Validating a low-cost seismometer using a shaking table

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Abstract. Ambient vibration measurement using a seismometer represent a non-invasive and non-destructive method for seismic-related studies. This method inhibits widespread applications, i.e., assessing site fundamental frequency, estimating bedrock level, calculating building natural frequency, deducing shear wave velocity profile. However, the instrument required to carry out such ambient vibration measurement is generally expensive. Recently, there is a low-cost Raspberry Shake 3D seismometer (RS-3D) available on the market. This seismometer is based on Raspberry Pi hardware. It contains three 4.5 Hz orthogonally oriented geophones, which can be set at a sampling rate of 100 Hz and a bandwidth of -3dB points at 0.6 to 34 Hz. Thus, laboratory testing was carried out to assess this device's performance in this demanding application. Generally, RS-3D demonstrates a great performance. Further detailed results are presented in this paper.

1 Introduction

Ambient vibration measurement using a seismometer represent a non-invasive and non-destructive method for seismic-related studies, i.e., [1], [2], [3], and [4]. This method may inhibit widespread applications, i.e., assessing site fundamental frequency ([5] - [8]), estimating bedrock level ([9] - [14]), calculating building natural frequency [15], deducing shear wave velocity profile ([16] - [20]). However, the instrument required to carry out such ambient vibration measurement is generally expensive. Recently, there is a low-cost Raspberry Shake 3D (RS-3D) seismometer available on the market. This seismometer is based on Raspberry Pi hardware. It contains three 4.5 Hz orthogonally oriented geophones, which can be set at a sampling rate of 100 Hz and a bandwidth of -3dB points at 0.6 to 34 Hz. Thus, laboratory testing must be conducted to assess this device's performance in this demanding application.

The purpose of the study is to investigate the performance of a low-cost RS-3D seismometer from which further suggestions will be proposed.

2 Methodology

The methodology in this study that is begun with sensor selection and experimental setting up. Then, it is followed by data acquisition and analysis.

2.1 Sensor

A low-cost Raspberry Shake 3D seismometer (RS-3D) was used in this study. The used sensor in this seismometer is a 4.5 Hz (electronically extended down to 2 seconds) Sunfull PS-4.5B geophones, 375 Ohm. It can

be set at a sampling rate of 100 Hz and a bandwidth of -3dB points at 0.6 to 34 Hz [21].

2.2 Shaking table

Multi-Axial Simulation Table (MAST) System was used in the present study. A schematic MAST System diagram, which consist of (1) Table, (2) Integrated hydraulic control manifold with optional isolation, (3) Fixed actuator assembly, (4) Close-coupled accumulation, (5) Mounting frame, (6) Optional chamber floor interface, and (7) Swivel and strut assembly, is presented in Fig. 1.

Fig. 1. Schematic system diagram of MAST System [22].

This study employed MAST System 354.20, which can provide simulation frequency of 0.8 - 100 Hz, linear displacement up to 140 mm, angular displacement up to 9 deg., linear velocity up to 1700 mm/s, and linear acceleration up to 15.9 g. Detail specification of the MAST System 354.20 can be seen in Table 1 [23].

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Table 1. Detail specifications of MAST System 354.20 [3].

Description	Units	Amount
Table Size (Square table)	mm	2.2 x 2.2
Simulation Frequency (bare table)	Hz	0.8-100
Simulation Frequency (max payload)	Hz	0.8-100
Maximum Payload	kg	2000
Table Mounting Pattern	mm	100 x 100
Actuator Peak Force (210 bar)	kN	67
Linear Displacement		
- Vertical (Z)	± mm	140
- Lateral (Y)	± mm	110
- Longitudinal (X)	± mm	125
Angular Displacement		
- Roll	± deg	9
- Pitch	± deg	8
- Yaw	± deg	6
Linear Velocity		
- Vertical (Z)	mm/s	1700
- Lateral (Y)	mm/s	1300
- Longitudinal (X)	mm/s	1350
Angular Velocity		
- Roll	deg/s	78
- Pitch	deg/s	70
- Yaw	deg/s	50
Linear Acceleration (bare table)		
- Vertical (Z)	g	15.9
- Lateral (Y)	g	11.6
- Longitudinal (X)	g	12.8
Linear Acceleration (max payload)		
- Vertical (Z)	g	6.0
- Lateral (Y)	g	4.2
- Longitudinal (X)	g	4.8

2.2 Experimental setting up

The overall experimental setting up is shown in Fig. 2. The RS-3D seismometer was clamped on a rock slap. The slap was tighten using a 12 mm screw bolt. A power bank of 12 AH lithium-ion battery was used to operate the RS-3D. A portable ethernet wifi-router was connected to the RS-3D to initiate the start-up of the instrument, collect the data, and shut down the instrument. The RS-3D seismometer on top of the table of the MAST System setting is shown in Fig. 3.

Fig. 2. The raspberry seismometer was set in the top-middle of the shaking table.

Fig. 3. Rock slap was used to tie the raspberry seismometer.

2.2 Data acquisition and analysis

The time histories data collection was recorded using RS-3D Raspberry seismometer. Four different trials were carried out, as shown in Table 2. The time histories data of these four trials are presented in Figs. 4 to 7.

Table 2. Experimental trials of the present study.

Trial No.	Frequency	Recording duration	Remarks
Trial#1	0.4 Hz	9 minutes	All axes of E-W, N-S, and U-D
Trial#2	0.4 Hz	9 minutes 18 seconds	E-W axis
Trial#3	1.0 Hz	10 minutes	E-W axis
Trial#4	1.0 Hz	10 minutes	All axes of E-W, N-S, and U-D

In this study, the experimental data were analyzed using the Geopsy software package (GSP) [24]. Two analyses were carried out. The first analysis is to discover the origin of the waves. Damping tool in the GSP was employed in the first analysis, from which the origin of the waves is concluded. The second analysis is to detect the frequency and source of the recorded waves. The Geopsy spectrum and 2D spectrum toolboxes were used to detect the frequency and source azimuth of the recorded waves. Spectral analysis using spectrum toolbox provides

a means of measuring the strength of periodic components of a wave at different frequencies. Spectral analysis includes the calculation of waves in a set of sequenced data. The 2D spectrum toolbox provides the spatial distribution of the spectral analysis by means of frequency and azimuth. The used parameters in the second analysis are window length (25s), smoothing using the Konno & Ohmachi [25] smoothing approach with a smoothing constant of 40, and window type of Tukey with width 5%.

Fig. 4. Time histories data for Trial#1.

Fig. 5. Time histories data for Trial#2.

Fig. 6. Time histories data for Trial#3.

Fig. 7. Time histories data for Trial#4.

3 Results and discussion

Shaking table tests were conducted at various trials, as aforementioned above. The collected data were analysed in two steps for detecting the origin of the waves and estimating the frequency of the shaking. The results are presented in Figs. 8 to 19.

Prior to the frequency analysis, a detection of the origin of the waves was carried, which suggests harmonic waves generated from the shaking table, as damping <1% is observed except for the vertical component of Trial#2, as shown in Figs. 8, 11, 14, and 17. The spectrum analyses results are shown in Figs. 9, 12, 15, and 18. The frequencies obtained from the spectrum analyses are tabulated Table 3.

Results of 2D spectrum analysis are shown in Figs. 10, 13, 16, and 19. This 2D spectrum analysis suggests that Trial#1 and Trial#4 receive wider spatial distribution wave sources than Trial#2 and Trial#3.

Fig. 8. Results of damping analysis of Trial #1 data.

Fig. 9. Summary spectrum analysis of Trial #1 data.

Fig. 12. Summary spectrum analysis of Trial #2 data.

Fig. 10. Azimuth wave-source at frequency between 0.25 Hz and 15 Hz for Trial #1.

Fig. 13. Azimuth wave-source at frequency between 0.25 Hz and 15 Hz for Trial #2.

Fig. 11. Results of damping analysis of Trial #2 data.

Fig. 14. Results of damping analysis of Trial #3 data.

Fig. 15. Summary spectrum analysis of Trial #3 data.

Fig. 18. Summary spectrum analysis of Trial #4 data.

Fig. 16. Azimuth wave-source at frequency between 0.5 Hz and 15 Hz for Trial #3.

Fig. 19. Azimuth wave-source at frequency between 0.5 Hz and 15 Hz for Trial #4.

Fig. 17. Results of damping analysis of Trial #4 data.

Table 3. Frequencies obtained from the spectrum analyses.

Trial No.	Frequency (Hz)	
	MAST System	Rs-3D Seismometer
Trial#1	0.4 Hz	0.394015 Hz
		0.394015 Hz
		0.394015 Hz
Trial#2	0.4 Hz	0.394015 Hz
		0.394015 Hz
		0.394015 Hz
Trial#3	1.0 Hz	0.978717 Hz
		0.978717 Hz
		0.978717 Hz
Trial#4	1.0 Hz	0.978717 Hz
		0.978717 Hz
		0.978717 Hz

To assess the performance of the RS-3D seismometer, the Raspberry Shake vibration data results of spectrum analysis, i.e. frequency, were compared against the frequency input from the shaking table. The comparison is presented in Table 3 and Fig. 20, which suggests in a great agreement.

Additionally, root mean square error (RMSE) was calculated to measures how much error there is between two data sets of MAST system input frequency and RS-3D seismometer response frequency. In other words, it compares an input (predicted) value of MAST system frequency and an output (observed) value of RS-3D seismometer frequency. RMSE can be approximated using an Equation 1 [26], as follow:

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (P_i - O_i)^2}{n}} \quad (1)$$

Predicted and observed values are represented by P_i and O_i , respectively. The number of observations is n .

Fig. 20. The performance of the RS-3D seismometer.

The RMSE is the square root of the variance of the residuals. RMSE in this study indicates the absolute fit of the RS-3D seismometer for measuring the input frequency of the shaking table. Generally, lower value of RMSE indicates better fit. The RMSE in this study is 0.016 g which suggests a good performance of the RS-3D seismometer. Based on a rule of thumb, RMSE values less than 0.1 shows that the model can relatively predict the data accurately. Furthermore, a RMSE value of the present study (0.016) that is smaller than both standard deviation values of observed data (0.305) and predicted data (0.313) is considered good [27].

In addition, scatter index (SI), as shown in Equation 2, is also calculated to assess the performance of the RS-3D seismometer. SI is simply the RMSE divided by the mean value of the observed data [28], as follow:

$$SI = \left(\frac{RMSE}{\text{Mean of observed value}} \right) \times 100\% \quad (2)$$

Generally, if $SI < 10\%$ is a good instrument, $SI < 5\%$ is a very good instrument. The present study estimates the SI of 2%, which suggests very good instrument.

4 Conclusion

Ambient vibration measurement using a seismometer may inhibit widespread applications. Recently, there is a low-cost seismometer (RS-3D seismometer) available on the market. RS-3D seems to be a feasible option in ambient low-noise measurement methods. However, the performance of this seismometer requires further study. This study presents the performance of this RS-3D by validating this seismometer using a shaking table. Four trials were carried out, from which twelve datasets were acquired using RS-3D seismometer. These datasets were analysed to obtain the observed predominance frequency. RMSE and SI calculations were used to deduce the comparison between input frequency of MAST system and an output frequency of RS-3D seismometer frequency. This study concludes that RS-3D seismometer provides a great performance. However, further testing using many different input frequencies is required.

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