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Development of low-cost high-frequency data acquisition system for energy harvesting applications

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Abstract. The presented work describes a method in which, using a dedicated system, it is possible to simultaneously transfer energy and data between two devices. The proposed solution allows for supplying power to the sensor with simultaneous data transmission. The power transmission mechanism is based on the excitation of the structure with a wave, which is converted into electricity by a harvester device. Data transmission is carried out using the Double Frequency F2F procedure, which is a type of frequency modulation.

Introduction

In the last few decades, it has been possible to reduce the power needed to supply electronic devices to just a few dozen milliwatts [1]. At these power levels, traditional batteries are limited to short-term operation, mainly due to dimensional limitations. In addition, in the event of prolonged use, the batteries need to be replaced or recharged, and at the same time, they degrade.

Energy Harvesting (EH), originally known as energy harvesting or energy scavenging, is a set of techniques that provide electricity by converting energy from various sources such as mechanical, thermal, solar, and electromagnetic energy and salinity gradients, etc., e.g., [2]. In general, the main goal is to use sources commonly available in the environment, which in most cases are undesirable and suppressed (e.g. or as a result of electric current flow and engine cooling, etc.). Currently, it is said that EH can be a useful source of "cheap or no-cost" (excluding installation costs) power to low-power electrical devices [3-7].

One source of energy wastage is structural vibration. Vibrations in engineering structures such as buildings or bridges have low amplitudes and frequencies (0.1 g and 0.1 Hz); at the same time, various small electrical appliances, such as ovens, microwave ovens, and others, have higher amplitudes and frequencies (0.5 g and about 150 Hz, respectively) [8]. The above conditions inspired the development and description of many types of combined harvesters in the literature.

Two types of harvester devices can be distinguished, i.e. passive materials and active materials. In the case of active harvesters, most devices are based on magnetostrictive or piezoelectric materials (PZT) [9, 10]. It should be noted here that piezoelectric harvesters are capacitive energy sources; therefore they have a high output impedance. This means that appropriate power management circuits must be used to power electrical devices. On the other hand, there are magnetostrictive harvesters that are inductive. Thanks to this, they can provide low impedance at frequencies characteristic of most common sources of vibration.

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Of the passive vibrational energy harvesters, the magnetostrictive devices deliver a higher energy density. Moreover, a comparison of magnetostrictive devices with devices based on piezoelectric material showed that both can generate similar levels of energy output; however, there is no need for additional special power management circuitry for solutions based on magnetostrictive material. Among magnetostrictive devices, the two most common types are the axial type and the bending type, based on the state of stress in the material. Axial devices are usually mounted in places where there is a high excitation force [11–19]. Thanks to such high loads, they can generate relatively high power densities, even up to 10 W/cm^3 [14]. In contrast to axle harvesters, the bending device for obtaining vibration energy can be mounted on any source of vibration [20–24]. It should be noted that in the case of magnetostrictive harvesters, their efficiency is variable and depends on many factors, such as load, operating frequency, mounting method, or the material from which the device is built.

In the literature on the subject, it can be seen that the research focused mainly on piezoelectric transducers [4–6,25,26]. It turns out, however, that in some cases a better solution is the use of magnetostrictive harvesters [27]. Taking into account the research conducted so far in this area, the main goals of this research are:

- development of a system enabling the transmission of energy and information through a solid body in the case of ultrasonic frequencies (the system should operate at frequencies above 20 kHz, ie inaudible to most people);
- use of intelligent materials (piezoelectric and magnetostrictive);

The paper presents a data acquisition system using an axle harvester. Such a harvester was selected after analyzing the already developed combines that can be found in the literature. In addition, such a solution was also associated with the expected amount of energy that could be generated using this type of device.

Magnetostrictive harvester

In the case of magnetostrictive devices, the most important component is the magnetostrictive core. Such a core may consist of one or more elements, depending on the size, length, and purpose of the device. The core material is also important. Such material must be characterized by gigantic magnetostriction (GMM - Giant Magnetostrictive Materials, e.g. Terfenol-D, nano-cobalt ferrite). An additional element is a system that allows you to adjust the initial magnetization of the material, which is usually properly selected neodymium magnets. The number of elements that make up the core of the device has a significant impact on the frequency of operation. The smaller the number of elements, the higher the operating frequency can be. To optimize the design of the actuator, magnetostrictive material and neodymium magnets are used alternately.

The actuators/harvesters presented in the article have relatively large dimensions: the diameter of the device was 44 mm and its height was 47 mm. The geometry was forced mainly by the need to apply the appropriate pressure of the cylinder to the tested structure. Inside the housing, there was a coil with resistance $R_{coil} = 5.5\ \Omega$. The devices operated over a wide frequency range from 10 Hz to 30 kHz to find the resonant frequency of the system within which the system achieved the highest voltage values. In addition, both the harvester and the actuator were pre-tensioned with a force of 400 N. This value was determined based on experimental tests, during which the magnetomechanical response of the system was determined depending on the applied load. Successive constructions and modifications allow for more and more power; therefore, these devices began to be used as a source of electricity (Fig. 1).

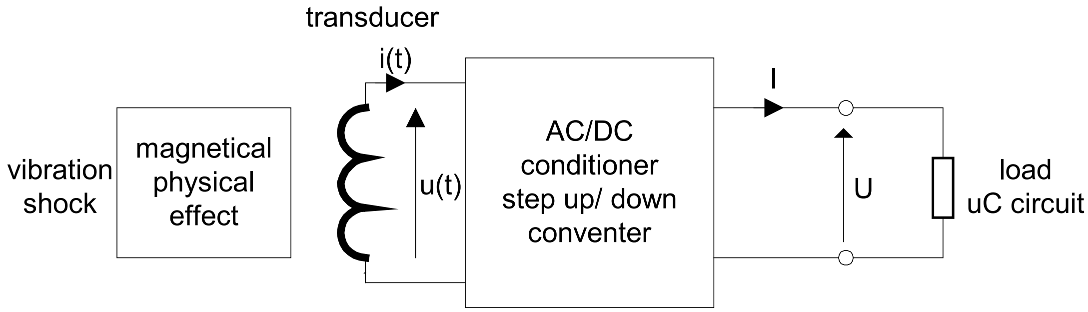

Figure 1. Harvester scheme.

Power and data transmission

In previous studies by the authors, it turned out that magnetic materials of the SMART type can be effectively used for the wireless transmission of energy and information [28]. The obtained results also indicate the high efficiency of this method. The system developed by the authors, which allowed the simultaneous transmission of data and power, is called SURPS (SMART Ultrasonic Resonant Power System). This system provides transmission through various solids as well as through liquids. An additional advantage of the system is the possibility of using various transmitter-receiver configurations [28]. The results presented in this work are a continuation of the work on the use of the magnetomechanical effect in the case of energy acquisition, described in more detail in [28].

The transmission was using an actuator that transfers the mechanical energy in the form of a pure sinusoidal ultrasonic wave, and then this wave was picked up by a harvester which converted this wave into an electric current through the magneto- or electrostrictive material contained therein. This way of transmitting energy also made it possible to transmit information. Moreover, it was possible to transmit energy through various materials, and the choice of material depended mainly on the distance over which the energy had to be transmitted.

For the transmission of information, the F2F procedure was used, which is a type of frequency modulation. The modulation worked in such a way that the data transmission frequency was an order lower than the structure's resonant frequency. Figure 2 shows schematically how the data was transmitted by the magnetostrictive actuator (AT) and how the signal was received by the magnetostrictive harvester.

System Structure

The newly developed system has been designed to work with various actuator-harvester configurations. One such configuration is a system where harvesters are connected in series and placed between two parallel beams. Such a system is characterized by a resonant frequency above 20 kHz. The test stand, consisting of two steel rails with magnetostrictive transducers placed between them, is shown in Fig. 3. This system enabled simultaneous powering of the microprocessor on the side of the power harvester and data transfer in both directions.

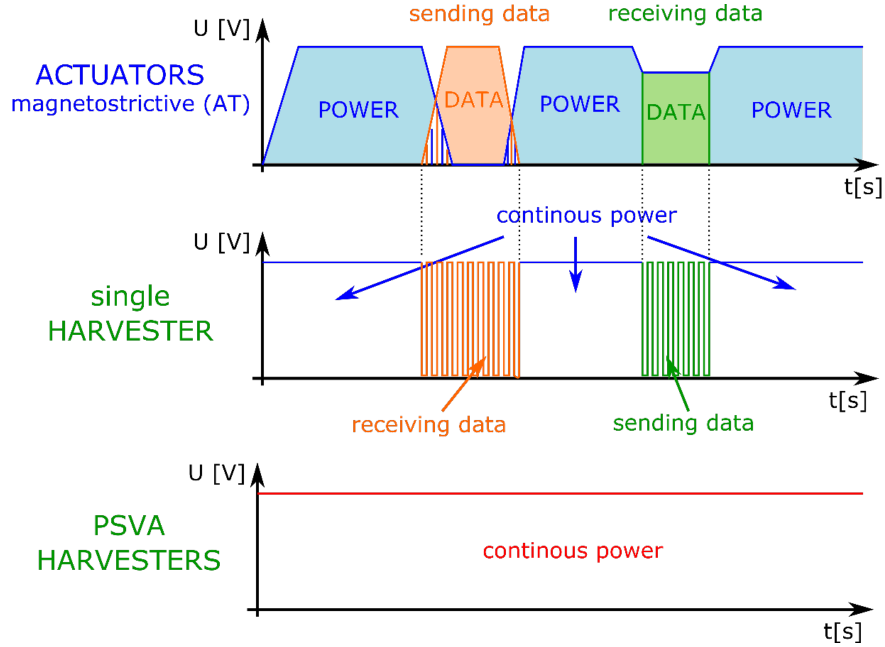

Figure 2. Scheme of data transmission and receiving information.

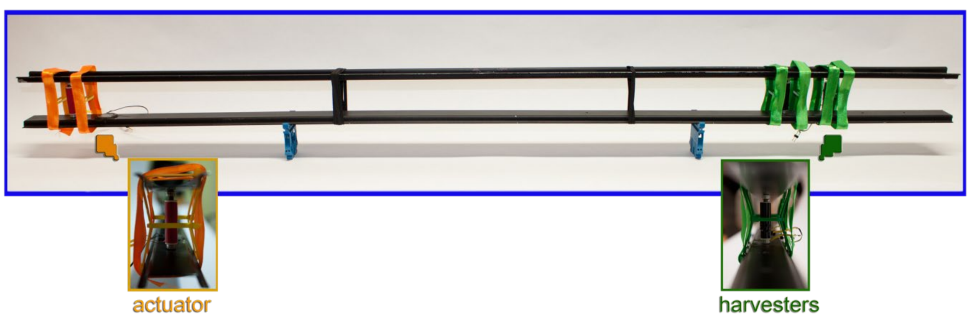

Figure 3. Actuator–harvester magnetostrictive system based on two beams.

Based on the above-described solution, supplemented with the current state of knowledge in the field of ultrasonic techniques and wireless power transmission, an original and innovative transmitting–receiving system was developed. The platform consists of a real-time module (STM32F411VE board) and a computer running Windows OS. A FTDI-bridge FT2232H was used to transfer data between the STM32-board and a personal computer. Figure 4 shows, the scheme of the system. Compared to Arduino-like solutions, this solution allows to reduce of the reaction time of the STM32-board to external events and provides a good data transfer rate (up to 8 Mbyte/Sec at FT245-Style Asynchronous FIFO mode). For software development, the non-commercial versions of IDE were used: Keil MDK 5.36 Community and Microsoft Visual Studio 2022 Community. The frequencies of the ultrasonic actuators were set in the standard way using an AD9850 DDS-generator. For each DDS frequency, 2048 16-bit words of ADC1-channel and 2048 16-bit words of ADC2-channel were recorded. To estimate the phase shifts, the IEEE standard three-parameter algorithm was used. Despite the non-optimal configuration of the ADC of STM32F411 (sequential sample and hold for each channel), a quantization frequency of 200 kHz was obtained for the two-channel measurement mode and transmission of a data packet through FTDI-bridge to the memory of a personal computer. This result was obtained for the layout on the contact breadboard and without software optimization. Optimal installation of modules and

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optimization of the program will increase the quantization frequency up to 500 kHz for the two-channel ADC mode and allow to make FFT analysis of the properties of different sensors in the frequency domain.

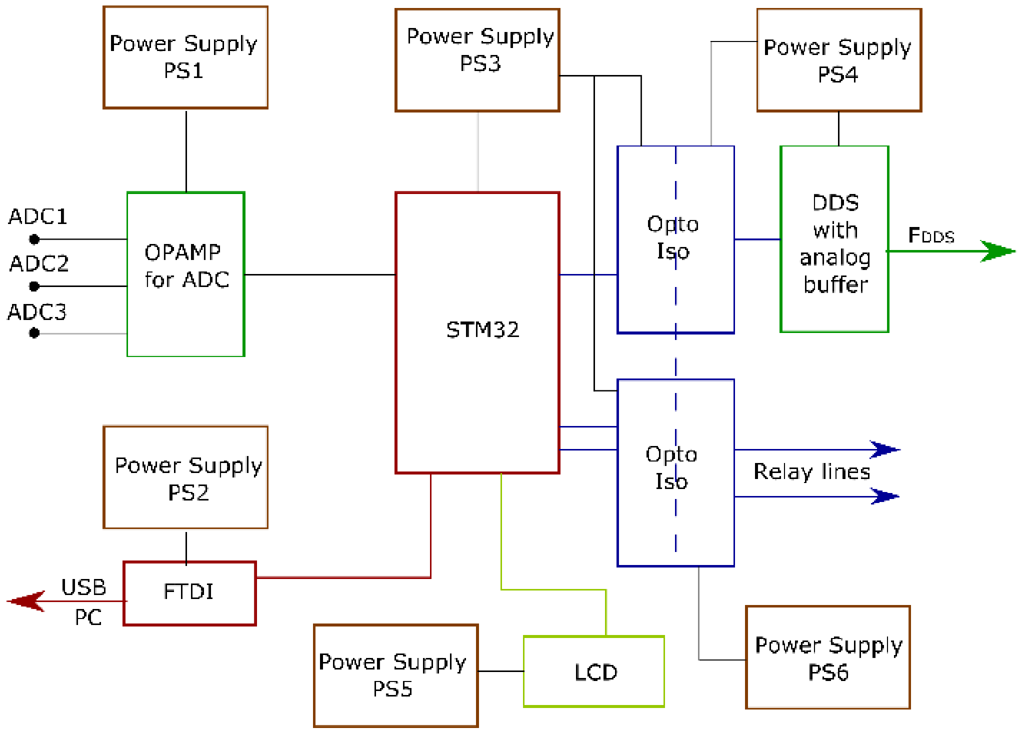

Figure 4. A block diagram of the developed system.

The main applications of the designed system are:

- service of piezoelectric or magnetic actuators/harvesters;
- scanning of the set frequency range using the actuator-harvester system with real-time performance reading;
- search and generation of the resonance frequency of mechanical structures;
- data transmission between the actuator and the harvester section in both directions;
- the ability to generate a signal for two actuators generating vibrations of the same frequency, but shifted in phase.

The results showing the frequency-amplitude characteristics for the circuit shown in Fig. 3 are shown in Fig. 5. It is worth noting that the highest voltage value (the highest efficiency) was obtained for the frequency in the above acoustic band (above 20 kHz). The zone marked SW in the figure defines the acceptable range of resonant frequencies and is about 20 kHz. The dashed line shows the voltage value at the level of 2.5 V, above which the microprocessor system was lost. In addition, point A indicate the most favorable frequency ranges for broadcasting information. As you can see, several frequency ranges can be distinguished that allow the system to be powered and depending on the conditions and needs, choices can be made between the required ranges of carrier signals. It should also be mentioned that it was possible to connect more microprocessors to the harvesters network, but in this case, it was necessary to maintain a strict order of their activation. This solution allows the system to be used in SHM (Structural Health Monitoring) applications with multiple sensors.

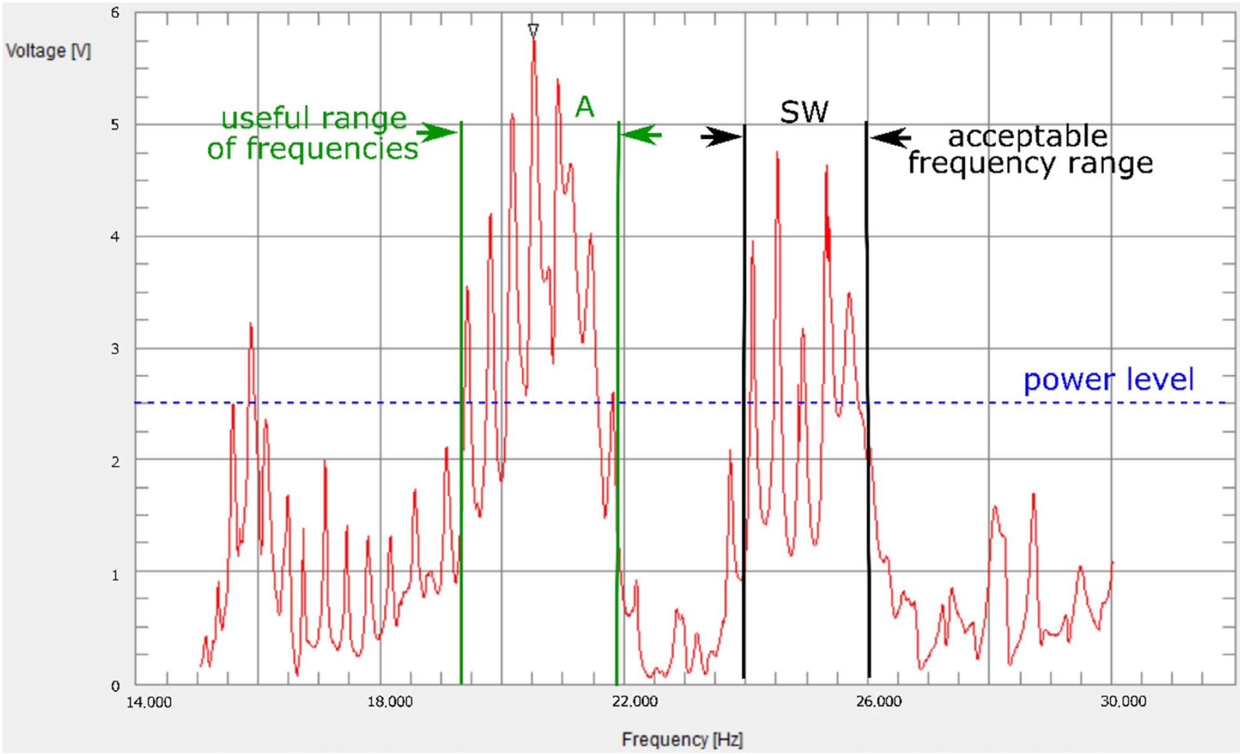

Figure 5. Frequency response of the dual-beam system.

The results obtained during the tests showed that the developed platform enables the transmission of energy over a distance of up to 3 m without the use of wires and using only various types of mechanical structures. This solution allows the use of various types of harvesters in many configurations, while the selection of the appropriate harvester system is influenced by the material and form of the medium through which energy and data are transmitted, as well as the ultrasound wavelength.

Conclusions

The article presents the results of work on the transfer of energy and information using various materials. The results achieved include:

- A platform that allows the transmission of power and information in relatively long rods using ultrasonic vibrations;
- The use of collectors/actuators based on both magnetostrictive and piezoelectric materials and the use of F2F (frequency/double frequency) procedures, which are a type of frequency modulation, to transfer information;
- Development of proprietary software for selecting the appropriate actuator and type of modulation as well as the recommended frequency band for energy and data transmission.

The results presented in the article are current and constitute the basis for further work in the field of energy and data transmission.

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