

Piezoelectric Power Scavenging of Mechanical Vibration Energy

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ABSTRACT

The process of acquiring the energy surrounding a system and converting it into usable electrical energy is termed power harvesting. With piezoceramic materials, it is possible to harvest power from vibrating structures. It has been proven that micro- to milliwatts of power can be generated from vibrating systems. The project targets the transformation of mechanical vibration into electrical energy using piezoelectric material. In some mining applications, eg water jet drilling; large high frequency vibrations may be present. If successfully harvested, this energy could be used to eliminate batteries in wireless sensors. This article presents a model of a piezoelectric transducer, a mechanical vibration spectrum, the simulation of the model, prototype of the power scavenging circuit, experimental results and its future perspectives.

INTRODUCTION

With the recent advances in wireless and microelectromechanical systems technology, the demand for portable electronics and wireless sensors is growing rapidly. Because these devices are portable, it becomes necessary that they carry their own power supply. In most cases this power supply is the conventional battery; however, problems can occur when using batteries because of their finite lifespan. For portable electronics, replacing the battery is problematic because the electronics could die at any time and replacement of the battery can become a tedious task. Supplying power through a long cable can be impractical, hard to install and maintain. Advances in integrated circuit manufacturing and low power circuit design have reduced the total power requirements of a wireless sensor node to well below 1 mW. The requirement of a power supply for small power electronics, a sensor in this case in the mining environment, is the main motivating factor of this project.

GENERAL POWER SCAVENGING

The following are several common energy conversion techniques (see Figures 1 - 3):

1. *piezoelectric*: strain in piezoelectric material causes a charge separation (voltage across capacitor);
2. *electromagnetic/inductive*: coil moves through magnetic field causing current in wire;
3. *capacitive*: change in capacitance causes either voltage or charge increase; and
4. *thermoelectric*: change in temperature between two physical locations can be used as a thermal source, which can be converted into electrical energy.

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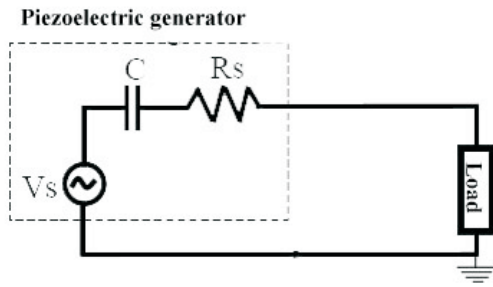


FIG 1 - Piezoelectric: strain in piezoelectric material causes a charge separation (voltage across capacitor) (after Roundy, Wright and Rabaey, 2003).

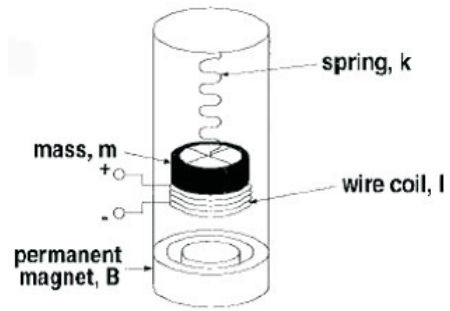


FIG 2 - Electromagnetic/inductive: coil moves through magnetic field causing current in wire (Amirtharajah *et al*, 1998).

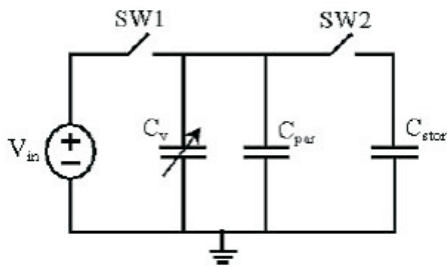


FIG 3 - Capacitive: change in capacitance causes either voltage or charge increase (after Roundy, Wright and Rabaey, 2003).

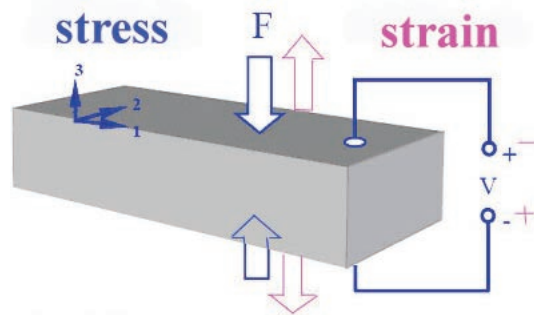


FIG 4 - Stress/strain on piezoelectric material.

PIEZOELECTRIC GENERATION

In this project, we are particularly interested in application to sensors for water jet assisted drilling. There are high frequency vibrations present in the nozzle in water jet assisted drilling. Generating electricity locally at the nozzle itself can solve many of the above problems. Piezoelectric material can be used to harvest energy from such vibration, and use the harvested energy as a power supply for the sensor.

The unique physical properties of piezoelectric material is that when a piezoelectric material is subject to stress/strain it produces electrical charge on its surface, and vice versa, ie when charge flows through such material, the material goes through physical deformation. Since vibrations cause stress and strain on to the piezoelectric material, the charge produced moves in one direction under positive stress and in the opposite direction under negative stress.

Vibration source

Water jet assisted drilling gives rise to large mechanical vibrations because of the natural pulsation of positive displacement high pressure pumps. Vibration from this source was measured with an accelerometer. The acceleration magnitude of the vibrations was plotted against frequency over the log scale. There are two main resonant peaks to consider and those peaks at about 400 Hz and 1400 Hz were chosen. Figure 5 shows the graphs of recorded spectral data supplied by CRCMining derived from the Tight Radius Drilling Project.

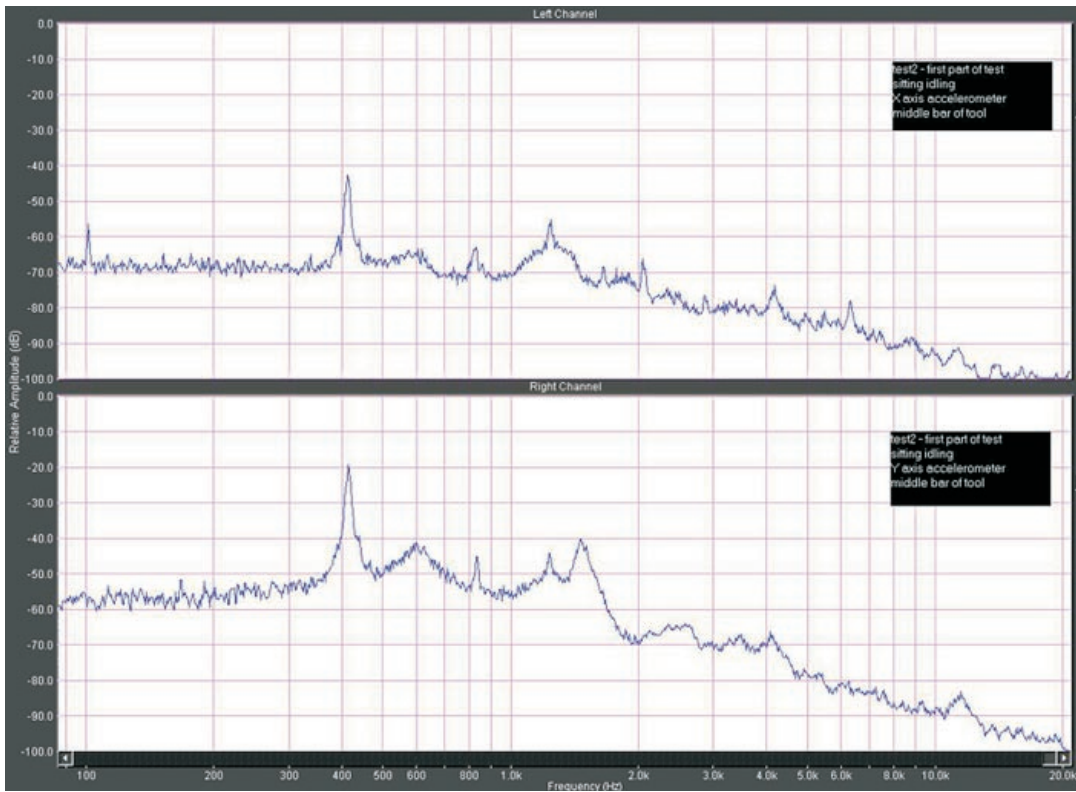


FIG 5 - Recorded spectral data supplied by CRCMining derived from the Tight Radius Drilling Project (courtesy of Prochon, 2007).

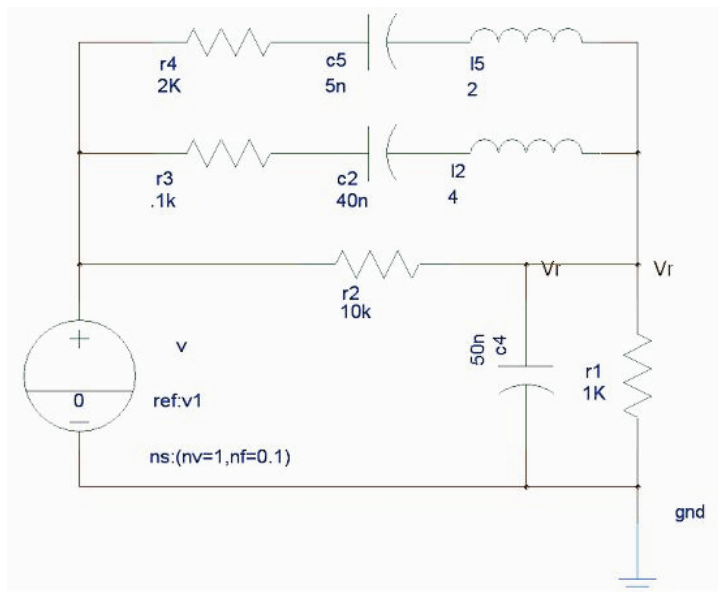


FIG 6 - Vibration simulation circuit model using Saber[®] by Synopsys Inc.

Modelling of the vibration spectrum

A ‘circuit’ for modelling mechanical resonance was designed as shown in Figure 6. The vertical scale of the supplied vibration is unknown since the required gains and calibration constants were not available. However, the model is adjustable to match the specifications or requirements.

The aim of the simulation model is to allow testing various circuit designs for efficiencies and power extraction ability.

Two main resonant peaks possibly due to mechanical resonance are modelled by RLC elements in circuit simulation package (see Figure 7).

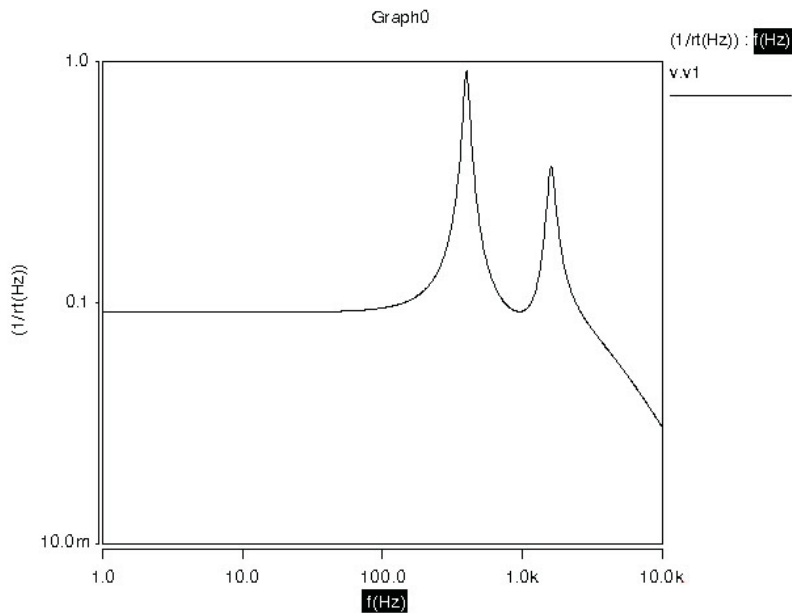


FIG 7 - Simulation result as per Cosmoscope in Saber®, Synopsys Inc.

Piezo model

Figure 8 shows the piezo model used for this design. C is the internal capacitance and Rs is the internal source resistance of the piezoelectric material.

The left hand part of the circuit before VCVS represents the source vibration signal with two resonant frequencies at 400 MHz and approximately 1400 MHz. The piezo model circuit is then extended to use DC-DC converter as below.

DC-DC converter technique

Due to stress and strain caused by vibration to the piezoelectric material, dual polarity of charge results in an alternating current (AC), which is then converted into direct current (DC) by a full bridge rectifier. The rectified current is then used to charge a capacitor or a battery, which can hold energy. The maximum power transfer technique will be used to design the circuit for this energy conversion. DC-DC converter is used to maximise the power transfer to the load. The reason to use DC-DC converter is to convert a variable input voltage into a constant output voltage. For example, if the bucket

capacitor 10 μF charges up with DC coming from the rectifier, the capacitor will have different values of charges stored at different times, and if we use PWM charging for the battery, the current into the battery will be regulated at desired level by changing the duty cycle of the PWM signal at the output of the DC-DC converter.

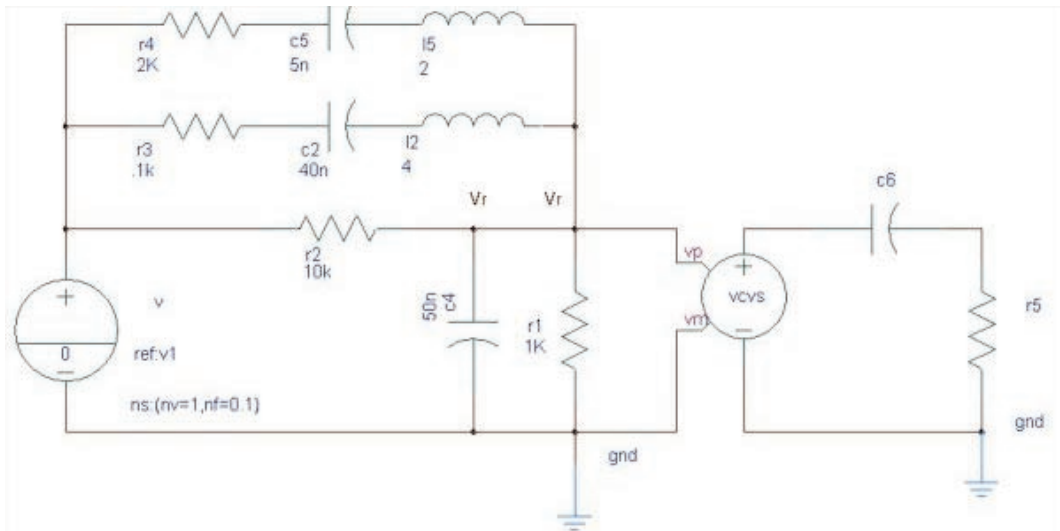


FIG 8 - Piezo model from Saber® Electronic Simulation Program by Synopsys Inc.

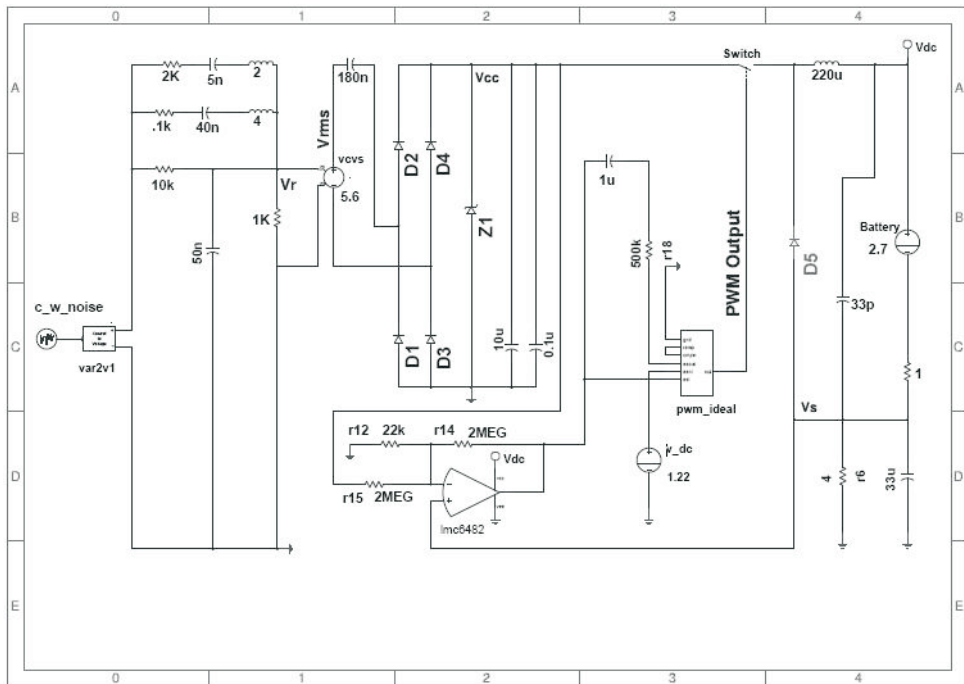


FIG 9 - Full circuit for piezoelectric generator and DC-DC conversion Saber® simulation by Synopsys Inc.

After fine tuning the circuit components to maximise power transfer to the load using Saber® Simulator, a schematic was prepared (Figure 10), and the prototype board was manufactured for experimental purposes.

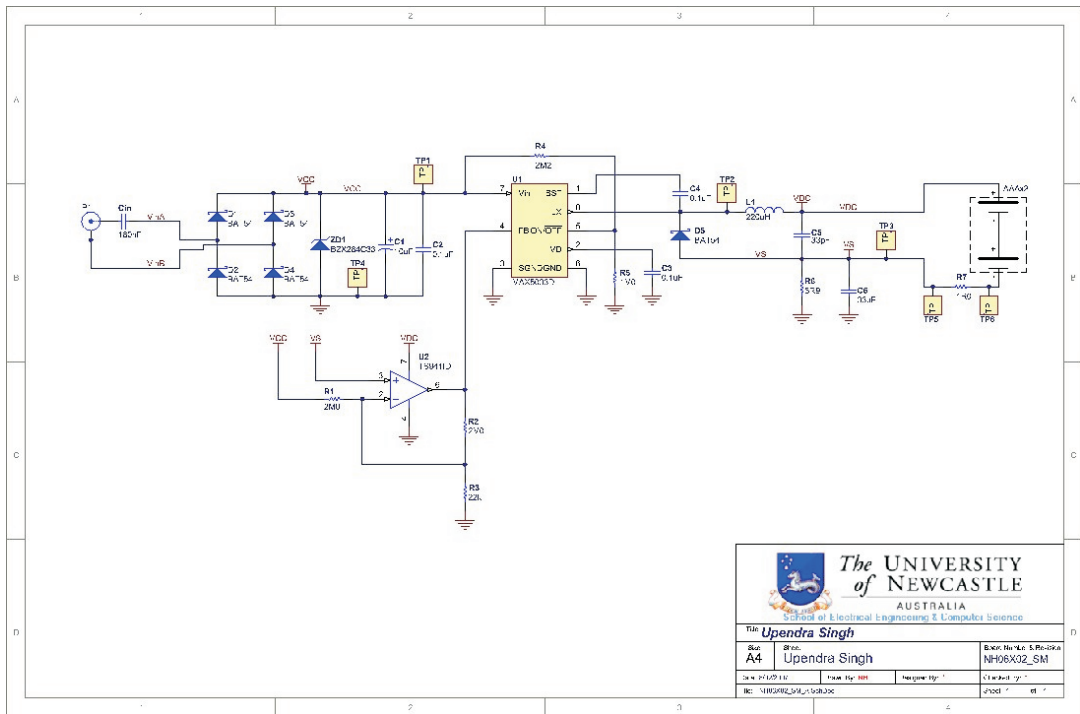


FIG 10 - Protel schematic of circuit in Figure 9.

Experiments

Using two AA size rechargeable batteries as the load in the above circuit, the input rms voltage was applied in the range 5 to 19V rms and the battery load current was observed. A current of 78 mA through the battery (2.7 V) was observed when the input rms voltage applied was 18.71 Vrms. The results are shown in Table 1.

TABLE 1
Experimental results for the circuit shown in Figure 10.

V_{rms}	V_{cc} (V)	Load current (mA)
5.27	3.181	6
8.55	5.5	16.8
11.7	6 7.77	32
15.6	10.16	52.7
18.71	12.54	78

CONCLUSION

A source vibration model was first designed and simulated to match the supplied spectrum from CRCMining. Then various loads were tested to achieve input and output impedance matching for the maximum power transfer. Input and output impedance matching were studied with having different loads. For example, in one case, a load resistance, R and in another case, a combination of load resistance R and an inductance L were connected to observe maximum power transfer to the load. To achieve impedance matching at high input rms voltages, a feedback circuit using low power OPAMP in conjunction with the DC-DC converter was used.

The input AC current was then rectified using full wave rectifier, and combination of highly efficient and low power rated PWM and rail-to-rail dual OPAMP were used to regulate the power at the maximum level as expected. Finally an ideal simulation with the RL load was considered to be included to be informative and relevant parts for this project. The power extracted from the given source to the battery is 210 mW.

This meets the power requirement of many wireless sensors. Thus this device can be used as power source for such low power electronics working in a suitable condition. Use of this device is scalable and viable in many other applications where vibration can be found as a source of energy.

The research has opened the door to explore a few more techniques that can improve the regulation of maximum power to the load. For example, one of the techniques to be explored is active front end (H-bridge) load. Also to completely get rid of the use of any inductor on the electronic board, the idea of synthetic impedance can be researched and the real inductance can be replaced by the synthetic impedance which will provide the same results with a lower risk of interferences in the environments.

The ICs used in this project do require some power initially to turn itself on. Two AA or triple AAA size batteries are enough to supply enough power to turn them on. Therefore, this project requires that the rechargeable batteries will have to be fully charged before the operation takes place. At the end of the life of the battery, the batteries need to be replaced by another set of fully recharged batteries.

The control mechanism of the whole unit to work as a power supply while batteries are being charged simultaneously and the intrinsic safety of the battery and the circuit itself are still to be researched and implemented further for this project.

Suggestions for further research

- A small inductor in series with the piezo-capacitance can be used to further boost the power flow. There were some preliminary experiments done as a part of this research and very promising results were seen, but are yet to be analysed in detail.
- An H-bridge can be used to implement an active front to allow short term reverse power transfer to piezo, so we can possibly achieve simulated source inductance.
- Intrinsic safety procedures may need to be considered depending on the physical conditions of the surroundings where the device may be used.

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