Design and build of shaking table prototype as short-period seismometer calibrator based on microcontroller

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Abstract. A seismometer is an instrument used to record ground motion, such as caused by earthquakes. It has a high sensitivity to ground motion, including noise. Its sensitivity to noise can result in unstable recording, even components damage, therefore calibration is very important to do. Calibration is an activity of comparing instruments with standard instruments ascertained to maintain the quality and quantity of data produced. One of the methods is shaking table that provides ground motion simulation as a seismometer input. This method moves the seismometer with up-down vertical translation. The goal of this study is to design and build a prototype seismometer calibrator using microcontroller-based shaking table method on TDV-23S (Short Period Seismometer with a frequency response of 1-50 Hz). The designed calibrator is divided into the drive (uses stepper motor) and data retrieval system (uses ADXL345 sensor) that used Arduino Uno as the microcontroller. Instruments testing is done by comparing with BMKG standard calibrators. The comparison results show the difference in structural displacement, 2 mm for the designed instruments and 0.8 mm for the standard calibrator, with signal amplitude difference produced by the designed tool is greater than the standard calibrator.

1. Introduction
Seismometer is a sensor that is used to measure the vibration at the ground surface so that it can record earthquake signals and has a high sensitivity to ground vibrations, including noise. Sensitivity to noise can result in unstable recording, even damage to components, so calibration needs to be done. Seismometers consist of several types based on their response, one of which is a short period seismometer. Short period seismometer is one type of seismometer that is capable of detecting earthquake waves with a frequency range of 1 Hz to ≥ 10 Hz [1]. The type of seismometer used in this study as standard is TDV-23S. TDV-23S is a seismometer that can detect ground vibrations in the frequency range of 1 - 50 Hz, and its natural frequency is 6 Hz. This seismometer has a sensitivity of 2000 V/ ms⁻¹ and 1000 V/ms⁻¹ as its optional sensitivity. TDV-23S is able to display the results of measurements in real time using its software [2].

Seismometer calibration consists of relative calibration and absolute calibration [3]. Shaking table is one of the absolute calibrations for the seismometer, which utilizes translational motion. The principle works is to make vertical translational movements as input vibrations resembling seismic waves [4]. One type of shaking table that BMKG uses to calibrate is the Calibration Table CT-EW1. CT-EW1
shifts the seismometer vertically using a DC motor. This instrument has 2 dial gauge to measure the displacement of the seismometer.

Figure 1. Working Principle of Calibration Table CT-EW1

CT-EW1 has two options to control the movement of the vibrating table (using a remote), the first is to move the vibrating table in 1 cycle, then the second is the movement of the table which is divided into ½ cycles and then given a time lag to do the next ½ cycle. Figure 1 shows there are part A and part B for calibration table working principle. Part A is a calibration method carried out on the vertical axis or Up-Down axis. Part B calibrates the horizontal axis (East-West and North-South axis) by requiring additional tables and poles. The calibration process on the horizontal axis depends on the true north direction of the seismometer. East-West axis calibration is done by placing the seismometer on the vibrating table where true north is parallel to CT-EW1, for the North-South axis component, seismometer is placed where true north is crossed with CT-EW1 [5].

2. Data and Methods

2.1. Hardware

2.1.1. ADXL345 sensor, this study uses a vibration sensor that utilizes the principle of Micro Electro Mechanical System (MEMS). This device is a micro system with a component size of between 1 µm to 1 mm that is designed to be able to achieve technical functions, such as electromechanical and electrochemical functions. This sensor has a digital signal output data, using SPI or I2C communication interface [6].

2.1.2. Stepper Motor is an electromagnetic device that works by converting electronic pulses into discrete mechanical movements. This tool works based on the order of pulses given to the motor [7]. Nema 23 stepper motor type J-5718HB3401 is a stepper motor that will be used in this study.

2.1.3. Microcontroller is a functional computer system on a chip. Microcontroller has a core processor, memory, and input output equipment. The microcontroller is programmed using software that can write, read and delete programs on the microcontroller [8]. This study uses two Arduino Uno microcontrollers that are used to acquire data from the measurement results of the ADXL345 sensor, drive a stepper motor, and send data to a personal computer.

2.2. Spectral Analysis

The method used to perform spectral analysis is Fast Fourier Transform (FFT), which is the transformation process from the time domain to the frequency domain. FFT is used to determine the dominant frequency, the frequency that dominates in a vibration signal by looking at the frequency
content of the signal [9]. Equation 1 is the equation used to transform the signal from the time domain into the frequency domain.

\[ X(f) = \int_{-\infty}^{\infty} x(t)e^{-i\omega t}dt \]

\[ X(f) = \int_{-\infty}^{\infty} x(t) \cos \omega t dt - i \int_{-\infty}^{\infty} x(t) \sin \omega t dt \]  

Where \( X(f) \) = Signals in the frequency domain, \( x(t) \) = Signal in the time domain, \( \omega \) = Angular frequency \( = 2\pi f \) (rad / s), \( f \) = Frequency (Hz) and \( t \) = Time (seconds).

2.3. Instrument Design
The system designed consists of two parts, namely the drive system and the data retrieval system. The system flowchart can be seen as follows on figure 2.

![Flowchart system](image)

**Figure 2. Flowchart system**

2.3.1. Drive system. It consists of Arduino Uno Microcontroller, Nema 23 Stepper Motor, TB6600 Motor Driver, Keypad, and LCD. The wiring diagram in this system can be seen as follows on figure 3:
Figure 3. Drive System Wiring Diagram

Figure 4 shows the design of the shaking table form that uses as basis for the design of the CT-EW1 design [10].

Figure 4. Dimension and simulation of shaking table structure

The initial stage of shaking table design is to calculate the size of the vibrating table following the design of Wielandt [10]. Shaking tables are made using alloy iron plates with a thickness of 5 mm (0.5 cm) and 10 mm (1 cm) as well as with some additional components. Shaking table operates when the user enters input through the keypad with available modes. There are 4 Modes that can be chosen by the user, namely:

a. Mode 1 (1 cycle)
   Mode 1 will drive the stepper motor to perform one cycle on a shaking table and then stopped. The time needed by the shaking table to do one cycle is 1 second.

b. Mode 2 (½ cycle)
   Mode 2 will move the stepper motor to do half cycle on the shaking table. The shift shaking table as much as half a cycle means the table will move vertically from the bottom side to the top side then stop. The time needed for the shaking table to do half a cycle is 0.5 seconds.

c. Mode 3 (5 cycles)
   Mode 3 is a mode that performs one cycle of shaking table movement five times at once in a span of 10 seconds. This mode can be said as a mode that moves the shaking table automatically because the table moves as many as 5 cycles at once within 10 seconds where there will be a pause of 1 second each cycle without the user having to press the button repeatedly as in Mode 1.

d. Mode 4 (10 Cycles)
   Mode 4 is a mode that performs one cycle of shaking table movement ten times at once in a span of 10 seconds. This mode is the same as "Mode 3" that drives the shaking table automatically, only on
this mode of shaking table will move as many as 10 cycles at once within 10 seconds with no break between each cycle or 5 cycle more than "Mode 3".

2.3.2. Data Retrieval System. It uses several electronic components such as ADXL345 sensor, Arduino Uno microcontroller, RTC DS1307, and SD card. The wiring diagram in this system can be seen as follows on figure 5.

![Wiring Diagram of the Data Retrieval System](image)

**Figure 5.** Wiring Diagram of the Data Retrieval System

Figure 5 explains the data retrieval system function to retrieve data generated vibrations when translating table, and then process the data, and display the data according to user needs for calibration.

a. Data collection stage

The system measures vibrations when the table is translating. The ADXL345 sensor records vibration data on the East-West (EW) axis, North-South (NS) axis, and Up-Down (UD) axis. Also recorded vibration by Short Period Seismometer Unit Under Test at the same conditions and time.

b. Data processing stage

The analog signal detected by the ADXL345 sensor is converted to a digital signal so that it can be processed by a microcontroller. The microcontroller will process the data and then send it to the personal computer and store it on the SD card according to the user's needs. The data processing is made using Matlab software.

c. Output system

Vibration signals generated by the ADXL345 sensor and Short Period Seismometer are displayed in the GUI to make it easier for users to compare and analyze the output frequencies of the prototype shaking table and the Short Period Seismometer.

2.3.3. Graphical User Interface. It function to display a graph of the output signal from the ADXL345 sensor and Short Period Seismometer. This program is designed using Matlab software with an open source method. The flowchart of the GUI program in Matlab is as follows on figure 6.
2.4. Implementation

The system that can be seen on figure 7 is designed to have dimensions that are small enough so that it is easy to use in various places when performing calibrations.

![System Implementation](image)

**Figure 7.** System Implementation

The GUI implementation as can be seen on figure 8 has open and reset features. Open button to download the recorded file and reset to delete the signal plot results. The three axes are used to plot shaking table vibration signals on the East-West, North-South and Up-Down axes. There are several
axes that display the measured vibration frequency in numerical form for easy reading. On the left to process the ADXL345 sensor recording results and on the right to process the Short Period Seismometer recording results.

![Graphical User Interface](image)

**Figure 8.** Implementation of the Graphical User Interface

3. Result and Discussion

The instrument experiment was carried out at the BMKG Geophysical Equipment Calibration Laboratory which explained on figure 9 below. System testing is carried out using the comparative method. The comparison method is carried out using the CT-EW1 calibration table, TDV-23S seismometer as Unit Under Test (UUT) and TDE-324CI Digitizer with 24-bit resolution. The following is a block diagram of a system test carried out.

![Instrument Experiment Diagram Block](image)

**Figure 9.** Instrument Experiment Diagram Block
The TDV-23S seismometer and the ADXL345 sensor are put together, where part A uses the CT-EW1 calibration table [5] and part B uses the prototype vibrating table. System testing is done by doing a step test as much as 10 times half a cycle with a time interval of 5 seconds every half cycle on each axis. Vibration signal data from CT-EW1 will be detected by TDV-23S seismometer and ADXL345 sensor. The vibration signal data detected by TDV-23S will be sent to the TDE-324CI digitizer for processing and then will be displayed real time in the Monost TDS software. The recording results by the ADXL345 sensor will be sent to the data retrieving system to be processed and displayed on the Graphical User Interface.

![Graphical User Interface](image)

**Figure 10.** Display of recorded UD axis test results on each shaking table.

The test results on the UD axis using CT-EW1 as can be seen on figure 10 showed the highest amplitude at 1135635 count at 6th seconds, while using the prototype shaking table showed the highest amplitude at 6375875 count at 11st seconds.

![Graphical User Interface](image)

**Figure 11.** Display of recorded EW axis test results on each shaking table.

Test results on the EW axis using CT-EW1 as can be seen on figure 11 showed the highest amplitude at 458320 count in the 14th second. The test results on the EW axis using a prototype shaking table showed the highest amplitude at 3235847 count in the 22nd second.

![Graphical User Interface](image)

**Figure 12.** Display of recorded NS axis test results on each shaking table.
The test results on the NS axis using CT-EW1 as can be seen on figure 12 showed the highest amplitude at 585382 count in the 7th second. The test results on the NS axis using a prototype shaking table showed the highest amplitude at 868665 count in the 22nd second. The comparison of the response values of the prototype shaking table amplitude with CT-EW1 amplitude is shown in the following table 1.

Table 1. CT-EW1 amplitude comparison with the prototype shaking table amplitude.

| Axis | Condition | Amplitude (count) |
|------|-----------|------------------|
| EW   | 10 cycles with a 5 second pause | CT-EW1: 458320, Prototype: 3235847 |
| NS   | 10 cycles with a 5 second pause | CT-EW1: 585382, Prototype: 868665 |
| UD   | 10 cycles with a 5 second pause | CT-EW1: 1135635, Prototype: 6375875 |

The results of the comparison of the prototype shaking table with CT-EW1 show that the average response value of the amplitude has a small difference with the TDV-23S seismometer. The results of frequency measurements on the two sensors using CT-EW1 and prototype shaking table can be seen in the following table 2.

Table 2. Results of dominant frequency measurements on CT-EW1.

| No. | Axis | Condition | frequency (Hz) |
|-----|------|-----------|----------------|
|     |      |           | ADXL345        | TDV-23S        |
| 1   | EW   | 10 cycles with a 5 second pause | 0,354004       | 0,341797      |
| 2   | NS   | 10 cycles with a 5 second pause | 0,366211       | 0,360107      |
| 3   | UD   | 10 cycles with a 5 second pause | 0,427246       | 0,494385      |

Table 3. Results of dominant frequency measurements on prototype shaking table.

| No. | Axis | Condition | Frequency (Hz) |
|-----|------|-----------|----------------|
|     |      |           | ADXL345        | TDV-23S        |
| 1   | EW   | 10 cycles with a 5 second pause | 0,732422       | 0,750732      |
| 2   | NS   | 10 cycles with a 5 second pause | 0,732422       | 0,750732      |
| 3   | UD   | 10 cycles with a 5 second pause | 0,476074       | 0,10376       |

Comparison of frequency values on the ADXL345 sensor and TDV-23S seismometer has a dominant frequency value that is close to and only differs on the UD axis when using the prototype shaking table. The comparison of the amplitude and frequency values of the two sensors on CT-EW1 and the prototype shaking table show a greater value on the prototype shaking table. The shaking table prototype has a faster time when the table is translating. The movement of 10 cycles with a gap of five seconds in each cycle on CT-EW1 is done on average for 55 seconds, while the prototype shaking table averages for 44
seconds. The time difference in the two shaking tables is due to the cycle rotation on the CT-EW1 done manually while the prototype shaking table has been set 10 cycles for 10 seconds automatically.

Several other factors also influence these differences. The human error factor due to improper placement of sensors at the midpoint causes the resulting value to be different. In addition, the movement of the prototype shaking table when translating is unstable such as the CT-EW1 calibration table, which is due to the slightly different structure of the prototype shaking table where the instrument shifts as high as 2 mm and CT-EW1 as high as 0.8 mm. Other factors are the type of sensor used, the sensor's response to the vibration frequency and the ADC sensor's resolution. The number of sample data generated between the ADXL345 sensor and the Short Period Seismometer shows the difference in the sample data more on the Short Period Seismometer because the ADC difference used is the 24-bit TDV-23S and the 10-bit ADXL345 sensor.

4. Conclusions
Based on the discussion above, the conclusions obtained are the results of the prototype shaking table drive system design show structural displacement as high as 2 mm, which results in higher amplitude values when using the instrument than when using a standard seismometer and shaking table. The difference in the value of the dominant frequency recorded on the ADXL345 sensor against the TDV-23S seismometer has a slight difference, which is due to the sampling ability of the different digitizers and the speed of each shaking table when translating.

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References
[1] Udias A, Madariaga R and Buform E 2014 Source Mechanisms of Earthquakes Cambridge University Press
[2] TAIDE 2010 TDV-23S Feedback Short-Periodie Seismometer Operator’s Manual TAIDE Enterprise Co., Ltd: Zhuhai City, China
[3] Wielandt E 2003 Seismometry Institute of Geophysics: University of Stuttgart
[4] Havskov J and Alguacil G 2004 Instrumentation in Earthquake Seismology Springer Science & Business Media
[5] Laboratorium Kalibrasi BMKG Peralatan Geofisika 2016 Metode Kalibrasi Absolut Shake Table CT-EW1 BMKG: Jakarta
[6] Risandriya S K and Muhammad Rivai 2011 Aplikasi Sensor Micro Electro Mechanical System (MEMS) sebagai Identifikasi Ketidaknormalan pada Conveyor Belt System Batam: Politeknik Negeri Batam
[7] Rusianto B H and Wijaya S K 2015 Perancangan Sistem Kalibrasi Seismometer Short period TDV-23S secara Relatif menggunakan Gelombang Sinus Jakarta: BMKG
[8] Montone D 2013 Applying Motors in Linear Motion Application Heydon Kerk Pittman Ametek Inc.: Pennsylavia
[9] Mariani M C, Gonzalez-Huizar H, Bhuiyan M A M and Tweneboah O K 2017 AIMS Press 3 438-449
[10] Wielandt E, 2013 Plywood Step-Table: Instructions for assembly OSOP