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Digital Vibration Sensor Constructed with MEMS Technology

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***Abstract*—In this paper, a new digital sensor of acceleration is described. The sensor is based on MEMS device and is capable of measuring both static (gravity) and dynamic (vibration) accelerations. Its primary application is the measurement of vibrations in buildings and other constructions. The aim of this project was to design a low-cost, small-weight small-size acceleration sensor that can operate within simple sensor networks.**

***Keywords*—accelerometer, vibration measurement, MEMS.**

I. Introduction

MEASUREMENT of physical conditions in buildings becomes more and more important problem. One of the most essential issues is the measurement of vibration. Because of safety reasons, this requirement applies mostly to large constructions, like bridges, towers and skyscrapers. The interesting parameters in this case are: the amplitude, frequency and mode of vibrations. Nowadays, the projects of some constructions, besides the strength calculations, require also estimation of vibration resonant frequency. The calculations of this parameter should be experimentally verified, so the proper measurement equipment is necessary.

A. Universal Measurement Module

For several years, in Polish Building Research Institute a project of Universal Measurement Module (UMM) is being developed. This equipment, depicted in Fig. 1, is intended for measuring physical conditions on a construction site and within the buildings. The current version of the module [1] supports several types of sensors (e.g. temperature, humidity, resistance). The measurement results are stored in internal FLASH memory and can be accessible via wireless connection (GSM, GPRS, Bluetooth).

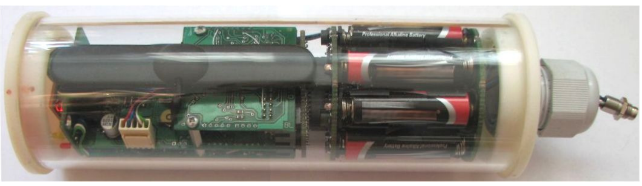

Fig. 1. Universal measurement module.

In order to measure the vibration of construction, a new kind of sensor has to be developed. A set of requirements to its functionality has been defined. The sensor should measure acceleration in three axes (X, Y, Z), in range ± 2 g and in bandwidth 0…100 Hz. In order to observe the mode of movement, it should be possible to connect a group of sensors in the network and perform coherent measurements. The sensors should have low power consumption, small size and weight to minimize the influence to measured objects. Measurement results should be available in digital format acceptable by the UMM.

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B. MEMS Accelerometers

During the last decade, we have noticed fast development of MEMS (Micro Electro-Mechanical Systems) technology. The employment of standard processes known from manufacturing of integrated circuits (e.g. photo-lithography) allows to create different mechanical objects in a silicon substrate, together with CMOS electronic circuits. This way the whole system, from sensor and filter to A/D converter and self test block, can be embedded in a single monolithic CMOS IC. When manufactured on a large scale, MEMS devices maintain relatively low unit cost.

Because of MEMS technology advantages, it has today many industrial applications. This technology is employed in manufacturing of different sensors, like accelerometers, magnetometers, gyroscopes, flow and pressure sensors. The accelerometers manufactured in MEMS technology can measure both static acceleration (gravity), as well as dynamic vibrations. Thus, a bandwidth of measured accelerations has no limit in low frequencies. This makes them very attractive solution in our application in measurement of vibrations in buildings.

The leading application of these sensors takes place in automotive systems, for example in air bag triggers, ABS, active suspension systems, headlight angle control, tilt sensing, antitheft systems and inertial navigation. They are also becoming more and more popular in consumer electronics (image stabilizers in digital cameras), in mobile phones, toys and generally – in computer peripherals (hard drive protection, joystick and other pointing devices, Virtual Reality input devices).

1) Convection-based Accelerometers: There are two basic methods of acceleration measurement in MEMS. The first method is based on heat transfer by natural convection inside of sensor chamber [2], [3]. As an example, in Fig. 2 we can see the structure of MXD2020 sensor manufactured by MEMSIC.

Inside the sensing chamber there is a heat source, centered in the silicon chip and suspended across a cavity [4]. Equally spaced aluminum/polysilicon thermopiles (groups of thermocouples) are located equidistantly on all four sides of the heat source. Under zero acceleration, a temperature gradient

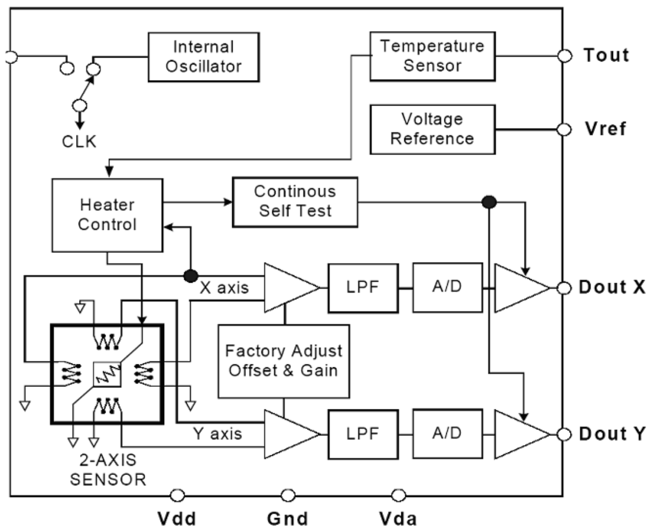

Fig. 2. Block diagram of MXD2020 sensor.

is symmetrical about the heat source, so that the temperature is the same at all four thermopiles, causing them to output the same voltage. Acceleration in any direction will disturb the temperature profile, due to free convection heat transfer, causing it to be asymmetrical. The temperature, and hence voltage output of the four thermopiles will then be different. The differential voltage at the thermopile outputs is directly proportional to the acceleration.

There are two identical acceleration signal paths on the accelerometer, one to measure acceleration in the X-axis and one to measure acceleration in the Y-axis. The voltage is amplified, filtered and converted to digital domain. The outputs are digital signals with duty cycles (ratio of pulse width to period) that are proportional to acceleration.

The study of convection-based accelerometers can be found in [5]. The advantage of this method is that the sensor has no solid proof-mass (and no moving parts) inside and is robust to very high level of vibrations and shock accelerations (up to 50 000 g). The disadvantage is that only two axes of measurement (X, Y) are available, and the bandwidth is limited ca. to 17 Hz due to physical constraints. Therefore, this kind of sensor does not fulfill the requirements of our application.

2) Capacitance-Sensing Accelerometers: The second family of MEMS accelerometers is based on capacitance measurement. The example of such a sensor (LIS3LV02DL made by ST Microelectronics) is shown in Fig. 3.

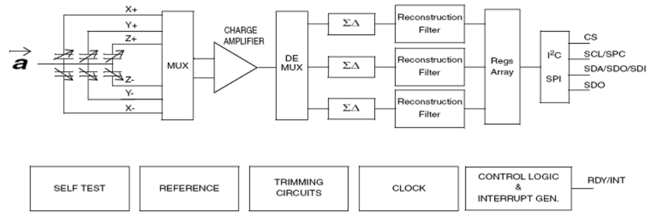

Fig. 3. Block diagram of LIS3LV02DL sensor.

The sensing element consists of three capacitive half-bridges [6]. When an acceleration is applied to the sensor, the proof mass displaces from its nominal position, causing an imbalance in the capacitive half-bridge. This imbalance is measured using charge integration in response to a voltage pulse applied to the sense capacitor. At steady state the nominal value of the capacitors are few pF and when an acceleration is applied the maximum variation of the capacitive load is up to 100 fF.

The complete measurement chain is composed by a low-noise capacitive amplifier which converts into an analog voltage the capacitive unbalancing of the MEMS sensor and by three $\Sigma\Delta$ analog-to-digital converters, one for each axis, that translate the produced signal into a digital bitstream.

The A/D converters are coupled with dedicated reconstruction filters which remove the high frequency components of the quantization noise and provide low rate and high resolution digital words. The charge amplifier and the $\Sigma\Delta$ converters are operated respectively at 61.5 kHz and 20.5 kHz. The data rate at the output of the reconstruction depends on the user selected decimation factor and spans from 40 Hz to 2560 Hz. The acceleration data may be accessed through an I^2C/SPI interface thus making the device particularly suitable for direct interfacing with a microcontroller.

II. Design of the Digital Accelerometer

In our project, we have decided to use MEMS sensor LIS3LV02DL manufactured by ST Microelectronics [6]. This device offers all the functionality required in our application with excellent performance. Most of the parameters of this sensor can be configured in the software level, by writing to control registers via SPI or I^2C interface.

The block diagram of the designed sensor is shown in Fig. 4. The MEMS device is controlled by Atmel ATmega48 RISC microcontroller. The blocks of samples of measured acceleration in X, Y, Z axes (see Fig. 6) are stored in RAM buffer. There is also an option of nonvolatile storage in FLASH memory.

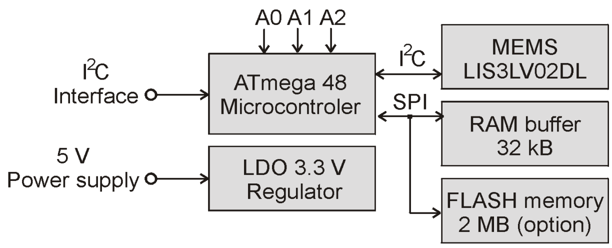

Fig. 4. Block diagram of designed sensor.

The sensor is powered from 5V DC source and connects directly with UMM via I^2C interface. Up to eight sensors can be connected together in a simple network. The lines A0, A1, A2 allow to assign unique address to each sensor. In Fig. 5 we can see the prototype sensor, and in Fig. 6 – the directions of the axes X, Y, Z relative to the sensor body. The specifications of the prototype are given in Table 1.

III. Example Results of Measurements

In order to verify the performance of the designed sensor in real conditions, a set of experiments has been carried out.

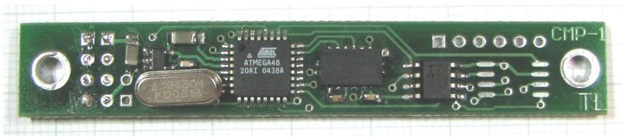

Fig. 5. View of prototype sensor.

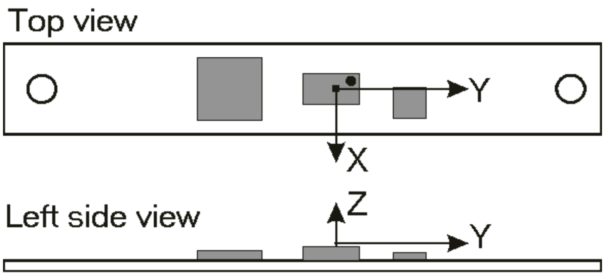

Fig. 6. Direction of sensor axes.

Fig. 7. Location of sensor on Gdanski Bridge in Warsaw.

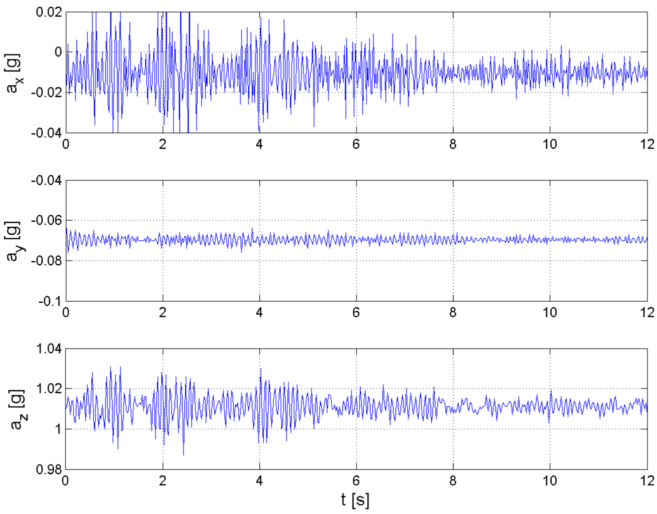

Fig. 8. Waveforms of the vibrations recorded on Gdanski Bridge.

A. Vibrations of Constructions

1) Gdanski Bridge: The first experiment took place in lower level of Gdanski Bridge in Warsaw (52°15'39,74"N, 21°00'40,41"E). In Fig. 7 we can see the place of measurements with arrow pointing the location of the sensor.

In Fig. 8 we can see the waveforms of vibrations recorded in all axes (a_x, a_y, a_z). The results are scaled in Earth gravity (g) units (1 g corresponds to 9.81 m/s^2). The sensor was magnetically attached to the steel railing on the edge of sidewalk. Y axis was the direction of the bridge, and Z was the axis of the gravity. The recording was started after a tram had passed through the bridge, initiating the vibrations of the construction. The FFT plot of the recorded signals is shown in Fig. 9. Sampling frequency was selected to 40 Hz, and the recording length was 512 samples. In the axes X, Z, perpendicular to the bridge direction, we can see clearly the vibrations with frequency around 11 Hz, probably caused by the railing construction. In the gravity axis Z we can see additional lower frequency (1.5 to 3.5 Hz) components, which could be caused by the bridge construction itself.

TABLE I
PARAMETERS OF PROTOTYPE SENSOR

Parameter	Value
Number of axes	3 (X, Y, Z)
Measurement range	±2 g or ±6 g
Sampling frequency	fs = 40 Hz, 160 Hz, 640 Hz
Measurement bandwidth	0. . .fs/4 (max. 0. . .160 Hz)
Resolution	1 mg (fs=40 Hz), 2 mg (fs=160 Hz), 3.9 mg (fs=640 Hz)
Max. offset error	70 mg (X, Y), 90 mg (Z)
Sample buffer size	5450 x 48-bit words
Sampling window	136 s (fs=40 Hz), 34 s (fs=160 Hz), 8.5 s (fs=640 Hz)
Operating temperatures	-30. . .+40°C
Power supply	3.6. . .6.0 V DC
Current consumption	0.63 mA (sleep), 4.3 mA (measure), 2.2 mA (read)
Weight	4 g
Dimensions	74 x 11.6 x 4 mm

2) Lazienkowski Bridge: In Fig. 11 we can see the vibrations recorded during the second experiment, which took place on Lazienkowski bridge in Warsaw (52°13'31,39"N, 21°02'54,81"E). The place of measurements is shown in Fig. 10 with arrow pointing the sensor location. As previously, the sensor was attached to the railing. The setup of the sensor parameters was identical as in previous experiment. The recording was started when two buses drove over the bridge one after another, causing clearly perceptible vibrations. We can see here strong, slow fading vibrations in Y axis. The corresponding spectral plot is shown in Fig. 12.

As we can see in FFT plot, there are clear components near the frequencies 7 and 10 Hz. Again, in Z axis there is additional low-frequency component (1.5 Hz) probably caused by the construction of the bridge. This time the amplitude of vibrations is 10 dB higher than in previous experiment, probably due to different construction of the bridge.

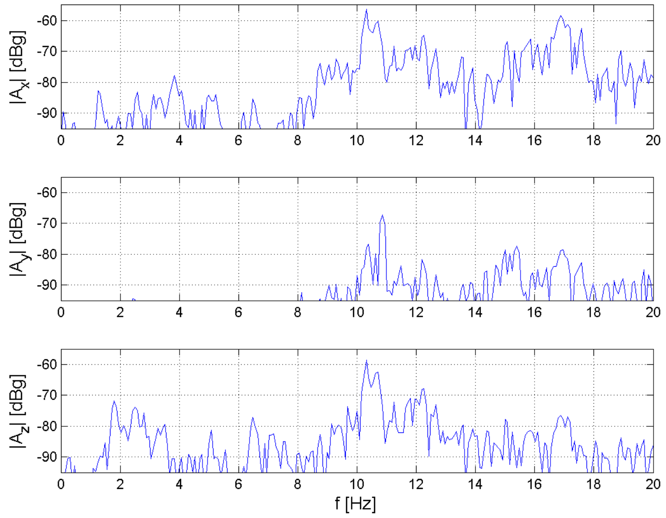

Fig. 9. Spectral plot of vibrations recorded on Gdanski Bridge.

Fig. 10. Location of sensor on Lazienkowski Bridge in Warsaw.

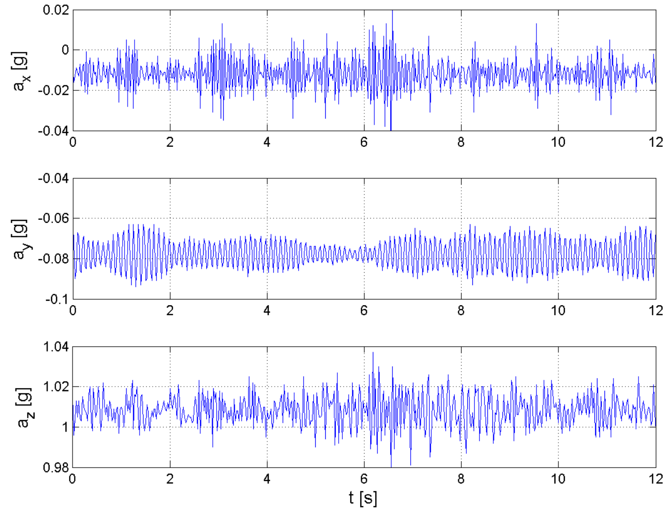

Fig. 11. Waveforms of vibrations recorded on Lazienkowski Bridge.

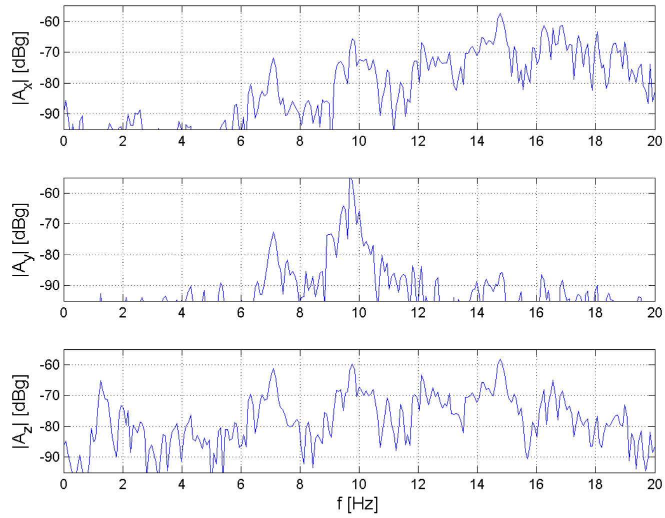

Fig. 12. Spectral plot of vibrations recorded on Lazienkowski Bridge.

B. Vibrations Inside Vehicles

Another experiment was carried out inside a streetcar in Warsaw. During the recording, the streetcar passed the junction, turned right and then was enetering the viaduct.

The acceleration was measured in three axes and sampled with 40 Hz frequency. The recording length was 512 samples. The sensor was attached to the window frame so that Z was the gravity axis (see Fig. 6) and Y axis was parallel to direction of movement. In the Fig. 13 we can see the waveforms of recorded vibrations.

As we can see in a_x and a_y plot, the streetcar changed its tilt after crossing the junction and when entering the viaduct. There are also low-frequency fading oscillations in Z axis, resulting from the suspension system that was excited at the junction. The FFT plot of the recorded vibrations is shown in Fig. 14.

Most of the vibrations falls into bandwidth $0 \ldots 5$ Hz. In X and Y axis there is a non-zero DC component resulting from tilt of the sensor. The suspension vibrations at ca. 1 Hz can be noticed in Z axis and also appear suppressed in X axis.

C. Vibrating Table in Laboratory

The vibrating table, shown in Fig. 15, is commonly used as a shaker in laboratory of building materials in Building Research Institute. In order to validate the working parameters of the shaker, and the vibrations applied to material during the experiments, the frequency and amplitude of vibrations should be measured in all three axes.

1) Empty table: During the first experiment, the table was operated without any load, as shown in Fig. 15. The block length was set to 5450 samples. Sampling frequency was initially selected as 40 Hz, but such a setup did not give any useful results due to aliasing effect. Finally, the sampling frequency was increased to 640 Hz.

The waveform of recorded vibrations is depicted in Fig. 16. The DC component was removed from all signals. As we can see, the amplitude of vibration in vertical axis a_z reaches 3 g, and in horizontal a_x, a_y axes: 0.6 and 0.3 g, respectively. The shape of vibrations is sinusoidal in all axes.

In order to determine the frequency of vibrations, FFT spec-

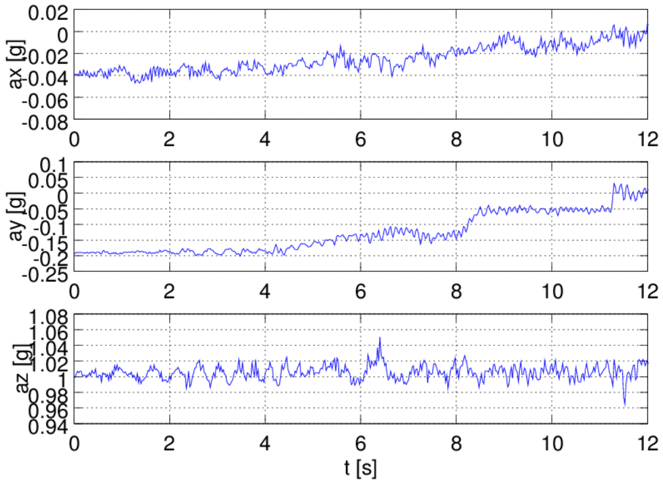

Fig. 13. Waveforms of the vibrations recorded in streetcar.

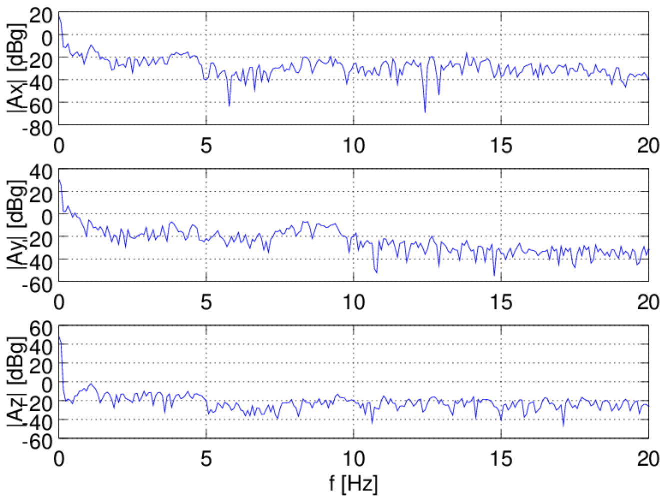

Fig. 14. Spectral plot of the vibrations recorded in streetcar.

Fig. 15. Vibrating table with attached accelerometer.

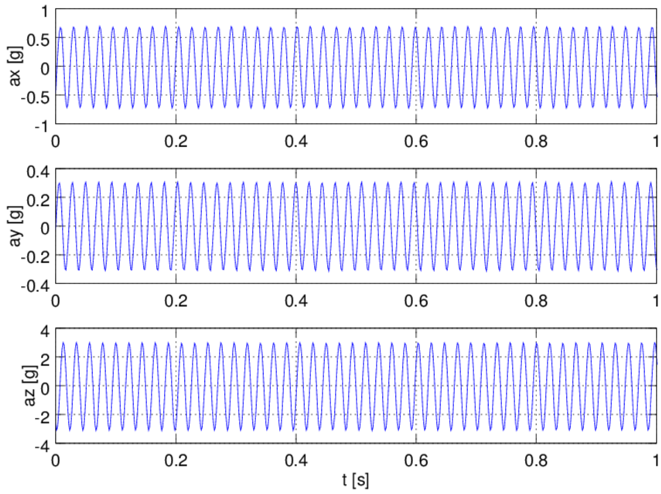

Fig. 16. Waveforms of the vibrations of unloaded table.

trum was calculated and plotted in Fig. 17. From the spectral plot we can see that the main frequency of vibrations is around 45 Hz. In horizontal axes X, Y we can see also components with frequency 100 Hz, which is twice the frequency of AC power line.

2) Loaded table: Before the second experiment, a container for material was attached to the table. The container was empty and its weight was about 3 kg. The experiment was started with such a load. The waveform of recorded vibrations (with removed DC component) is depicted in Fig. 18.

After loading the table, the amplitudes of vibration in horizontal a_x, a_y axes have fallen to 0.3 and 0.2 g, respectively. At the same time the amplitude of vibration in main axis a_z has increased to 4.5 g. Therefore, the load of the table has an impact to the vibration levels in all three axes. As previously, FFT spectrum was calculated and plotted in Fig. 19.

The main difference from the previous case without load, shown in Fig. 15, is the increased level of 45 Hz component in A_z spectrum. This time, in A_z spectrum, 100 Hz component is also present. The rest of components in higher frequencies did not change amplitudes significantly.

IV. Conclusion

In the paper, a new digital sensor of acceleration has been described. The sensor was designed to measure vibrations of constructions and buildings, as a part of research project developed in Polish Building Research Institute. The designed sensor enriches the set of sensors currently supported by the Universal Measurement Module.

The experiments have proved that the sensor can be employed to measurements of vibrations with small amplitudes (0.01 g or 0.1 m/s^2) with bandwidths 0…160 Hz. The results are available directly in digital format and thus can be easily processed in DSP algorithms. The small size of the sensor, low weight and low costs of production make it possible to be used in different areas. Besides the primary application (i.e. examining bridges, towers, buildings and other constructions), this sensor can be successfully used for example in mechanical machinery, cars and transportation units. It can also be used as a reference in experiments carried out in laboratories with vibrators and shakers, since the load size has a significant impact to the vibration parameters during each experiment.

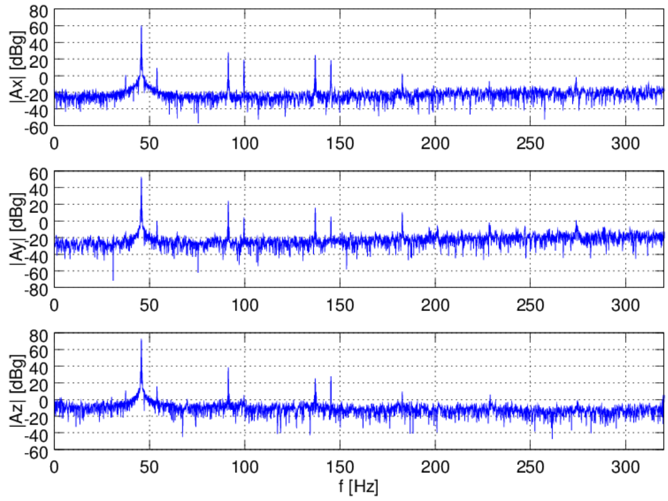

Fig. 17. Spectral plot of the vibrations of unloaded table.

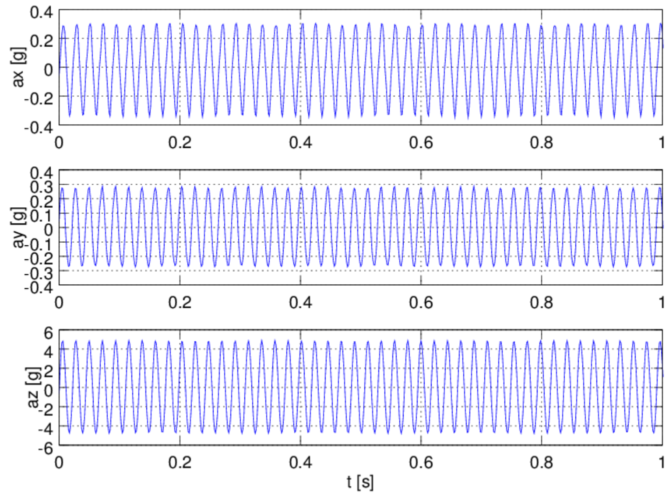

Fig. 18. Waveforms of the vibrations of loaded table.

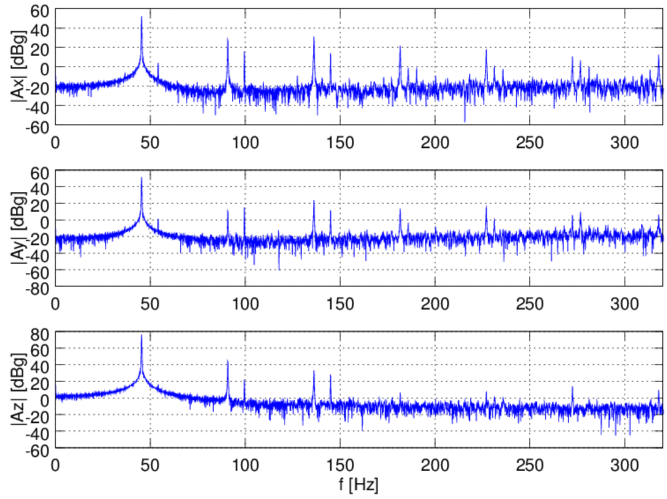

Fig. 19. Spectral plot of the vibrations of loaded table.

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