Life-Cycle of Structures and Infrastructure Systems – Biondini & Frangopol (Eds)
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Improving the resolution and accuracy of low-cost Arduino-based accelerometers

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ABSTRACT: An increasing number of researchers are working on Structural Health Monitoring (SHM) applications. However, the high price of traditional commercial accelerometers is known to be one of the significant drawbacks of SHM methods. On the one hand, to apply SHM applications to structures with a lower budget dedicated for their health and safety assessments, development of low-cost sensors can be an answer. On the other hand, low-cost sensors are known to have lower accuracy and resolution compared with those of traditional commercial accelerometers. For the first time in the literature, this paper represents a methodology for improving the resolution and accuracy of low-cost, low-resolution accelerometers. To do so, this paper proposes averaging the outputs of several aligned synchronized low-cost accelerometers.

The validity of the proposed methodology has been examined through a series of laboratory experiments. These experiments tested accelerometers made from one, two, three, four and five combined MPU9250 chipsets on a shaking table. Moreover, two commercial accelerometers (393A03 and 356B18) were used to validate the accuracy of the developed solutions.

1 INTRODUCTION

Structural Health Monitoring (SHM) systems are composed of sensors that measure the structural response (such as accelerations, rotations, strains, or deflections) over time. This information can be used to estimate changes in the structural performance of infrastructures (Gómez, Casas, & Villalba, 2020). The time variation of some environmental factors (such as temperature or humidity) that could produce crack opening (Komarizadehasl & Khanmohammadi, 2021), rotations, settlements, corrosion and other pathologies is so slow that they can be considered quasi-static or static (Baraccani et al., 2017)(Turmo, Lozano-Galant, Mirambell, & Xu, 2015). However, some events (such as the wave response due to earthquake ground motion, traffic-induced vibrations, or ambient activities) need to be accounted for for the dynamic nature of the structural response they induce. To observe and control them, dynamic SHM Systems are required (Chae, Yoo, Kim, & Cho, 2012). The modal parameters needed for SHM application are acquired mainly by accelerometers (Feng & Feng, 2015). MEMS (micro electro mechanical system) accelerometers are silicon-based micromachined devices that traditionally incorporate an accelerometer sensor and a signal conditioning

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circuitry (Khandpur, 2020)(Komarizadehasl, Lozano, Lozano-Galant, Ramos, & Turmo, 2022) .The low-cost MEMS accelerometers have found their way to various industrial applications due to their significant ongoing technology developments (Behnam Mobaraki et al., 2022). Some of these accelerometers offer low-cost alternatives compared with traditional applications (Looney, 2014)(J. A. Lozano-Galant & Turmo, 2014). Information on various MEMS accelerometers from various structural health monitoring applications is summarized in Table 1. This Table has been ordered by the price of the accelerometers.

Table 1. Summary of the characteristics of the accelerometers commonly used in the literature.

N°[1]	Name[2]	Price (€)[3]	Spectral noise (μg/√Hz)[4]	Operation Temperature (C°)[5]	Structural Type[6]
1	3713B112G (PCB Piezotronics, 2012)	2070.0	22.90	[-54, +121]	Wind Turbine (Botz, Oberlaender, Raith, & Grosse, 2016)
2	3711B1110G (PCB Piezotronics, 2015)	870.0	107.90	[-54, +121]	Railroad Bridges (A. Ozdagli, Liu, & Moreu, 2019)
3	ADXL335 (Analog Devices, n.d.)	10.7	300.00	[-40, +85]	Bridges (Grimmelsman & Zolghadri, 2020)
4	LIS344ALH (ST, 2008)	12.0	50.00	[-40, +85]	Steel beam (Girolami, Zonzini, De Marchi, Brunelli, & Benini, 2018)
5	MPU9250 (Aguero, Ozdagli, & Moreu, 2019)	5.8	300.00	[-40, +85]	Steel Pile and Column (Chatterjee et al., 2017)
6	MPU6050 (InvenSense, n.d.)	5.4	400.00	[-40, +85]	Building Model (Varanis, Silva, & Mereles, 2018)

The analysis of Table 1 shows that low-cost sensors generally have higher noise density. This high noise density results in a lower resolution in comparison with expensive MEMS accelerometers.

Arduino is an open-source electronics platform based on easy-to-use hardware and software. The Arduino Due is a microcontroller board based on the Atmel SAM3X8E ARM Cortex-M3 CPU. Unlike most Arduino boards, the Arduino Due board runs at 3.3V. The maximum voltage that the I/O pins can tolerate is 3.3V. Applying voltages higher than 3.3V to any I/O pin could damage the board (Blum, 2013) (Komarizadehasl, Komary, et al., 2022). In fact, many of the MEMS sensors can interact directly with an Arduino microcontroller (Man & Chang, 2016). Sensors 2 to 6 from Table 1 are low-cost MEMS accelerometers. They need an external power supply and could work with Arduino (B. Mobaraki, Komarizadehasl, Pascual, & Lozano-Galant, 2020). The low-cost sensors in the literature are primarily dedicated to projects with low frequencies and strong acceleration amplitude (A. I. Ozdagli, Liu, & Moreu, 2018)(Mobaraki*, Komarizadehasl, Pascual, & Galant, 2021) as they do not have enough resolution to read low amplitude acceleration.

The literature review shows no solutions for improving the resolution of low-cost accelerometers. To fill this gap, this work investigates the increasing number of aligned accelerometers located in the exact location for measuring the same vibration is beneficial. In fact, individual sensors' individual noise density can better be detected by a Fast Fourier Transformation (FFT)

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1. Sensor number.
2. Sensor name.
3. Sensor price: the prices are obtained from retailers (VAT excluded).
4. Spectral Noise: the power spectral density of noise per unit of bandwidth (1 Hz).
5. Operational temperature: temperature range where the sensor works accurately.
6. Structural type: where the sensors are used.

when the average results of a few sensors are evaluated (Jose Antonio Lozano-Galant, Nogal, Turmo, & Castillo, 2015)(Farré-Checa, Komarizadehasl, Ma, Lozano-Galant, & Turmo, 2022).

To validate the performance of the proposed device on laboratory conditions, five accelerometers (MPU9250) were aligned and tested on a hydraulic jack. The jack induced a number of low-amplitude vibrations, and the increasing benefit of accelerometers for decreasing the noise density of the whole system was evaluated (Komary et al., 2023)(Atencio, Komarizadehasl, Lozano-Galant, & Aguilera, 2022).

This paper is organized as follows: In section 2, the proposed system for validating the proposed theory is introduced. Then, in section 3, the laboratory test is used to validate the proposed methodology, and the obtained results are detailed. Finally, the main conclusions are drawn in Section 4.

2 ACQUISITION SYSTEM

In this section, the used equipment for making a vibration acquisition system is illustrated.

Five MPU9250 accelerometers were attached to an Arduino by a multiplexer. It is essential to report that although the sensors are not synchronized, the lag is known.

When the code is executed, the Arduino opens the library and uses the information to get the acceleration from the first sensor, and after the second one, and so on. The lag between each sensor-print is about 2.2 milliseconds. As the lag is known, the average of the measurement (information given by the proposed accelerometer) can also be located in time.

In a nutshell, the proposed accelerometer is working with the average value of the sensors. Therefore, this lag would not interfere with the needed information or the process as the FFT application, which is the heart of this system, and only requires amplitudes and frequency sampling. Frequency sampling is the number of acquired outputs in one second.

3 LABORATORY TESTS

This section compares the sensitivity, ND, and resolution of a single MPU9250 accelerometer This section studies the performed experiments on the proposed accelerometer in laboratory conditions.

For validating the beneficial effect of using several sensors, an experiment on a hydraulic jack was performed. This jack (INSTRON 8803 (INSTRON, 2017)) is located at the Structural Laboratory Lluís Agulló of Technical University of Catalonia (Spain).

A sinus signal has been programmed with a dynamic jack, and the accelerometer has saved the vibrations. This jack can vibrate its lower jaw as was programmed. The hydraulic jack's instructions were to make a wave with a fixed frequency of 0.5 hertz (one complete wave in two seconds). The jack's movement was to go up to 0.1 millimeters up and -0.1 millimeters down from its null axis to make a sinus wave. With a two-time elementary differential, the acceleration equation could be calculated.

$$y = d * \sin(\omega * t + \varphi) \tag{1}$$

$$\omega = 2 * \pi * f \tag{2}$$

In the above equations, y is the displacement in time t, d is the maximum allowed movement of the jack in each cycle, ω is the angular frequency, and f is the set frequency, which equals 5Hz, and φ is the phase constant. On Eq.3, acceleration has been calculated from Eq.1. This was done by getting the second-order derivative of Eq.1. By putting all the data in Eq.3, the Input Acceleration (IA) was calculated as 0.1006 g*10^{-3} m/s^2.

$$a = (d^\wedge 2 * y)/(dt^\wedge 2) = \ddot{y} = -d * \omega^\wedge 2 * \sin(\omega * t + \varphi) \tag{3}$$

4 EFFECT OF THE NUMBER OF SENSORS

In this section, the beneficial effects of adding an increasing number of averaged sensors are studied.

In Figure 1, estimated errors obtained for a different number of sensors in are compared. The Max and the Min in each graph represent the enveloped error for all the possible sensor selections from the five available accelerometers (the proposed accelerometer represents the proposed kit with five sensors). The results of the increasing number of sensors are presented in Figures 1, 1.a (one sensor), 1.b (two sensors), 1.c (three sensors), 1.d (four sensors). In all these figures, the horizontal axis presents the frequency of the experiment, and the vertical one illustrates the MA error in percentage. The MA for 0.5 Hz is not presented in Figure 1.a and b because the system resolution for acquiring low acceleration amplitudes was insufficient.

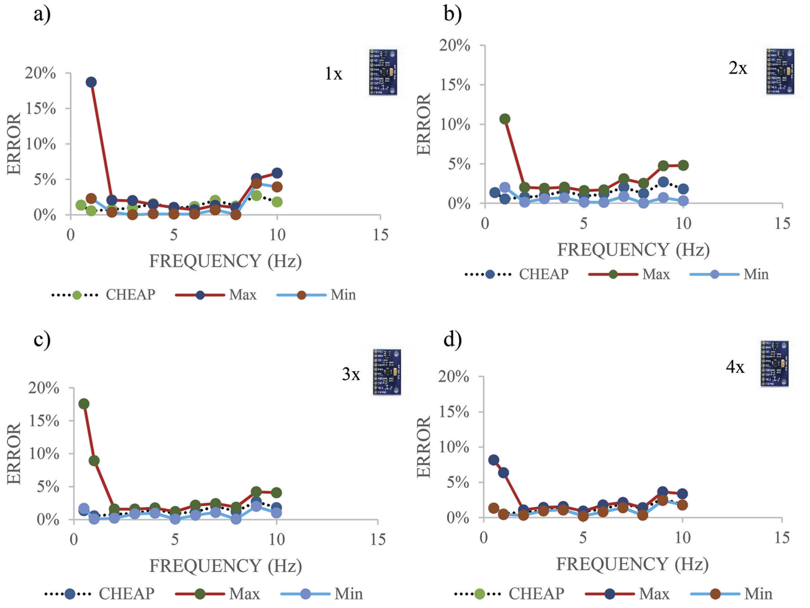

Figure 1. Estimated measured amplitude acceleration (MA) error for different number of sensors: one sensor (a), two sensors (b), three sensors (c), four sensors (d).

The analysis of Figure 1 shows that, as expected, the error depends to a greater extent on the number of sensors and the analyzed frequency. The experienced error for one, two, three, four and five (the proposed accelerometer) were at the worst-case scenario, 18.67%, 20.12%, 17.58%, 8.17%, and 1.55%, respectively. Therefore, it can be concluded that lower errors are obtained when the number of accelerometers is increased, especially on the tests with lower acceleration amplitude (less than 0.4 milli-g). Results in Figure 1 also show that the part of the experiment that had the lowest frequency (0.5 Hz) could be considered the most important one for the following reasons. Firstly, the highest experienced error appears there. Secondly, the lowest acceleration amplitude (0.1022 milli-g) is in this part of the experiment. In a nutshell, locating this low-level acceleration amplitude (MA) from the FFT evaluation was an opportunity to compare the resolution and accuracy of the proposed accelerometer with a different number of sensors.

For a single MPU9250 accelerometer, the resolution for this part of the experiment was not enough. The resolution of the kit with a single accelerometer appeared to be at least 0.19 Milli-g. The amplitude of the needed signal was less than this resolution. As a result, finding and reporting this signal from the FFT output was not possible. The resolution for the kit of sensors with two MPU9250 accelerometers was not entirely clear either. This resolution was at least 0.13 milli-g, which is still 0.03 milli-g higher than the value of the captured signal. The resolution for the kit of sensors with three MPU9250 was about 0.10 milli-g. As a result, finding the amplitude of this part of the experiment was still impossible. The analysis of the same experiment with four MPU9250 accelerometers shows that the resolution of the system is slightly less than 0.08 Milli-g. This resolution made locating the needed signal from the FFT output diagram possible. This test reports the MA of the signal as 0.10384 Milli-g, which has a 3.22% error from the IA. On the other hand, the analysis of the kit of sensors with five MPU9250 (the proposed accelerometer) provides a resolution of around 0.06 Milli-g. In addition, it was deducted that the proposed accelerometer had an error of 1.55% from the IA.

5 CONCLUSION

In order to determine maintenance applications, minimize the reparation costs, and guarantee the safety of the structures, Structural Health Monitoring (SHM)systems are required. For applying the SHM application to structures with a lower budget for assessing their health state, this paper presents a novel method for enhancing the accuracy of low-cost accelerometers.

Adding an increasing number of averaged sensors is investigated to have beneficial effects on the resolution and accuracy. For example, it was seen on an experiment with a frequency of 0.5 Hz that a kit of sensors with four MPU 9250 had a resolution of about 0.08 Milli-g while with five accelerometers (the proposed accelerometer), the resolution became around 0.06 Milli-g.

In conclusion, the proposed methodology can solve the low resolution and high noise density of low-cost accelerometers. However, further research for implementing this idea on bridges and structures is needed.

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