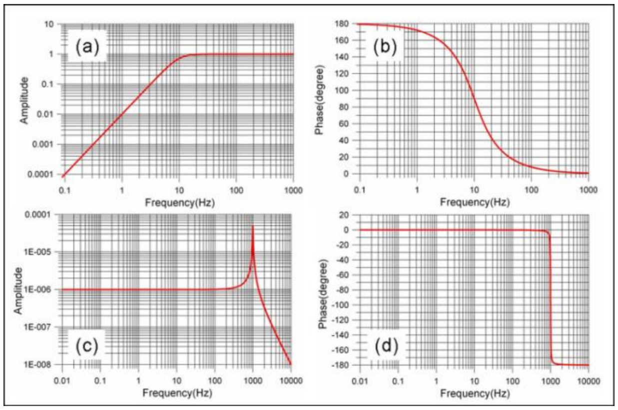

Fig.6. Amplitude and phase response of MEMS accelerometer and 10 Hz geophone (a) Amplitude response of geophone. (b)Phase response of geophone. (c) Amplitude spectrum of MEMS accelerometer. (d)Phase response of MEMS accelerometer [9].

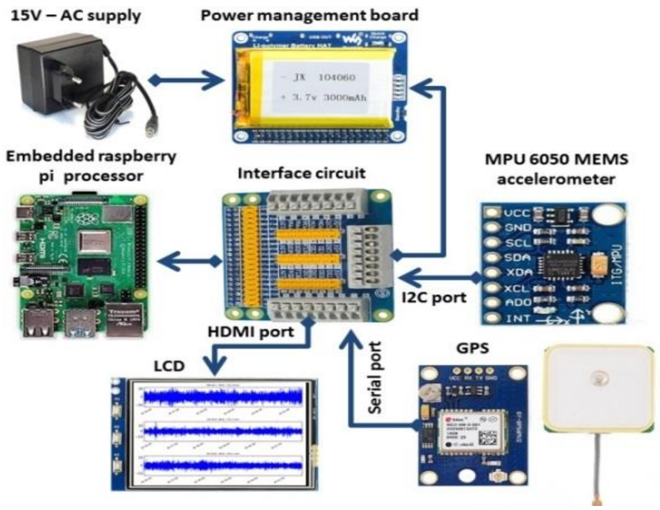

Fig.7. PRO-MATE, hardware description diagram

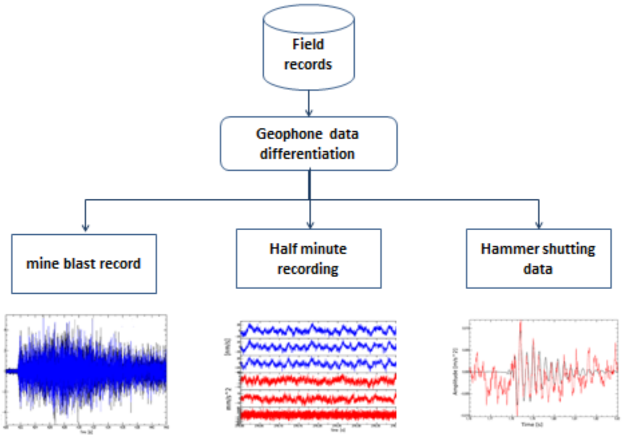

Fig.8. Field data collection; preparation; and processing diagram

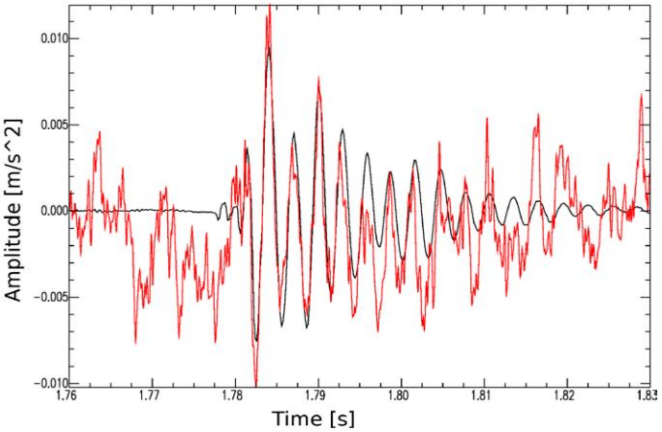

Fig.9. hammer shooting record, black lines for geophone and red lines for accelerometer

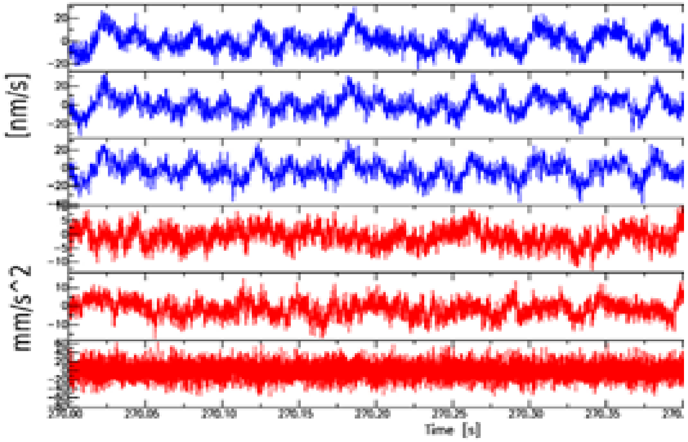

Fig.10. continuous data recording red lines for accelerometer and blue colors for geophone

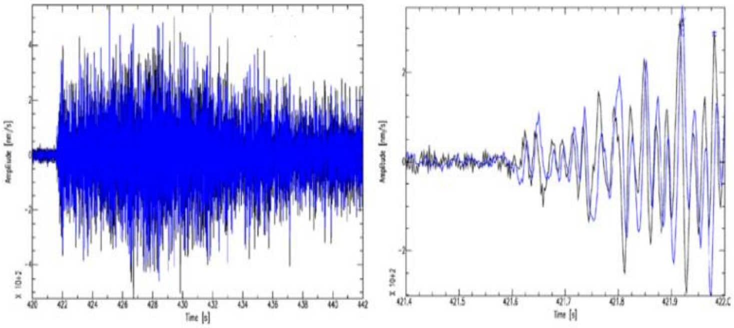

Fig.11. recording of blast from mining site 30 km away from installation site

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