A NON-HARMONIC MOTION-POWERED PIEZOELECTRIC FM WIRELESS SENSING SYSTEM

H. Jiang, M.E. Kiziroglou, D.C. Yates, and E.M. Yeatman
Optical and Semiconductor Devices Group, Imperial College, London, UK

ABSTRACT

This paper reports a wireless sensing device which is completely powered by inertial motion. Self-synchronous switching is applied to the device using switching diodes and reed switches, which allows the system to function in response to its moving proof mass. By combining piezoelectric energy harvesting and radio frequency (RF) transmission, a fully functional piezoelectric system is achieved, for the first time, allowing instantaneous wireless monitoring of signals from a passive sensor using frequency modulation (FM).

KEYWORDS

Piezoelectric pulse generator, Wireless sensor network, Energy harvesting.

INTRODUCTION

In recent years, electronic applications in wireless sensing and wearable or implantable devices have drawn considerable research interest [1]. With increasing demand on such wireless devices in various areas, such as body condition monitoring and therapy in health care, one major concern regards maintenance issues in relation to their power supply, as the inconvenience and cost of recharging and replacement of traditional batteries [2], [3]. Therefore, exploring alternative power sources has become a key factor to fulfill the requirement of wireless miniature devices with long and maintenance-free life-times. This leads to the popular approach of energy harvesting from different ambient sources, and one of the promising sources is inertial energy from ambient motion [4].

Unlike machine motion, which in many cases is periodic with a limited range of amplitude and frequency, body motion is typically non-harmonic with a wide range of amplitudes [4]. In this case, an energy harvester using an external proof mass without suspension is more suitable to obtain energy from body motion [5], [6]. Using a rolling rod as an external proof mass, a self-powered electrostatic wireless sensor network (WSN) node was designed in our group, which can operate at a random low frequency [7], but the power density is restricted by the low variable capacitances achievable with the electrostatic transduction. Another energy harvester from our group using piezoelectric transduction, which is also suitable for operation at a random low frequency [8], demonstrates enhancement of power density compared to the electrostatic approach. In addition, a rolling ball piezoelectric pulse generator was built combining features of the two devices in [7] and [8], and demonstrated the feasibility of implementing it as an impulse power supply for electronic devices [9].

Instead of testing the piezoelectric pulse generator and the load circuit separately as described in [9], a fully functional wireless sensing platform is tested here by powering the load circuit with the pulse generator. In addition, a pendulum proof mass is used to replace the rolling ball proof mass, which allows the device to be powered not only by linear motion but by rotational motion as well.

In this paper, the operating mechanism of the presented device is described in detail. Measurement results are demonstrated and the performance of the device is evaluated.

STRUCTURE OF THE SYSTEM

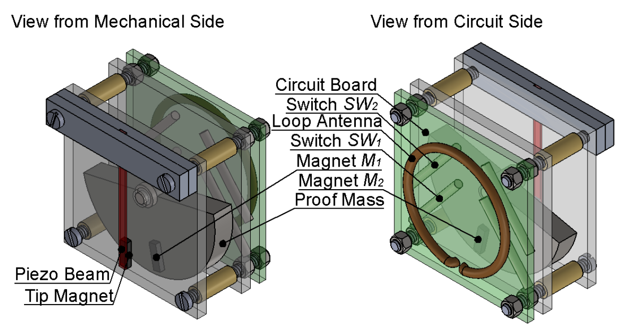

Figure 1: Structure of the piezoelectric wireless sensing platform.

The structure of the wireless platform is presented in Figure 1. A piezoelectric cantilevered beam is mounted on one side of the device, and a circuit board is mounted on the other side. A pendulum proof mass is suspended between the two frames of the platform, which can be excited to rotate by ambient motion.

Three magnets are applied to this design, as can be seen from the structure. The tip magnet is attached to the free end of the piezoelectric beam, and the magnet M_1 is attached to the proof mass on the mechanical side. These two magnets are used together to actuate the piezoelectric beam for piezoelectric energy generation. The third magnet, M_2, is also attached to the proof mass but on the circuit side, which controls the synchronous switching of the platform together with the switches shown in the figure.

The device presented here can be divided into two main parts as shown in Figure 2: the electromechanical module and the circuit module. The electromechanical module extracts the inertial energy from its rotating proof mass, and converts and stores it as electrical energy to power the circuit module. The circuit module is an FM based load transmitter for instantaneous RF transmission of a sensor signal, which can be detected by a receiver.

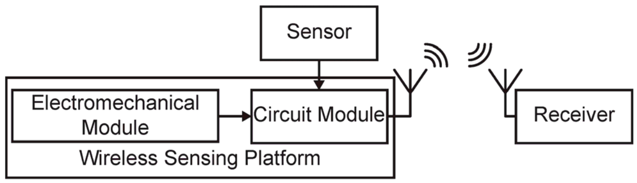

Figure 2: Architecture of the motion-powered wireless sensing platform.

OPERATING PRINCIPLE

In order to realize the proposed function, the two modules described above are required to operate in sequence. In this section, the operating principle is described in detail by dividing the system into the two main parts.

Electromechanical Module

The electromechanical module, whose schematic is shown in Figure 3, is the power supply of the system. The component *PIEZO* represents the piezoelectric beam. The two diodes, D_1 and D_2, are used as electrical switches to control the connection and disconnection between the piezoelectric beam and the storage capacitor, C_L. The four switches, *SW*, are the reed switches, controlled by the magnet, M_2, on the proof mass.

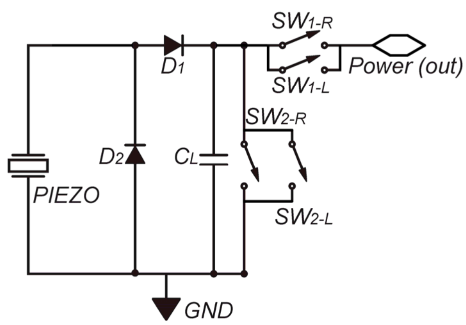

Figure 3: Schematic of the electromechanical module.

The operating principle of the module is described in Figure 4, which takes the anti-clockwise swing cycle as an example. When the pendulum proof mass rotates from the left of the beam to the right, magnet M_1 on the proof mass approaches the piezoelectric beam making the beam deflect via the magnetic coupling between M_1 and the tip magnet, and a negative charge is generated by the piezoelectric beam, which is dissipated by diode D_2 directly as shown in Figure 4(a). The piezoelectric beam is pre-biased by D_2 during its deflection [10] and when M_1 moves away from the tip magnet, the beam starts vibrating. During the vibration, each time the surface charge on the beam is positive and high enough to forward-bias diode D_1, the generated charge is shared and stored to the load capacitor, C_L, and when the beam stops vibrating, D_1 will stay reverse biased, which isolates C_L from the piezoelectric beam. In this case, a fixed amount of energy is extracted from the piezoelectric beam and stored in C_L, which can be used to power a load circuit.

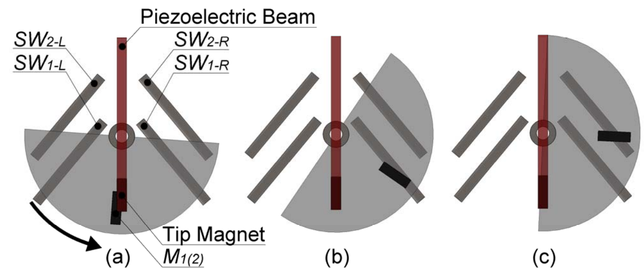

Figure 4: Operating principle of the power supply part (anti-clockwise). (a) M_1 actuates the piezoelectric beam. (b) M_2 closes SW_1 on the right side. (c) M_2 closes SW_2 on the right side.

The beam actuation phase described above will finish while the magnets on the pendulum are moving to $SW_{1\text{-}R}$, as indicated between Figure 4(a) and Figure 4(b). When the magnets are close enough to $SW_{1\text{-}R}$ in Figure 4(b), the magnetic field from M_2 closes $SW_{1\text{-}R}$ so that the energy stored in C_L can be supplied to its load circuit from the port, *Power (out)*. After powering the load circuit, the two magnets continue moving with the rotating pendulum and approach $SW_{2\text{-}R}$ as shown in Figure 4(c), and the closure of $SW_{2\text{-}R}$ dissipates the remained energy in C_L and the piezoelectric beam, if any, to "empty" them to their initial states for the next operating cycle. It is worth pointing out that when the proof mass rotates clockwise, $SW_{1\text{-}L}$ and $SW_{2\text{-}L}$ are respectively used as the effective SW_1 and SW_2 instead of $SW_{1\text{-}R}$ and $SW_{2\text{-}R}$.

Circuit Module

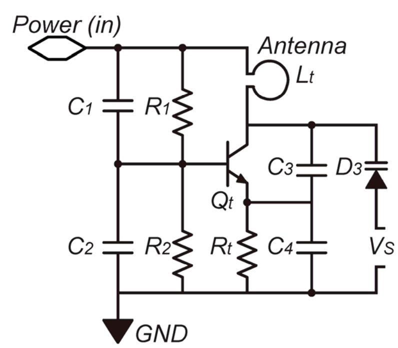

Figure 5: Schematic of the circuit module.

The electromechanical module of the wireless sensing platform operates as a discontinuous power supply providing a fixed amount of energy to its load circuit in each operating cycle. Figure 5 illustrates the schematic of the circuit module based on the Colpitts oscillator [11], which is suitable to be powered by a discontinuous power supply. The purpose of this circuit is to transmit a radio frequency (RF) pulse which encodes the voltage output of a passive sensor in the form of a modulated frequency, which is insusceptible to the environment noise and no reference signal is required for calibration compared to the approach of amplitude modulation.

As shown in the figure, R_1 and R_2 are the series resistors to bias the transistor, Q_t, which is a high-frequency NPN bipolar junction transistor (BJT). The small capacitors, C_1 and C_2, are added to increase the response speed of the circuit module due to the discontinuous powering mechanism. The resistor R_t is the emitter resistor to control the power consumption of the circuit, and the antenna, L_t, forms an LC tank together with capacitors C_1 and C_2, which will generate resonant signals when powered by the electromechanical module. A varactor diode, D_3, is connected at the collector of the BJT. It is reverse biased and its capacitance is controlled by the sensor voltage V_s. By adding this component, the resonant circuit can be used as a voltage controlled oscillator (VCO), whose resonant frequency can be tuned by the voltage, V_S, as indicated in the figure. In this case, the circuit module is expected to encode the signal of V_S with frequency modulation and transmit it immediately to a receiver once it is powered up by the energy stored in the load capacitor, C_L.

EXPERIMENTAL MEASUREMENT

A 30 mm × 30 mm prototype was built based on the proposed concept, as presented in Figure 6. The piezoelectric beams used in the measurement are from Johnson Matthey, and the antenna of the platform is made of a copper wire and its inductance can be evaluated as [12]:

$$L_t = \mu_o \mu_r \frac{D}{2}\left(ln\frac{8D}{d} - 2\right) \quad (1)$$

where μ_o is the permeability of free space, μ_r is the relative permeability of the medium, which is ~1 for copper, d is the diameter of the wire and D is the diameter of the circle, with values of 1.5 mm and 26 mm respectively for this prototype. The receiving antenna is identical to the transmitting one on the platform and is connected directly to an oscilloscope via an SMA-to-BNC cable for measurement. All the parameters of the experimental set-up are listed in Table 1.

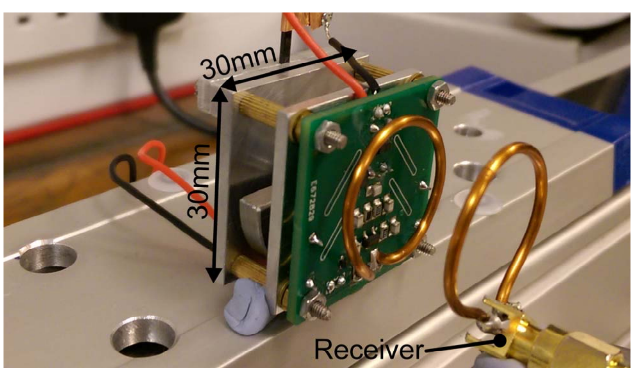

Figure 6: Piezoelectric wireless sensing device and receiving antenna.

Table 1: Parameters of the components for the experimental set-up.

D_1&D_2	BAS116H	R_t	787Ω
C_L	3.3nF	L_t	~48nH
C_1&C_2	12pF	C_3	1pF
R_1&R_2	10KΩ	C_4	3.9pF
Q_t	BFR35AP	D_3	BBY51-02W

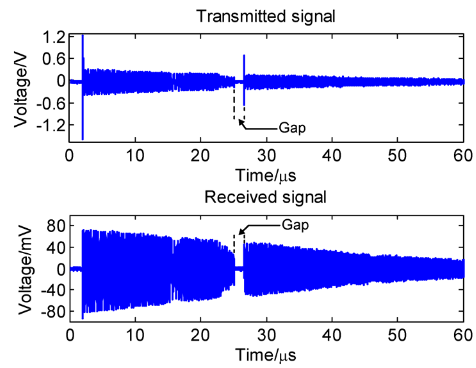

Figure 7: Experimental results of transmitted and received signals in one operating cycle (V_S=0).

In order to demonstrate that the prototype can be powered only by the energy from the piezoelectric beam, measurements are made when no voltage source is connected to the signal port V_S, and the results in the time domain are illustrated in Figure 7 during one operating cycle of the sensing platform.

The results present the transmitted signal measured across L_t, and the successful detection of the signal by the receiving antenna during the closure of SW_1 after the energy extraction from C_L. It can be seen that when C_L is powering the circuit module, the amplitudes of the signals gradually decrease due to the fixed amount of energy stored in C_L, which is as expected. In addition, gaps occur between the resonant signals as indicated in the figure. This is because the reeds of SW_1 bounce during its closure, and in terms of frequency modulation, these gaps do not affect the detection of the signal.

Figure 8 illustrates the frequency measurement of the received signals when a DC voltage supply is connected to the port V_S as a dummy sensor. The results show that by increasing the amplitude of V_S from 0.5V to 2.5V, the frequency of the received signal decreases correspondingly ranging from ~504MHz to ~494MHz, which demonstrates that the wireless sensing system manages to frequency modulate the output pulse using voltages from V_S, and that the transmitted signal can be picked up simply by a loop antenna. The glitches on the plots are due to the limited sampling rate of the oscilloscope in use. The sensitivity of the prototype is expected to be improved, since the frequencies of the measured signals show overlap with each other when the sensing step is 0.5V.

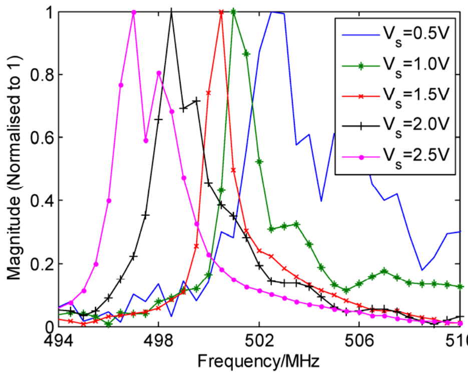

Figure 8: Frequency measurement of the received signals with different DC voltages from V_S.

To further evaluate the performance of the prototype, Figure 9 presents the results when two thermo-electric generators (TEGs) in series are used instead of the dummy sensor voltage. In this way, a battery-less, motion powered wireless temperature sensing system is built. The frequency range of the results is slightly shifted, in comparison to the dummy sensor voltage, due to the change of the piezoelectric beam in the experimental set-up. Successful reception of temperature information is demonstrated using the experimental prototype. This result proves the concept of motion-powered wireless sensing.

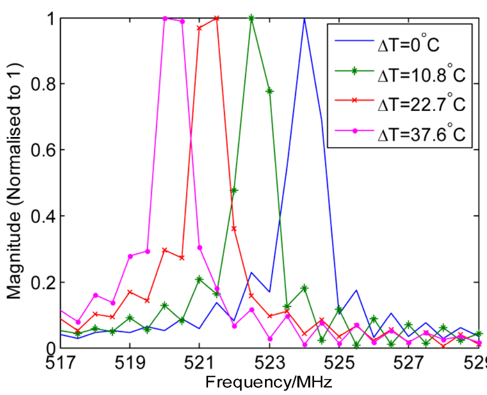

Figure 9: Frequency measurement with thermo-electric generators.

CONCLUSIONS

A motion-powered wireless sensing device is reported in this paper. Operating principles are described in detail and an experimental set-up is built for testing. According to the measurement results, the experimental prototype can be powered solely by the energy extracted from the motion of the proof mass via the piezoelectric transduction, and successful wireless transmission can be achieved. In addition, frequency modulation is successfully implemented in the design, by using a varactor as a voltage-controlled variable capacitor. Successful transmission and detection of information is demonstrated by using a dummy sensor voltage and also by two TEGs in series. These results prove that the prototype can be adapted to encode signals for any suitable passive sensor with FM for instantaneous wireless sensing.

ACKNOWLEDGEMENTS

The authors would like to thank Dr. Steven Wright at Imperial College for his technical help.

REFERENCES

[1] G.Z. Yang, and M. Yacoub, *Body Sensor Networks*, 2nd ed. Springer, 2014.

[2] D. Son, et al. "Multifunctional wearable devices for diagnosis and therapy of movement disorders", Nature Nanotechnology, 9.5 (2014): 397-404.

[3] S. Sudevalayam, and P. Kulkarni, "Energy harvesting sensor nodes: Survey and implications", Communications Surveys & Tutorials, IEEE, 13.3 (2011): 443-461.

[4] P.D. Mitcheson, E.M. Yeatman, G.K. Rao, A.S. Holmes, and T.C. Green, "Energy harvesting from human and machine motion for wireless electronic devices", Proceedings of the IEEE, 96.9 (2008): 1457-1486.

[5] B.J. Bowers, and D.P. Arnold, "Spherical, rolling magnet generators for passive energy harvesting from human motion", Journal of Micromechanics and Microengineering, 19.9 (2009): 094008.

[6] C.R. Saha, T. O'Donnell, N. Wang, and P. McCloskey, "Electromagnetic generator for harvesting energy from human motion", Sensors and Actuators A: Physical, 147.1 (2008): 248-253.

[7] C. He, M.E. Kiziroglou, D.C. Yates, and E.M. Yeatman, "A MEMS self-powered sensor and RF transmission platform for WSN nodes", Sensors Journal, IEEE, 11.12 (2011): 3437-3445.

[8] P. Pillatsch, E.M. Yeatman, and A.S. Holmes, "A scalable piezoelectric impulse-excited generator for random low frequency excitation", Micro Electro Mechanical Systems (MEMS), 2012 IEEE 25th International Conference on, IEEE, Paris (2012), pp. 1205–1208.

[9] H. Jiang, and E.M. Yeatman, "A piezoelectric pulse generator for low frequency non-harmonic vibration", Journal of Physics: Conference Series, IOP Publishing, 476.1 (2013): 012059 2013.

[10] H. Jiang, M.E. Kiziroglou, D.C. Yates, and E.M. Yeatman, "A Motion-Powered Piezoelectric Pulse Generator for Wireless Sensing via FM Transmission", Internet of Things Journal, IEEE, 2.1 (2015): 5-13.

[11] D.C. Yates, A.S. Holmes, and A.J. Burdett, "Optimal transmission frequency for ultralow-power short-range radio links", Circuits and Systems I: Regular Papers, IEEE Transactions, 51.7 (2004): 1405-1413.

[12] C.A. Balanis, *Antenna theory: analysis and design*, John Wiley & Sons, 2012.

CONTACT

*H. Jiang; hao.jiang10@imperial.ac.uk