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Design and Validation of an Accurate Low-Cost Data Acquisition System for Structural Health Monitoring of a Pedestrian Bridge

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Abstract: Structural health monitoring (SHM) is an effective operating technique devoted to enhance the robustness of an infrastructure, and to validate its safety requirements. The aim of SHM is to determine a structure's reaction when subjected to any type of excitation, by means of identifying modifications in basic vibration measurements and modal parameters such as natural frequencies, damping and mode shapes. Consequently, sensors are mounted on a structure intending to record data on equal time intervals basis prior to, during and after an induced stimulation. Therefore, the necessity to adopt a computer-based data acquisition (DAQ) technique is required in this analytical approach in order to evaluate vibrational signals collected by sensors placed on a structure. In this work an accurate microcontroller-based DAQ system is proposed to monitor a pedestrian bridge located in Athens Greece for the purpose of characterizing the system state and evaluate the modal properties of the investigated structure. Four low-cost yet accurate triaxial accelerometers were systematically placed along the bridge intending to report the system response toward different generated perturbations. The proposed monitoring and computational system was tested in laboratory conditions prior to the bridge assessment. Three triaxial accelerometer were installed on a steel cantilever beam. A comparative analysis between the results of the suggested DAQ system and that of the standard laboratory DAQ system National Instrument DAQ was performed to test the accuracy of the suggested framework.
Keywords: Structural health monitoring; Damping; Eigenfrequency; Mode shape; Pedestrian bridge; Data acquisition system; Microcontroller.

1. Introduction

Structural health monitoring (SHM) is an effective operating technique devoted to enhance the robustness of an infrastructure by assessing its health condition, and to validate its safety requirements by detecting anomalies and damages. Consequently, the necessity to adopt structural assessment approaches in the civil engineering field is considered crucial in order to investigate the structural aspect and identify suspicious deterioration seeking the infrastructure sustainability for future innovation [1-2].

These techniques are classified as static and dynamic assessment. Static monitoring is a nonstop recording for a considerable time span, with the evaluation of slow-changing factors [3]. Makoond et al., in 2020's work describes a data evaluation approach for static health monitoring using dynamic linear regression approach. As it aims to continuously assess critical low-varying measurements that may endanger the safety of masonry historic constructions. The approach effectively detected degradation parameters in Mallorca's cathedral and the monastery of Sant Cugat located in Spain [4]. Whereas Dynamic monitoring is adopted to quantify and assess the system dynamic properties. [5-10]

The aim of SHM is to determine a structure's reaction when subjected to any type of excitation or a seismic activity, by means of identifying modifications in basic vibration measurements and modal parameters. Natural frequencies, damping and mode shapes are considered the most important modal parameters to evaluate in order characterize the system state [11-12]. Therefore, evaluating the dynamic behavior of a structure requires the employment of modal analysis. [13-18]. Accordingly, Operational Modal analysis [OMA] in a structure's health monitoring is implemented to identify changes in vibrational system measurements [19-21]. This technique is adopted to convert the recorded oscillation waveform of a perturbated structural framework into measurements that can be easily evaluated.

Hence, sensors are mounted on a structure intending to record data on equal time intervals basis prior to, during and after an induced stimulation, characterizing any skeptical response threatening the safety of the structure and assessing the ongoing system state [22].

When a structure is excited by a constant force with variation in the frequency of the applied loading, it performs an intensified reaction as the vibration rate of the exerted force approaches its natural frequency, to attain an ultimate response when the rate is equivalent to the system's natural frequency. Dynamic vibrations can be represented either in time domain or in frequency domain [23]. Sensors employed on the structure reports the amplitude of the reaction in time domain. Fast Fourier Transform function is computed in the reported time data to calculate the frequency domain in order to identify the dynamic parameters. It is observed that spikes in frequency domain correspond to the structure's natural frequencies [24]. There is a minimum of one inherent natural frequency in every structure. At each resonant frequencies, the system deforms in distinct patterns. It is known as mode shapes [25].

Damping properties detection is considered to be an important component in SHM [26]. However, unlike eigenfrequencies and mode shapes, it is considered critic to define and requires considerable effort due to its relevance in anticipation and managing the response to dynamic loading that a structure is subjected to [27-29]. The difficulty in calculating damping derives from its fundamentals, since this parameter estimates the energy dissipation from an unconfined system known as radiation damping and evaluate the hysteretic performance of a matter subjected to nonlinear stress known as material damping [30]. Damping is the rate of progressive release of the oscillation energy, a structure holds after getting stimulated, leading to a decrease of a non-restricted vibration amplitude [25].

Considering the fast development and the ease of operating programming software, identifying modal parameters in terms of eigen frequencies, mode shapes, and damping has become effortlessly accessible after recording acceleration data in function of time [31]. Distance measurement calculation were operated previously to evaluate damped harmonic oscillation under laboratory condition [32]. However, collecting displacement data to compute velocity after first derivation, then acceleration after the second, creates unfavorable noise. Therefore, accelerometer sensors are more favorable to consume for the noise and evaluate accurate results.

A predefined sensor network collects frequent readings of a structure questioning its present health status doubting the existence of unusual behavior, fundamental damage, or dangerous condition [33]. Hinrinchsen (2019) adopted MEMS accelerometers to record acceleration for immediate and precise monitoring. Integrations were performed to calculate velocity and displacement in order to assess the damped oscillation of a glider with a magnet on an air track [34]. Bongiovanni et al., (2021) exerted a vibration assessment in ambient condition on the Marcus Aurelius Column, located in Rome. Seismometers were implemented to record the vibration of the column to calculate the eigenfrequencies, displacement, as well as damping. The results were acceptable with a 1% damping at the tip of the column and a maximum displacement of 0.1mm with two eigenfrequencies of 1.26 and 1.33Hz [35]. In order to depreciate the noise impact and improve the efficacity in calculating damping properties, Wang et al., (2018) proposed a technique that relies on the "Principal Component Analysis" approach. The acceleration response of a planar truss and a planar frame were recorded, and damping was derived from the motion equation of a damped linear framework [36].

In this research, the main focus was on the dynamic monitoring. Therefore, the necessity to adopt a computer-based data acquisition (DAQ) framework is required in this analytical approach in order to evaluate vibrational signals collected by accelerometers placed on a structure. DAQ systems incorporate collecting and evaluating either electrical or physical occurrence through the employment of an operational controller [37]. An entire DAQ system comprise sensors to collect data, and convert it from physical values to electric waveform. An acquisition hardware component based on digital computer [38] to process the recorded signal and encodes it from signal to numerical data. And a server to receive the data and calculate the output through a programming software such as MATLAB and LabVIEW.

Commercial DAQ solutions are developed with high accuracy, but are not customized to meet the needs of the consumer besides, they are considered to be expensive [39]. The increased usage of microcontrollers managing open-source hardware projects as Teensy and Arduino has created additional possibilities for researchers to develop and design their own analytical software for data processing with high accuracy and for a limited budget. Munoz et al., (2021) proposed a microcontroller based DAQ framework for continuous monitoring of a hydroelectric dam. The microcontroller dsPIC33EP256MC [40] was connecting MEMS accelerometer to a single board computer Raspberry Pi 3[41], integrated with Linux operating system. Seismic motion was detected in both longitudinal and horizontal directions and compared with the results of a validated accelerograph component showing a difference of 19% in the first and 15% in the second direction [42]. Nuhu et al., (2021) integrated a new DAQ system that incorporates using temperature and vibration readings with integrating fuzzy interference using WSN, to assess the health of a residential structure on a long-term basis. The framework is composed of a piezo vibration along with LM35 sensors connected to Arduino Nano microcontroller where data is analyzed. Laboratory experiment showed high accuracy but the operational efficiency was decreasing to reach near to 50% after a 10-year experiment use [43]. Prasath et al., (2018) designed a DAQ that delivers the records through WIFI as a wireless data network, deployed in industrial fields as gas and power plant. Data collected by gas and temperature sensors was processed by an ARM 9 Mini 2440 [44] processors, where analog signal was converted by the implementation of ADC to modify recorded data to digital value. Then monitored by a single board PC through WIFI unit [45]. Barsocchi et al., (2021) introduced and evaluated an assessment framework that comprised a ST Microelectronics STM32F4 microcontroller to process and send the measurements of MEMS accelerometers, displacement transducers and environmental sensors integrated by a wireless connection, to remote server. The topology of the sensors arrangement system was suggested for long-term monitoring in order to monitor a masonry, Matilde Tower [46]. Hercog and Gergič (2014) described in their study an inexpensive DAQ system based on a microcontroller, a Microchip PIC18F27J53 microcontroller. The designed framework was programmed to allow a simple data collecting technique from a MCP9701A temperature sensor [47]. LabView software has been built to analyze the collected data showing a sinewave of the voltage-time diagram of a frequency of 100Hz [37].

This work proposes an accurate microcontroller-based DAQ system to monitor a pedestrian bridge located in Athens, Greece for the purpose of characterizing the system state and evaluate the modal properties of the investigated structure. Four low-cost yet accurate triaxial BDI accelerometers were systematically placed along the bridge with a predefined sensor placement scheme deemed as the optimal sensors placement intending to report the system response toward different generated perturbations.

The evolution that has occur to bridge construction and the improvement in assessing its conditions and analyzing its status lays in monitoring its behavior from construction phase till maintenance [48]. During a bridge's tenure, a number of critical challenges and serious difficulties may immerge. Consequently, bridge health monitoring is taking on a great significance not only to assess and anticipate the system state and modal properties but also to predetermine any harm that may occur to the structure by validating its safety directly through a robust assessment after the construction has taken place. As Peng et al., (2017) stated the causes of degradation of a bridge structure can include material decrepitude and weakness, deterioration and metal corroding, aside from exerting over-load. Furthermore, the surrounding disturbance has critical significance in vibration-based bridge monitoring. Disturbance or stimulation can be induced by congestion or crowding, wind force and ground vibration during its existence [49]. Significantly, the lifespan of an operative pedestrian bridge depends on and is associated with the influence of the people crossing it, causing a modification of its dynamic aspect and modal characteristics [50]. Zall et al., (2017) suggested an approach to calculate the acceleration of a simply supported footbridge but is limited to vertical direction only [50]. Omidalizarandi et al., (2020) introduced a new technique based on time series investigations called RT-MPI that can automatically calculate modal parameters. MEMS accelerometers were installed on Mensa foot bridge located in Germany. The suggested methodology outperformed SSI-COV, a covariance driven stochastic subspace identification method when estimating the parameters by 0.2% [51]. Ehrhart and Lienhart (2015) implemented a Leica MS50 image-assisted total station (IATS) with a HBM B12/200 accelerometer of Fs = 200 Hz and a RTS of model Leica TS15 to estimate the displacement and analyze the vibration of a pedestrian bridge [52]. Roberts et al., (2004) employed a triaxial accelerometer of sapling frequency of 200Hz along with a GPS for BHM purposes in order to measure a bridge deflection. The GPS readings reduced the cumulative drifts of the acceleration measurement through time by adjusting the coordinates [53]. Neitzet et al., (2012) performed a vibrational testing on a bridge using low-cost accelerometer system of a sapling frequency of 600Hz, a laser scanner measuring a single-point data and an interferometric of simulated aperture scanning system used as validation device. Eigenfrequencies and damping coefficients were determined using a damped harmonic oscillation (DHO) paradigm and estimated using the least square adjustment method [54]. Gao et al., (2021) developed a monitoring framework aiming to ensure a sustainable successful performance of Xiangshan Port Bridge in China. The suggested monitoring technique comprises sensor network topology, data acquisition system to process and transmit the recorded data and an assessment system. The employed sensors covered temperature and humidity, acceleration and displacement. The bridge assessment operated effectively and can detect modifications in the system parameters [48].

The proposed computational system was tested in laboratory conditions prior to the bridge assessment. Three triaxial accelerometers were installed on a steel cantilever beam, where they recorded measurements at ambient condition and at perturbation. A comparative analysis between the results of the suggested DAQ system and that of the accurate National Instrument DAQ was performed to test the accuracy of the suggested framework.

2. System configuration

Three low-cost triaxial accelerometers employed in the laboratory experiment were ADXL335, with a measurement range of +/- 3.6g and a bandwidth range of 0.5 to 1600 Hz for X and Y axes, whereas from 0.5 to 500 Hz for Z axes. The analog signal from the three triaxial accelerometers is first processed in an Analog-to-Digital converter, based on ADS1256 with a resolution of 24bits and consisted of 8 channels, and then converted to digital values. A thermometer was implemented for temperature compensation. A Teensy 4.1 development board microcontroller of resolution 32 bits was adopted to process the collected data by a Serial Peripheral Interface (SPI) communication port and record the signal from the sensors and pass it to its Flash and then its Ram memory. The microcontroller (Fig. 1) is a 60.96 x 17078 x1.57 mm^3 board is an Arm based Coretx-M7 at 600 MHz.

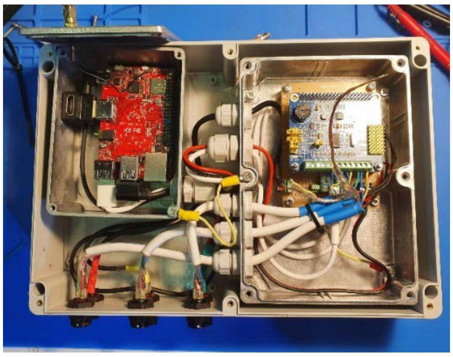

Figure. 1. Proposed data acquisition system hardware

Subsequently, the collected data is transferred to a 64bits server single board PC vis USB communication port aiming to process the data and record it if needed. The treated data are then converted into their real physical values as acceleration per unit time.

The server used in this investigation is a Rock Pi X B. It is a X86 single board compute (SBC) with the dimensions of 85 x 54 mm^2 that can run both Windows and Linux distributions, with a memory of 64bits dual channel and a high performance 32 GB eMMc module micro-SD card for storage purposes. All data received from the microcontroller is first conditioned and stored, then interfaced to the server pc where they are stored for further processing. The single board server PC plays the role of bringing the entire system together, since it provides both the controller and the client pc with a standardized interface, making it possible to concentrate on their tasks during development.

The microcontroller sends Acceleration Time domain data to the server. A limit is set for the acceleration, when the measurements sent exceeds the limit, LabVIEW program starts saving the result on the server and does not stop until a specific period of time after the measured data return within their preset limits. It saves a copy of data file, store it on the server and send a copy to the client pc present in the laboratory via WIFI, or Ethernet, with a time stamp of 2digits for hours, 2digits for minutes, 2digits for seconds, and 3 for milliseconds.

LabVIEW software was used to convert the signal data into numbers saved as a .txt file and ready to be treated through LabVIEW or MATLAB. First a digital buffer run by system where acceleration time domain graph can be constructed and the Acceleration Frequency domain can be developed. Then the noise is filtered out from the recorded acceleration using Bandpass Butterworth Filter in order to clean the obtained signal. To finalize the process an envelope for acceleration peaks is then developed to optimize a damping coefficient calculation from the envelop equation.

A 15 volts dc power supply was introduced for supplying power along with a Photovoltaic (PV) panel (Fig. 2). Both generated power to a charger control, but separated by 2 diodes to ensure that no mixing signals will occur and to isolate the signal from one of the two supplies when the second is providing power so they can work alternatively. A rechargeable sealed led acid battery of 12 volts and 9 Ah was implemented to supply the microcontroller. The charger control provided the server pc with a 12 volts DC and both the microcontroller and the Analog-to-Digital converter with a 5 volts DC.

The general budget of the suggested DAQ system is about 500 euros.

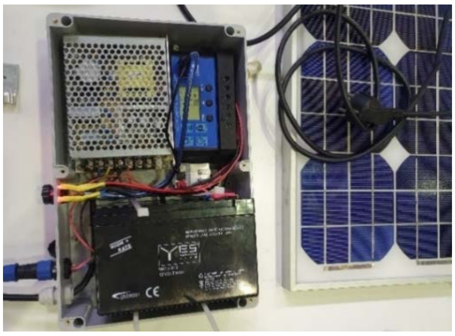

Figure. 2. Power supply system feeding the proposed DAQ

This work consists of developing a framework suitable for accurate assessment using DAQ system (Fig. 3).
It is considered cost-effective with ten times cheaper than any DAQ adopted for structural health monitoring purposes. This framework circumvents many of the difficult issues associated with distributed systems, making it more usable even by less-experienced developers.

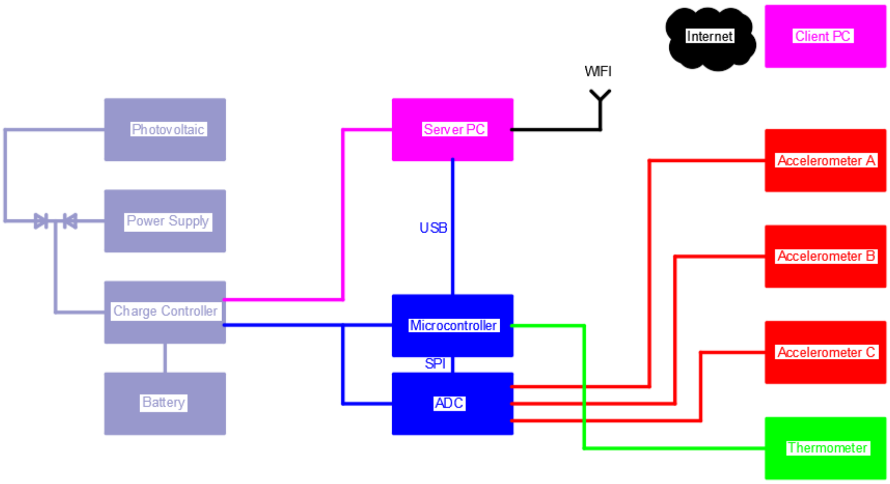

Figure. 3. Schematic presentation of the designed DAQ network

3. Experimental procedure

3.1 Test and validation

In order to test the accuracy of the suggested low-cost microcontroller based DAQ hardware system, a comparative analysis was performed between the results of the designed DAQ and the results of the National Instruments DAQ system that is presumed to be the standard system the laboratory relies on in assessment fields (Fig. 4). Sensors were mounted on the edge of a steel cantilever beam (Fig. 5), and measurements were recorded at ambient and at perturbation, by releasing mass (10 Kg) settled on the steel beam IPE 160 with a length of 2046mm. The whole system including the accelerometers, beam and holders weighted 34.505 Kg. Data from BDI connected to NI: CDAQ – 9135, and data from triaxial accelerometers ADXL335 connected to the suggested DAQ were recorded at the 3 directions.

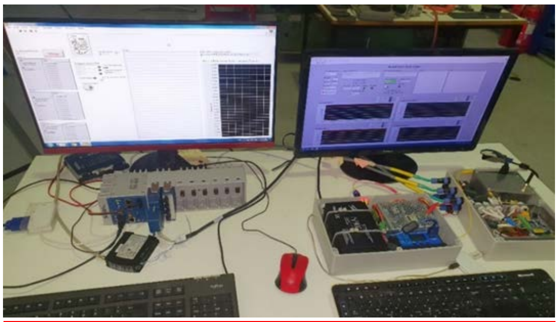

Figure. 4. The proposed DAQ system and NI DAQ system experimental set up

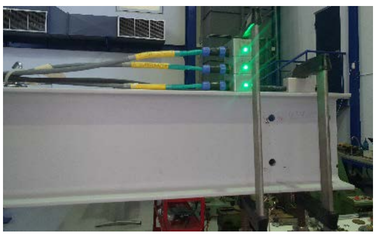

Figure. 5. The setup of the accelerometers connected to the suggested DAQ system and the BDI connected to standard DAQ system

3.2 Results

The first part of the study consists of performing a comparative analysis between the suggested DAQ system with the three ADXL335 accelerometers, and the accurate DAQ system from the NI: CDAQ – 9135 connected to BDI sensor, subjected to the same experiment in order to test the accuracy of the methodology.

LabView derives automatically the results after the server receives acceleration exceeding the limits, to store them as .txt files, then they are imported to MATLAB in order to calculate the dynamic parameters. This software mainly operates by acquiring the signal from the impacted structure's data collected by the sensors, performing FFT and determining natural frequency, to finally obtain the fitted curve after applying a filter across a specific frequency band, and calculate the damping ratio.

The calculated eigenfrequencies and damping values for both studied sensor types at perturbation in lateral and vertical directions are presented.

The BDI connected to the standard DAQ recorded a maximum acceleration at +/- 0.22 m/s^2, before gradually decrease to reach a negligible value within 10 seconds. It has a sampling frequency equal to 250 Hz. The reported acceleration includes noise that will be removed by using a proper filter. Fast Fourier Transform function built in MATLAB was performed on the BDI data showing two major peaks at 22.70 and 30.31 Hz (Fig. 6). These peaks present the eigenfrequency of the beam.

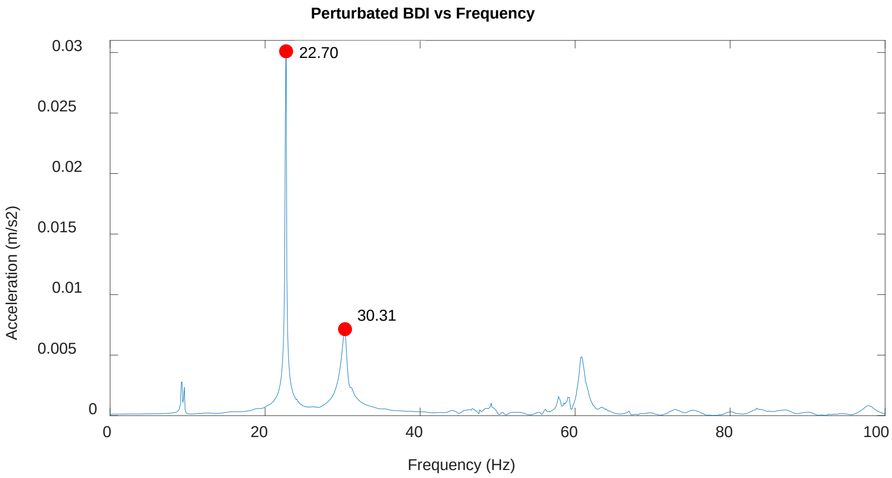

Figure. 6. Acceleration Frequency domain of the BDI accelerometer connected to the standard DAQ system in lateral direction at perturbation

Accelerometer C was able to record a maximum acceleration of +0.24/-0.25 m/s^2, accompanied with noise as well. It has a sampling frequency equal to 263.192 Hz. Applying FFT function, Figure 7 shows same peaks were detected revealing that the same eigenfrequencies were recorded by the studies accelerometer

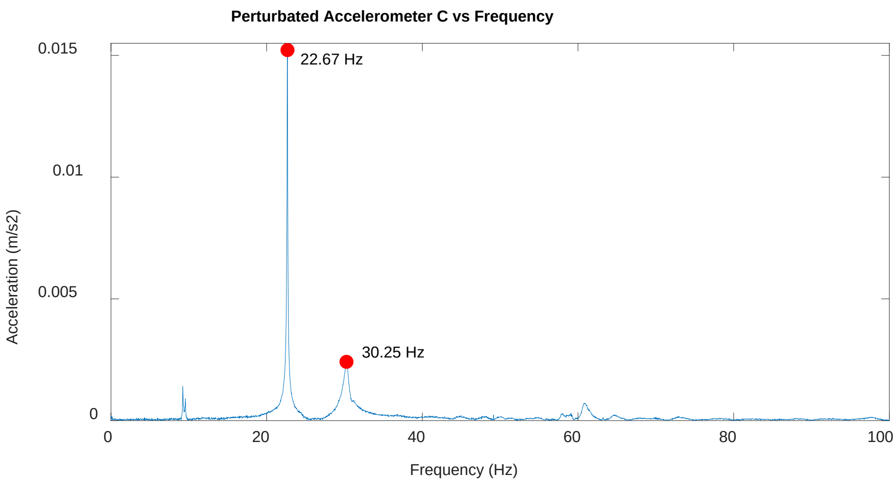

Figure. 7. Acceleration Frequency domain of accelerometer C connected to the suggested DAQ system in lateral direction at perturbation

To consume for the noise, Bandwidth Butterworth Filter was adopted with frequency cutoffs 21 and 24 Hz surrounding the first eigenfrequency happening at a higher amplitude with the second order. Filter was applied on both accelerometers data.

According to [34] and [55]: logarithmic decrement leads to the following equations

$$A(t) = A_0 \ e^{-\beta t} \tag{1}$$

$$\beta = \zeta \omega_0 \tag{2}$$

$$\omega_0 = 2\pi * f_0 \tag{3}$$

$$\text{Damping } \zeta\,(\%) = \frac{\beta}{2\pi * f0} \text{x100} \tag{4}$$

where f_0 is the natural frequency, ω_0 is the angular frequency, ζ is the daming ratio, β is the decay constant, A_0 is the initial amplitude, and $A(t)$ is the amplitude at a given moment of time.

Logarithmic decrement of Accelerometer C equation retrieved from Figure 8 is: $y(t) = 0.1084 \ e^{-0.2448\,t}$

Damping of accelerometer C $= \frac{0.2448}{2\pi * 22.67}$ x100 = 0.172%

Logarithmic decrement of BDI equation is: $y(t) = 0.0876 \ e^{-0.2470\,t}$

BDI damping $= \frac{0.2470}{2\pi * 22.70}$ x100 = 0.173%

The calculated damping of the two studied methodologies proved the accuracy of the suggested DAQ system with a damping difference of 0.57% in the lateral direction.

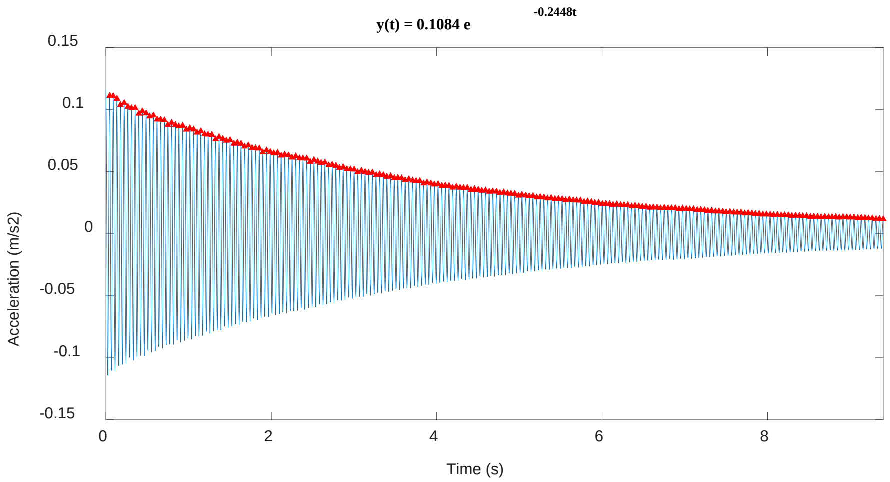

Figure. 8. Damping Equation of Accelerometer C in lateral direction

The following results were extracted from perturbation condition in vertical direction.

The BDI sensor recorded a maximum acceleration of +0.44/-0.48 m/s^2, decreasing within 2 seconds to reach an amplitude close to zero for the rest 8 seconds for recording. Noise was detected as well and will be filtered. Fast Fourier Transform function was built in MATLAB was performed on the BDI data shower two major peaks of 22.71 and 30.23 Hz. These peaks present the eigenfrequency of the beam.

Accelerometer B was able to record a max acceleration of +0.4/-0.35 m/s^2, accompanied with noise as well. Applying FFT function, same peaks revealing same eigenfrequencies were recorded by the studies accelerometer.

To consume for the noise Bandwidth Butterworth Filter was adopted with frequency cutoffs 27.5 and 31 Hz surrounding the second eigenfrequency happening at a higher amplitude with the second order.

Logarithmic decrement of Accelerometer B equation is: $y(t) = 0.2235 \ e^{-1.8372\,t}$

Damping of accelerometer B $= \frac{1.8372}{2\pi * 30.29}$ x100 = 0.965%

Logarithmic decrement of BDI equation is: $y(t) = 0.3039 \ e^{-1.8593t}$

BDI damping $= \frac{1.8593}{2\pi * 30.23}$ x100 = 0.978%

Same for the vertical direction, calculating the damping of the two studied methodologies proved the accuracy of the suggested DAQ system with a damping difference of 1.3% in the vertical direction.

The suggested framework proved its accuracy and was able to calculate the eigenfrequencies and damping ratio of a steel cantilever beam with finding the exact eigenfrequencies of 22.7 and 30.3 Hz for both directions with a difference of 0.57% in the lateral and a 1.3% difference in the vertical direction.

4. Case study

The Technical Description of the project provides testing the dynamic behavior of a pedestrian bridge situated in Athens, Greece after the completion of construction. The bridge is an arch-and tie bridge with a span of 43.0 m. The arch is placed eccentrically of the 2.7 wide m deck (Fig. 9). The tests were performed in 2 stages as described below. The purpose of stage 1 tests is to determine the physical eigenfrequencies, the eigenmode and the damping of the carrier with emphasis on the vertical and lateral oscillations. To this end, the bridge is subjected to abrupt disturbances coming from Pedestrian A weighting 80.7 Kg, who through one impact jump at the mid length of the bridge excited the structure. The pedestrian's free response was measured until calm.

Figure. 9. Case study pedestrian bridge

The time-varying oscillations was recorded by 4 BDI accelerometers. Three sensors were placed along the bridge in the middle of the deck where the biggest disturbances are expected, while the fourth was placed for control purposes at the end of the deck in the middle of the bridge. The arrangement of the sensors in the plan view is shown in Figure 10.

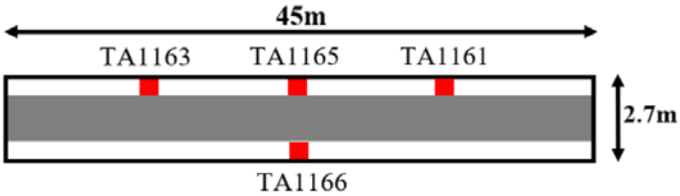

Figure. 10. Sensor Network mounted on Mesogeion pedestrian bridge

The purpose of stage 2 tests is to check the fulfillment of the prescribed oscillation comfort criteria of the footbridge during pedestrians crossing. Data was measured for pedestrian A (80.7 Kg), and then for 12 pedestrians (923 Kg), walking at 2 Hz frequency, the running at 3.6 Hz frequency. According to EN 1990, A.2.4.3.2 the comfort criteria are defined in terms of maximum acceleration and are:

1) 0.7 m /sec2 for vertical vibrations
2) 0.2 m /sec2 for horizontal vibrations due to normal use

In the following, an evaluating of pedestrian's A jumping at mid length of the bridge is reported.

4.1 Acceleration

It is shown that there exists a synchronisation between both directions by reporting maximal acceleration amplitudes at 9.7 seconds for +/- 0.37 m/s^2 for the vertical vibration (Fig. 11) and a +/- 0.04 m/s^2 for the lateral vibration and it is shown that both optimal values were recorded by the accelerometer employed at mid edge of bridge.

The BDI accelerometers has a sampling frequency equivalent to 169.77 Hz. Frequency domain was obtained after performing FFT on the recorded acceleration time domain.

For the lateral vibration, the calculated eigenfrequencies were 3.63 Hz reported by TA1161 and 7.55 Hz reported by TA1166. Same for the vertical vibration the calculated eigenfrequencies were 3.65 Hz reported by TA1165 and 7.55 Hz reported by TA1163 (Fig. 12).

Accordingly, Bandwidth Butterworth filter was applied to eliminate unnecessary noise. It was applied particularly on the data, each time the accelerometer recorded a peak in the frequency domain leading to the natural frequency.

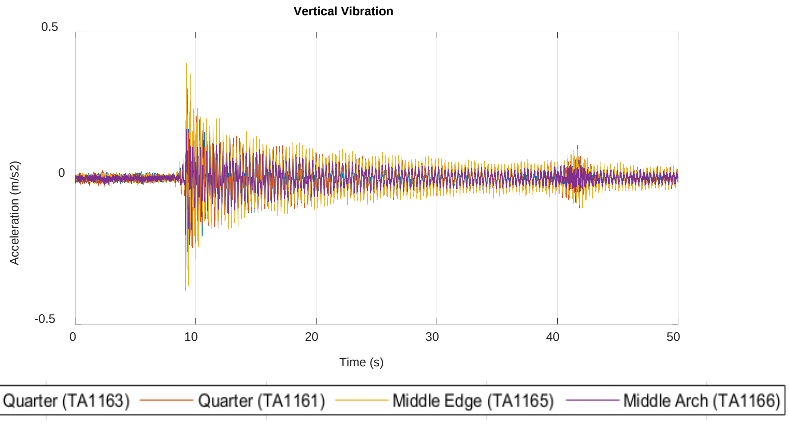

Figure. 11. Acceleration Time Domain of BDI accelerometers in vertical direction

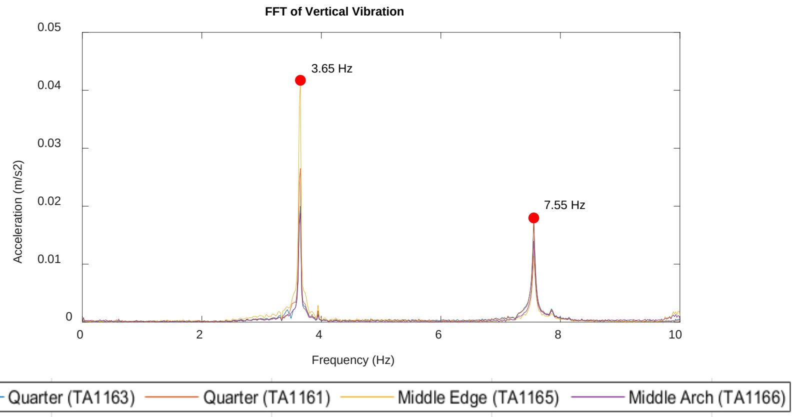

Figure. 12. Acceleration Frequency Domain of BDI accelerometers in vertical direction

4.2 Damping

The peak envelops showed a smooth decrease in the acceleration recorded by the accelerometer. It was obtained after applying the filter for the first eigenfrequency is the lateral direction (3.63 Hz) detected by accelerometer TA1161 with frequency cutoffs equal to 3.59 and 3.689 Hz with order 3.

Logarithmic decrement of accelerometer TA1161 equation retrieved from Figure 13 is: $y(t) = 0.0023\ e^{-0.0501\ t}$.

Accelerometer TA1161 damping = $\frac{0.0501}{2\pi * 3.63}$ x100 = 0.219%

Then the peak envelops were calculated for the second eigenfrequency in the lateral direction (7.55 Hz) showing a smooth decrease in the acceleration recorded by the accelerometer TA1166. It was obtained after applying the filter with frequency cutoffs equal to 7.515 and 7.613 Hz with order 3.

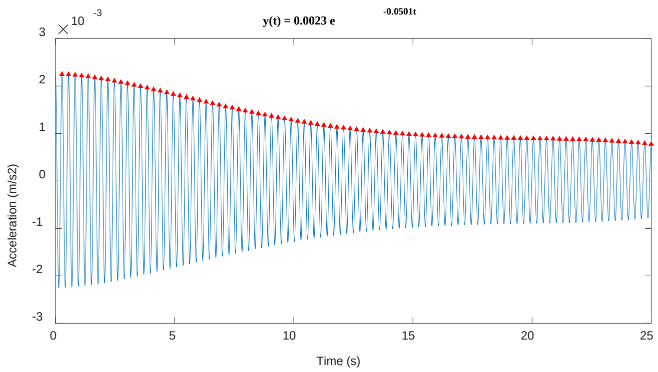

Figure. 13. Damping equation of accelerometer TA1161in lateral direction

Logarithmic decrement of accelerometer TA1166 equation is: $y(t)$ =0.0464 $e^{-0.1046t}$.

Accelerometer TA1166 damping = $\frac{0.1046}{2\pi*7.55}$ x100 = 0.22%

Same calculation was obtained for the vertical direction. The peak envelops were obtained after applying the filter to accelerometer TA1165 recording the first eigenfrequency (3.65 Hz) with frequency cutoffs equal to 3.571 and 3.69 Hz with order 3.

Logarithmic decrement of accelerometer TA1165 equation is: $y(t)$ =0.1056 $e^{-0.0457t}$.

Accelerometer TA1165damping = $\frac{0.0457}{2\pi*3.65}$ x100 = 0.2%.

For the second eigenfrequency in the vertical direction (7.55 Hz), the peak envelops showed a smooth decrease in the acceleration recorded by the accelerometer TA1163. It was obtained after applying the filter with frequency cutoffs equal to 7.456 and 7.692 Hz with order 3.

Logarithmic decrement of accelerometer TA1163 equation retrieved from Figure 14 is: $y(t)$ =0.0768 $e^{-0.1098t}$

Accelerometer TA1163damping = $\frac{0.1098}{2\pi*7.55}$ x100 = 0.23%

Damping calculated from both axes with different eigenfrequencies reveals a damping ratio of 0.22% from the lateral for both eigenfrequencies and 0.20% conducted from the first vertical eigenfrequency and 0.23% from the second vertical eigenfrequency.

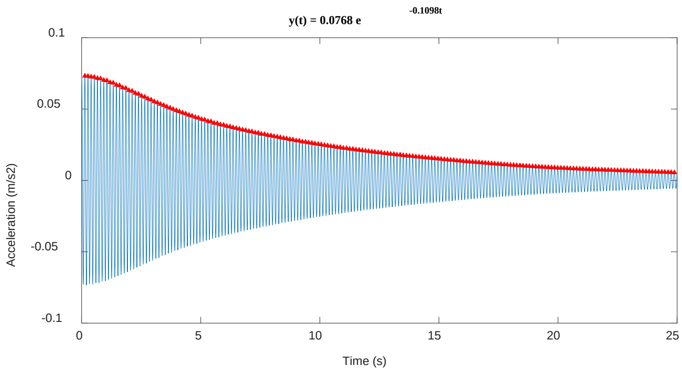

Figure. 14. Damping equation of accelerometer TA1163 in vertical direction

4.3 Mode shapes

Acceleration is proportional to displacement [34] since a double integration is needed to calculate displacement. Therefore, the mode shapes of the bridge can be pictured by reporting the filtered acceleration for each eigenfrequency.

It is shown for the first eigenfrequency the three accelerations along the bridge length synchronize, having the same phase at a specific moment with different altitude (Fig. 15). Whereas from the reported data of the second eigenfrequency both accelerometers installed on the quarter edges of the bridge share the same phase, yet the accelerometer mounted on the mid length of the bridge is shifted by $\pi/2$ (Fig. 16). The amplitude of the accelerometers indicates the displacement aspect at each sensor location, revealing the two consecutive mode shapes of the bridge (Fig. 17).

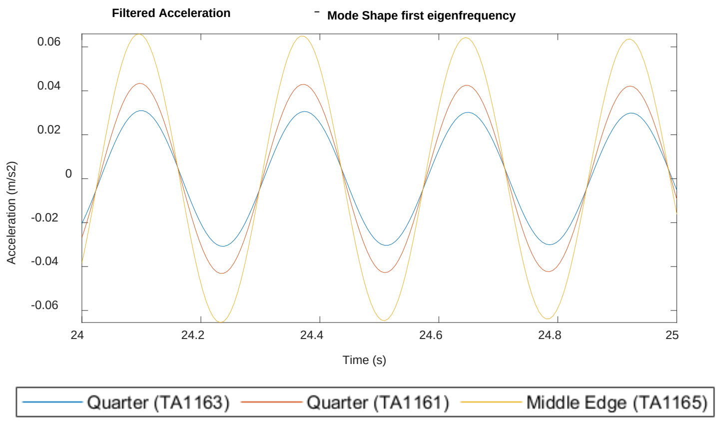

Figure. 15. Mode shape for the first eigenfrequency in vertical direction

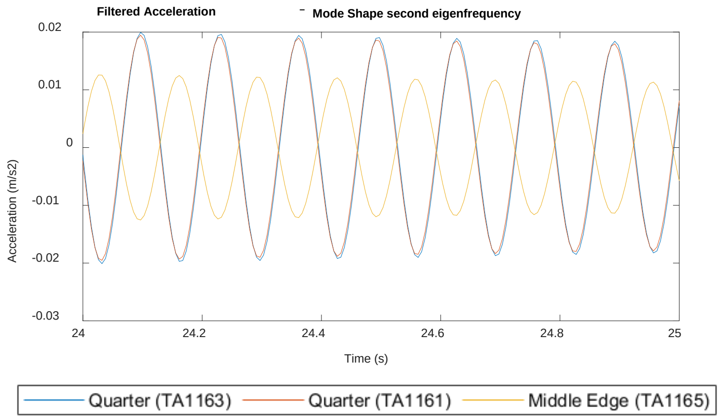

Figure. 16. Mode shape for the second eigenfrequency in vertical direction

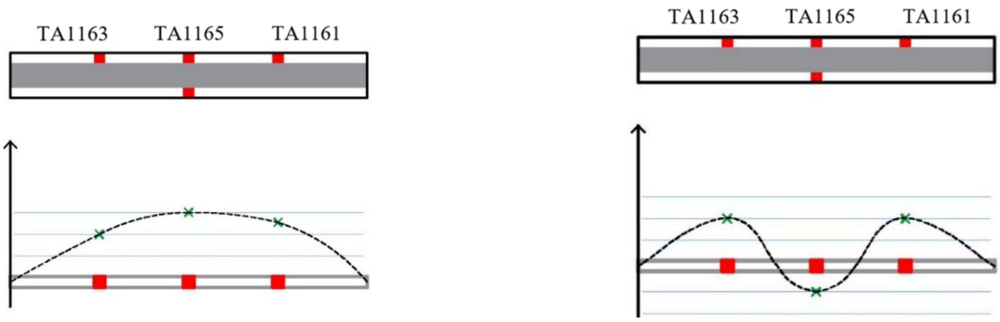

Figure. 17. Bridge Mode shapes in vertical direction from the first and second eigenfrequencies

Concluding it may be said that the analysis of the dynamic behavior of the tested pedestrian bridge after the completion of construction showed 2 eigenfrequencies of 3.65 and 7.55 Hz for both directions, a damping of 0.22% found in lateral and a damping of 0.2% for the first and 0.23% for the second eigenfrequency conducted from the vertical direction. For each eigenfrequency a distinct mode shape was found.

4.4 Comfort level

The second phase referred to finding the comfort levels for one pedestrian and a group of 12 people.

The activities of pedestrian A (80.7 Kg) and the group of 12 pedestrians (923 Kg) were recorded when crossing the bridge through a predetermined path for a 2Hz walk and a 3.6 Hz run for both lateral and vertical directions. The comfort feeling was observed in pedestrians for all activities in lateral direction and the walk in the vertical direction. But when crossing the bridge at 3.6 Hz the comfort limits were passed for both activities of one and the group of pedestrians as it is shown in Figures 18 and 19.

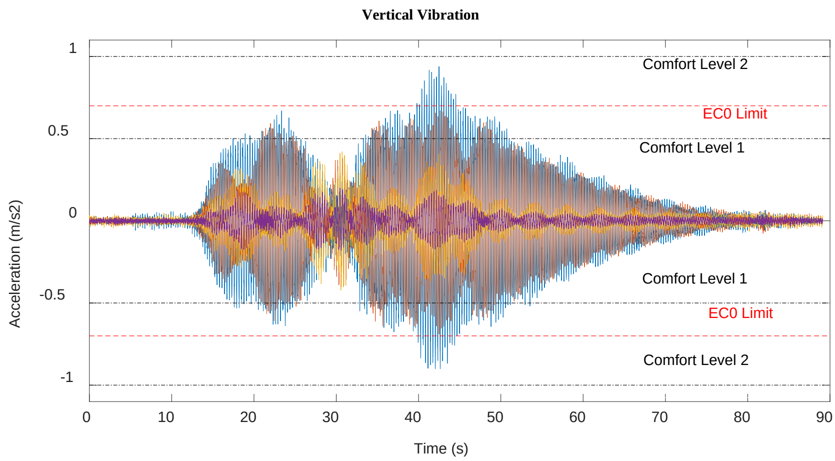

Figure. 18. Comfort level for pedestrian A running at 3.6 Hz frequency in vertical direction

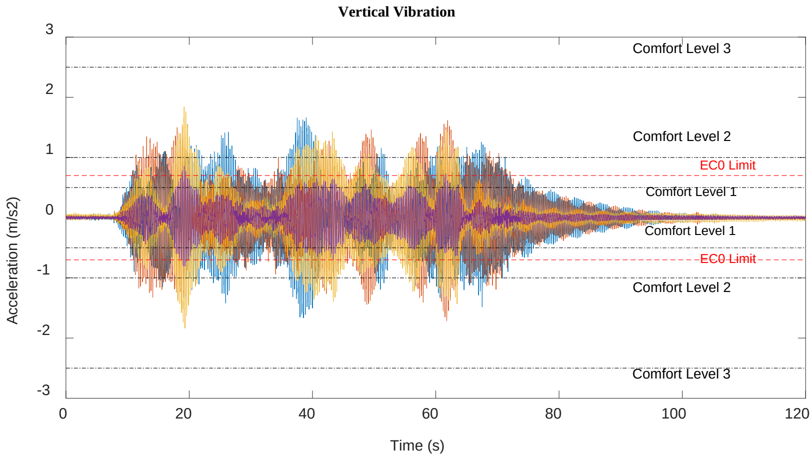

Figure. 19. Comfort level for a group of 12 pedestrians running at 3.6 Hz frequency in vertical direction

Comfortability does not have to reduce the bridge safety regulations, since damping calculations indicate and affirm having a safe structure. However, the movement of bridge is due to its capability of absorbing the energy produced by pedestrian by using it.

5. Conclusions

In this research the design of an accurate microcontroller based DAQ system for structural health monitoring purposes and its successful implementation to assess the safety of Mesogeion pedestrian bridge and calculate its dynamic properties is presented.

As the general budget of the suggested DAQ system is about 500 euros. It is considered cost-effective with ten times cheaper than any DAQ capable of assessing the structural state with such accuracy.

Before assessing the health aspect of the pedestrian bridge, the suggested DAQ was tested under laboratory conditions. A comparative analysis was performed between the designed DAQ system with the three ADXL335 accelerometers, and the accurate DAQ system from the NI: CDAQ – 9135 that is presumed to be the standard system the laboratory relies on in assessment fields, connected to BDI sensor, subjected to the same experiment in order to test the accuracy of the methodology. The suggested framework proved its accuracy and was able to calculate the eigenfrequencies and damping ratio of a steel cantilever beam with finding the exact eigenfrequencies of 22.7 and 30.3 Hz for both directions with a difference of 0.57% in the lateral and a 1.3% difference in the vertical direction.

The case treated in this paper provided the results of testing the dynamic behavior of an arch-and-tie pedestrian bridge after the completion of construction. Dynamic properties were found to have 2 eigenfrequencies of 3.65 and 7.55 Hz for both directions, a damping of 0.22% found in lateral and, 0.2% and 0.23% conducted from the vertical direction. For each eigenfrequency a distinct mode shape was found.

As safety was proven the comfort level according to EN 1990, A.2.4.3.2 during pedestrians crossing was tested and checked by many different runs exerted by one and 12 pedestrians. The results proved the comfort of crossing the bridge in both directions till the limit of a 3.6Hz running activity was performed, where the bridge absorbed the dissipated energy from the pedestrians by vibrating for seconds to finally restore to its initial posture.

Structural health monitoring assessment allowed the researchers to evaluate the dynamic response of the investigated structure for the purpose of characterizing the system state, calculating the modal properties and detecting damages, therefore for future work we recommend adopting the suggested DAQ system to quantify displacement measurements from the recorded acceleration. As displacement measuring is considered a significant challenge.

6. References

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