ENERGY HARVESTING FOR HIGH-SPEED SENSOR TELEMETRY

D. Hoffmann[1], A. Willmann[1], B. Folkmer[1], and Y. Manoli[2]
[1]HSG-IMIT – Institute of Micromachining and Information Technology, Villingen-Schwenningen, Germany
[2]Fritz Huettinger Chair of Microelectronics, Department of Microsystems Engineeing – IMTEK, University of Freiburg, Germany

Abstract: In this paper we demonstrate an energy autonomous wireless sensor system (V-PowerNode) including a vibration based energy harvester for high-speed sensor telemetry in continuous wave transmission. For the first time an energy autonomous sensor telemetry system is employed in the harsh field of the construction and manufacturing industry. Typical applications include soil compacting and concrete block manufacturing posing a challenge for the harvester and sensor system due to the extreme environmental conditions and high acceleration amplitudes (5g to 400g). The vibration based energy harvester generates electrical output power (5V regulated output voltage) in the range from 100 mW to 500 mW when operated at frequencies between 35 Hz and 60 Hz and when acceleration amplitudes between 2g and 13g are present.

Keywords: vibration energy harvester, high-speed sensor telemetry, energy autonomous wireless sensor system

INTRODUCTION

In typical energy harvesting applications small amounts of non-electrical energy are converted and accumulated by small PowerMEMS devices over a longer period of time [1]. In this manner electrical energy is made available for discontinuous operation of a sensor application. In general, the activity cycle of such a sensor system is typically low and depends on the energy available from the vibrations. However, there are applications that require continuous data acquisition and transmission at high sample rates in order to facilitate a closed loop control of the relevant process parameters. Considering high-speed sensor telemetry, MEMS based energy harvesting devices are less appropriate to meet the power requirements.

In this paper we present an energy autonomous sensor node (V-PowerNode) for high-speed sensor telemetry in the construction and manufacturing industry. Both, wireless data transmission and maintenance-free operation over a long period of time are essential key characteristics required for the V-PowerNode. The V-PowerNode will be employed in two specific pilot applications: road construction (in particular the process of soil compaction) and concrete block manufacturing. For both applications, the objective is to improve the quality of the product by optimization of the operation conditions. Moreover, the prevention of failure and the increase of the operation efficiency are further aspects to be achieved by the employment of the sensor telemetry system. In this paper we focus on the soil compaction application.

Figure 1 shows a soil compactor device, which is composed of a frame, four suspensions and a vibrating plate being excited by an eccentric motor. The compactor device is being used as an attachment by an excavator. There are three different operation frequencies available for the soil compaction process. The quality and grade of the soil compaction depends on three operation parameters: vibration frequency, load and process time. In order to achieve both, improved soil compaction and increased process efficiency, continuous condition monitoring as well as the control of the process parameters are necessary. Since hard-wired sensor systems or regular maintenance of wireless sensor systems (e.g. change of batteries) is not acceptable in this kind of application environment, a wireless and energy autonomous sensor system is mandatory. Therefore, an appropriate energy harvester must be developed, which complies with the high-level requirements.

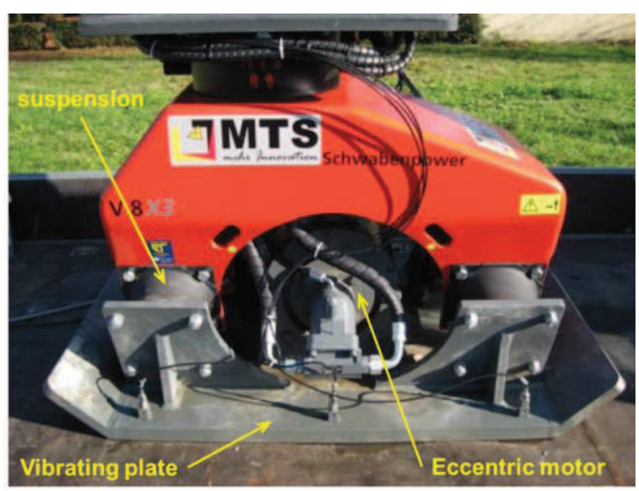

Figure 1: Soil compactor device

DESIGN & MODELLING

In order to achieve real-time process monitoring and closed-loop control of the process parameters, continuous data acquisition at high sample rates and real-time data analysis is necessary. In the first phase of the device development we aim to detect the grade of the soil compactness. This is accomplished by computing the total harmonic distortion from the frequency spectrum of the vibration profile. For measuring the vibration profile of the vibrating plate a wireless sensor module was developed by a project partner (Figure 2). This sensor module incorporates an accelerometer and a Bluetooth transmitter. The required sample rate for acquisition of the vibration profile is 5000 samples per second. At 16 bit resolution the data transfer rate results in 115 kbps. Due to the permanent transmission of data (without any interruptions) the continuous power demand is 350 mW. In a further development we aim to reduce the power demand of the sensor module to about 200 mW.

The requirements, which must be considered for the development of the energy harvester are summarized in Table 1. Most importantly, the vibration energy harvester must be capable to provide the required output power of 350 mW (at 5V regulated output voltage) for excitation frequencies between 30 Hz and 80 Hz. Within the given frequency band the acceleration amplitudes are typically in the range between 5g and 50g. The corresponding displacement amplitudes are between 1 mm and 3 mm. Shocks up to 100g are also possible considering the soil compactor application. Since the V-PowerNode is also used for condition monitoring of concrete block manufacturing machines, the energy harvester must withstand shocks up to 400g, which may occur in the production process of concrete blocks. Moreover, the harvester should be as small as possible in size.

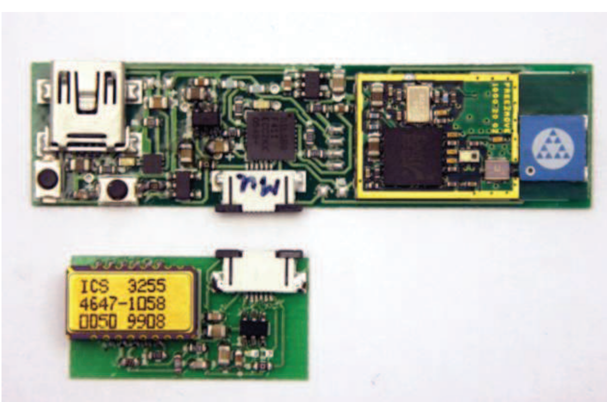

Figure 2: Wireless inertial measurement unit including an accelerometer and Bluetooth transmitter

Table 1: Requirements for V-PowerNode

Requirements for V-PowerNode	Value
Operation frequency band	30 Hz – 80 Hz
External acceleration amplitudes	5g – 50g
External displacement amplitudes	1 mm – 3 mm
Robustness / shock resistance	400g
Water proof	
Voltage output (regulated)	5 V
Power output	350 mW
Size	minimize

Based on the list of requirements and boundary conditions a vibration based energy converter was developed for effective operation in the required frequency band. The design of the energy harvester is shown in Figure ***3*** including the electromagnetic energy conversion architecture and the power management. The wireless sensor module will be mounted on top of the energy harvester in a special cap, which is made from a specific plastic material. This will allow the transmission of the sensor data via Bluetooth. The casing of the energy harvester is made from a metallic material, thus the sensor module must be outside the casing.

The choice of the electromagnetic coupling architecture is based on a comparative study, in which the effectiveness of several different architectures is compared [2]. Architectures which incorporate a closed magnetic circuit by means of back iron parts show the highest effectiveness. With respect to the present boundary conditions (e.g. large displacement amplitudes, strong metallic environment and necessity for limit stops) we selected architecture A-VIII (see Figure 4) as the most suitable coupling architecture

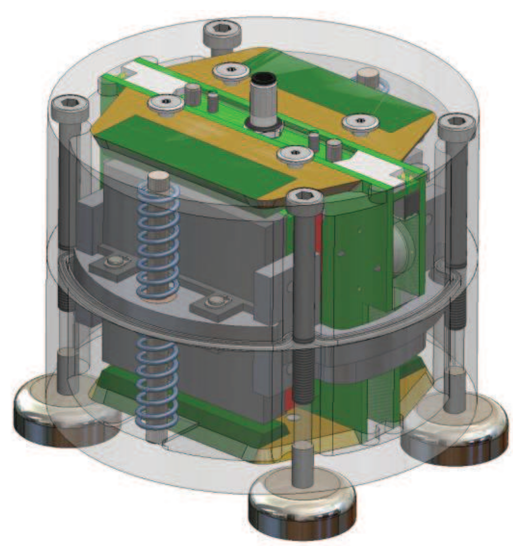

Figure 3: Design of V-PowerNode

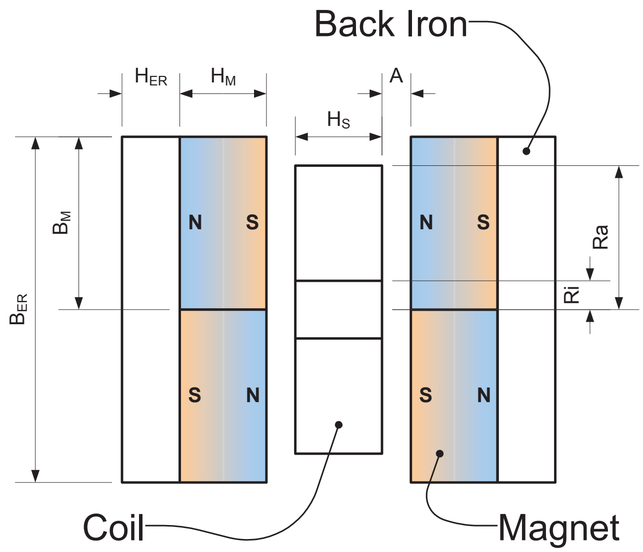

Figure 4: Coupling architecture of V-PowerNode

for the V-PowerNode. The coupling architecture A-VIII incorporates 4 magnets, 2 back iron sheets and a single coil, which is placed in the air gap between the two pairs of magnets. In this architecture a constant magnetic field is present in the air gap. The change of magnetic flux in the coil emerges from the differential area function of the coil. The coupling factor is maximal at the initial position (as shown in Figure 4) and reduces with increasing displacement in either direction.

The coupling architecture of the V-PowerNode was parameterized (Figure 4) and incorporated into a system model. Optimization algorithms were applied in order to obtain optimum parameter values for which the power requirements are fulfilled at minimum device size.

A further aspect is the mechanical coupling of the vibrations to the energy converter structure. The well-known mass-spring structure was selected in order to couple the vibrations to a seismic mass, which is then electrically damped. However, due to the strong external acceleration amplitudes the eigenfrequency of the mechanical system must be carefully designed. In order to avoid mechanical destruction and to facilitate effective energy conversion in the required frequency band, an amplification factor of 1 is preferable. Therefore, the mechanical eigenfrequency was designed to be 20 Hz, which is well below the operation frequency band. The internal displacement amplitude was limited to 2 mm by mechanical stoppers. Here, a special material is utilized to obtain a soft limit stop and also to achieve high durability of the energy harvesting device.

A further challenge was the development of the power management circuitry. At start-up the sensor module draws a current of about 100 mA at 5V input voltage. In normal operation mode the current consumption is about 70 mA. Therefore, suitable energy buffers and the employment of threshold switches are important key elements of the power management electronics. Moreover, during operation the energy harvester may generate voltages up to 10 V. Since the maximum rating of most energy buffers are 5 V or below, the voltage output from the harvester must be limited. At the same time the efficiency of the power management electronics must be maintained at a high level for voltages up to 5 V.

Figure 5: V- PowerNode on laboratory shaker

CHARACTERISATION

The V-PowerNode was first characterized without any power management electronics using a laboratory shaker. For measuring the power output a load resistance was directly connected to the coil. The value of the resistor was selected to be equal to the internal resistance of the coil. In this manner an optimum load resistance is obtained for which the output power becomes maximal. This is because the energy harvester is operated off-resonance. In a second phase, the energy harvester was characterized together with the power management circuit. In this case a variable resistor was connected to the 5 V output port. The value of the resistor was then reduced to a point at which the energy harvesting system was just capable to provide the regulated output voltage of 5 V. In this manner the maximum output power was obtained. The output power was then measured as a

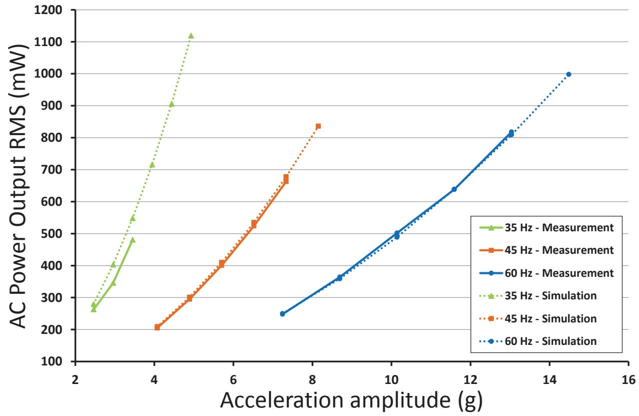

Figure 6: Direct AC RMS output power at optimum load resistance (simulation & experiment) as a function of acceleration amplitude.

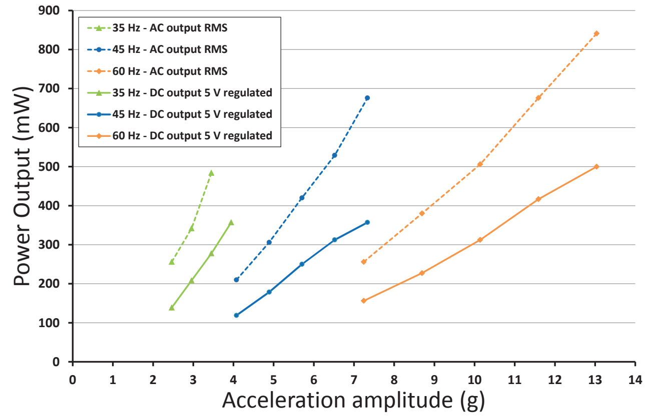

Figure 7: Output power: comparison between direct AC output at optimum load and DC output (5V regulated) at maximum possible load

function of acceleration amplitude.

Results of experimental characterization are summarized in Figure 6 and Figure 7. The excitation amplitude was varied between 2g and 13g. Data points at which the energy harvester is in impact mode are not shown. When impacts occur due to the internal displacement limits, the power output increases only slightly with increasing acceleration amplitudes. In Figure 6 the direct AC output power is shown in comparison to the simulation results. The power predictions from our system simulation are in very good agreement with the measurements. At lower operation frequencies (here 35 Hz) the oscillation of the seismic mass is not exactly translational, therefore the measured output power is less than predicted by the simulation. The power output ranges from 200 mW to 800 mW.

The DC power output at the regulated output port is shown in Figure 7. For comparison, the AC output power is also shown. From the data it is evident that the effectiveness of the energy harvester is reduced by about 40% when the power management circuit is used. The fact that the harvester is not operated at optimum operation conditions (impedance matching) causes a significant reduction in effectiveness: at an operation frequency of 60 Hz, the energy harvester is able to produce 850 mW power output (at 13g) if the load is matched to its impedance. However, using the power management circuit an effective power of only 500 mW is available for the sensor module. At lower frequencies the minimum power requirement of 350 mW is achieved. The V-PowerNode was also successfully operated in a field test. The device was placed onto a vibrating plate of a soil compactor. The compactor was then used to compact the ground of a test field at the three different operation frequencies. The V-PowerNode successfully transmitted the measured data at the required sample rate. However, when the energy harvester was in impact mode, the sensor data was influenced by the impacts at the mechanical limit stops.

CONCLUSION

An energy-autonomous wireless sensor node (V-PowerNode) for high-speed sensor telemetry was developed. The development comprised the wireless sensor module, the energy harvester and the power management circuitry. Typical applications for the V-PowerNode include soil compaction (road construction) and concrete block manufacturing. In case of the road construction, the wireless telemetry system is used for detecting the grade of the soil compaction in order to improve the quality and to increase the operation efficiency. Moreover, the use of several sensor nodes at different positions enables to identity the vibration mode of the vibrating plate. Thus, prevention of failure is possible by adjusting the process parameters if specific vibration modes occur.

ACKNOWLEDGEMENTS

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REFERENCES

[1] Mitcheson P. D., Yeatman E. M., Rao G. K., Holmes A. S. and Green T. C. 2008 Energy Harvesting From Human and Machine Motion for Wireless Electronic Devices, *Proc. IEEE*, **96**

[2] Spreemann D., Folkmer B. and Manoli Y. 2008 Comparative study of electromagnetic coupling architectures for vibration energy harvesting devices, *Proc. PowerMEMS (Sendai, Japan, Nov. 2008)*, pp. 257-260