Development of a Cantilever Beam Generator Employing Vibration Energy Harvesting

R.N.Torah[1], S.P.Beeby[1], M.J. Tudor[1], T.O'Donnell[2], S.Roy[2]
[1]University of Southampton, School of Electronics and Computer Science, Southampton, SO17 1BJ, UK.
[2]Tyndall National Institute, Microelectronics Applications Integration Group, Cork, Ireland.
rnt@ecs.soton.ac.uk - University of Southampton, UK, SO17 1BJ.

Abstract

This paper details the development of a generator based upon a cantilever beam inertial mass system which harvests energy from ambient environmental vibrations. The paper compares the predicted results from Finite Element Analysis (FEA) of the mechanical behaviour and magnetic field simulations and experimental results from a generator. Several design changes were implemented to maximise the conversion of magnetic energy into generated power and a maximum power output of 17.8μW was achieved at a resonant frequency of 56.6Hz and an applied acceleration of 60m***g*** (***g*** = 9.81ms^{-2}).

Keywords: Energy Harvesting, Electromagnetic Generator.

1 – INTRODUCTION

The rapid growth in wireless sensor network applications has highlighted the requirement for in-situ power generation. A typical wireless micro-system will use battery power but this has a limited life cycle and therefore limits the placement and application of the sensor node. In addition, the size of the battery can have a prohibiting effect on the volume of the micro-system.

Numerous sensor applications have sufficient vibrations present in the environment to make ambient vibration energy harvesting a feasible option for powering wireless sensor nodes [1].

This paper presents the development of an electromagnetic micro generator designed to harvest such vibration energy. This work was carried out as part of the European Union funded project 'Vibration Energy Scavenging' (VIBES). A cantilever structure is excited into resonance and an electromagnetic induction circuit is used to extract electrical power. Comparison between the simulation results and practical measurements are presented and the direction of future work discussed.

2 – THEORY

Using a previous analysis of the fundamental equations for excitation of an oscillating beam, with stiffness and damping present [2], it is possible to predict the maximum power generated by an inertial generator. The theoretical maximum power generated in the load is given by Equation 1.

$$P_d = \frac{ma^2}{4\omega_n \zeta_T} \tag{1}$$

Where P_d, m, a, ω_n and ζ_T are total damped power (W), mass (kg), acceleration (ms^{-2}), resonant frequency (rads) and total damping respectively. This equation highlights the important variables in the design of an inertial generator. To generate the optimum power for a particular application, the inertial mass and its amplitude of vibration should be maximised within the specified volume in order to maximise the mechanical energy stored within the generator. The frequency of operation and amplitude of environmental vibrations are application specific and therefore the generator design must conform to these particular characteristics. The generator must also be designed to couple the maximum energy from the mechanical domain to the electrical domain and therefore obtain the highest efficiency. This is achieved by optimising the design of the electromagnetic circuit.

3 – CANTILEVER GENERATOR DESIGN

The cantilever micro generator is a miniaturised form of a previous design developed at the University of Southampton [3]. The design uses four magnets configured in opposite polarities above and below the beam producing a concentrated flux gradient through the coil as the magnets move [4]. The magnets are mounted on a cantilever spring which is used since it can be simply fabricated and is a space efficient structure for obtaining low frequencies. The intended application, an air compressor unit, produces large vibration maximas at frequencies between 50Hz and 60 Hz and therefore this micro version of the generator was designed to operate within this range. The dimensions of the beam were determined using ANSYS finite element analysis in order to obtain the required frequency with the minimum feasible package size.

The main components of the generator are shown in figure 1. It comprises a base to which the coil is fixed, four magnets and associated keepers attached to the beam, two large masses fixed to the free end and a bolt and washer to clamp the beam at one end whilst maintaining a degree of adjustability.

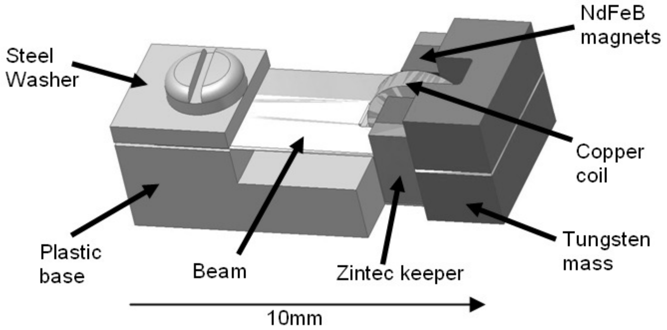

Figure 1- Completed design for the cantilever generator.

As the device is driven into resonance the amplitude of the inertial mass vibrations increase and the moving magnetic flux lines cut through the stationary copper conductors thereby inducing an electro motive force (emf) within the coil. The package shown in figure 1 has a volume of less than 150mm^3.

4 – MATERIAL SELECTION

The copper coil has outer and inner diameters of 2.4mm and 0.6mm respectively. It is wound with 25µm diameter copper wire achieving 600 turns and a resistance of ~100Ω. The coil is bonded directly to a purpose made base machined from Tecatron GF40, a hard easily machineable plastic that can provide a rigid clamp for the beam. The inertial mass is maximised within the given volume by using wire eroded high density tungsten blocks.

Four Neodymium Iron Boron (NdFeB) magnets are bonded to the two tungsten masses again increasing the inertial mass within the volume. NdFeB rare earth permanent magnets have the highest flux density of any commercially available magnets. In addition, zinc coated mild steel (Zintec) keepers are bonded to the magnets to act as flux guides completing the magnetic flux circuit. The beam in this study was etched from a sheet of 50µm thick beryllium copper. Stainless steel and silicon beams have also been employed with this design, the results of which have been previously reported elsewhere [4,5].

5 – MAGNETIC MODELLING

Ansoft Maxwell 3D magnetic FE modelling software was used to optimise the magnet size in order to achieve maximum open circuit voltage. Simulation results were obtained for a selection of magnet widths (X) and heights (Y) as shown in figure 2. D is the distance between the magnets and was fixed at 1mm. The depth of the magnet was fixed at 1.5mm to conform to the existing dimensions of the beam structure. The simulations were carried out with an excitation vibration frequency of 60Hz, a magnet displacement of 0.57mm and a Q-factor of 140. This equates to an acceleration of 60m***g*** (***g***=9.81ms^{-2})

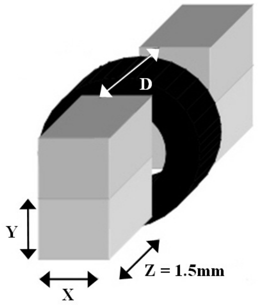

Figure 2- Magnet dimensions for simulation results

Dimension Y was initially fixed at 1mm and X was varied between 1 and 3 mm. The optimum X dimension occurs between 2 and 3 mm. Since, for a given volume, increasing magnet width causes a reduction in the size of the proof mass, dimension X was therefore limited to 2.5 mm. Given this value for X, the subsequent simulations adjusted the Y dimension, again between 1 and 3 mm. The simulation results again show an improvement with an increase in magnet size. The optimum practical dimension for Y was identified as 2 mm. The optimum magnet size of 2.5x2x1.5mm produces 120 mVrms compared to 52 mVrms for a generator with 1x1x1.5 mm size magnets (see figure 3). This is a factor of improvement of 2.5 in the open circuit voltages (see figure 4) whilst maintaining the volume of the cantilever generator within practical limits.

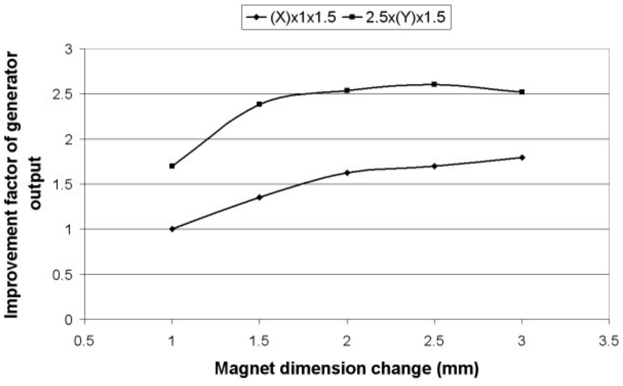

Figure 3 – Simulated generator output improvement vs. magnet size.

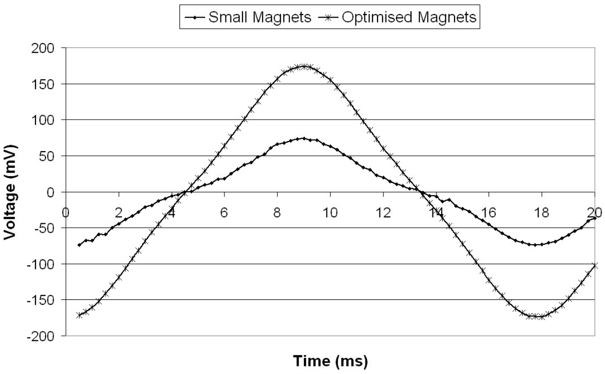

Figure 4 – Simulated output voltages for optimised and small magnet generator configurations.

6 – ASSEMBLY, TESTING AND RESULTS

To confirm the simulation results, two cantilever beam generators were assembled, one generator having 1x1x1.5mm magnets and the other using the optimized magnet size of 2.5x2x1.5mm. Each of the magnets were poled in the 1.5mm (Z) direction. Assembly of the generators required bonding the magnets to the tungsten mass and subsequent bonding of the mass/magnet assembly to the beam using cyanoacrylate adhesive. The beam assembly was then attached to the base and coil structure using an M1 bolt and purpose made square steel washer. The completed generator was mounted on a standard 8 pin DIL package (shown in figure 5) for compatibility with the testing setup.

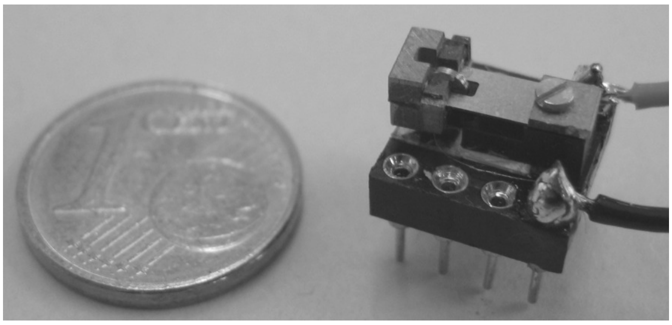

Figure 5 – Cantilever generator with small magnet configuration.

Testing of the generator was conducted using proprietary vibration test equipment. The vibration rig consists of an accelerometer feedback controlled shaker unit, programmable resistance box and a PC with LabView software collecting the data. This system allows the user to obtain reliable, repeatable results and program long sequences of tests to fully characterise each generator over a range of acceleration levels, load resistances and frequencies.

Each generator was first analysed to determine the resonant frequency. The generators were subjected to a vibration acceleration of 60m***g*** throughout the tests. Figure 6 shows the measured load voltage outputs from the two generators. The generators were connected to a 9MΩ load resistance, effectively open-circuit, and the frequency was slowly increased through resonance.

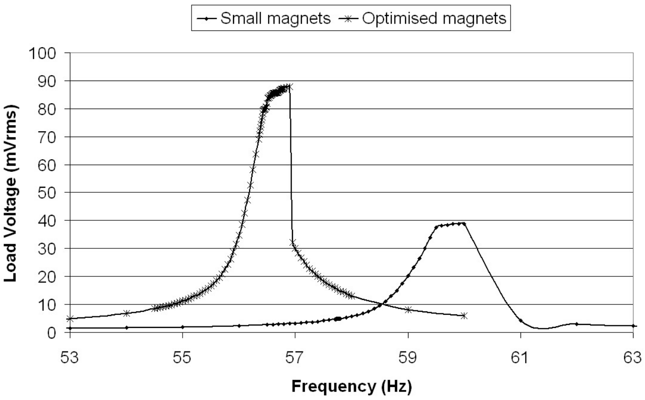

Figure 6 – Generated output voltages for the small and optimised magnet configuration cantilever generators.

The results show the small and optimised magnet configurations produced peak output voltages of 39mVrms and 87mVrms respectively. Next, the optimum power output was measured for the optimum configuration. The optimum load resistance was determined by driving the device into resonance over a wide range of resistance values and was found to be 150Ω.

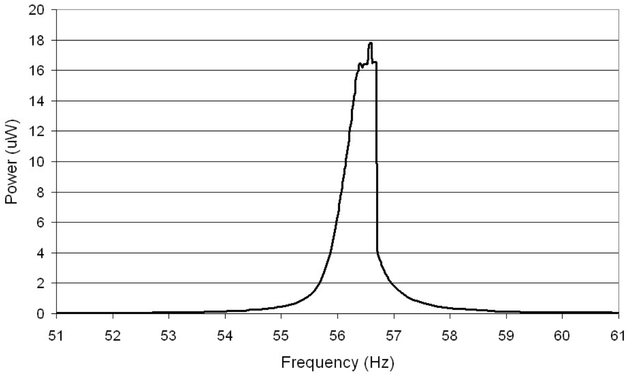

Figure 7 – Optimum Power output of the optimised magnet configuration generator.

Figure 7 shows that the maximum power generated by the optimised generator was 17.8µW and the voltage output was 52mVrms. This power output was achieved across the optimum load resistance, at a resonant frequency of 56.6Hz with an applied acceleration of 60mg.

7 – DISCUSSION OF RESULTS

The results from the practical generators show excellent correlation with the simulation results. Figure 6 shows that the generated output voltage measured experimentally increases by a factor of 2.23 with the optimisation of the magnet size for the same cantilever structure. This compares favourably with the simulated factor increase of 2.5. The simulation predicted 52mVrms and 120mVrms for the small and large magnet configurations respectively, compared with 39mVrms and 87mVrms for the practical generators. The experimental results are approximately 25% lower than the simulated values. The difference is predominantly due to assembly tolerances in the actual devices. In particular, variations in the gap between magnets and the presence of small air gaps and adhesive layers within the magnetic circuit will reduce the magnetic flux gradient achieved in practice.

The optimised generator power output is 17.8µW compared to 1.7µW for the smaller generator. The considerable improvement is due to the increased magnet dimensions which mean the magnetic flux gradient is intersecting a larger proportion of the coil throughout the full cycle of the beam motion. This level of power compares very favourably with other devices described in the literature. Table 1 lists devices by year and gives their power output, testing conditions and, for comparison purposes, the normalised power density (NPD, nW/mm^3). This figure is the power output scaled to a 60m*g* acceleration divided by the volume of the device. The power output scaling uses the relationship shown in equation 1 where $P \propto a^2$. The range of devices includes electromagnetic, piezoelectric and electrostatic transduction mechanisms. Table 1 shows that the generator presented here is a considerable improvement with a NPD 5.5 times that of the next best device.

Table 1: Comparison between vibration powered generators

Device	Power	Volume	Conditions	NPD
Shearwood 1997 [6]	0.3 µW	5.4 mm^3	382ms^{-2}/4.4kHz	1.4x10^{-4}
White 2001 [7]	2.1 µW	124 mm^3	2.3ms^{-2}/80Hz	1.2
Roundy 2003 [8]	375 µW	1 cm^3	2.5ms^{-2}/ 120Hz	21.6
Arakawa 2005 [9]	6 µW	800 mm^3	3.9ms^{-2}/ 10Hz	1
Cantilever Generator	17.8 µW	150 mm^3	0.6ms^{-2}/ 60Hz	119

8 – CONCLUSIONS AND FURTHER WORK

This paper has presented the design, construction and testing of an electromagnetic micro-generator based on a cantilever beam structure. The dimensions of the generator have been simulated and subsequent assembly of a practical generator has confirmed those simulations. The optimised generator produced an output voltage of 87mVrms across a 9MΩ load from 60m*g* vibrations at 60Hz. The maximum power was 17.8µW across 150Ω. However, whilst the power output from such modest vibrations is impressive, the generated voltage of 52mVrms is still too low and needs to be increased before the generator can be used in practical wireless sensing applications. This could be achieved by increasing the number of turns in the coil. The next stage in this project will be to evaluate a generator assembled with a coil of the same dimensions with 2300 turns wound with enamelled copper wire of 12 microns diameter. In addition, the magnetic field strength is proportional to the inverse cube of the distance from the dipole. Therefore, reducing the distance between the magnets by just 0.2mm should double the field strength. Thus, future designs of the cantilever generator will attempt to reduce the gap between the magnets and the coil.

9 – ACKNOWLEDGEMENTS

This work has been funded by the European Commission through a research project VIBES (IST-1-507911) (Vibration Energy Scavenging) of the 6th Framework Program.

10 – REFERENCES

[1]Roundy S, “On the Effectiveness of Vibration-based Energy Harvesting”, Jnl of Intelligent Material Systems and Structures, Vol. 16, pp. 809-823, 2005.

[2] Williams C.B, and Yates R.B, “Analysis of a micro-electric generator for Microsystems” Sensors and Actuators, A52 8-11, 1996.

[3] P.Glynne-Jones, M.J.Tudor, S.P.Beeby, N.M.White, “An electromagnetic, vibration-powered generator for intelligent sensor systems”, Sensors and Actuators A, 110, pp. 333-349, 2004.

[4] S.P.Beeby, M.J.Tudor, R.N.Torah, E.Koukharenko, S.Roberts, T.O’Donnell, S. Roy, “Macro and micro scale electromagnetic kinetic energy harvesting generators” Proceedings of DTIP conference, Stresa, Italy, 2006.

[5]Torah, R. N., Beeby, S. P., Tudor, M. J., O’Donnell, T., Roy, S. Kinetic energy harvesting using micro scale electromagnetic generators. 17th MicroMechanics EuropeWorkshop (MME 06), September 3-5th, Southampton, UK, pp.189-192 2006

[6] Shearwood C and Yates R B Development of an electromagnetic micro-generator, Elect. Letts 33 (22), pp. 1883-1884, 1997.

[7] Glynne-Jones P, Beeby S P and White N M Towards a piezoelectric vibration powered microgenerator IEE Proc.-Sci.Meas. Technol. 148, pp. 68-72, 2001

[8] Roundy S, Wright P K and Rabaye J 2003 A study of low level vibrations as a power source for wireless sensor nodes, Computer Communications 26, pp. 1131-1144 2003.

[9] Y Arakawa, Y Suzuki and N Kasagi Micro seismic power generator using electret polymer film PowerMEMS, Kyoto, Japan, pp. 187-190, 2004