Energy Harvesting for Wireless Sensors by Using Piezoelectric Transducers

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ABSTRACT

Wireless sensor technology, which integrates transducers, measurement electronics and wireless communication, has become increasingly vital in structural health monitoring (SHM) applications. Compared to traditional wired systems, wireless solutions reduce the installation time and costs and are not subjected to breakage caused by harsh weather conditions or other extreme events. Because of the low installation costs, wireless sensor networks allow the deployment of a big number of wireless sensor nodes on the structures. Moreover, the nodes can be placed on particularly critical components of the structure difficult to reach by wires. In most of the cases the power supply are conventional batteries, which could be a problem because of their finite life span. Furthermore, in the case of wireless sensor nodes located on structures, it is often advantageous to embed them, which makes an access impossible. Therefore, if a method of obtaining the untapped energy surrounding these sensors was implemented, significant life could be added to the power supply. Various approaches to energy harvesting and energy storage are discussed and limitations associated with the current technology are addressed. In this paper we first discuss the research that has been performed in the area of energy harvesting for wireless sensor technologies by using the ambient vibration energy. In many cases the energy produced by the ambient vibrations is far too small to directly power a wireless sensor node. Therefore, in a second step we discuss the development process for an electronic energy harvesting circuit optimized for piezoelectric transducers. In the last part of this paper an experiment with different piezoelectric transducers and their applicability for energy harvesting applications on vibrating structures will be discussed.

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INTRODUCTION

Wireless sensor devices have the advantage of eliminating wiring installation expense as well as connector reliability problems [1]. However, portable wireless devices require batteries as a power source in order to operate. The disadvantage of traditional batteries, however, is that they become depleted and must be periodically replaced or recharged [2, 3]. This constitutes an additional maintenance task that must be performed.

Many environments are subjected to ambient vibration energy that commonly goes unused. Several methods exist for obtaining electrical from it source including the use of electromagnetic induction, electrostatic generation, dielectric elastomers and piezoelectric materials. While each of the aforementioned techniques can provide a useful amount of energy, piezoelectric materials have received the most attention due to their ability to directly convert applied strain energy into usable electric energy and the ease at which they can be integrated into a system.

In a previous work we developed a wireless sensor network for Structural Health Monitoring applications by using piezoelectric elements and guided ultrasonic waves [4]. As piezoelectric transducers we used Active Fiber Composites because they are light and flexible and therefore they can be applied on curved structures.

The aim of the present project is to develop an energy harvesting circuit which can be integrated into the existing wireless sensor nodes. For converting the ambient vibration into an electrical current we use also the AFC elements which are used for exciting ultrasonic waves into a structure and for measuring the response of the structure. In a first step we defined the electrical and mechanical parameters of the AFC element. In a next step we develop the energy harvesting circuit adapted to the AFC element. In the end the whole energy harvesting circuit was tested.

ELECTRONIC CIRCUIT FOR ENERGY HARVESTING OF AMBIENT VIBRATION ENERGY

Active Fiber Composite

The main electrical parameters of the AFC, the internal resistance $R_{AFC} \geq 1$ GΩ and the internal capacitor $C_{AFC} = 0.7$ nF, were measured with a simple multimeter. The coupling coefficient between the electrical and mechanical behavior of the AFC element was estimated with a four-point bending test. The test was performed on a custom-made test-rig with a servo-hydraulic actuator. Therefore, the AFC was bonded on a carbon reinforced composite (CFRP) plate. The stress on the CFRP plate was measured by four strain-gauges bonded on the CFRP plate and connected to an instrumentation amplifier. The output signal coming from the AFC was measured by a charge amplifier. Both output signals are displayed on a two channel oscilloscope.

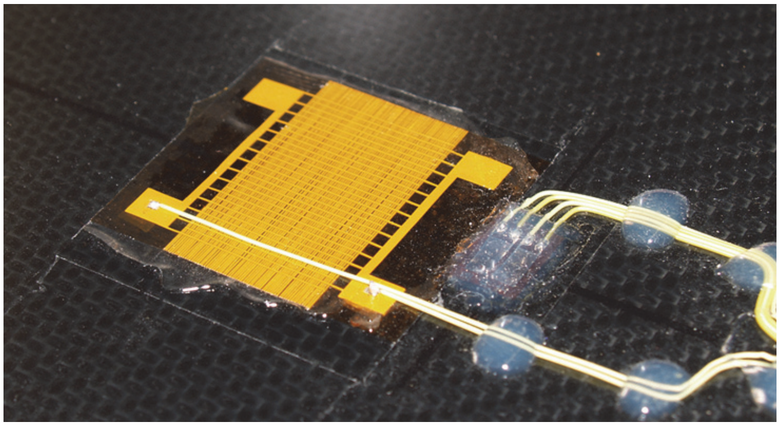

Figure 1. Active Fiber Composite element bonded on a CFRP plate.

By using the output signal (voltage) coming from the instrumentation amplifier the strain ε in the CFRP plate can be calculated by,

$$\varepsilon = \frac{1}{k_{DMS} \cdot V_{Supply} \cdot 2 \cdot G} \cdot V_a = \frac{1}{2.1 \cdot 5.9\,V \cdot 2 \cdot 99.7} \cdot V_a = 4.2289e^{-4}\frac{V_a}{V}$$

where k_{DMS} is the gauge factor of the strain gauge, V_{Supply} is the supply voltage of the strain gauge, G is he gain of the instrumentation amplifier and V_a is the measured voltage on the output of the instrumentation amplifier. The coupling factor k of the AFC element can than calculated by,

$$k = C_{AFC} \cdot \frac{\Delta V_C}{\Delta \varepsilon}$$

where C_{AFC} is the capacity of the AFC elment, ΔV_C is the voltage difference between the output AFC element and output of the instrumentation amplifier. With the now known parameters of the AFC element the expected current output of the element can be calculated by,

$$I(t) = \frac{2\pi \cdot f \cdot \hat{\varepsilon} \cdot k}{\sqrt{2}} = \frac{2\pi \cdot 10\,Hz\ 300\,\mu\varepsilon \cdot 2.2\,mAs}{\sqrt{2}} = 29.62\,\mu A$$

The used AFC element has in total an area of A = 620 mm^2 and therefore a calculated current of 47.77 nA/mm^2.

Energy harvesting circuit

In order to perfect a wireless sensor device which exploits energy harvesting, the entire system must be considered. The power consumed by all of the system's components (sensor, conditioner, processor, data storage, and data transmission) must be compatible with the energy harvesting strategy and the available power levels. Obviously, minimizing the power required to collect and transmit data correspondingly reduces the demand on the power source. Therefore, minimizing power consumption is as important a goal as maximizing power generation.

For our SHM applications we use a wireless sensor network with a number of four wireless nodes. For the power supply of each single wireless node a Lithium-Polymer battery with a power capacity of 330 mA/h is embedded. The wireless senor network was developed primarily for applications on transportation systems. Hence, the time duration before a recharging of the battery should be at least between 3 and 6 hours. To guarantee this duration with the limited capacity of the battery a software function for optimizing the power consumption was developed. The software function was split in four different operation modes, (1) sleeping mode, (2) waiting mode, (3) actuator mode and (4) sensor mode. With the aspect of energy harvesting the software function for the power consumption has to be extended for a further operation mode – (5) harvesting mode. If no measurement is requested the wireless sensor node is switched in "energy harvesting mode".

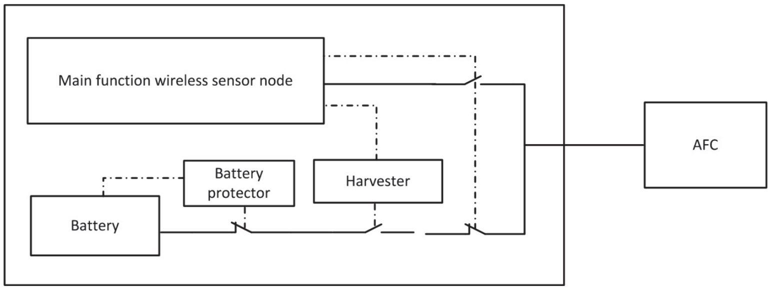

Figure 2.Wirless sensor mode with integrated energy harvesting circuit and AFC element.

Basically the wireless sensor node is switched into "harvesting mode". That means, the path AFC to the main function module inside the wireless sensor node is disconnected from the AFC element. The AFC element is connected direct to the internal battery. This function is controlled by the Harvester module. For protection the battery against total discharge a battery protector is integrated into the harvesting circuit. If the energy level is too low for driving the main function of the wireless node the wireless senor node will be switched into the harvesting mode until the energy level is high enough for the main function of the node. Periodically the wireless senor node checks if a measurement is requested or not. This is done with an interrupt. If a measurement is requested the AFC element will be connected direct to main function of the wireless node and the harvesting path will be disconnected.

The main components of the electronic circuit are, (1) a rectifier which converts the alternating current coming from the AFC element into a direct current, (2) intermediate accumulator consisting of a capacitor, (3) a direct current to direct current (DC-DC) converter for adapt the voltage of the intermediate accumulator to the level of the supply battery and (4) a battery protector against overvoltage. All above described functions are integrated on the energy harvesting chip LTC3588-2 from Linear Technology. This chip has relatively low energy consumption. The function of the LTC3588-2 is as follows, if the voltage on the intermediate accumulator capacitor reaches 16 V, the internal buck converter charges an output capacitor through an inductor to a value slightly higher than the regulation point. It does it by ramping the inductor current up to 260 mA through an internal PMOS switch and then ramping it down to 0mA through an internal NMOS switch. This efficiently delivers energy to the output capacitor.

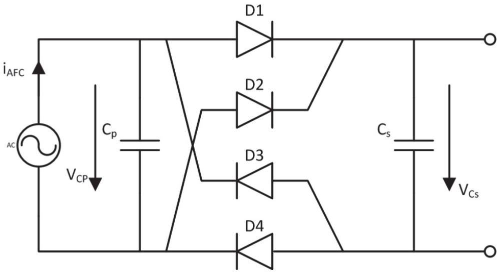

Figure 4. Electric circuit of the energy harvesting charging part.

Figure 4 shows the electrical circuit drawing of the charging function for the energy harvesting function. The current source on the left side is equivalent to the AFC element. The main parts of the circuit are the rectifier consisting of the four diodes D1 – D4, and the capacitor C_s as intermediate accumulator. The current coming from the AFC element is diagramed by the current source on the left and the internal capacitor of the AFC element is shown as $C_{p.}$

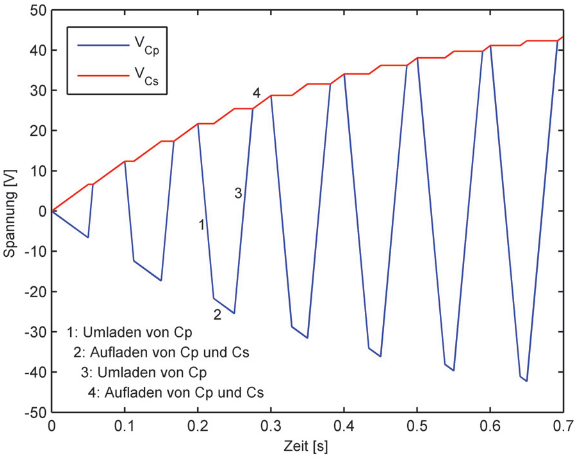

Figure 5. Steps of the charging process of the energy harvesting circuit.

The charging process of the harvesting circuit is illustrated in figure 5 and works as follows:

i. In the beginning the voltage V_{CP} over capacitor C_p and the voltage V_{CS} over capacitor are of the same level.
ii. After extending the AFC element the negative current discharge the capacitor $C_{p.}$ The absolute vale of $|V_{CP}|$ is lower than V_{Cs} and therefore all diodes of the rectifier are closed. The whole current coming from the AFC element is flowing through the capacitor C_P, until V_{Cp} reaches the level of $-V_{Cs}$.
iii. Until $V_{Cp} = -V_{Cs}$, D2 and D3 are conducting and conductor Cp charges the conductor C_S.
iv. Until V_{Cp} reaches the level V_{Cs}, the diodes D1 and D4 are conducting and the current i_{AFC} is charging C_P and C_S.

Because of the non-defined potential on the output of the AFC element we integrated two optical metal-oxide-semiconductor field-effect transistors

(OptoMOSFET) type PBA150 from CLARE as connection between energy harvesting circuit and AFC element.

Estimation of the output power

For calculating the efficient output power P_{out} of the energy harvesting circuit equation 1 is used,

$$P_{out} = f \cdot (4 \cdot A \cdot k \cdot V_{out} - 4 \cdot C_p \cdot Vout^2)$$

where f is the oscillating frequency of the AFC element, k is the coupling coefficient of the AFC element. With a oscillating frequency of f = 3 Hz, A = 0.616 ‰, k = 0.0022 As, V_{OUT} = 15 V, C_P = 0.7 nF the output power of the energy harvesting circuit is about 242 µW.

VALIDATION OF THE DEVELOPED ENERGY HARVESTING CIRCUIT

For testing the energy harvesting circuit we used the above described four-point bending test equipment with the AFC bonded on the CFRP plate. The bending test was driven with a frequency of about 1 Hz.

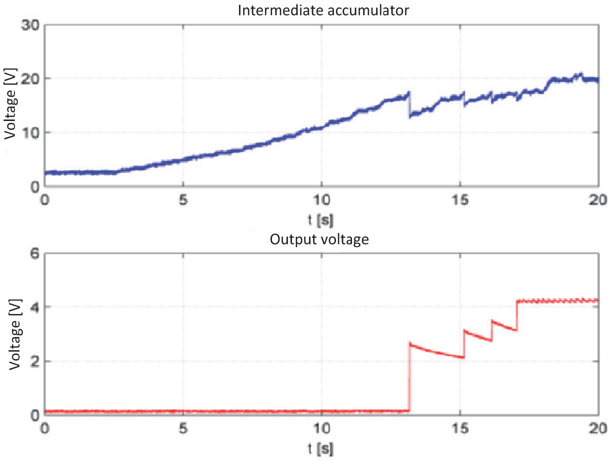

Figure 6. Real charging process for the energy harvesting circuit.

Figure 6 shows the charging process of the energy harvesting circuit. The curve above shows the voltage on the intermediate accumulator versus time and the curve below shows the output voltage of the energy harvesting circuit. The voltage on the intermediate accumulator rises after a voltage level of 16 V is reached. Now the energy harvesting circuit switches the current through the circuit and charges the output capacitor and the voltage on the intermediate accumulator drops to a level of 14 V. Again, the AFC element connected to the rectifier charges the intermediate accumulator up to the 16 V voltage level. This process will be repeated until the output voltage reaches the voltage level of 4.1 V.

VALIDATION OF THE DEVELOPED ENERGY HARVESTING CIRCUIT

With the in this work described energy harvesting circuit it is principle possible to charge the battery for wireless sensor nodes which are used for Structural Health Monitoring applications. For converting the ambient vibration of a CFRP plate we used Active Fiber Composite elements bonded on the plate. The same elements are used for exciting guided ultrasonic waves into the CFRP plate for monitoring the plate. Also the energy management for the exciting wireless sensor nodes was optimized.

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