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A design of soft-gauge for elevator vibration analysis based on low-cost accelerometer MMA7361L and LabVIEW

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ABSTRACT

This paper presents a design of soft-gauge using the low-cost triple-axis accelerometer MMA7361L and LabVIEW software for the purpose of elevator vibration analysis with accuracy according to national standards. The 3-dimensional vibration signals measured and collected respectively by MMA7361L and NI USB6009 are fed into a soft-gauge programmed on LabVIEW to filter, then the fast Fourier transform (FFT) is applied to determine the power spectral density (PSD) and spectrogram of vibrations of filtered vibration signals. The soft-gauge also allows real-time 3-dimensional vibration data to be recorded, this data is used for analyzing later by another professional data software. Practical test results applied for the elevator of the DONGA Plaza building show quite good vibration analysis. Class 1.5 accuracy of the soft-gauge can be obtained by experimental test. This is a fairly cost-effective and inexpensive application that can be made in conditions with limited funds that cannot afford expensive accelerometers in the training of vibration measurement and analysis in high schools and vocational schools in developing countries, like Vietnam.

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1. INTRODUCTION

Today elevators are an important and indispensable device in buildings of urban areas and cities. Rapid urbanization in developing countries has led to a rapidly increasing demand for elevators in recent decades. The safe operation of the elevators and the quality of the elevator's movement is an important issue, that is evaluated by many parameters during the using of the elevator such as the 3-dimensional vibration, smoothness, and the noise level of the cabin in the operation process. Among those parameters, the vibration of the elevator is a very important parameter, it determines the smoothness, the negative effects on passengers during transportation, safety, and usability in long-term use of the elevator. Normally, the level of vibrations of the elevator will increase gradually along the time of use, which is caused by the failed moving parts (tracker, hoist rope, and driving machine), and the damping parts being aging. Therefore, checking the vibration of the elevator is an important technical issue that needs to be carried out in order to maintain, repair, and prevent dangerous damage from the elevator [1]–[3]. Measuring the vibration of elevators is a rather complicated technical problem, an international standard ISO 18738-1:2012 (measurement of ride quality-Part 1: Lifts (elevators)) [4] has been established to help supports vibration and noise measurement methods. Passenger comfort is highly dependent on the peak-to-peak amplitude of vibration accelerating in the transportation [5], [6]. Manufacturers of elevator vibration measurement equipment often make exclusively a set of measuring probes, measuring devices, and closed source software. There is very difficult to repair when the failure occurring, and the data is less compatible with scientific data analysis software. Elevator vibration instruments have many types, they depend on the level of accuracy and frequency range measured, the cost is often high and very high [7], [8]. The wider the frequency range is, the smaller the sampling period, the faster the data sampling rate are (when the elevator is operated with a high speed), the more expensive the software and the vibration sensor is. For example, the Hoki MR8880-20 measuring device costs about 3,700 USD on eBay, the EVA-625 device costs about 5,000 USD, and so on [9], [10]. On the other hand, the filtering algorithms and calculating of the vibration characteristics are difficult to intervene and adjust as necessary in educational work. Moreover, for developing countries, such as Vietnam, the cost to buy these devices is often beyond the tolerance of customers, especially in vocational schools, training schools of maintenance and elevators operation for workers. The above difficulties are the motivation for us to find a way to overcome above obstacles. In this paper, we propose a soft-gauge design for elevator vibration analysis and measuring, integrated from the low-cost accelerometer MMA7361L [11] and soft-gauge written by using the educational version LabVIEW (free of charge) [12]. This design ensures to measure the vibrations of the elevators with national standard accuracy, has the potential to display fast Fourier transform (FFT), power spectral density (PSD), and spectrogram of 3-axis vibration x, y, z of elevator platform frame [13]–[15]. This soft-gauge also has the ability to store data in an appropriate Excel file format for later analysis by the professional data analysis software. This design is easy to implement and improve according to user's requirements. The rest of the paper is structured: section 2 is the presentation of hardware design, section 3 is an algorithm for vibration measuring and analyzing data, section 4 is some experimental results obtained by testing for practical elevator operation process, and some discussion results and future works are presented in section 5.

2. THE HARDWARE DESIGN

The measuring device is designed according to the principle as shown in Figure 1, in which: i) '1' is a low-cost 3-dimensional accelerometer MMA7361L with main technical characteristics listed in Table 1, ii) '2' is an anti-aliasing filter, iii) '3' is a digital signal processor, and iv) '4' is USB communication. The anti-aliasing filter is designed with an electronic circuit, NI USB6009 [16] data acquisition module has the parameters given in Table 2 NI USB6009 performs processing and transforming the 10 bits serial digital signals to the soft-gauge. A laptop with LabVIEW software installed (educational version) is used to write a soft-gauge to measure and analyze the vibration data of the elevator.

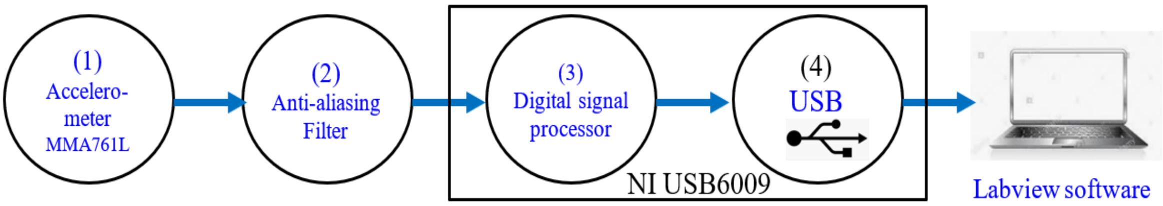


Figure 1. The design hardware of equipment

Table 1. Device specifications of MMA7361L [11]

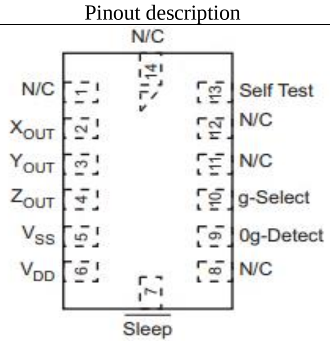
Features	Values	Pinout description
Current Consumption	400 µA	
Sleep mode	3 µA	
Operation voltage	2.2-3.6 V	
Sensitivity	800 mV @ 1.5 g	
Selectable Sensitivity	±1.5 g, ±1.6 g	
Response Time	0.5 ms	
Signal conditioning	Low pass filter	
Freefall protection	Yes	

Table 2. Device specifications of NI USB6009 [16]

Features	Values	The layout of NI USB6009
Input/output	Analog Input Channels 0 to 7—For single-ended measurements, each signal is an analog input voltage channel. For differential measurements, AI 0 and AI 4 are the positive and negative inputs of differential analog input channel 0.	
AI resolution	14 bits differential, 13 bits single-ended	
Maximum AI sample rate	48 kS/s	
Maximum AI sample rate, multiple channels (aggregate)	48 kS/s	
DIO configuration	Each channel individually programmable as open collector or active drive	

For the sensor MMA7361L, the output voltages for vibration direction x, y, z have a range depending on the selection of the sensor mounting direction on the object to be measured. The offset voltage of the directions x, y, z in the static state (no vibration) can be values of $0.85\ V$, $1.65\ V$, or $2.45\ V$. If the scale is selected as $1\ g$, with a sensor sensitivity of $800\ mV/g$, the measurement voltages of the 3 directional vibrations range from $0\ V$ to $3.25\ V$. Offset voltages for the axes x, y, z with respect to the directions of the sensor mounted on the platform are shown in Figure 2.

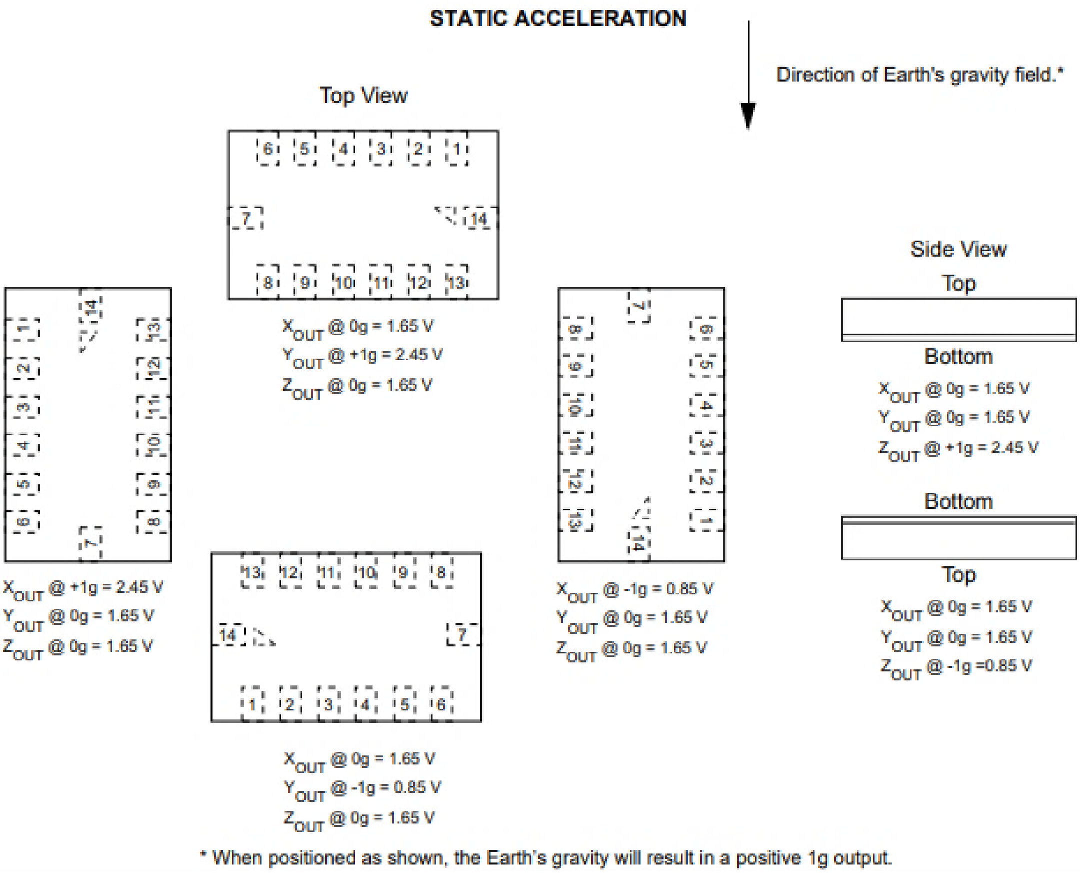


Figure 2. Offset voltages of MMA7361L in the static state [11]

For NI USB6009, the maximum sampling frequency for 8 single-end channels is $48\ ksamples/s$, so the maximum number of sampling points for each channel is 6ksamples/s for each channel. The resolution of NI USB6009 is 12 bits, so the resolution corresponding to the voltage for each channel can be determined by $(3.25\ V)/2^{12} = 0.00085449\ V$. In this application, we only use 03 channels for directions x, y, and z. So, the maximum sampling frequency that can be selected for each channel is $16\ ksamples/s$.

3. ALGORITHM FOR VIBRATION MEASUREMENT AND ANALYSIS OF ELEVATOR

The vibration of the elevator in the operating depends on the vibration characteristics of the main components in the elevator such as the platform, the car frame, the transmission system, the hoist rope, the load in the car frame, and the car frame's movement direction of going up or down. Because the length of the hoist rope changes continuously during operation, the kinematic characteristics of the elevator at different positions are different. The quality of the elevator vibration analysis generally depends on the number of vibrations measuring points at different locations, each that point has information about 3-dimensional vibration x, y, z collected and analyzed. If the number of measurement points is large, we will obtain more vibration characteristics at different points of the elevator and thus it gives a more comprehensive description of the vibration characteristics of the whole elevator system. The PSD is used mainly to analysis the of mechanical vibration characteristic in the frequency-domain [17], [18]. Since the integral of a random time-varying signal does not asymptotically converge, so its Fourier transform cannot be ether obtained directly or described exactly by mathematical expressions. Thereby, a random time-varying signal can only be represented by statistical methods. The PSD represents the statistical average of the power spectral characteristic of a signal. PSD can be used to analyze the strength and weakness of a signal in the frequency domain in terms of energy [19]–[22]. Therefore, to analyze the vibration signal at the measuring points, in this paper, PSD analysis is used. A flowchart of the algorithm to perform at a measuring point is shown in Figure 3. To start the measurement process, the signals from the sensor are scaled at $1\ g$ or $6\ g$. Usually, a low-speed elevator scale at $1g$ is chosen. The calibration according to sensitivity, in the case at $1\ g$, is $800\ mV/g$. The main functions that need to be performed at each block of the flowchart in the algorithm in Figure 3 are in the steps:

- Step 1: acquire vibration signal data 3 of channels x, y, z by NI USB6009. This data is stored in the NI USB6009's buffer, the number of samplings of channels depends on the maximum frequency of vibration, the multiplier must be greater than 2 and is chosen satisfies Shannon's sampling theorem [23]. The number of samplings in one processing cycle is N_s, the unit of the acquired data is V.
- Step 2: split the acquired data into 03 channels x, y and z to proccess.
- Step 3: determine the direct current (DC) component in the acquired data for each channel, then the DC component is subtracted from the data to receive the final vibration data which is only the vibration component.
- Step 4: convert unit of final vibration data from V to g to obtain the vibration signal with unit g.
- Step 5: filter the final data. There are three kinds of filters to be chosen: the low-pass filter, the high-pass filter, and the band-pass filter [24]. For any kind of filter, suitable parameters including calibration factors, low cut-off frequency, type, topology, and order are chosen appropriately. The filtered signals for 03 channels are displayed. In this study, we use the band-pass filter, but when measuring with specific elevators, the filter is necessary to choose accordingly because the vibration characteristics of different elevators are different, so there is no general filter selection for all categories of elevator. Sometimes it takes a lot of experimentations to get a suitable filter and its parameters. This depends on the experience of the person carrying out the measurements and observations.
- Step 6: convert the vibration signal data from g to m/s^2.
- Step 7: analysis FFT and PSD. The vibration signal data are integrated twice to obtain the position signal data of axes x, y, z . Then the root mean square (RMS) analysis is applied. The unit of RMS signals is m^2/s^3. Suppose that the harmonic signal $x(t)$ is written in term of Fourier series given by (1) [25]–[27]:

$$x(t) = \alpha_0 + \sum_{k=1}^{\infty} \frac{\alpha_k + j\beta_k}{2} e^{-jk\omega_0 t} = s_0 + \sum_{k-1}^{\infty} (s_k e^{jk\omega_0 t} + s_k^* e^{jk\omega_0 t}) \quad (1)$$

Lets $s_0 = \alpha_0; s_k = \frac{\alpha_k - j\beta_k}{2}; s_k^* = \frac{\alpha_k - j\beta_k}{2}; S_k = 2|s_k|; S_k^* = 2|s_k^*|; \alpha_0 = 0$, so (1) is rewritten as

$$x(t) = \sum_{k=1}^{\infty} \frac{S_k e^{jk\omega_0 t} + S_k^* e^{-jk\omega_0 t}}{2} = Re(\sum_{k=1}^{\infty} S_k e^{jk\omega_0 t}) \quad (2)$$

The RMS value of $x(t)$ signal is $x(t)_{RMS}$, it is calculated as (3).

$$x(t)_{RMS} = \frac{1}{T} \int_0^T x^2(t) dt = \frac{1}{T} \int_0^T \frac{(S_k + S_k^* e^{-jk\omega_0 t})^2}{4} dt = \frac{1}{2} \sum_{k=1}^{\infty} |S_k|^2 = \frac{1}{4} \sum_{k=1}^{\infty} \left(\frac{|S_k|^2}{\sqrt{2}}\right) \quad (3)$$

The equation $W(f_k) = \frac{1}{2} S_k S_k^* = \frac{1}{2} |S_k|^2$ describes the k^{th} component of harmonic signal, the part $\frac{1}{2} \sum_{k=1}^{\infty} S_k S_k^*$ shows the total of power of signal $x(t)$ at all frequencies [28], [29]. So, RMS of $x(t)$ can be expressed by summing the spectral power and it is called PSD and it is calculated by (4).

$$x(t)_{RMS} = \sum_{k=1}^{\infty} W(f_k) \quad (4)$$

The power spectral indicates the distribution of energy of the signal at all its power components. The PSD $G(f_k)$ is calculated by dividing the power spectral by the frequency interval Δf as (5).

$$G(f_k) = \frac{W(f_k)}{\Delta f} \quad (5)$$

The relationship between the RMS and PSD is:

$$x(t)_{RMS} = \sum_{k=1}^{\infty} G(f_k)\Delta f \quad (6)$$

– Step 8: Save the data of FFT, PSD and spectrogram

Based on the knowledge in advance of the vibration characteristic of the elevator being tested, the tester needs to choose properly parameters in the measure and analysis process in order to obtain good results. This depends mainly on the tester’s experiences and choosing the test point. Vibration data are stored properly to help analyzing accurately FFT and DSP of 03 axis $z, y,$ and x.

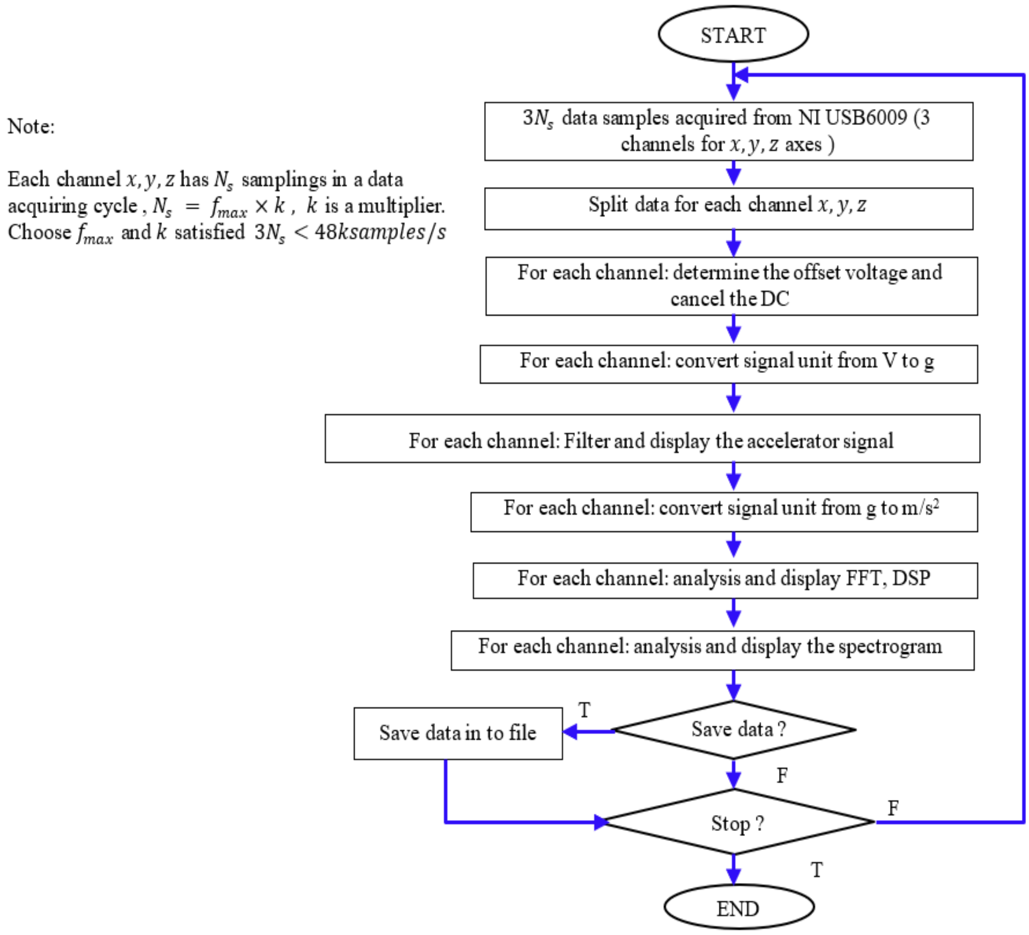


Figure 3. The algorithm of vibration measuring and analyzing at a measuring point

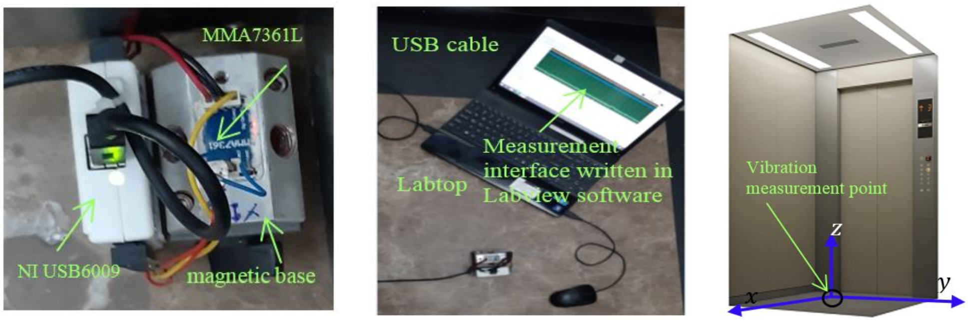
4. THE EXPERIMENTAL RESULTS

This section presents some experimental results of elevator vibration measurement at the DONGA Plaza building (Dong Quang district, Thai Nguyen City, Vietnam), which is a 5-floor elevator with physical parameters given in Table 3. Experimental results were performed for 03 measurement points: the platform, the right side of the cabin wall, and the cabin wall opposite the door. Test results were also conducted for the cases where the elevator went up and down and went down with 20% of the load.

Because of the limited page number of the paper, we only present the experimental results at the elevator platform when going up at 20% of the load. Accelerator sensor MMA7361L and NI USB6009 mounted on the magnetic base is shown in Figure 4(a), Figure 4(b) is the setup of vibration measurement at the platform of DONGA Plaza building elevator. The position of the sensor and the test directions are set as shown in Figure 4(c). The sampling period of the signal for 03 channels is $T = 0.001\ s$.

Table 3. The specifications of the elevator of DONGA Plaza building

Features	Values
Number of floors	5
Maximum speed	2.5 m/s
The maximum load	450 kg
The power	5.5 KW
The height of hoist rope	14 m
Kind of power source	AC, 380 V, 3 phases



(a) (b) (c)

Figure 4. Physical setup of the experiment including: (a) accelerator sensor MMA7361L, NI USB6009 mounted on the magnetic base, (b) setup of vibration measurement at platform of DONGA Plaza building elevator, and (c) the test position in the platform and the direction x, y and z

Vibration measurement results and vibration analysis results (FFT, PSD, and spectrogram) for 03 axes x, y, and z are depicted in Figures 5, 6, and 7, respectively. Figure 5 describes the vibration accelerators at the test point for 3 axes z, y, and x, respectively, they reflect the intensity of vibration. The z-direction intensity of vibration is much larger than that of the x and y axes. The vibration of the y axis and the vibration of the x axis is approximately equal. At the time of 7.615 s, the z axis occurs a vibration with a high accelerator amplitude of $4.258\ m/s^2$. The statistics of vibration acceleration for z axis is $std = 0.2651\ m/s^2, meadian = -0.008358\ m/s^2, mean = -0.007913\ m/s^2$. Similarly, the statistics the y and x axes are $std = 0.08159 \frac{m}{s^2}$, $median = -0.00687 \frac{m}{s^2}$, $mean\ = -0.005853\ m/s^2$; $std = 0.1309\ m/s^2$, $median = -0.005016\ m/s^2$, $mean = -0.005682\ m/s^2$, respectively. From the FFT analysis results shown in Figure 6, we see that there are 05 frequencies that make the vibrations with high amplitudes at the z axis, they are the pairs of frequency and amplitude arranged in order of decreasing amplitude as $(2.955\ Hz, 0.04779\ m/s^2)$, $(23.99\ Hz, 0.039\ m/s^2)$, $(40.55\ Hz, 0.015\ m/s^2)$, $(61.3\ Hz, 0.00762\ m/s^2)$, and $(85.91\ Hz, 0.0092\ m/s^2)$. For the y axis, there are 04 frequencies with high vibration amplitudes corresponding to the pairs $(3.993\ Hz, 0.0188\ m/s^2)$, $(11.98\ Hz, 0.0162\ m/s^2)$, $(24.87\ Hz, 0.015 m/s^2)$, and $(64.51\ Hz\ 0.002\ m/s^2)$. The x axis only has 02 frequencies with high amplitudes as pairs $(3.117\ Hz, 0.0319\ m/s^2)$ and $(27.01\ Hz, 0.019\ m/s^2)$. Figure 7 is PSD analysis of vibrations for 3 axes, it shows that the power of vibration energies is concentrated highly at several frequencies. The vibration energy of z-axis is high at frequencies as $2.955\ Hz$, $23.99\ Hz$, $40.55\ Hz$, $59.19\ Hz$ and $83.96\ Hz$ respectively with the power spectral density respectively $0.03517\ m^2/s^3$, $0.02319\ m^2/s^3$, $0.02319\ m^2/s^3$, $0.0006748\ m^2/s^3$, and $0.00115\ m^2/s^3$. There are 03 frequencies concentrating highly vibration energy in the y axis as $3.993\ Hz$, $11.98\ Hz$, and $24.87\ Hz$, the power spectral density of these frequencies is $0.005406\ m^2/s^3$, $0.004013\ m^2/s^3$, and $0.003591\ m^2/s^3$. There are only 02 pairs of frequency and the high-power spectral density in the x axis as $(3.117\ Hz, 0.01567\ m^2/s^3)$ and $(27.0\ Hz, 0.006025\ m^2/s^3)$. The vibration energy in the z axis is largest, which is 7 times higher than that in the y axis and 2.3 times higher than that in the x axis.

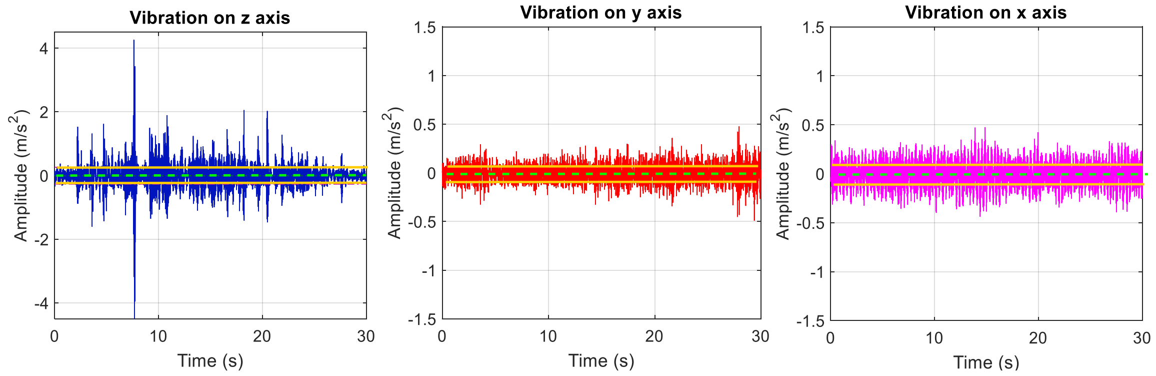


Figure 5. The vibration of 03 axis z, y and x at the test point

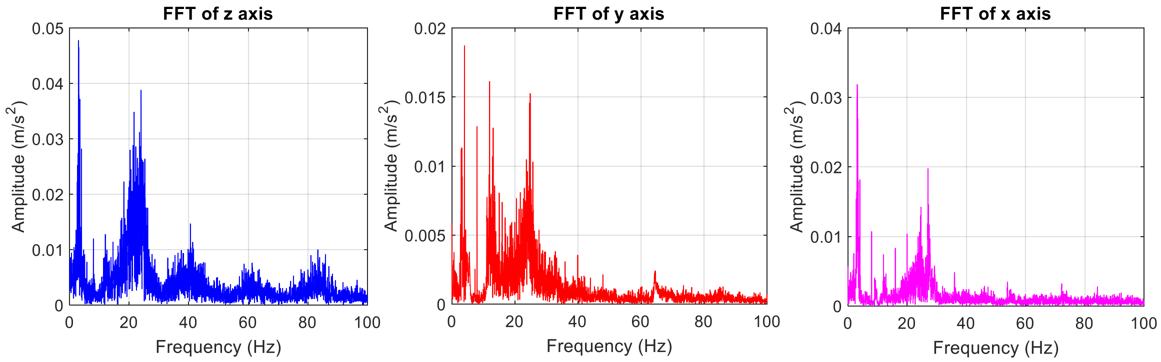


Figure 6. The vibration's FFT of 03 axis $z, y,$ and x at the test point

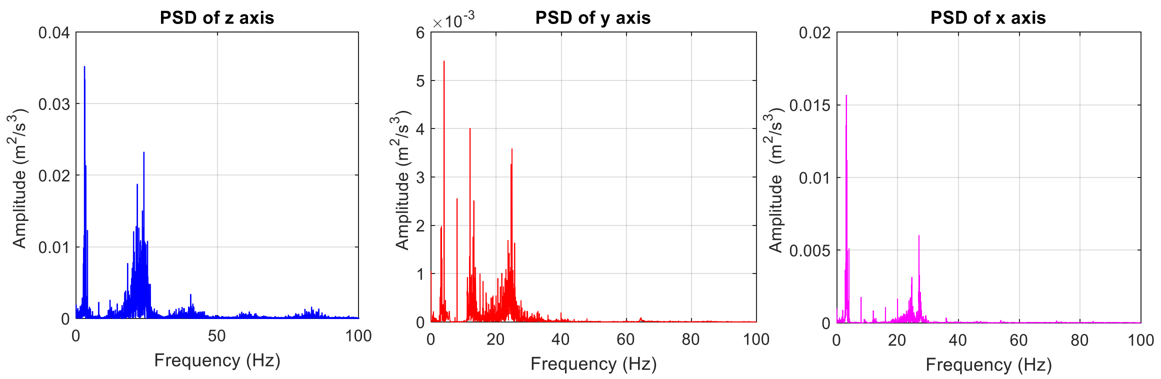


Figure 7. The vibration's DSP of 03 axis $z, y,$ and x at the test point

Figure 8 plots the spectrogram 3D of the vibrations at the test point, we can see the amplitudes of every frequency of vibration at every time of test, it supplies the visual picture of vibration of the elevator at the test point. For example, at the time of 4.5 s, the x axis has a vibration with a frequency of 12 Hz and an amplitude of power spectral of -1.705 (see the circle marked on the figure). Therefore, the spectrogram is a useful analysis for visualizing the elevator vibrations of the test in 3D. The roughness of the spectrogram surface shows how the elevator vibration over test time. If this surface is flatter, there is less vibration in the elevator during movement, the roughness of the spectrogram surface affects the comfort level of the passengers. The structure of the fields in the data file stored in an Excel file with the fields is shown in the Table 4, this data file is used for later vibration analysis by other vibration analysis software or used for storage.

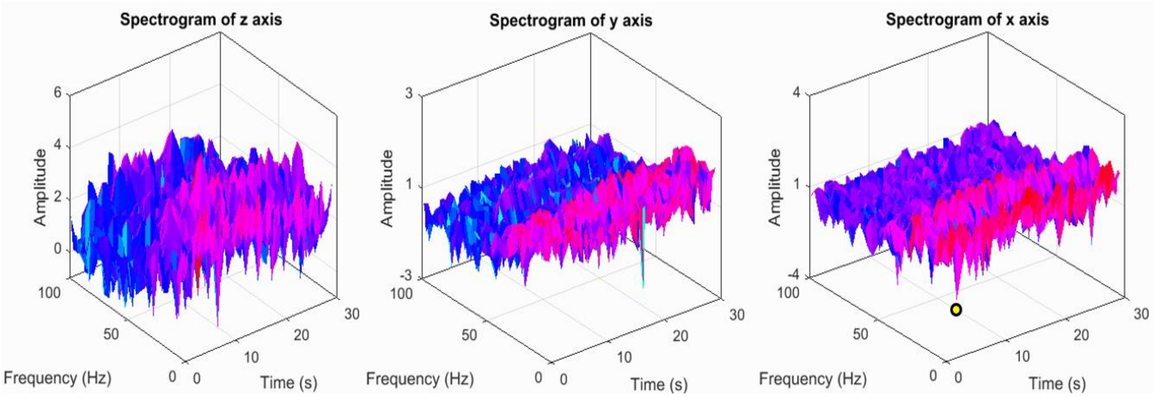


Figure 8. The vibration's spectrogram of 03 axis z, y, and x at the test point

Table 4. The fields of data stored in the Excel file

Time(s)-Voltage_1	Amplitude(g)-Voltage_1	Time(s)-Voltage_1(Filtered)	Amplitude(g)-Voltage_1(Filtered)
0	0.00796041	0	6.86E-06
0.00130208	-0.0111446	0.00130208	2.48E-05
0.00260417	0.00159208	0.00260417	-5.04E-08
0.00390625	-0.0143287	0.00390625	-0.000133733
0.00520833	0.00796041	0.00520833	-0.000227801
0.00651042	-0.00796041	0.00651042	5.49E-05
0.0078125	0.00477625	0.0078125	0.00066386
0.00911458	-0.00159208	0.00911458	0.000824334
0.0104167	0.0175129	0.0104167	-0.000118599

5. CONCLUSION AND FUTURE WORKS

This paper presented a method of designing a soft-gauge for elevator vibration analysis using the cheap accelerometer chip MMA7361L and LabVIEW software. The measured signals from the accelerometer sensor in three directions are acquired, filtered, and processed by NI USB6009. LabVIEW software is used to write algorithms to analyze and display graphics over time of vibration characteristics as FFT, DSP, and 3D spectrogram in 3 directions x, y, z. The software can also allow vibration data to be recorded to use for other vibration analysis software. This method is very flexible in the selection of filtering algorithms as well as allows expressing the vibrational characteristics in different forms by writing the code. Cheap and easy to implement are the advantages of this method in the field of training and vocational training. The vibration test results of the elevator at the DONGA Plaza building gave quite good results of vibration analysis. This is a fairly cost-effective and inexpensive application that can be made in conditions with limited funds that cannot afford expensive accelerometers in the developing countries in the world. This application can be used for training in vibration analysis and measurement in schools and vocational schools. The integrating the ability to transmit data via Bluetooth or Wi-Fi to make it more convenient in the measurement process is our future work. Data can be stored in the cloud for remote real-time monitoring and analysis. By comparison with the national testing equipment, class 1.5 accuracy of the soft-gauge can be obtained by experimental test.

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REFERENCES

[1] K. Szydło, P. Wolszczak, R. Longwic, G. Litak, M. Dziubiński, and A. Drozd, "Assessment of lift passenger comfort by the Hilbert-Huang transform," *Journal of Vibration Engineering and Technologies*, vol. 8, no. 2, pp. 373–380, Apr. 2020, doi: 10.1007/s42417-019-00184-3

[2] Y. Zhang, X. Sun, X. Zhao, and W. Su, "Elevator ride comfort monitoring and evaluation using smartphones," *Mechanical Systems and Signal Processing*, vol. 105, pp. 377–390, May 2018, doi: 10.1016/j.ymssp.2017.12.005.

[3] Q. Peng, A. Jiang, H. Yuan, G. Huang, S. He, and S. Li, "Study on theoretical model and test method of vertical vibration of elevator traction system," *Mathematical Problems in Engineering*, vol. 2020, pp. 1–12, Mar. 2020, doi: 10.1155/2020/8518024.

[4] ISO, *Measurement of ride quality Part 1: lifts (elevators)*, 1st edition, BSI, 2012.

[5] ISO, *Mechanical vibration and shock-human exposure-vocabulary*. Polish Committee for Standardization, 2002.

[6] ISO, *Mechanical vibration and shock, evaluation of human exposure to whole-body vibration. Part 1: General requirements*, 2nd editio. ISO 2631-1:1997, 1997.

[7] Euro Tech, "EVA-625-Ride quality measurement and analysis." https://euro-techfe.com/product/eva-625/ (accessed Feb 20, 2021).

[8] HIOKI, "Testting and analysis," *HIOKI*. https://www.hioki.com/global/industries-solutions/testing (accessed Feb 20, 2021).

[9] Linkedin, "PMT USA elevator vibration analyzer-EVA-625," 2015. https://www.linkedin.com/pulse/pmt-usa-elevator-vibration-analyzer-eva-625-jl-seagull-power-products (accessed Oct 15, 2021).

[10] "MMA7361L Sensor." Accessed Feb 20, 2021. [Online]. Available: https://www.alldatasheet.com/datasheet-pdf/pdf/246143/FREESCALE/MMA7361L.html.

[11] "Introduction to LabVIEW." https://manual.eg.poly.edu/index.php/Introduction_to_LabVIEW (accessed Feb 20, 2021).

[12] E. Wescoat, L. Mears, J. Goodnough, and J. Sims, "Frequency energy analysis in detecting rolling bearing faults," *Procedia Manufacturing*, vol. 48, pp. 980–991, 2020, doi: 10.1016/j.promfg.2020.05.137.

[13] M. Cerna and A. F. Harvey, "The fundamentals of FFT-based signal analysis and measurement," National Instrument, Application Note 041, 2000.

[14] B. Pappachan, W. Caesarendra, T. Tjahjowidodo, and T. Wijaya, "Frequency domain analysis of sensor data for event classification in real-time robot assisted deburring," *Sensors*, vol. 17, no. 6, 1247, May 2017, doi: 10.3390/s17061247.

[15] "User guide and specifications NI USB-6008/6009," National Instruments Corporation.

[16] Z. Yang, Q. Zhang, R. Zhang, and L. Zhang, "Transverse vibration response of a super high-speed elevator under air disturbance," *International Journal of Structural Stability and Dynamics*, vol. 19, no. 09, Art. no. 1950103, Sep. 2019, doi: 10.1142/S0219455419501037.

[17] Q. Zhang, Y. Yang, T. Hou, and R. Zhang, "Dynamic analysis of high-speed traction elevator and traction car-rope time-varying system," *Noise and Vibration Worldwide*, vol. 50, no. 2, pp. 37–45, Feb. 2019, doi: 10.1177/0957456519827929.

[18] R. Zhang, C. Wang, Q. Zhang, and J. Liu, "Response analysis of non-linear compound random vibration of a high-speed elevator," *Journal of Mechanical Science and Technology*, vol. 33, no. 1, pp. 51–63, Jan. 2019, doi: 10.1007/s12206-018-1206-5.

[19] N. B. M. Noor and M. R. Ahmad, "Modeling the vibrational dynamics of piezoelectric actuator by system identification technique," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 7, no. 3, pp. 1506–1512, Jun. 2017, doi: 10.11591/ijece.v7i3.pp1506-1512.

[20] K. Jayakumar and S. Thangavel, "Vibration analysis of industrial drive for broken bearing detection using probabilistic wavelet neural network," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 5, no. 4, pp. 541–551, Apr. 2015, doi: 10.11591/ijpeds.v5.i4.pp541-551.

[21] N. Mamat, F. Yakub, S. A. Z. Shaikh Salim, and M. S. Mat Ali, "Performance comparison of controllers for suppressing the structural building vibration," *Indonesian Journal of Electrical Engineering and Computer Science (IJEECS)*, vol. 10, no. 2, pp. 537–544, May 2018, doi: 10.11591/ijeecs.v10.i2.pp537-544.

[22] L. Tan and J. Jiang, "Signal sampling and quantization," in *Digital Signal Processing*, Elsevier, 2019, pp. 13–58, doi: 10.1016/B978-0-12-815071-9.00002-6.

[23] L. Litwin, "FIR and IIR digital filters," *IEEE Potentials*, vol. 19, no. 4, pp. 28–31, 2000, doi: 10.1109/45.877863.

[24] Q. Peng *et al.*, "Analysis of vibration monitoring data of flexible suspension lifting structure based on time-varying theory," *Sensors*, vol. 20, no. 22, Nov. 2020, doi: 10.3390/s20226586.

[25] M. Giliberto, F. Arena, and G. Pau, "A fuzzy-based solution for optimized management of energy consumption in e-bikes," *Journal of Wireless Mobile Networks, Ubiquitous Computing, and Dependable Applications (JoWUA)*, vol. 10, no. 3, pp. 45–64, 2019.

[26] H. Aljarajreh, D. D.-C. Lu, Y. P. Siwakoti, R. P. Aguilera, and C. K. Tse, "A method of seamless transitions between different operating modes for three-port DC-DC converters," *IEEE Access*, vol. 9, pp. 59184–59195, 2021, doi: 10.1109/ACCESS.2021.3073948.

[27] Y. C. Liu, J. Zhang, C. K. Tse, C. Zhu, and S.-C. Wong, "General pathways to higher order compensation circuits for IPT converters via sensitivity analysis," *IEEE Transactions on Power Electronics*, vol. 36, no. 9, pp. 9897–9906, Sep. 2021, doi: 10.1109/TPEL.2021.3062228.

[28] F. Arena and G. Pau, "An overview of big data analysis," *Bulletin of Electrical Engineering and Informatics*, vol. 9, no. 4, pp. 1646–1653, Aug. 2020, doi: 10.11591/eei.v9i4.2359.

[29] C. Nguyen Van, "State estimation based on sigma point kalman filter for suspension system in presence of road excitation influenced by velocity of the car," *Journal of Control Science and Engineering*, vol. 2019, pp. 1–16, Nov. 2019, doi: 10.1155/2019/6898756.

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