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EVALUATION OF ENERGY HARVESTING CONCEPTS FOR TIRE PRESSURE MONITORING SYSTEMS

M. Löhndorf¹, T. Kvisterøy², E. Westby³, and E. Halvorsen³

¹Infineon Technologies AG, 81726 Munich, Germany.

²Infineon Technologies SensoNor AS, Horten, Norway.

³Vestfold University College, Norway.

Abstract: Using mechanical vibrations as energy source is of great interest for industrial and automotive applications, since engines and turbines are inherent sources of vibrations. Thus, an efficient vibration generator must be custom designed for the target application. In comparison to most wireless network applications, the Tire Pressure Monitoring System (TPMS) application in the tire/wheel assembly should provide significantly more vibrations at higher amplitude. SPICE simulations have shown that MEMS based electrostatic vibration energy harvester deliver 10 μ W average power to supply a TPMS. This paper gives background information about the application as well as requirements for an energy harvesting system.

Key Words: Energy Harvesting, MEMS, Tire Pressure Monitoring, Wireless Sensors

1. INTRODUCTION

The continuous reduction in size and power consumption of active electronic devices as well as the advances in wireless communications enables the extended use of wireless sensors in industrial and automotive applications. The biggest motivation for using wireless links in industry is potential cost saving. The cost savings from not having to install cables can be very substantial. This is particularly relevant in many process industries where sites are very large or spread out (e.g. water utilities). While the vast majority of wireless sensors and transducers are used in process industries where they are used for monitoring many different criteria e.g. temperature, fluid levels, humidity. In addition there are applications where connecting a sensor or transducer with cables is either difficult or impossible. In the automotive industry the numbers of sensors have continuously increased over the last decade, but wireless sensors have been used only in cases where direct cabling is not possible (e.g. on rotating parts). Self-powered sensor devices are of great interest in the automotive and aviation industry due to the limitations of the available power and inaccessibility related maintenance costs.

The National Highway Traffic Safety Administration (NHTSA) has issued a mandatory

regulation for TPMS [1] in the United States. This mandatory regulation has led to a significant increase of wireless sensors during the phase-in period from Aug. 2004 until Sept. 2007. Furthermore, future developments might enable the combination/implementation of wireless sensors with the rubber tire. However, new power sources such as energy harvesting are needed in order to fulfill the requirements of lifetime, robustness and weight.

2. TIRE PRESSURE MONITORING SYSTEMS

2.1 General Information

Most so-called direct TPM systems [2, 3] consist of a Sensor/ASIC IC, LF interface, RF transmitter, antenna and a primary battery as power source.

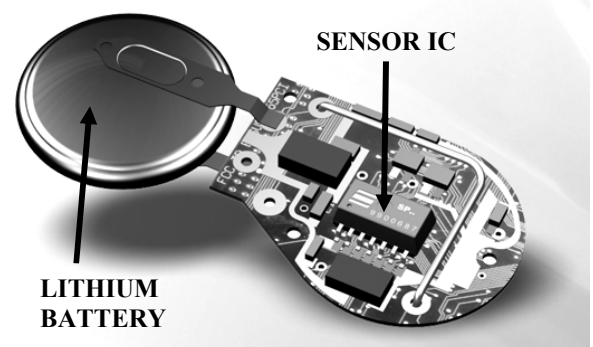


Fig. 1: Schematic illustration of TPMS module.

Figure 1 shows a schematic of a standard battery powered TPMS module. For the RF-transmission from the wheel to the electronic central unit (ECU) the Industrial Scientific Medical (ISM) frequency bands are used (in Europe 434 MHz / 868 MHz and in the USA 315 MHz / 915 MHz). The TPMS module is fixed in an airtight housing by a molding process except for the pressure hole. Due to high acceleration forces in the wheel a safe installation of the module on the rim is required. Therefore, the modules are affixed direct on the valve or with a rotary belt on the rim.

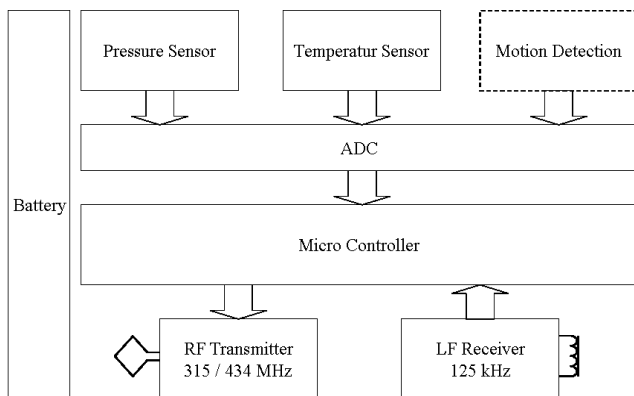


Fig. 2: Electrical components of a TPMS module.

The electrical components of a TPMS module are shown in Fig.2. Besides a pressure and temperature sensor an accelerometer is often used as a motion detector and enables the possibility to decide whether the car is parking or driving. Based on this information, the microcontroller will manage how often the pressure and temperature measurement is performed and transmitted via the RF link. The majority of the commercial available direct TPM systems are using lithium-based primary batteries. Lithium (Li) - ion coin cells exhibit an excellent energy-density vs. weight ratio with an open-circuit voltage (V_{oc}) of about 3-3.5 V as well as an extended operating temperature range. However, the Lithium-Ion battery takes about 30-40% of electronic volume of a TPMS module, due to the needed capacity of approx. 400-550mAh in order to fulfill the OEM 10 year lifetime requirement. In addition to size and cost related issues the battery weight is a major drawback for further integration of TPMS modules into the wheel/tire assembly. In the drive mode (vehicle is moving) each TPMS

module transmits approx. every 30sec. via RF link the absolute pressure, temperature and supply voltage to a common receiver unit. An indicator lamp displays if the tire pressure of a single or multiple tires are below a certain threshold. During parking and stand still the transmission intervals are increased in order to save battery power.

2.2 Power requirements

Each RF transmission of a datagram with a length of 100bit with a transmission rate of 10kbit/sec takes about 200-250 μ Ws for a State-of-the-Art TPMS module [4]. According to the 10 year lifetime, the data transmission is a significant part of the power consumption, but the largest contributor is the power-down current (stand-by current) of the Sensor IC. Fig.3 shows a typical distribution of the power consumption.

Ongoing developments are focused on the reduction of the power-down current and on increasing transmission rates in order to reduce the overall power consumption. By optimization of the transmission boot routine, transmission power level and an increase of the transmission rate to 100kbit/sec. the average power consumption for each datagram can be reduced to 10-15 μ Ws.

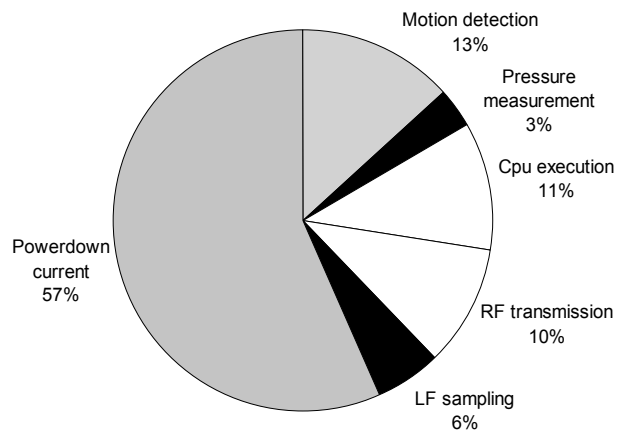


Fig. 3: Pie-chart showing the distribution of the power consumption for a TPMS.

Thus, a micro scale or MEMS (micro- electro-mechanical- systems) based vibration energy harvester must provide an average power level of several μ W in order to promote transmission intervals in the range of 5-10 sec. In addition a smart power management and reliable energy storage device are necessary to enable the use of

vibration energy harvesters in safety relevant applications such as tire pressure monitoring.

3. EVALUATION OF VIBRATION ENERGY HARVESTING FROM THE WHEEL/TIRE

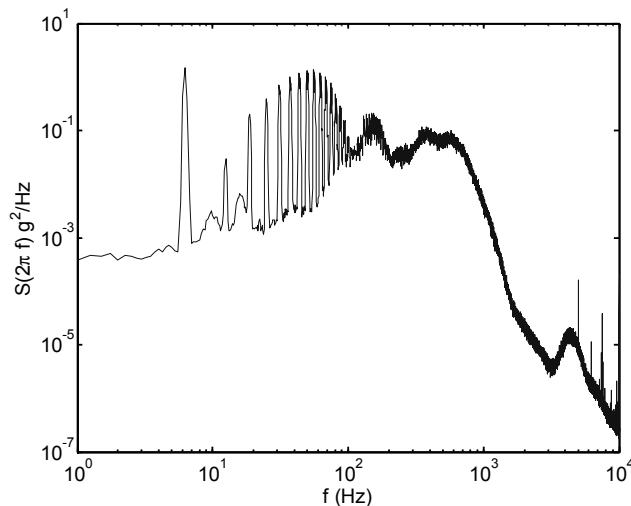


Fig. 4: Power spectral density of acceleration along tangential direction of tire estimated from signal measured at 50km/h.

A vibration energy harvester mounted on the inside of a car tire at the so-called inner liner position is subject to acceleration in three directions. The two main directions are the radial and the tangential directions, which are both dominated by the revolution of the tire. Both directions have characteristic signatures when the part of the tire where the device is mounted, hits or leaves the ground. These two positions, known as leading and trailing edge, are defining the contact area of the tire with the road. In addition, other factors such as surface roughness of the road, fluctuations in driving speed and the detailed dynamics of the tire (torsion- and vibration modes) itself contributes to the acceleration signal

Fig. 4 shows the power spectral density (PSD) of an acceleration signal measured at the inner liner of a car tire driven at 50km/h. At a little above 6Hz there is a strong peak corresponding to the revolution period of the wheel, but there are also a number of higher harmonic peaks of comparable magnitude. For frequencies above 100Hz the peaks get smeared out. However, there are substantial signal levels all the way up to about 1 kHz. By integrating the power spectral

density, it was found that half the weight of the PSD is above 340Hz.

As a conclusion from the PSD of accelerations for different tires, different road conditions as well as different driving speeds an efficient vibration energy harvester must be sensitive to a wide range of frequencies between 5Hz and 1 kHz. Thus, increasing the average power level merely by making use of a resonant energy harvesting concept is not optimal for the TPMS application. Even though it is easy design the resonance to fall within the signal bandwidth, there is much to be gained by increasing the harvester bandwidth.

For vibration energy harvesting purposes both radial and tangential accelerations could be exploited. Assuming that the device is mounted with the chip plane parallel to the inner liner tire surface, the energy harvesting from radial acceleration dictates a device with proof mass motion out-of-plane, while harvesting from tangential accelerations calls for in-plane motion.

In addition to the broadband energy harvester concept, the maximum acceleration peaks of 4000-5000g must be taken into account for the design in order to fulfill the lifetime and automotive quality requirements. Due to weight, size and integration issues two main harvesting principles have been evaluated for TPMS applications so far: piezoelectric and electrostatic (capacitive). Depending upon the effective harvester volume both principles show advantages and disadvantages. For the development of a MEMS device, that will allow a later integration of the harvester with the TPMS sensor, the electrostatic concept has been chosen.

The electrostatic energy harvesters can be based on either in-plane or out-of-plane motion of the proof mass [5]. We have considered in-plane designs that utilize high aspect ratio micro machined springs, mechanical stoppers, and various proof mass sizes. Details will be disseminated elsewhere.

In order to provide a first evaluation of the average output power, simulations of one of these devices have been done. The simulations were performed in SPICE. The parameters of the SPICE model were found by finite element analysis. A resistive load was used in these simulations.

Using several measured time series of accelerations at different car velocities, we have simulated the average output power of the MEMS electrostatic harvester device. The total proof mass was 1.5×10^{-5} kg with the dimensions of 4mm x 4mm x 400 μ m and the silicon density of 2.33 g/cm³.

The result is shown in Fig. 5. For velocity of 30km/h the average output power of this device was simulated to be 3 μ W, for a velocity of 50km/h the power was 8.5 μ W and for 110km/h the output power level was 13.5 μ W.

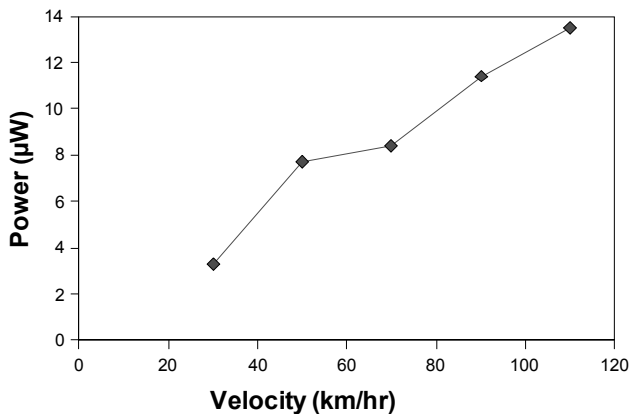


Fig. 5: Simulated output power vs. car velocity.

It is interesting to notice that the output power scales almost linear with the velocity or acceleration level of the tire as seen in Fig.5. In addition the output power strongly depends on the proof mass. Therefore, the power level can be adjusted to fit the target application. However, for industrial application the cost/performance ratio is the most important factor.

4. CONCLUSION

The evaluation of a MEMS based electrostatic energy harvester has shown that an average output power level of about 10 μ W depending upon the velocity can be obtained. The power level might be adjusted by using a different proof mass. However, the AC output voltage of the energy harvester must be converted into a stabilized DC voltage in order to power the electronic device (ASIC). Therefore, a power management and intermediate storage device have to be included. First simulations of the power management circuit have shown conversion efficiency of up to 60%.

Thus, for the TPMS application a average power level of 5-6 μ W are expected using an electrostatic MEMS based energy harvester with the dimensions of 4 x 4 x 0.4mm and a proof mass of 1.5×10^{-5} kg. As discussed earlier the needed power for a transmission of the tire pressure information depends upon the transmission data rate. For standard TPMS with a 10kbit/s data rate about 200 μ Ws are needed. Thus by using an energy harvester as described before it would take about 40-50 sec to harvest enough energy for a single transmission. However, for the future TPMS module with a higher data rate and improved power consumption 10-15 μ Ws are sufficient to transmit the TPMS protocol. Here, a transmission interval of less than 5sec might be achieved, which would fit with the OEM requirements for standard battery powered TPMS.

Further improvements on the conversion efficiency of the energy harvester as well as on the data rate and power consumption of the TPMS might enable the use of power MEMS devices in automotive applications. However, there is the constraint that the overall costs for energy harvesting systems can not be significantly higher than a similar possible battery powered solution.

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