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LOW-COST ARDUINO-BASED HORIZONTAL SENSOR AND DATA ACQUISITION SYSTEM FOR LOW-LEVEL AMBIENT VIBRATION MEASUREMENTS

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Abstract. The measurement of ambient vibrations to be used in system identification, model updating and structural health monitoring applications is already common practice in civil engineering. When the structure under study is very stiff, as in the case of concrete dams, and the level of ambient excitation is very small due to the absence of wind, running water or other vibration sources, the requirements and cost of the equipment needed to capture and process the vibrations tend to be elevated. At the same time, the deployment of the above-mentioned system identification, model updating and structural health monitoring applications may involve the use of a significant number of sensors or the need for keeping the sensors installed and acquiring data for long periods of time. In these cases, the economic cost of the sensors may represent a barrier to the use of this technology. At the same time, the availability of low-cost open platforms to perform this type of measurements is very useful not only in research but also in educational frameworks, because it allows students not only to use the technology but also to participate in its development and learn in the different fields (structural dynamics, electronics or programming) involved in a system of this kind. For these reasons, the paper presents the proposal of a low-cost horizontal sensor and data-acquisition system for low-level ambient vibration measurements. The mechanical sensor is based on the Lehman pendulum (or Garden Gate) design, with a coil-permanent magnet transducer and a data acquisition system based on the Arduino platform. The design of all elements involved in the system is presented in detail, and data obtained from a prototype of the design is presented and analyzed, showing the capabilities of the device.

Key words: Ambient vibrations, experimental structural identification, Arduino, experimental techniques

1 INTRODUCTION

Most civil structures, such as towers, bridges and dams, accumulate damage during their service life or can suffer a sudden damage due to natural disasters. So, an important issue is the detection of the structural damage since if the damage remains undetected the structure may have a reduced margin of safety. Formerly, the traditional procedure for evaluating the structural integrity was through visual inspections, and most recently, by means of destructive or forced vibration methods. Nowadays, numerous studies on damage detection use non-destructive evaluation methods such as Structural Health Monitoring (SHM) which can be conducted by means of ambient vibration through a sensor network that monitor the behaviour of the structures while they are in service, in order to extract information about displacement, velocity and acceleration from them. Commercially, there are a wide variety of seismic acquisition equipments but they are relatively expensive, which could restrict the number of stations that can be deployed simultaneously. However, the prices and accesibility to electronic components have helped to develop systems at low prices where geophones and accelerometers are the most widely used sensors. Thus, different research groups develop their own equipments. For instance, J.L. Soler-Llorens et al. [1] showed a low cost Arduino-based seismic recorder by means of vertical geophones and tested the system by comparing the registered signals with the ones obtained through different comercial data recording systems and different kind of geophones. In order to test the system, a sine wave was used as input signal where a function generator provided this input; S. Valenti et al. [2] proposed a low cost wireless sensor node for building monitoring by means of accelerometers where the performance of the sensor was evaluated through comparison of results, in terms of modal frequencies and displacements, with those of a typical wired system using the Tower of the Engineering Faculty of the Università Politecnica delle Marche as demo structure.

This paper presents a low-cost Arduino-based horizontal sensor and data acquisition system to record low-level ambient vibration measurements with the following specifications (Fig.1):

- Electronic devices with very low power consumption.
- High sensitivity.
- Price of the sensor, amplifiers, filter, analog to digital converter and Arduino UNO board in their standard configuration is below 100 €.

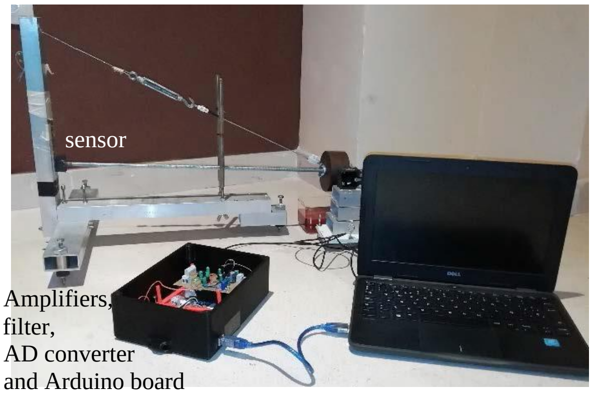

Figure 1: Proposed system.

The general design and the validation test of the system are reported in the paper to demonstrate its functionality. In order to validate it, two field tests have been conducted with ambient vibration comparing signals recorded by the proposed system with those obtained by a commercial high-precision and high-sensitivity seismograph. The outcome of those tests has shown the suitability of the proposed system to acquire and record low-levels signals and has also highlighted some of the limitations and areas for improvement of this proposal.

2 DESCRIPTION OF THE PROPOSED SYSTEM

The proposed system consists of four different parts: a) sensor; b) amplifiers, c) digital converter; and d) a microcontroller. This modular design allows more flexibility for future modifications (Fig.2).

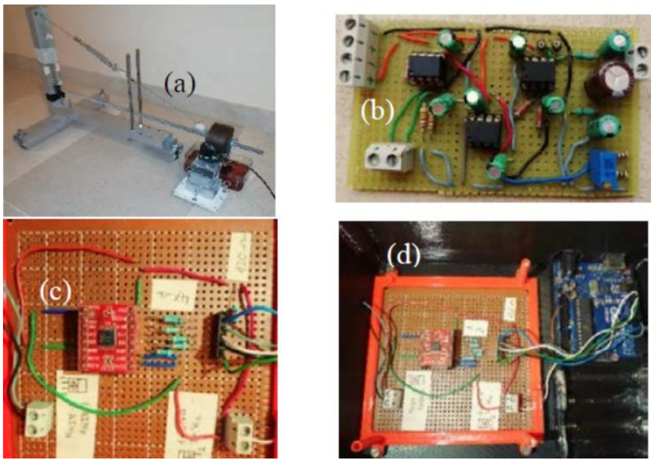

Figure 2: Components of the proposed system: (a) sensor (b) amplifiers and filter for signal conditioning (c) analog-to-digital converter (d) analog-to-digital converter connected to Arduino board microcontroller.

2.1. Sensor

A sensor is an instrument that measures the displacement of a vibrating body. The simplest type of sensor can be illustrated by a mass-spring-damper single-degree-of-freedom (SDOF) system mounted inside a box that is attached to the surface whose motion is to be measured, as shown in Fig. 3. The mass is connected to the box by a spring and a damper, while the box is attached to the ground. Since the spring and the damper are not rigid, the motion of the mass will be different to the motion of the ground. The relative motion between the mass and the box will relate to motion of the ground.

Thus, as illustrated in Fig. 3, the points 1 and 2 of the spring and damper, respectively, will have the same motion as the box (which is to be measured, x_g) and their vibration excites the mass into motion.

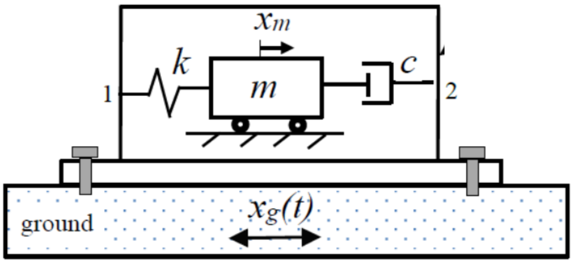

Figure 3: Simple mass-spring-damper sensor to record horizontal motions.

Being the displacement of the mass relative to the box $x=x_m-x_g$, where x_m denotes the horizontal displacement of the mass, the equation of motion of the mass m can be written as [3]:

$$m\ddot{x}_m + c(\dot{x}_m - \dot{x}_g) + k(x_m - x_g) = 0 \qquad (1)$$

As mentioned above,

$$x = x_m - x_g \qquad (2)$$

So, Eq. (1) can be written as

$$m\ddot{x} + c\dot{x} + kx = -m\ddot{x}_g(t) \qquad (3)$$

If we assume the motion x_g to be harmonic,

$$x_g(t) = X_g(\omega)\sin(\omega t) \qquad (4)$$

Here ω is the circular frequency and $X_g(\omega)$ is the amplitude of the base displacement. Thus, Eq. (3) becomes

$$m\ddot{x} + c\dot{x} + kx = m\omega^2 X_g(\omega)\sin(\omega t) \qquad (5)$$

The particular solution of Eq. (5) is also harmonic; we assume the solution $x_p(t)$

$$x_p(t) = X(\omega)\sin(\omega t - \phi) \qquad (6)$$

Where $X(\omega)$ and ϕ, amplitude and phase angle of the response, respectively, are constants to be determined. By substituting Eq. (6) into Eq. (5), we arrive at

$$X(\omega)[(k - m\omega^2)\sin(\omega t - \phi) + c\omega\cos(\omega t - \phi)] = m\omega^2 X_g(\omega)\sin(\omega t - \phi) \quad (7)$$

Using the trigonometric relations in Eq. (7)

$$\cos(\omega t - \phi) = \cos(\omega t)\cos(\phi) + \sin(\omega t)\sin(\phi)$$
$$\sin(\omega t - \phi) = \sin(\omega t)\cos(\phi) - \cos(\omega t)\sin(\phi) \quad (8)$$

And equating the coefficients of *cos*(*ωt*) and *sin*(*ωt*) we obtain:

$$X(\omega)[(k - m\omega^2)\cos(\phi) + c\omega\sin(\phi)] = m\omega^2 X_g(\omega)$$
$$X(\omega)[-(k - m\omega^2)\sin(\phi) + c\omega\cos(\phi)] = 0 \quad (9)$$

Solution of Eq. (9) gives:

$$\phi = \tan^{-1}\left(\frac{c\omega}{k - m\omega^2}\right) \quad (10)$$
$$\frac{X(\omega)}{X_g(\omega)} = \frac{m\omega^2}{\sqrt{(k - m\omega^2) + (c\omega)^2}} \quad (11)$$

Eq. (10) and Eq. (11) can be expressed in a different form by introducing the notation

$$\omega_n = \sqrt{\frac{k}{m}} \quad (12)$$
$$\xi = \frac{c}{2m\omega_n} \quad (13)$$
$$r = \frac{\omega}{\omega_n} \quad (14)$$

Where ω_n is the undamped natural circular frequency, ξ is the damping ratio and r is the frequency ratio. Thus, Eq. (10) and Eq. (11), can be rewritten as

$$\phi = \tan^{-1}\left(\frac{2\xi r}{1 - r^2}\right) \quad (15)$$
$$\frac{X(\omega)}{X_g(\omega)} = \frac{r^2}{\sqrt{(1 - r^2) + (2\xi r)^2}} \quad (16)$$

Hence, when $r \to \infty$, Eq. (16) becomes

$$\lim_{r\to\infty}\frac{X(\omega)}{X_g(\omega)} = \frac{r^2}{\sqrt{(1 - r^2) + (2\xi r)^2}} \approx 1 \quad (17)$$

So, according to Eq. (17), for larger values of r, the relative displacement (X) and the base displacement (X_g) have the same amplitude. Therefore, in order to satisfy Eq. (17), the natural frequency of the sensor must be low compared to that vibration to be measured.

The variations of X/X_g with respect to r are shown in Fig. 4 for different values of ξ. As can be seen, the damping ratio does not need to be present to satisfy Eq. (17), but its presence will improve the range of application of the instrument. For example, for ξ=0,7, *X*(ω)≅*Y*(ω) if r is greater than 2.

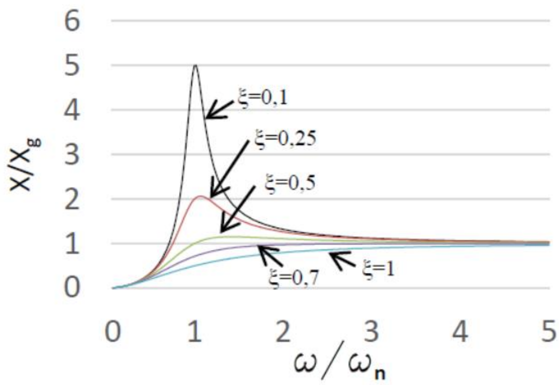

Figure 4: Response of a vibration-measuring instrument.

The device proposed here is based on the Lehman pendulum, sometimes also called the Garden Gate configuration, is a horizontal pendulum which is based on a system slightly tilted from horizontal where the mass of the system tends to remain suspended. When the ground moves, due to the vibrations caused by any excitation, the suspended mass of the system remains stationary, so we can directly measure the relative motion between the ground and the suspended mass by a coil which converts that movement into a little current [4].

The sensor structure is made of extruded aluminum rectangle (5 cm x 2,5 cm) with two horizontal bars and one vertical bar joined between them by means of nuts and bolts. Fig. 5 shows a sensor structure picture, and the top, left side and front views of the structure.

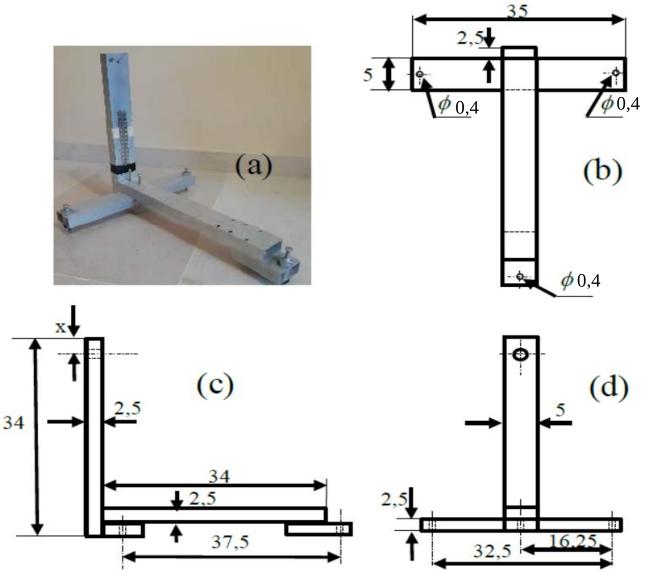

Figure 5: a) Sensor structure picture; b) Top, c) left side and d) front structure views (all dimensions in cm).

Fig. 6 presents a picture of the sensor. The movable arm (40 cm length) rests on a knife edge which is held against the vertical bar [5]. The knife edge is a very important part of the system since it avoids movable arm torsional oscillations. The other side of the movable arm, where it can swing freely, is hold up by a cable brake which is attached to the top of the vertical bar [6]. In this side, it can be seen the mass joined to the movable arm whose weight is 1,65 kg. In order to convert sensor structure movement into a little current, a neodymium magnet has been mounted on the mass (Fig. 7.a).

The oscillations of the movable arm must be damped. There are different damping techniques, but in this work, the damping is obtained by means of two fins which are immersed in a tray filled (Fig. 7.b) with monograde diesel engine oil (SAE 30) insomuch as it is easier to control and to adjust than magnetic damping.

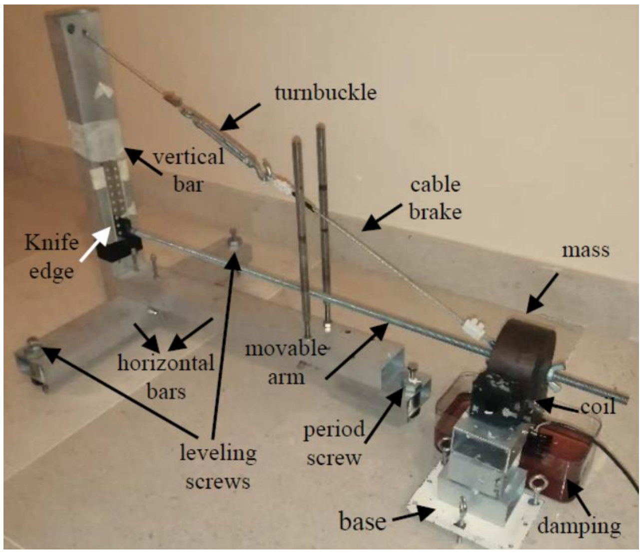

Figure 6: Proposed sensor.

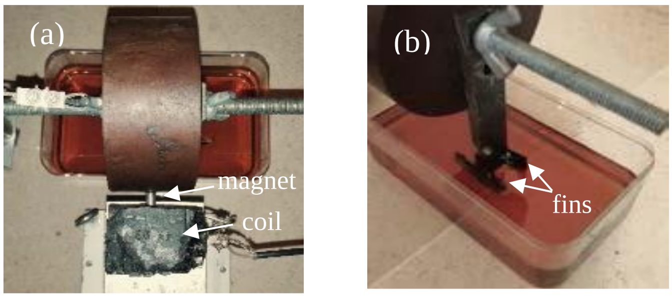

Figure 7: a) Coil mounted on the mass and magnet position. b) Fins immersed in a tray filled with monograde diesel engine oil.

On the other hand, the pickup coil has been mounted on a base which is independent from the sensor structure. When the ground moves, the sensor structure and the pickup coil move at the same time while the mass remains stationary. In this way, the relative motion between the magnet (mounted on the inertial mass) and the coil induces a small voltage in the coil which will be amplified and filtered.

One of the most important parts of the sensor are the screws. We can difference two screws types: Leveling and period screws. The two leveling screws have the purpose of leveling the movable arm while the period screw allows the adjustment of the movable arm inclination; this inclination gives us the sensor natural cyclic frequency (see section 2.1.1.). Periods of up to 6 to 8 seconds (equivalent to 0,12 Hz and 0,17 Hz), have been achieved, which allows to measure vibrations in structures with very low natural frequencies.

2.1.1. Sensor mathematical model

In order to obtain the sensor natural circular frequency and damping ratio, it will be considered the sensor showed in Fig.8

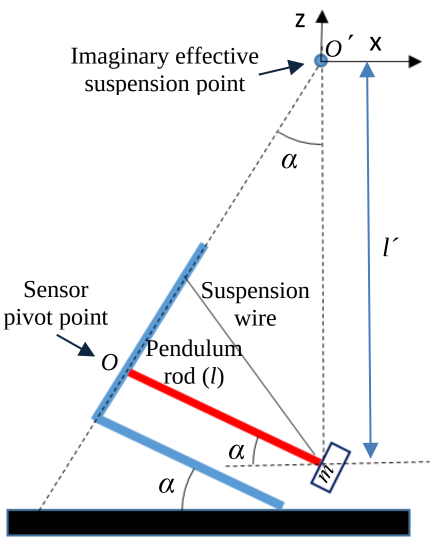

Figure 8: Schema of the sensor with angle of tilt (α) exaggerated [4].

The sensor is a horizontal pendulum which consists of a mass *m* swinging at the end of a rigid massless rod pivoted at point *O* with a length *l*; *l´* is the effective pendulum length of a simple pendulum.

In Fig.9.a, the pendulum is in its equilibrium position; when the mass is displaced a small angle from its equilibrium position and released, a restoring forces appear (Fig.9.b), being $\overrightarrow{f_d} = -c \cdot \vec{v}$ the damping force which is acting at the end of the rigid massless rod (with $v = l' \cdot \dot{\theta}'$, tangencial component of the velocity of the mass *m*); a_t is the tangential component of the acceleration of the mass *m* ($a_t = l' \cdot \ddot{\theta}'$). Taking sum of moments respect to *O´*:

$$-mg\sin(\theta')\,l' - c\dot{\theta}'l'l' = m\ddot{\theta}l'l' \qquad (18)$$

The motion can be considered as a simple harmonic motion since *θ'* is small, and we can say that sin(*θ´*) ≈ *θ´*. Operating with Eq. (18) we have:

$$\ddot{\theta}' + \frac{c}{m} \cdot \dot{\theta}' + \frac{g}{l'} \cdot \theta = 0 \qquad (19)$$

From the Fig. 8 we can obtain sin (*α*) = *l*/ *l´*, and from Fig. 9.b we can get the relation *θ´*=*θ·l/l´*, thus, operating with (19) we get:

$$\ddot{\theta} + \frac{c}{m} \cdot \dot{\theta} + \frac{g}{l} \cdot \sin\alpha \cdot \theta = 0 \qquad (20)$$

Where Eq. (20) is the equation governing the free motion of the Lehman pendulum.

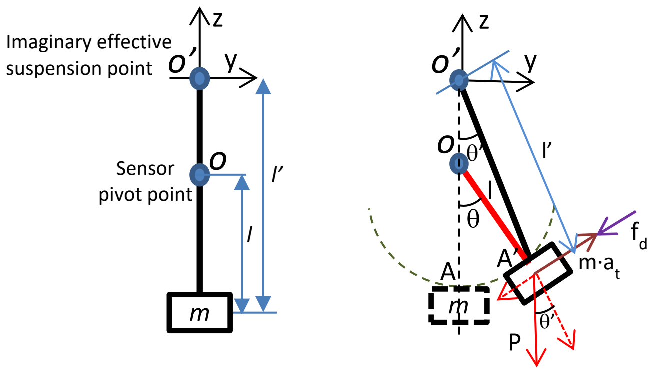

Figure 9: Pendulum from y-z plane: (a) equilibrium position (b) mass displaced a small angle θ´.

The sensor undamped natural circular frequency will be obtained from Eq. (20) when *c*=0, so:

$$\ddot{\theta} + \frac{g}{l} \cdot \sin\alpha \cdot \theta = 0 \qquad (21)$$

The solution of the linear, homogeneous, second-order differential equation with constant coefficients, Eq. (21), has the form $\theta = e^{\lambda t}$, thus, substituting into Eq. (21) yields:

$$\lambda^2 + \frac{g}{l} \cdot \sin\alpha = 0; \ \lambda_{1,2} = \pm i\omega_n \qquad (22)$$

Where ω_n is: $\omega_n = \sqrt{\frac{g}{l} \sin\alpha}$ (23)

Thus, the differential equation of motion, Eq. (20), upon rearrangement and simplification, taking account Eq. (13), becomes:

$$\ddot{\theta} + 2\xi\omega_n\dot{\theta} + \omega_n{}^2\theta = 0 \qquad (24)$$

Thereby, in according Eq. (23), the resonance frequency in a Lehman pendulum depends on the length of the movable arm and the angle of the structure (α) with respect to the horizontal plane. As can be seen in the spectra from Fig. 19 to Fig. 24, one frequency component, or peak, is highlighted in blue rectangle, being located between 0,12 Hz and 0,17 Hz; this peak corresponds to the sensor natural frequency in each measure (using a movable arm 40 cm length).

2.2. Amplifiers and filter for signal conditioning

This part of the proposed system is formed by four stages (Fig.10): 1) a precision instrumentation amplifier; 2) an offset adjustment circuit; 3) an operational amplifier; and 4) an analog input filter; these four stages are powered with the same dual supplies, at least ±3.0 V, using external batteries.

2.2.1. Precision instrumentation amplifier

The small signal induced in the pickup coil by the movement, proportional to ground velocity, is amplified using an instrumentation amplifier (Fig.10 – label 1 or Fig.11) which provides an amplified output signal (Vo) with a single external resistor. The INA 114, which is a low cost, general purpose instrumentation

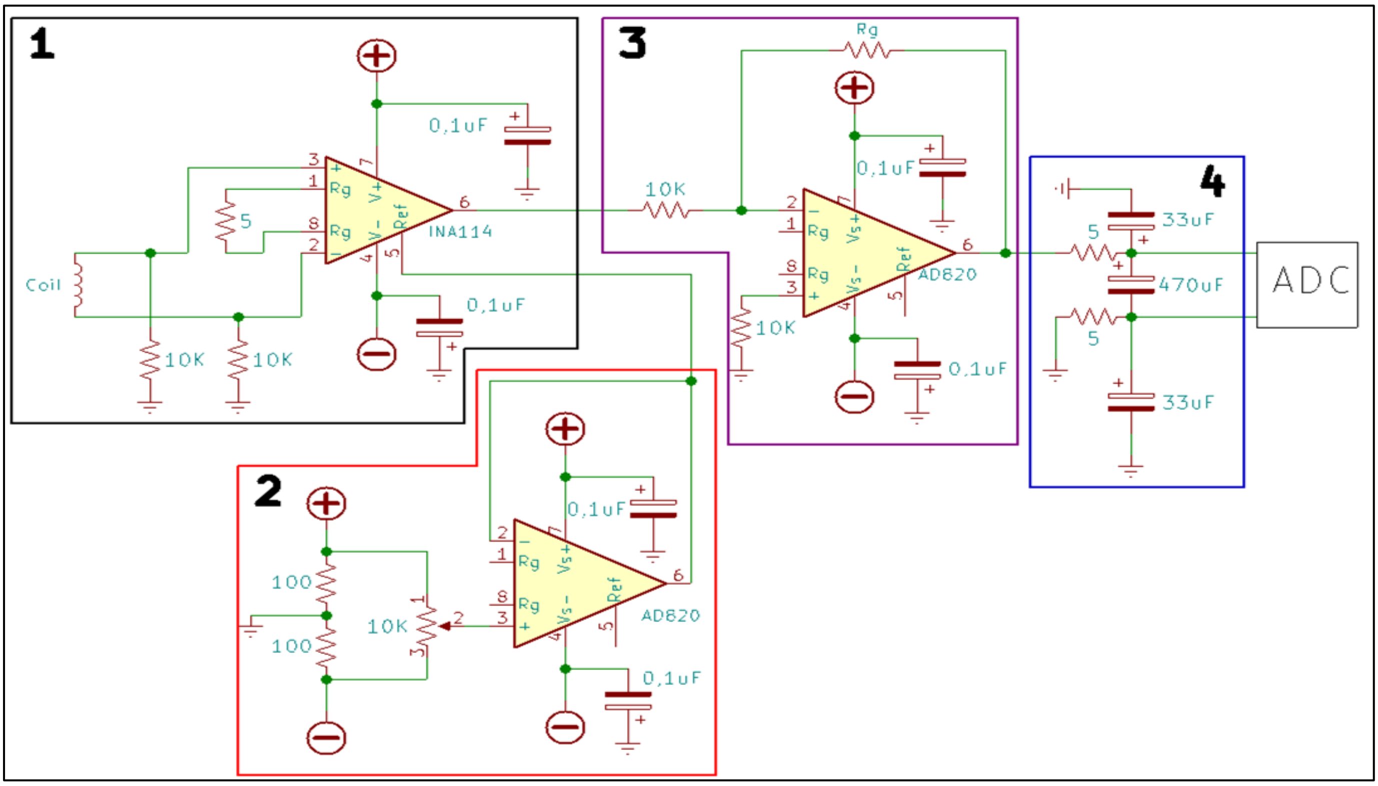

Figure 10: Electronic scheme for signal conditioning.

amplifier offering excellent accuracy and providing very low noise, has been selected. The single external resistor (R_G) sets any gain from 1 to 10000 [7]; the gain is obtained by using the equation:

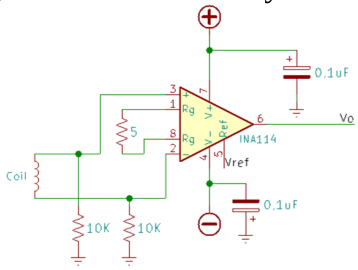

Figure 11: Precision instrumentation amplifier.

$$G = 1 + {}^{50\,K\Omega}/_{R_G} \qquad (25)$$

We have used a resistor of 5 Ω obtaining a gain of 10000 V/V, approximately. The output (V_o) is referred to the output reference (Ref) terminal which is grounded through the offset adjustment circuit.

2.2.2. Offset adjustment circuit

The offset voltage will be trimmed with the circuit shown in Fig. 10 – label 2 or Fig.12. The voltage applied to Ref terminal is summed at the output.

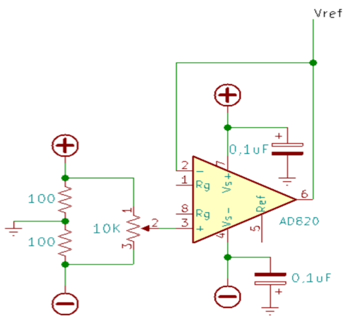

Figure 12: Offset adjustment circuit.

2.2.3. Operational amplifier

Then, a second amplification is carried out. The output signal from INA114 (*Vo*) is amplified by an operational amplifier (Fig. 10 – label 3) being given the circuit gain by the relationship:

$$G' = R'/10K \qquad (26)$$

This gain is set means of *R´*. The AD820, which is a precision, low power FET input op amp that can operate from a single supply of 5 V to 36 V, or dual supplies of ±2,5 V to ±18 V, has been chosen. In the AD820, N-channel JFETs are used to provide a low offset, low noise, high impedance input stage [8].

2.2.4. Analog Input filter

Analog input filtering serves three purposes: first, to limit the effect of aliasing during the sampling process, second, to reduce external noise from being a part of the measurement and third, to filter high frequency signals; therefore, a low pass resistor-capacitor (RC) filter will be placed at the input of the analog to digital converter for improve performance (Fig. 13). R_1/R_2 and C_1/C_2 form a bridge circuit so any mismatch between C_1 and C_2 will unbalance the bridge and reduce common-mode rejection; to avoid it, a differential input capacitor, C_{dif}, is placed, which mitigates the effects of mismatch in C_1 and C_2, being the effect of mismatched reduced with a larger C_{dif} ($C_{dif} \geq 10 \cdot C_1$, $C_1 = C_2$) [9].

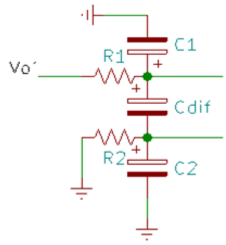

Figure 13: Low pass RC filter.

Considering that the frequencies we are interested in are under 10 Hz, the cutoff frequency has been configured to approximately 35 Hz, therefore, by applying (27) it results a C_{dif} of 470 µF, and we can select a C_1(=C_2) of 33 µF (Fig.10 – label 4 or Fig. 14). This output signal will be directly connected to the analog to digital converter.

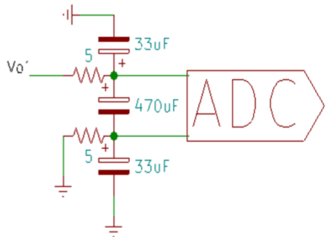

Figure 14: Analog Input filter.

$$f_{cutoff} = [2\pi(R_1+R_2)\cdot C_{dif}] \qquad (27)$$

2.3. Analog-to-digital converter

Then, after the process of amplification and filtering, the signal will be connected to the analog-to-digital converter (ADC). In this system, we have selected the ADS1220 analog-to-digital converter, which is a precision, 24-bit, that offers many integrated features to reduce system cost and component count in applications measuring small sensor signals, with a wide supply range (2,3V to 5,5V). Moreover, the device features a low-noise, low-drift, high input impedance and programmable gain amplifier which is changed inside the device using a variable resistor [9]. In this case, we have selected a gain of 128 obtaining a full-scale input voltage of ±0,016V. The ADC operates with a single power supply provided through the 3,3V pin of the Arduino UNO. The principle serial interface connections for the ADS1220 are shown in Fig.15. It is important to remark that deviations in the internal clock of the ADS1220 of around 2% where found during the tests.

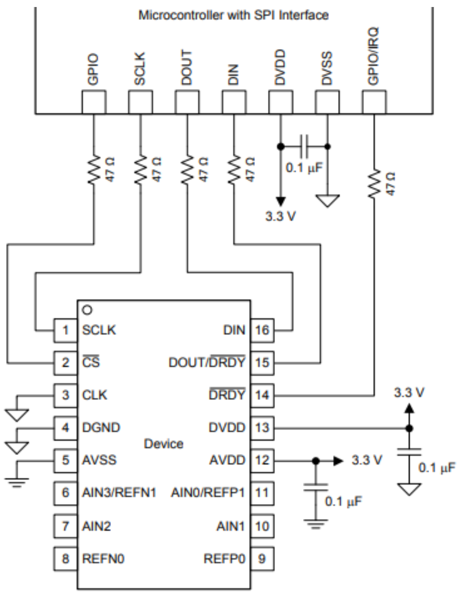

Figure 15: Serial Interface Connections [9]

2.4. Microcontroller

The Arduino Uno board has been used for commanding the analog-to-digital converter, process the information, and send the data to a computer through the USB port. The Arduino Uno is an open-source microcontroller board based on the Microchip ATmega 328P microcontroller and developed by Arduino.cc. The board is equipped with sets of digital and analog input/output (I/O) pins that may be interfaced to various expansion boards (shields) and other circuits. The arduino code is not presented herein due to space restrictions, but will be readily provided upon request to the authors by e-mail.

3 MATERIALS COST

Table 1 presents a list of materials and approximate costs at the time of assembly of the prototype. The total material cost lies below 100 €.

	Unit	Unit cost	**Cost**
Sensor parts			
Extruded aluminiun (structure)	2 m	5,00 €/m	10,00 €
Mass	1,65 kg	2,50 €/kg	4,12 €
Turnbuckle	1	2,50 €	2,50 €
Screws	1 pack	1,50 €	1,50 €
Movable arm	1	1,50 €	1,50 €
Cable brake	1	1,00 €	1,00 €
Magnet (neodymium)	1 pack	4,60 €	4,60 €
Amplifiers and digital converter			
Resistors, capacitors, potenciometer and hook up wires			4,00 €
INA 114 (Instrumentation amplifier)	1	12,00 €	12,00 €
AD820 (Operational amplifier)	2	8,00 €	16,00 €
ADS1220 (analog-to-digital converter)	1	12,00 €	12,00 €
External batteries – AA, 1,5 V	4	0,50 €	2,00 €
Arduino UNO.	1	11,00 €	11,00 €
	TOTAL COST		**82,22 €**

Table 1: Materials cost.

4 EXPERIMENTAL VIBRATION TESTS AND ANALYSIS OF THE RESULTS

In order to test the behavior of the proposed low-cost acquisition system, this section presents comparison results between this acquisition system with the ones obtained by a commercial seismograph; the commercial seismograph used is Tromino® by MoHo s.r.l., which is a high-resolution all-in-one system for passive and active seismic surveys and vibration monitoring.

Two different campaigns have been carried out in the Island of Gran Canaria (Canary Island-Spain) conducted only with ambient vibration where the systems were configured with the following characteristics:

	First campaign	Second campaign
Recording time	15 min	15 min
Tromino ® - Sampling frequency	128 Hz	512 Hz
Lehman - Sampling frequency	88,2 Hz	88,2 Hz

Table 2: Systems configuration.

The first campaign took place on June 20th 2019. The seismographs were installed on the third floor of a five-storey building located in Las Palmas city where the distribution of the measurement points is shown in Fig. 16. The data acquisition systems were installed at the same place but the measurements were carried out at different times with a difference of 30 minutes between one and the other.

The second campaign was carried out in a dam, called Soria dam, located in the south of the Island and it took place on June 27th 2019. The distribution of the measurement points is shown in Fig.17. The proposed system has been protected from wind using a box (Fig.18). The proposed system and the data acquisition systems were installed close to each other so the measurements were carried out at the same time.

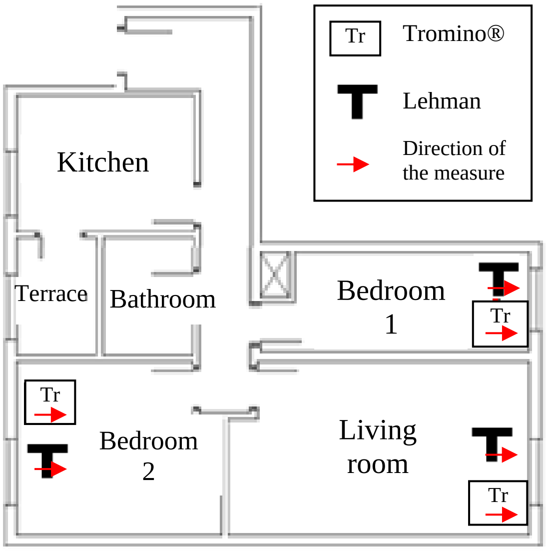

Figure 16: House plan. First campaign.

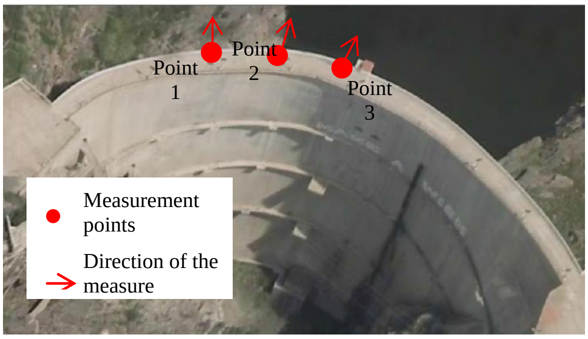

Figure 17: Soria dam. Second campaign.

Fig.18: (a) Proposed system inside the box (b) Proposed system box and Tromino®.

Figures 19 to 21, and Figues 22 to 24, present the Power Spectral Density plots corresponding to the signals recorded at the building and the dam respectively. We can observe a very good agreement between the two systems, in terms of both frequency and amplitude, being the frequencies from both devices very close with a maximum divergence of 0,06 Hz which contributes to validate the proposed system.

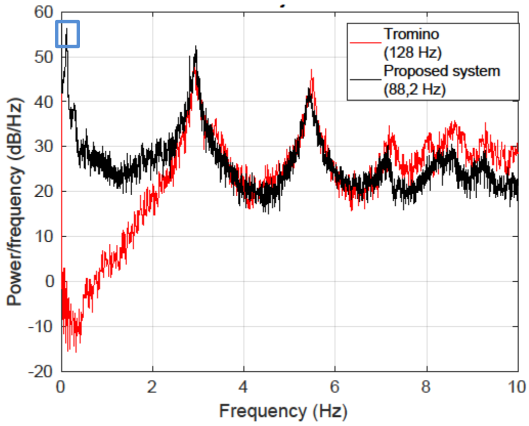

Fig.19: PSD of the recording. Bedroom 1.

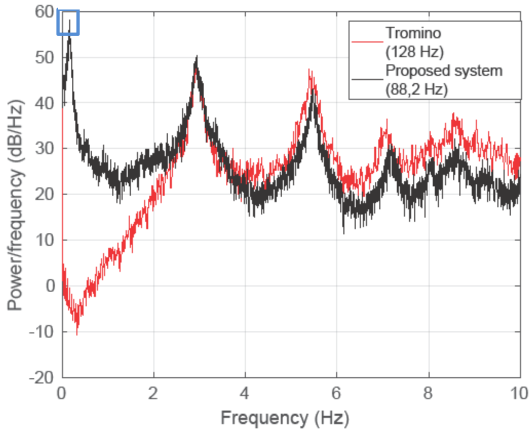

Fig.20: PSD of the recording. Living room.

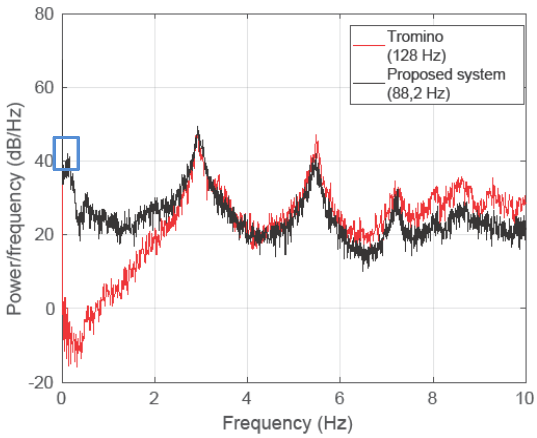

Fig.21: PSD of the recording. Bedroom 2.

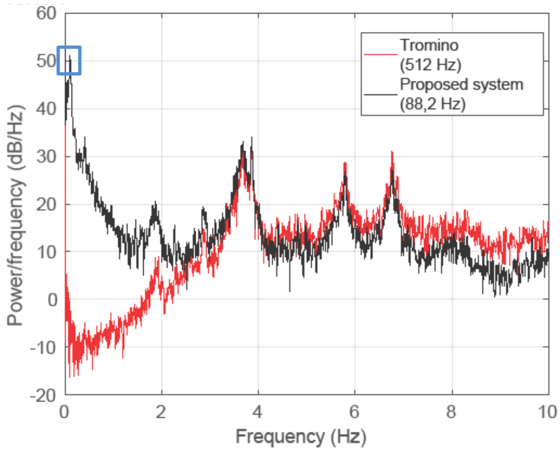

Fig.22: PSD of the recording. Dam, point 1.

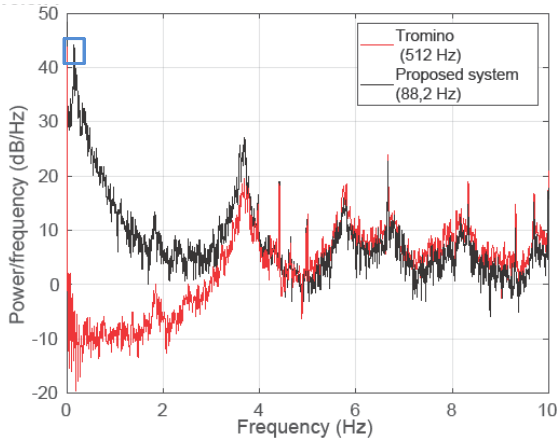

Fig.23: PSD of the recording. Dam, point 2.

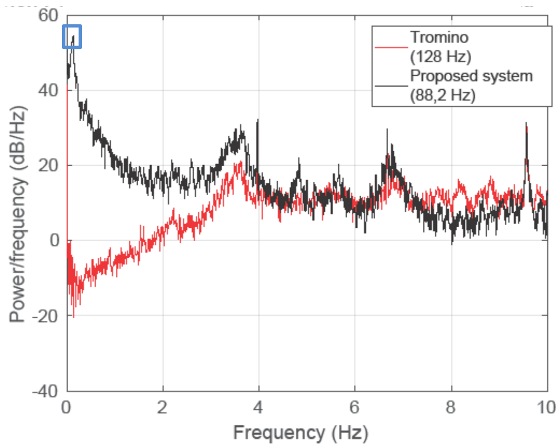

Fig.24: PSD of the recording. Dam, point 3.

5 CONCLUSIONS

This paper presents the design and preliminary results of a low-cost arduino-based prototype system for measurement of structural low-level vibrations. The cost of the proposed system is below 100 €. In order to test the accuracy of the design, two in situ tests were conducted for field validation of the system where the data obtained with the proposed system were compared with data recorded by commercial seismograph (Tromino®). The results obtained from these experiments surpassed our expectations: the match in terms of frequency response is very high, and the sensitivity of the device is also really good. On the other hand, the device present several important drawbacks: the time needed for the set-up (as it must be disassembled for transportation), its sensitivity to wind and its size and weight. There are also some areas that would need improvement and/or further developement, especially the calibration and reproducibility in terms of amplitude of the measured vibrations.

All in all, the proposal can be used as a basis to teach, learn, measure vibrations and develop other types of devices for this purpose.

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REFERENCES

[1] J. L. Soler-Llorens, J. J. Galiana-Merino, J. Giner-Caturla, P. Jauregui-Eslava, S. Rosa-Cintas, J.Rosa-Herranz. *Development and programming of Geophonino: A low cost Arduino-based seismic recorder for vertical geophones*. Computers & Geosciences. Volume 94, Pages 1-10, September 2016.

[2] S. Valenti, M. Conti, P. Pierleoni, L. Zappelli, A. Belli, F. Gara, S. Carbonari, and M. Regni. *A low cost wireless sensor node for building monitoring*. Environmental, Energy, and Structural Monitoring Systems, Proceedings, art. no. 8405827, Pages 1-6, 2018.

[3] Singiresu S. Rao. *Mechanical vibrations* (fifth edition). Addison-Wesley Publishing Company, 2011.

[4] Paul Denton. *Building a simple seismometer*. British Geological Survey. Natural environment research council.

[5] Knight K. "Instructions for construction of a Lehman Seismometer", Redwood city public seismic network (http://www.seismicnet.com/lehman.html) , 2000

[6] Bernd Ulmann. *Grundlagen und Selbstbau geophysikalischer Meßinstrumente*, Der Andere Verlag, 2004 (also in http://www.vaxman.de/projects/lehman_seismometer/seismometer.html)

[7] Burr-Brown Corporation; INA 114. Precision instrumentation amplifier. Technical datasheet printed in U.S.A., March, 1998.

[8] Analog devices; AD 820. Single-Supply, Rail-to-Rail, Low Power, FET Input Operational Amplifier.

[9] Texas Instruments; ADS1220. 4-Channel, 2-kSPS, Low-Power, 24-Bit ADC with Integrated PGA and Reference. Technical datasheet revised august 2016.