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Design and Testing of Low-cost MEMS Accelerometer on 1D Shake Table

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***Abstract*— This paper presents a system that integrates a low- cost Micro Electro-Mechanical Systems (MEMS) accelerometer sensor with a Raspberry Pi to evaluate its effectiveness in detecting and measuring seismic activity. The MEMS accelerometer is employed to measure ground motion intensity in terms of acceleration, while the Raspberry Pi functions as the central processing unit, managing data processing, storage, and analysis. Data is stored on external memory for further analysis. The primary objective of this research is to explore a cost-effective solution for enhanced seismic monitoring and research. The effectiveness of the MEMS-based system is assessed by comparing its performance with that of a calibrated accelerometer, which is placed on a shake table at Khwopa Engineering College designed to simulate seismic activity. The shake table generates controlled oscillations that mimic natural vibration patterns. By analyzing the output of the MEMS accelerometer, the study examines whether the sensor accurately follows the vibration patterns produced by the shake table. The findings indicate that the acceleration data captured by the MEMS sensor closely aligns with the oscillations provided by the shake table, exhibiting minimal offset and noise factor. This study concludes that low-cost MEMS-based accelerometers can serve as a viable alternative to conventional, high-cost mechanical geophones, provided that proper noise filtration and thorough analysis of any offset are conducted. The results underscore the potential of MEMS technology in advancing the field of seismic research through cost-effective solutions.**

I. Introduction

According to the National Earthquake Monitoring and Research Center (NEMRC) of the Government of Nepal, reducing seismic risk primarily relies on assessing earthquake hazards using seismic instrument data and other pertinent research. Presently, there are 42 seismic stations dedicated to earthquake monitoring, 50 GPS stations for monitoring crustal deformation, and 36 accelerometers for collecting strong motion data [1].

Conventional seismometers commonly employ mechanical geophones as their primary sensing elements. These mechanical devices are designed to detect ground movement caused by seismic waves. Typically, a geophone consists of a coil suspended within a magnetic field, attached to a mass that moves in response to ground motion. When seismic waves pass through the ground, they cause the mass to move relative to the coil, producing an electrical signal that corresponds to the ground motion. However, traditional seismometers equipped with geophones have their limitations. They can be quite expensive, especially the advanced models with extra features. Additionally, mechanical geophones are vulnerable to environmental factors such as temperature, humidity, and background noise, which can affect their accuracy and reliability. Furthermore, conventional geophones typically require a direct connection to data acquisition systems, limiting their flexibility in certain situations [2].

In the current context, advancements in internet of things (IoT) technology and development of Micro Electro-

Mechanical System (MEMS) based accelerometer sensors have increased the potentials for developing more seismic monitoring systems. MEMS sensors are tiny, highly sensitive devices that can detect and measure seismic waves [3]. These sensors are often more compact and cost-effective compared to traditional seismometers, making them suitable for deployment in large numbers across a wide area. MEMS-based seismic sensors can be integrated into IoT networks to create dense arrays of monitoring stations, providing comprehensive coverage and high-resolution data for seismic analysis and early warning systems. Thus, this paper includes the testing of low-cost MEMS sensor, namely ADXL345 sensor. Testing is done by placing the ADXL345 sensor and calibrated accelerometer on shake table, where controlled input is provided.

II. Literature Review

MEMS sensors play a vital role in addressing challenges related to spatial resolution and network coverage in Earthquake Early Warning (EEW) systems. The Quake-Catcher Network and the MyShake application demonstrate the real-time earthquake detection capabilities of MEMS accelerometers. The adaptability and cost-effectiveness of MEMS sensors show promise in filling station coverage gaps in densely populated areas. The positive influence of MEMS-based sensors on seismic monitoring capabilities is clear from the valuable recommendations they provide for improving earthquake preparedness and response efforts [3].

Advancements in seismic monitoring had been achieved by integrating MEMS accelerometers with NodeMCU, enabling real-time data transmission for analysis. However, the processing speed may restrict real-time access to data concerning seismic events [4].

MEMS technology is well-suited for battery-powered industrial devices because it uses minimal power. It also allows digital components to be built directly on the same chip as the accelerometer, so the sensor's output is digital without needing extra parts to convert it later [5]. Expanding the use of a dense seismic network through IoT nodes would enhance real-time monitoring. These nodes can improve our understanding of how structures respond to different environmental factors, providing seismologists with accurate data to better analyze seismic activity in various settings. By detecting seismic signals in real-time, IoT can send out timely warnings, giving people in affected areas valuable seconds or minutes to take protective actions. The early warning system can greatly reduce the potential damage to infrastructure, save lives, and protect communities. Additionally, IoT's fast processing capabilities allow for quick data analysis and decision-making during seismic events [6].

Traditional seismic sensors are typically designed to measure ground velocity, as well as ground displacement and acceleration. These sensors rely on the spring-mass principle, where the movement of a damped, heavy mass is converted into an electrical signal. In contrast, the compact size and light weight of MEMS devices require a much smaller proof mass. This reduction in mass means that a stronger force is needed to produce a detectable electrical output. As a result, MEMS accelerometer are naturally more sensitive to higher levels of acceleration within the seismic spectrum [7]. MEMS technology has made a substantial impact on sensing techniques, and with the development of more advanced and complex devices to address growing demands in diverse industries, its future appears very promising [8].

Camerino was an ideal historical setting for the application of MEMS based urban seismic network. The deployment of the urban seismic network based on MEMS sensor, achieved using affordable materials (costing between a few hundred and up to one thousand euros per station), marks a significant accomplishment [9]. The dataset collected from the MEMS based system was valuable for research on earthquake and structural health monitoring [10]. Utilizing low-cost sensors for monitoring small or localized earthquakes will enable the creation of dense accelerometric networks [11].

Shake tables are vital resources for evaluating the robustness of structures to earthquakes. Through the application of controlled seismic conditions, they enable thorough performance investigation of structures during seismic events. It allows for a thorough examination of how structures behave during seismic occurrences by exposing them to controlled earthquake conditions [12]. By providing the controlled input conditions, the output can be estimated and calculated. The know values of input to shake and output of the system under test is compared.

To address the problem of economic factor, this study aims to investigate the potential of low-cost sensors in the development of high-performance seismometers. By leveraging cost-effective sensing technologies, the research seeks to determine whether these sensors can achieve the precision and reliability required for accurate seismic monitoring. The objective is to assess the feasibility of using affordable components to create seismometers that can effectively detect and analyze seismic waves, thereby making advanced seismic monitoring more accessible and widespread.

To overcome challenges mentioned in real time access of seismic data, the study aims to utilize Raspberry Pi as a more powerful processing unit and develop a user-friendly GUI interface for researchers, structural and civil engineers. By enhancing processing capabilities and user interfaces, the proposed study seeks to improve real-time execution and data visualization for comprehensive seismic analysis and decision-making.

III. Working Mechanism

A. Working of System

We utilized the digital MEMS accelerometer, namely ADXL345. The working principle of ADXL345 is based on the deflection of tiny MEMS structures in response to acceleration forces. When the sensor experiences acceleration, these tiny structures move, causing a change in capacitance or resistance, which is then converted into an electrical signal resulting in a proportional change in charge. This charge is integrated and converted into a voltage signal. In addition, the ADXL345 accelerometer incorporates a built-in 10-bit successive approximation analog-to-digital converter (ADC) for converting the analog voltage signal generated by the sensor into digital data that represent the acceleration along the sensor's axes. This digital output typically ranges from 0 to 1023[13]. However, these raw values of digital output can be converted into g units (the acceleration due to gravity) of acceleration measurement by dividing the obtained value by sensitivity of ADXL345 sensor. This can be illustrated by the equation given in equation (1).

$$Acceleration(g) = \frac{\text{Digital output} - \text{Zero g offset}}{\text{Sensitivity}} \quad (1)$$

Here,

Digital output is the raw output from the accelerometer.

Zero g offset is the digital output value when the accelerometer is at rest.

Sensitivity is the sensitivity of the accelerometer in volts per g.

g unit or $1g = 9.81 m/sec^2$

Further considering the small deflection during the seismic events, the data related to seismic events is obtained in the unit of cm/sec^2 by processing in Raspberry Pi. So, the modified equation for this system can be written as in equation (2).

$$\text{Acceleration} = \text{Aceleration(g)} \times 981 \quad (2)$$

Here,

Acceleration is in the unit of cm/sec^2 .

Digital output is the raw output from the accelerometer.

Zero g offset is the digital output value when the accelerometer is at rest.

Sensitivity is the sensitivity of the accelerometer in volts per g.

g unit or $1g = 9.81 m/sec^2$

$1 m/sec^2 = 100 cm/sec^2$

These obtained acceleration data is stored with the respective time information in external memory unit. The block diagram for the overall integrated system is shown in the Fig. 1.

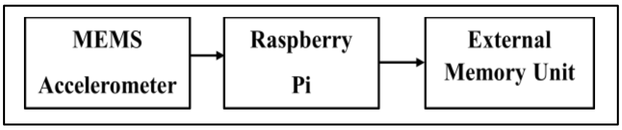

Fig. 1. Working Block Diagram of System

B. Shake Table Test

The functioning of a 1D shake table is centered on an actuator mechanism powered by an electric motor, which produces controlled oscillations along a single axis. These vibrations are managed by a control system featuring automated computerized control. For calibration, the device is mounted securely on the shake table and the shake table is activated. The actuator induces oscillatory motion to the platform, simulating the seismic waves or vibrations that the specimen might experience in real-world conditions [13]. The hardware setup of Shake table available at Khwopa Engineering College is shown in the Fig. 2.

Fig. 2. Shake Table at Geology Lab of Khwopa Engineering College

The output of device under test is compared with the previously calibrated accelerometers. If the value of acceleration provided by the previously calibrated system on shake table and the MEMS accelerometer matches, it is the required result. Otherwise, it needs to be calibrated further and consistent system must be developed. The process of testing the system integrated from MEMS accelerometer can be demonstrated on the flowchart as in Fig. 3.

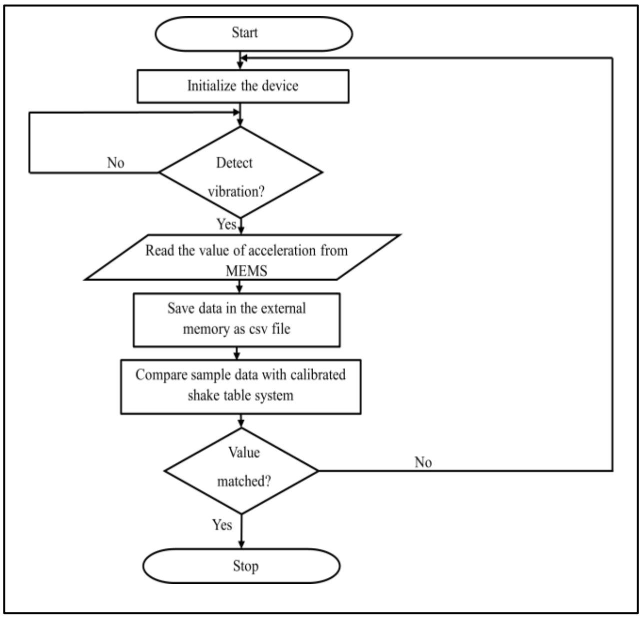

Fig. 3. Flowchart for System Test

For the acceleration test of x-axis direction, the MEMS accelerometer sensor is placed in parallel with the shake table facing the x-axis of sensor towards the direction of displacement of shake table.

The hardware setup for the system developed with MEMS accelerometer is shown in Fig. 4. Here, the accelerometer is placed in stabilize condition with the help of a 3D printed enclosure.

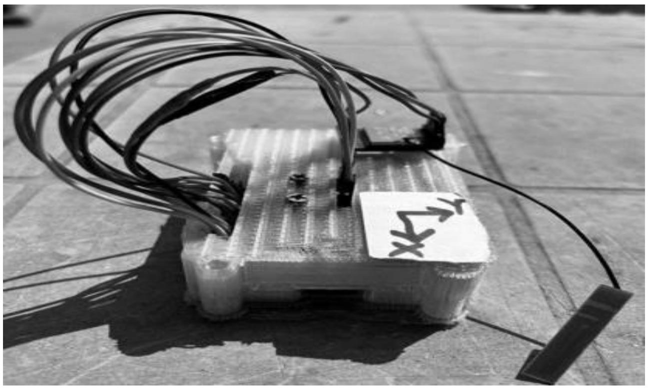

Fig. 4. Hardware Setup for MEMS Integrated System

The 3D printed enclosure is placed on the shake table for the analysis of data.

Through the shake table input, sine wave input is provided with parameters:

Frequency = 80 Hertz (Hz)

Amplitude = 50 millimeter (mm)

IV. Result And Discussion

The data obtained from both the setup i.e., MEMS setup and standard shake table setup is obtained as CSV file on USB drive. With the help of this file, the comparison and plotting of data is done through MS Excel. The curve of distribution pattern for obtained from the data in x-axis at the initialization stage of MEMS accelerometer and calibrated system installed in shake table is shown in Fig. 5.

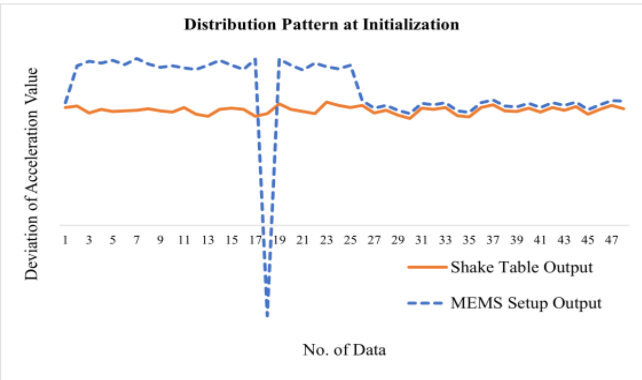

Fig. 5. Distribution Pattern at Initial Stage

The comparison of data is done on the basis of acceleration values provided by both of the system at same time. The graph plot for the already calibrated setup is denoted by solid line whereas the distribution pattern obtained from the MEMS setup i.e. the system under test is denoted by dotted line.

The pattern of distribution curve shows that the distribution of data from MEMS setup is not synchronized with the standard shake table output. This indicates that at the initialization of system, the garbage values are provided by the MEMS setup. To overcome this problem, the hardware setup is placed on the shake table at the stable condition for some times after the initialization of the device. By applying this solution, numbers of data are observed repeatedly.

Thus, after stabilizing MEMS setup for some time, another set of data are observed from the MEMS setup for 3 seconds. The data distribution pattern is plotted again by using line chart for further calibration of MEMS setup with respect to the standard shake table. The deviation curve visualized from the data obtained from two different system is shown in Fig. 6.

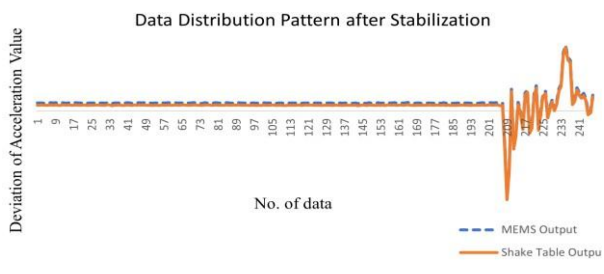

Fig. 6. Data Distribution Pattern after Stabilization

Further evaluation is done by observing the distribution pattern of data for both MEMS setup and shake table setup for another 6 seconds. The distribution pattern of data obtained from these two setups for another six seconds is shown in the Fig. 7.

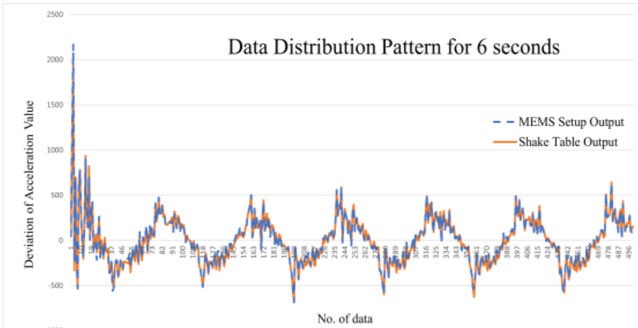

Fig. 7. Data Distribution Pattern Obtained for 6 seconds.

The distribution pattern of data obtained from the calibrated shake table system and MEMS accelerometer setup shows similarities among the system when viewed after stabilizing the MEMS accelerometer sensor for some time. The increasing and decreasing pattern of curve shows the change in acceleration values in each system has linear relationship. However, the amplitude values of obtained data show some variation of data with some offset value and noise factors. To mitigate this problem, the zero-state offset value will be deducted from the actual output from MEMS accelerometer for further calibration. Along with this, filtering of instrumental noise must be carried out with the detailed study of frequency spectrum provided by the obtained data.

V. Conclusion

To validate the performance of the low-cost MEMS accelerometer, specifically the ADXL345, a series of tests were conducted using a shake table at Khwopa Engineering College. During the tests, the ADXL345 MEMS accelerometer recorded a data distribution pattern that closely matched the readings from the calibrated shake table. This indicates that the accelerometer is capable of capturing seismic data with small offset value. It is aimed to develop the seismic monitoring system with remote logging capacity utilizing internet of things (IOT) technology and cost-effective MEMS accelerometer.

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