OPEN-SOURCE EMM-ARM IMPLEMENTATION FOR MORTARS BASED ON SINGLE-BOARD COMPUTER

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Abstract. The EMM-ARM (Elastic Modulus Measurement through Ambient Response Method) allows the continuous monitoring of the elastic modulus of cementitious materials from early ages. The idea is to subject a beam, made of the specimen in its mould, to an excitation and monitor its response via an accelerometer. The excitation can either rely on naturally occurring vibrations, or on a controlled excitation system creating a signal with the necessary characteristics. The resonant frequency of the tested beam can be assessed with modal identification techniques, whereas the E-modulus of the tested material can be directly calculated with the dynamic equations of motion of the system.
The original implementation of EMM-ARM uses specialized devices for the acquisition and excitation systems, which results in a relatively high price, as well as limited options for customization. The software used is based on proprietary systems (LabView), which further brings limitations on sharing for other institutions to use. On the other hand, one should bear into account that cyber-physical systems have shown significant evolutions in the last decade. Open-source platforms are increasingly popular and low-cost single-board computers are becoming widespread (e.g. Raspberry Pi). Electronic components have evolved parallel to these platforms, offering decent performances for low prices nowadays. The work hereby presented took inspiration from these cyber-physical systems to develop an open-source and cost-effective system able to conduct EMM-ARM tests independently from any other computing device. The system will be integrally presented as well as results obtained in comparison with the original implementation of the system.

Keywords: Elastic modulus, Cementitious materials, Cost-effective, Open source, Monitoring.

1 Introduction

The study of elastic modulus (E-modulus) for cementitious materials is of prime importance, especially from a structural analysis point of view. Measuring the E-modulus evolution at very early ages, in the vicinity of the setting process can even bring further valuable information about the performance of a mix [1]–[3]. For these interests, the work presented hereby focuses on monitoring the E-modulus of mortars.

The Elastic Modulus Measurement through Ambient Response Method (EMM-ARM) is a resonant-based method designed to continuously monitor the E-modulus of a material under test since casting into the testing mould, forming a composite beam. EMM-ARM is based on the determination of the first resonant frequency of the testing beam, which changes over time as the tested material hardens. The tested material E-modulus can be calculated from the identified first resonant frequency using the testing system's dynamic equations of motion [4]. The current measurement system to conduct EMM-ARM tests is based on specialized equipment, as well as licensed software (MATLAB/LabView). Therefore, a setup for EMM-ARM can be relatively expensive and not adequate to adapt for specific and original applications.

The presented work seeks the idea of making developments efficient to deploy and implement for any potential user, without needing a high budget or licensed software. Therefore, all the developments disclosed herein have been made using only open-source software, and cost-effective electronic components. Using open-source software allows the possibility to modify the code, in order to custom design it for other situations, or even components. In this paper, the term "cost-effective" is employed, instead of "low-cost", because a balance between the price of the components, the performances, and the time invested to get the expected results was made. The system developed could have been made for an even lower price with thorough optimization in terms of electronics, but that was not the point of the research.

With open-source and cost-effective developments, the performance requirements to conduct EMM-ARM tests on mortars can be reached, and the system offers the possibility to be custom designed for various applications. For example, additional measurements could be easily made and upgraded in a customized system, in parallel to the measurement of the E-modulus, such as temperature, humidity, gas composition analysis, etc. The number of specimens to monitor can also be adjusted from one unique specimen to 16 or more, using custom-built multiplexers. All these possible customizations are key elements for research, where original measurements are often targeted, but also for the industry that frequently lags behind the capabilities of measurement of research (either due to difficulties in implementing or due to the lack of commercial systems for the purpose at acceptable prices).

2 EMM-ARM application to mortars: original setup

The EMM-ARM was developed in 2008-2009 by Azenha [5] initially to monitor the E-modulus of hardening concrete. Since then, EMM-ARM was applied to a large variety of materials, such as cement mortar, lime-cement blended mortars, cement paste, stabilized soils and even epoxy resins [4], [6]–[9]. Continuous efforts were produced in order to enhance the performances of EMM-ARM. In its most basic version, EMM-ARM merely relies on the measurement of accelerations at a relevant point in the tested beam (either mid-span for a simply supported setup, or extremity for a cantilevered beam), with the beam solely subjected to the environmental vibrations. This setup, which was the initial implementation and gave its name to EMM-ARM, is currently reserved for cement paste tests only.

As a matter of fact, to enhance the reliability of the results for stiffer specimens (e.g. with smaller spans), such as the ones used for concrete, stabilized soils and mortars, an electromagnetic actuator was designed to excite the beam in a controllable way [4]; thus, the tested beam can be subjected to a controlled excitation that over the testing period, with better capacities being attained in terms of modal identification. This setup is currently used for concrete, mortar and stabilized soil specimens. A scheme representing the test setup for such materials can be visualized in Fig. 1. In order to identify the resonant frequency of the testing beam, an excitation signal is sent to an electromagnetic actuator. The response of the beam to this excitation is measured via an accelerometer by an ADC. It can be noticed in the scheme presented in Fig. 1 that a wire links the generated excitation signal to another input of the ADC; indeed, in order to apply the modal parameters identification method, the excitation signal, as well as the accelerations of the beam, have to be measured simultaneously [4].

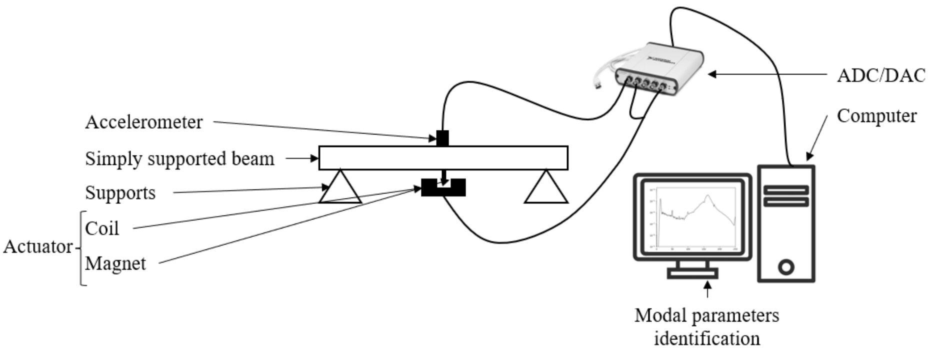

Fig. 1. Illustration of EMM-ARM setup for mortars

The original setup for the application of EMM-ARM to mortars is composed of specialized equipment, ensuring laboratory-grade measurements. For the acceleration measurements, the system relies on the PCB TLD352C04, which is a light sensor (5.8g), perfectly adapted to conduct EMM-ARM tests. The sensitivity of this sensor is 10mV/g and its typical resolution is rated at 0.5 mg rms. The acquisition system, also in charge of generating the excitation signal is the NI USB-4431. This ADC/DAC is able to acquire 4 channels simultaneously at 102.4 kS/s with a resolution of 24-bits. In the original version of EMM-ARM application for mortar, the data is collected by the ADC and transferred to a computer, where it can be stored and post-processed.

3 Hardware of the new design

3.1 Computing device

On the market of programmable boards, a wide range of brands and types of boards can be found. It is firstly interesting to distinguish the two principal types of boards available: microcontrollers, and microcomputers. Microcontrollers are the most basic boards, as they simply run a script that is in their memory as soon as they are power supplied. They have the advantage to be, for most models, significantly cheaper than microcomputers, and to be simple to use: once the script is transferred to the microcontroller, the only action needed is plugging it to a power supply; furthermore, it can be unplugged at any time. They also consume very little amount of energy, which makes them ideal for remote projects, where the use of batteries as a power supply is required. The main drawback of microcontrollers is their low processing power, and often very limited memory, which prevents more complex programs involving a high number of variables to be implemented [10]. On the other hand, microcomputers can usually be found at a higher price, depending on the models. They come with the advantage of having much higher processing power and relatively low energy consumption which therefore makes them more flexible and extends the possibilities compared to microcontrollers. However, their architecture is similar to regular computers, which makes them more complex than microcontrollers. For instance, the time to power on a microcomputer can be approximated to a minute, while it takes merely one second for a microcontroller to start executing its script. A microcomputer, as well as a regular computer, cannot be unplugged from its power source without any risk [11].

Due to the relatively high processing power necessary to perform an EMM-ARM test, in this project, it was decided that the best solution was to use a microcomputer. More precisely, a Raspberry Pi (RPi) 4 model B with 8GB of RAM was chosen, as it was adequate for the application. The RPi comes with many features, such as WiFi connectivity, 40 global purpose input/output (GPIO) pins, I2C and SPI serial interfaces for peripherical (such as analogue to digital converter). An important feature that comes with RPi is the large community working on it and sharing issues and solutions online, providing relevant resources for initial and intermediate users. Many electronic components were also specifically designed to adapt efficiently to the GPIOs of the RPi (Pi hats) that can extend the functionalities of this microcomputer. With these functionalities and its large RAM, the RPi is suitable to conduct EMM-ARM tests and for post-processing of the data.

The RPi runs on a variation of the Debian exploitation system, Raspbian, and offers most of the functionalities of a regular computer, coupled with a development board thanks to its GPIO pins. These pins are used to interact with electronic components and can be controlled via Python programs.

3.2 Excitation of the specimen

In order to excite the beam and monitor its response to the excitation, a predefined signal needs to be generated to the actuator. The signal to be generated is a sine sweep, ranging on the interesting frequency domain that is repeated indefinitely during the measurement period.

In practice, to generate an analogue signal, an analogue to digital converter (DAC) is required. A DAC converts discrete digital values into a continuous analogue signal. For this application a 12-bit DAC was selected, the MCP4725 from Adafruit, which uses the communication protocol I2C. This DAC, connected to the RPi, can generate a sine signal at up to 8000 Hz, which is more than required for this case.

A common issue with low-cost DACs found on the market is that they are not able to generate negative voltage signals. In the application of this project, it is important to generate a sine signal centred around 0V, to obtain an average force of excitation null. The chosen DAC suffers from this issue: the sine at its output pin ranges from 0V to 5V. The signal needs to be shifted down to be centred around 0V. Another issue common to most DACs is their low capacity for amperage output. Indeed, when the DAC is connected directly to the electromagnetic actuator, a voltage drop can be observed due to a lack of power. The consequence is that the signal emitted to the actuator doesn’t have constant amplitude along interesting frequency domain. In order to counter these two issues, an amplifying and shifting circuit was designed, and is presented in Fig. 2. The circuit is based on two key components, a transistor and an amplifier operational (op-amp). The transistor allows the draw of electricity from an external power source for supplying the actuator and the op-amp is in charge of shifting down the signal, as well as slightly amplifying it to reach a range of [-4V; +4V]. The circuit was implemented into a PCB to simplify the cable management in the device.

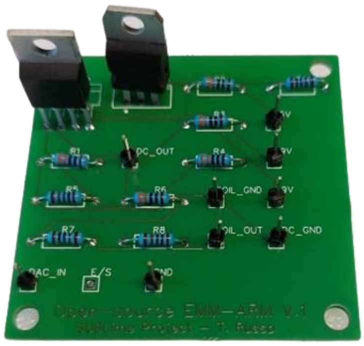

Fig. 2. Amplifying and shifting circuit

An objective of this research was to have the possibility to monitor several specimens during the same test. The strategy chosen to reach this objective, considering the limited capacities of the analogue to digital converter (ADC), is to excite and measure each specimen in sequence. Therefore, the system should have the capacity to activate an actuator when the associated specimen is being measured. Several solutions can be considered to achieve this task, for example, the use of multiplexers. The device presented in this paper relies on a custom-made multiplexer to select the specimen that is being measured.

3.3 Response acquisition of the specimen

The response acquisition of the specimen corresponds to its acceleration measurement. This measurement is made via an accelerometer. The selected accelerometer is the ADLX203EB from Analog Devices, with a sensitivity of 1000 mV/g, a resolution of 1 mg and a range of ±5 g.

This accelerometer is an analogue sensor, which means that it produces an analogue signal (a voltage), which then needs to be converted to digital data, to be interpreted by the computing device. This conversion is made via an ADC. The RPi does not have any integrated ADC; consequently, to read the signal of an accelerometer, an external ADC must be added. The principal criteria to choose an ADC are its sampling frequency and resolution. The sampling frequency corresponds to the number of data converted per second. To reliably measure a signal, the Nyquist law states that the sampling frequency should be at least twice the maximum expected frequency [12]. For example, if one expects to measure a signal ranging from 0 Hz to 250 Hz, the sampling frequency should be at least 250*2=500 Hz. In practice, and for conservative reasons, factor 3 is commonly used. Another parameter to consider is that the sampling frequency is divided by the number of channels simultaneously measured. In the case of this project, two channels need to be simultaneously acquired, the excitation signal and the acceleration one. Consequently, considering a conservative expected maximum frequency of 250Hz, the ADC should have a sampling frequency higher than 2*3*250=1500 Hz. Regarding the resolution, in order to get the best out of the selected accelerometer, the resolution should allow the reading of 1mV changes.

The ADC chosen for this application is the 24-bit high-precision AD/DA board from Waveshare. This ADC is rated for up to 30kHz of sampling frequency, even though in practice, with an RPi, the maximum sampling frequency achievable is around 5000 Hz, which is still suitable for the targeted application. Fig. 3 presents a scheme showing the different electronic components constituting the developed device and their connections.

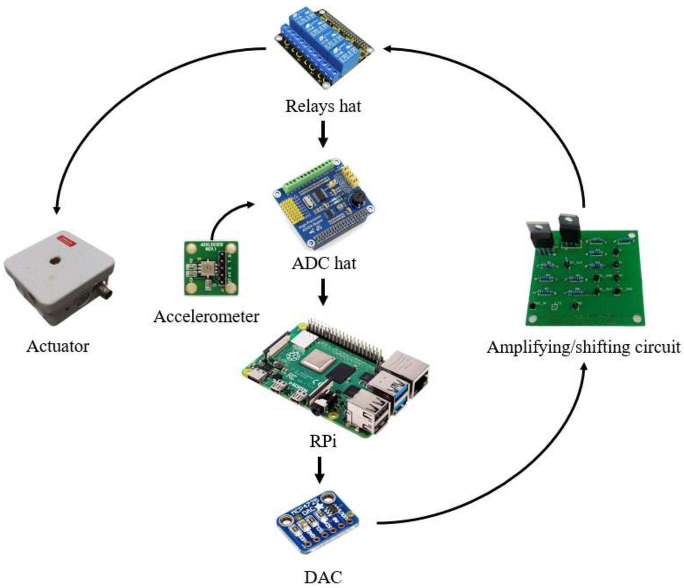

Fig. 3. Connections scheme of the developed device components

4 Software of the new design

4.1 Multiprocessing on Raspberry Pi

In this research, as previously mentioned, two functions should take place in parallel two acquisitions and one excitation. To efficiently archive this, the software should be designed in a way that allows it to run these functions in parallel. The coordinated execution of programs by multiple computer processors is known as multiprocessing. As a broad word, "multiprocessing" can refer to either the dynamic assignment of a program to two or more computers working together or to many computers working on the same program concurrently (in parallel) [13]. Multiprocessing is therefore conceived for applications requiring the execution of several functions simultaneously, running on distinct cores of a machine.

The RPi used as a computing device integrates four cores. However, for coding simplicity, the designed program does not take benefit from the simultaneous use of more than 1 core. The software will, in the near future, be upgraded with a multiprocessing method.

Two techniques are particularly recommended to substitute pure multiprocessing: multithreading and asynchronous methods. It should be clarified though, that the name multithreading refers to a software method, and cannot produce the same results as simultaneous multithread (SMT) hardware (which is absent on RPi), as it is explained below.

Synchronous execution is a usual method for coding; a function is entirely executed when called. For the targeted application of this paper, this classic method is not suitable, since channels need to be monitored while generating a signal; if a synchronous method was used, the result would be as illustrated in Fig. 4. The excitation function in charge of generating the excitation signal finishes before the recording is made, which makes it irrelevant.

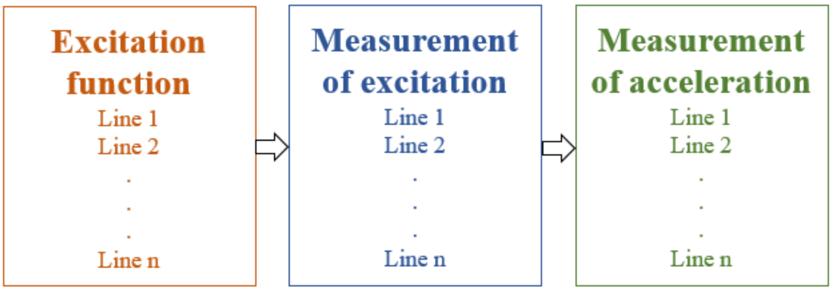

Fig. 4. Illustration of synchronous programming method

On the other hand, asynchronous and multithreading programming methods allow the possibility of running parts of different functions in sequence. Due to the speed of the RPi processor, 1.5GHz, switching between each function part could be, at our scale (measurements at 1.5kHz), considered *instantaneous*, making possible the imitation of multiprocessing. When using the multithreading method on a device whose hardware does not possess SMT, each function will be executed line by line in sequence. The first line of each function will be executed, then the second one, until the last line is executed.

The major difference between the multithreading and the asynchronous method is the control of the blocks executed in sequence: in the asynchronous method, the program will execute a block of function until it is indicated to switch to the next function. The asynchronous method consequently offers more consistent control over the timing of execution and was for this reason selected for the development of this project.

4.2 Modal parameters identification method

The modal identification process corresponds to the post-processing aspects and consists in extracting relevant information from vibration data. These modal parameters refer to eigenfrequencies, damping ratios, mode shapes and modal participation factors.

In this research, a parametric method, named Stochastic Subspace Identification (SSI) method was used to identify the first resonant frequency during the tests made to validate the developed device. This method was initially conceived for Operational Modal Analysis (OMA) when the excitation parameters of the system are unknown. This method allows the identification of the modal parameters in the time domain, which has the advantage of being less sensible to external noises than frequency domain methods, such as peak picking. A thorough presentation of the SSI method can be found in [14].

Even though SSI is a robust method, it does not consider the excitation signal, that is measured during the test. With the excitation signal, it is possible to calculate the Frequency Response Function (FRF), which is defined as:

$$H_{ij}(w) = \frac{\bar{y}_j(w)}{\bar{x}_i(w)} \tag{1}$$

Where $\bar{y}_j(w)$ and $\bar{x}_i(w)$ are the complex amplitudes of the input and output respectively. For optimal modal parameters identification, the SSI method using FRF data will be implemented in the developed device in the near future.

5 Preliminary results and discussions

5.1 Tests conducted

The objective of the conducted tests was to validate the developed device. Consequently, the developed device was systematically compared to the original EMM-ARM setup.

To this day, two tests were conducted for the system validation: (i) resonant frequency measurement of a hardened cement paste specimen, with ambient vibration excitation (no use of electromagnetic actuator);, with execution of 6 runs of 10 minute-long measurements; and (ii) resonant frequency measurement of a hardened mortar specimen, using the original system excitation system, with execution of 6 runs of 5 minute-long measurements.

The specimen used for the cement paste test was made according to the latest cement paste mould developments, presented in [4]. The mould is constituted by a 550 mm long acrylic tube with internal and external diameters of respectively 16mm and 20 mm. The specimen is in cantilever conditions with a span of 450 mm. The accelerometer is placed in the free end of the specimen.

Regarding the mortar specimens, the mould used was made according to the tests performed in [9]. The mould is a 550 mm long PVC tube with internal and external diameters of respectively 44 mm and 50 mm. the specimen is simply supported with a span of 500 mm. The accelerometer is placed at midspan.

The results of these tests will be detailed in the following subsection.

5.2 Results

The results of the conducted tests are presented in Table 1 and Table 2. For each test conducted, the developed device revealed satisfactory results, with an identified resonant frequency in the same range as the one identified with the original setup. The resonant frequencies obtained from the two systems were obtained with the same identification method, SSI. Fig. 5 presents the power spectrum that resulted from the experiment on the mortar specimen. The peak exhibited on the graph represents the 1st resonant frequency of the system composed of the specimen in its mould.

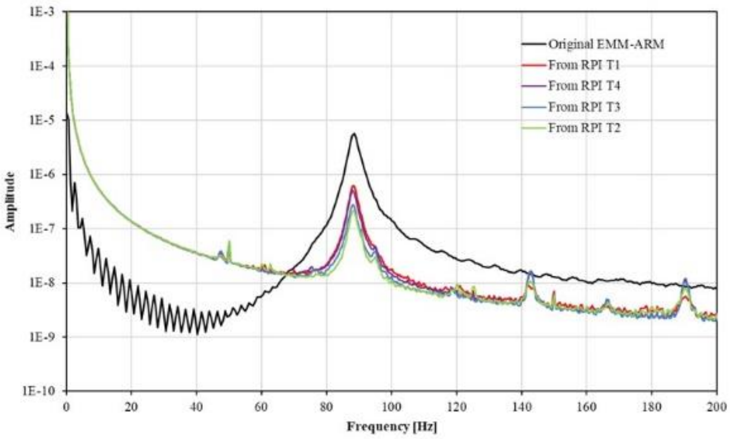

Fig. 5. Comparative power spectrum obtained with the mortar specimen

Table 1. Comparative results on 1 hardened cement paste specimen

Cement paste specimen test; Ambient vibration excitation								
Original setup								
	Run 1	**Run 2**	**Run 3**	**Run 4**	**Run 5**	**Run 6**	**Average**	**Standard deviation**
Frequency (Hz)	25,36	25,42	25,54	25,36	25,17	25,42	**25,4**	**0,12**
Developed device								
Frequency (Hz)	25,35	25,21	25,35	25,28	25,21	25,35	**25,3**	**0,07**
Gap (%)	**0,04**	**0,83**	**0,74**	**0,32**	**0,16**	**0,28**	**0,39**	

Table 2. Comparative results on 1 hardened mortar specimen

Mortar specimen test; Excitation of specimen generated by original setup								
Original setup								
	Run 1	**Run 2**	**Run 3**	**Run 4**	**Run 5**	**Run 6**	**Average**	**Standard deviation**
Frequency (Hz)	87,89	87,89	88,5	88,5	88,5	88,5	**88,3**	**0,32**
Developed device								
Frequency (Hz)	88,04	88,08	88,04	88,04	88,33	88,33	**88,1**	**0,15**
Gap (%)	**0,17**	**0,22**	**0,52**	**0,52**	**0,19**	**0,19**	**0,30**	

5.3 Discussions

For every test, the developed system identified resonant frequencies within less than 1% of gap compared to the original setup. The standard deviation of the developed device measurements is consistent and in the same order as the one of the original setup. These elements prove that the resonant frequencies identified by the developed device are reliable, and this device can be considered validated for single sample monitoring.

To complete the validation process, the developed device now needs to be tested for multi samples monitoring, as well as for monitoring the full hydration process of mortars. The tests should be conducted using the developed device's excitation for the electromagnetic actuator. These tests will be performed in the near future.

Even though the pure multiprocessing method was not used, the developed device exhibited very reasonable results, which prove the absence of necessity for it to achieve EMM-ARM tests.

Some aspects of the developed device should however be considered. Due to its limited acquisition capabilities, the developed device can only monitor a single specimen at a time; when several specimens are to be monitored during the same test, they are monitored in sequence, one after the other. For most applications, this aspect is not an issue considering the time scale of the hardening process of cementitious materials, but it could appear as one for some specific applications. Moreover, as RPi is not specifically designed to be used as a measurement system, the sampling frequency of acquisition can slightly vary from one run to another, which can partly explain the observed gaps with the reference original device in Table 1 and Table 2.

6 Conclusion

In this research, the aim was to develop an open-source and cost-effective device able to reliably conduct EMM-ARM tests. Therefore, different electronic components such as computing devices, ADC, DAC and accelerometers available on the market were investigated in order to select the most adequate ones. Some issues inherent to low-cost components were overcome, such as the ones related to the DAC, detailed in section 3.2.

In conclusion, an open-source and cost-effective EMM-ARM device was developed and presented in this paper. The device exhibited results comparable to those obtained with the reference original setup of EMM-ARM, costing approximately 12 times less. The validation process of the device will be completed with additional tests, to ensure its reliability and a multiprocessing programming method will be implemented.

The results obtained comfort the choice of electronic components for the targeted application. The system carries the advantage to be easily implementable and modulable, contributing to the development and dissemination of EMM-ARM.

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