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# PORTABLE SYSTEM WITH HIGH SAMPLING-FREQUENCY MEMS ACCELEROMETER

**ABSTRACT**

Vibration monitoring is a well-known and widely-used technique for technical diagnosis of devices. Using this technique, it is possible to foresee an incoming problem with a technical device, and avoid excessive environmental noise pollution. Vibration monitoring mainly uses piezoelectric accelerometers, which are high-precision and wide bandwidth devices, with price being the only serious disadvantage. Modern MEMS sensors, on the other hand are cheap, but usually with highly limited frequency bandwidth. The latter does not apply to the ADXL100x series of accelerometers by Analog Devices, which have a linear frequency response from DC to 11 kHz and the resonant frequency of 21 kHz. Such devices allow for application technical diagnosis using cheap hardware solutions. The goal of this paper is to present an example of a portable device built using two ADXL1001 accelerometers and a popular BeagleBone Black development board. The system allows for a maximum of 96 kHz sampling rate, which is more than required for the goal application. The system was tested using a calibration setup with a reference accelerometer.

**MEMS** accelerometers, vibration signal processing, BeagleBone, mobile system.

# 1. INTRODUCTION

Sounds and vibrations are inherently correlated: sounds are produced by vibrations of objects, which in turn cause movement in the surrounding medium molecules. The connection works also the other way: sound can induce vibration of an object–a useful phenomenon which is a principle of microphone operation. Sounds can be pleasant and wanted, or unpleasant and unwanted, in which case we call them 'noise'. However, noise can also be useful, even if it is unpleasant for humans. This unwanted sound can contain a lot of information about its source vibrations, and therefore be used to observe and diagnose the source. If the source is a technical object, one can use the sound and vibrations it produces for detection of possible faults and malfunctions.

Early detection of machinery faults and failures is nowadays an important issue in industry and other applications, due to the fact that it allows to reduce maintenance costs and downtime. It is a branch of more general technique that is known under the 'condition monitoring' term. Condition monitoring usually uses microphones and accelerometers as a measurement sensors, with the latter being more frequently used [1].

There are several types of accelerometers, e.g. piezoelectric, piezoresistive, capacitive, and others. Piezoelectric accelerometers are the most popular in industrial applications due to their very good properties, like wide frequency and dynamic ranges, good linearity, etc. Their only drawback is the price, which is not very low. Therefore, capacitive accelerometers, manufactured as microelectromechanical systems (MEMS), gained considerable attention in recent years [2]. This type of accelerometers is nowadays very popular and present in many different types of portable devices, e.g. cell phones, automobiles, remote controls, game controllers. The main drawback of MEMS accelerometers is a relatively narrow frequency range, which can be as low as from zero to a couple of hundreds Hz. Fortunately, this drawback is slowly eliminated, since there are already accelerometers with the frequency range exceeding 10 kHz. One of such accelerometers, namely ADXL1001 by Analog Devices [3], is the central component of the mobile system presented in this paper.

## 2. HARDWARE DESIGN

The design of hardware presented in this publication was based on the following functional requirements.

- The designed system should be portable, capable of operation with its own power supply.
- The system should be able to acquire at least two channels, with the sampling frequency at least 16 kHz.
- The data should be stored in persistent memory and available for later retrieval.
- The system should be compact and shock-resistant.
- The design should be cost-effective.

The above requirements resulted in selection of the BeagleBone Black (BBB) embedded system as a core of the developed solution. The BeagleBone Black is one of commercially available, low-cost development platforms, produced by Texas Instruments, featuring a powerful OMAP3530 System-On-Chip with ARM Cortex-A8 core. It is also open-source and community-supported, requiring no licenses or other charges. It allowed to speed up the development by omitting a very time-consuming phase of hardware design and prototyping. The main specifications of the BBB are presented in Table 1. The board price varies from $100 to $150.

**Table 1.** The BeagleBone Black main specifications [4].

| | |
|---|---|
| Processor | Sitara AM3358BZCZ100, 1 GHz, 2000 MIPS |
| Memory | SDRAM 512 MB, Flash 4 GB |
| General purpose IO ports | 69 |
| Power source | miniUSB or DC Jack |
| Power consumption | 210-460 mA |
| Other connectors | Ethernet, USB, microSD, HDMI |
| Dimensions and weight | 86x53 mm, 40 grams |

The main goal of the BBB platform was to acquire and process data from the ADXL1001 accelerometer, which was available in a form of the ADXL1001Z evaluation module. The ADXL1001 is a single in plane axis MEMS accelerometer, with ultra low noise density, analog output and linear frequency response from DC to 11 kHz. The main specifications of the ADXL1001 are presented in Table 2.

**Table 2. The ADXL1001 main specifications [3].**

| | |
|---|---|
| Measurement range | ±100 g |
| Linear frequency range (3 dB) | 0-11 kHz |
| Resonant frequency | 21 kHz |
| Noise density | 30 μg/√Hz |
| Power supply | 3.3-5.25 V |
| Sensitivity | 20 mV/g |
| Temperature range | -40-125 °C |

To connect the BBB and the accelerometer boards, add power supply (with basic protection) and a minimalistic user interface, a simple electronic circuit was designed, as presented in a form of a block diagram in Figure 1. The circuit comprises a power supply board, which was designed with the aim of providing a basic protection (over-voltage and reverse polarization) and automatic switching from internal to external power supply. The power supply uses the LM7805 stabilizer to provide a stable 5 V output to the BBB board for a wide range of the input voltage (9–14 V). The circuit also includes an LED diode and a switch, which allow the user to used to select one of the two operating modes and provides a visual output.

Another important function of the designed electronic circuit is anti-aliasing filtration. Although the ADXL1001Z board contains a basic anti-aliasing filter, the filter order is too low (1$^{st}$ order Butterworth filter), the filter cutoff frequency is too high (around 23 kHz) and the filter is located near the sensor, allowing the spurious signals induced in the connection wires to enter the analog-to-digital converters (ADCs). Therefore, an additional 3$^{rd}$ order Butterworth filter was designed, with the cutoff frequency equal to 8 kHz. The filter also serves as a voltage divider, as the ADCs input range is 0-1.8 V. Unfortunately, even such filter provides only around 10 dB of attenuation at the accelerator resonant frequency (21 kHz), which is not enough to effectively filter aliasing signals. For this reason, an oversampling and digital filtration was also implemented, as discussed in the next section.

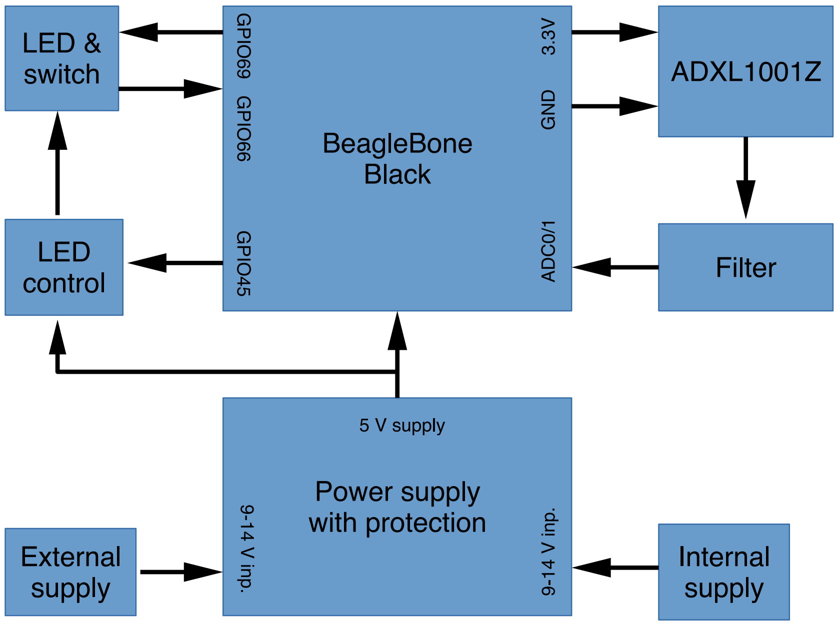


**Figure 1.** Hardware design block diagram.

## 3. SOFTWARE DESIGN

By default, the BBB board ships and operates under the Linux Debian operating system, although other OS are also available [5]. Therefore, once powered, the board starts the Linux kernel and accompanying processes first. The general purpose input-output (GPIO) ports and the ADCs are managed by the part of the kernel called the *device tree*, which is a data structure and language for describing hardware and its configuration. By simple means of editing selected text files, the device tree kernel subsystem allows to configure the hardware. In case of this work, the device tree was used to set the ADCs sampling frequency to 96 kHz. Such high sampling frequency was selected to oversample the input signal and allow for effective anti-aliasing filtration.

The next step was to write a software that will be responsible for final configuration, data acquisition, filtration and storing the acquired data on an SD card. The program was created in the C language, in a modular form, containing the following five modules:

- **configurator** – the module responsible for final configuration of GPIO ports and internal data structures,
- **acquisitor** – the module responsible for data acquisition from the ADCs,
- **gpioManager** – the module which allows to read and write the GPIO ports,
- **fileManager** – the module responsible for SD card mounting, file creation, data storage, etc.,
- **filter** – the module designed to perform the final data filtration and decimation.

The last of the above modules was designed to downsample the acquired accelerometer data from the original sampling frequency 96 kHz to the desired 16 kHz. To avoid aliasing, the procedure must be preceded with effective digital filtration [6], and the whole process is called *decimation*. On the other hand, the filtration must be fast, as it will be implemented in the real time. Therefore, a cascaded integrator-comb (CIC) filter was selected, which in fact is an optimized finite impulse response (FIR) filter combined with the downsampling.

The CIC filter transfer function is given by [7]:

$$H(z) = \frac{\left(1 - z^{-RM}\right)^N}{\left(1 - z^{-1}\right)^N} \tag{1}$$

where $R$ is the decimation ratio, $M$ is the number of samples per stage (usually 1), and $N$ is the number of stages. In the discussed case, the decimation ratio is equal to 96/16 = 6, while the number of stages was selected as $N = 5$. Figure 2 presents the frequency response of the selected CIC filter. It can be observed that the filter exhibits a deep null around the frequency 16 kHz, i.e. the Nyquist frequency after decimation, and the largest side lobe has magnitude -60 dB, which is quite enough for the discussed application.

Figure 3 presets the estimated power spectral density (using the Welch method) of the unfiltered and filtered accelerometer exemplary data before downsampling. One can notice that the frequency components above 8 kHz (the new sampling frequency) are effectively attenuated after the filtration. Therefore, no aliasing will occur during the downsampling of such signal.

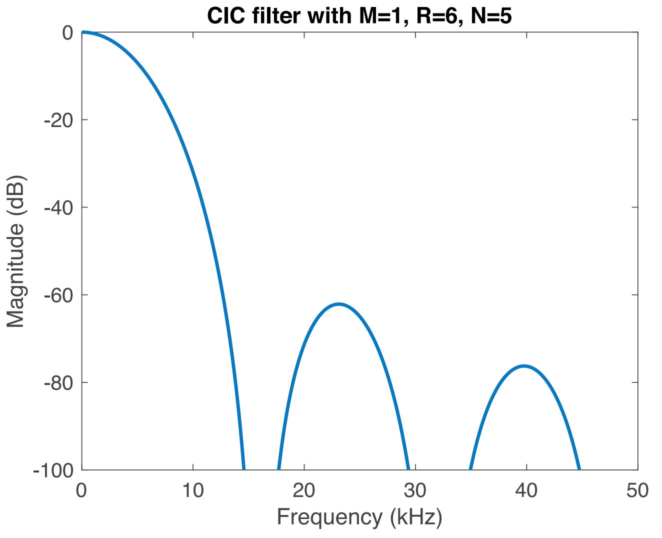


**Figure 2.** Frequency response of the CIC filter with M=1, R=6 and N=5.

# 4. CALIBRATION AND TESTS

The device was tested using a dedicated laboratory setup, consisting of the Brüel&Kjær Type 4809 vibration generator, equipped with the reference accelerometer and the Type 2525 Measuring amplifier. The accelerometers were excited using a single sine signal, with frequencies 160 Hz and 500 Hz, and with different amplitudes of vibrations. The acquired data were then analyzed to determine the amplification factor necessary to scale the data properly. This was necessary due to the fact that the accelerator sensitivity was only given for the supply voltage of 5 V, while in the developed solution the accelerators were supplied with 3.3 V. Moreover, the electronic circuit introduced a voltage divider, with a division factor imprecise due to imprecise resistor values.

An exemplary signal recorded during this calibration is presented in Figure 4. The accelerometer was excited with the frequency of 160 Hz, and with an amplitude of acceleration of 13.86 $m/s^2$. From the figure it can be observed that the amplitude of the recorded signal (that is half of the peak-to-peak value) is around 0.02 V. Therefore, the scaling factor should be around 700.

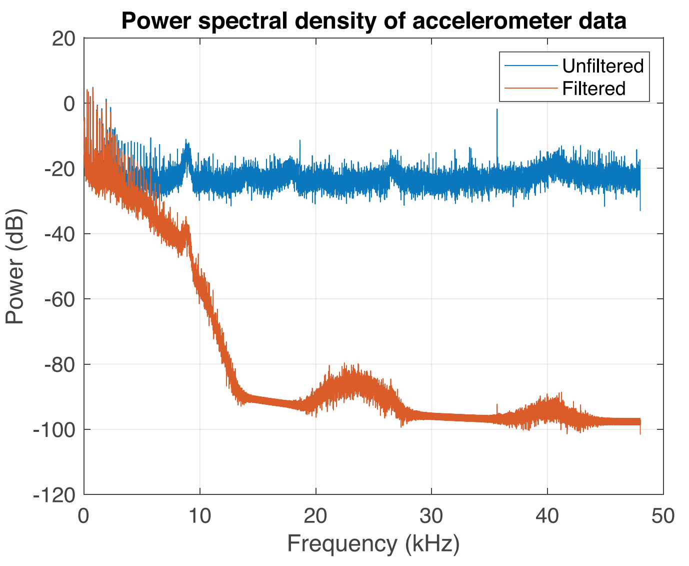


**Figure 3.** Exemplary power spectral density of the accelerometer data.

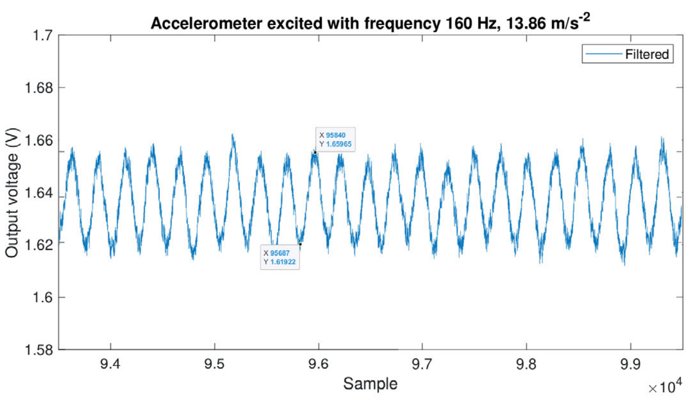


**Figure 4.** Data recorded during the device calibration.

# 5. CONCLUSIONS

A portable device for vibration measurement and recording using MEMS accelerometers were designed and constructed. The device is based on the BeagleBone Black development board, which provides a processing power necessary for fast sampling at a price of reasonable power consumption. The device uses the ADXL1001 MEMS accelerometers, offering a wide frequency range, exceeding 10 kHz, therefore, the sampling frequency of 96 kHz was seleted. However, due to potential application of the device [8], the frequency band was narrowed down to 8 kHz using digital signal filtration and decimation. The device was calibrated using a vibration exciter and a reference accelerometer.

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