SIMULATION TOOLKIT FOR ENERGY SCAVENGING INERTIAL MICRO POWER GENERATORS

G. Kondala Rao, P. D. Mitcheson, T. C. Green
Imperial College London, Department of Electrical Engineering
Exhibition Road, South Kensington, London, SW7 2AZ, UK.

Abstract: A critical issue to the optimization of a micro generator is the electromechanical link between the transducer and power processing circuitry because the performance of each subsystem depends on the behavior of the other. In order to accurately simulate and optimize a micro generator system, a combined electromechanical simulation is required. In this paper, a PSpice based electromechanical simulation tool kit for energy harvesting inertial micro generators has been developed. The tool kit consists of a generic Mass-Spring-Damper (MSD) model coupled to models of Electromagnetic (EM), Electrostatic (ES) and Piezoelectric (PZ) transduction mechanisms. Additional features of the physical systems that affect the overall performance such as end stop dynamics and parasitic damping are also included. The realisation of these models in PSpice is explained and case study simulation results of these models are also presented.

keywords: Energy scavenging, PSpice modeling, inertial micro generator

1. INTRODUCTION

Motion and vibration are attractive sources for microengineered energy scavenging generators [1]. The most universal motion scavengers are of the inertial type, i.e. having a proof mass suspended within a frame, and energy extracted by a transducer that damps the motion of the proof mass within the frame. These devices have the advantage that they can function simply by being attached to a source of motion at a single point, rather than relying on the relative motion of different parts of the host structure. Thus they are also well suited to miniaturisation. However in [2], it has been shown that the reported inertial micro generators are operating well below their maximum power limit. Improving the performance of micro generators is important either to increase the power output for a given size or to reduce the size of the micro generator for the required power. In [3] and [4] methods for optimization of an electromagnetic micro generator are given. These methods are theoretical and only part of the system was modeled before making a practical device. Complete physics based models of the micro generator systems have not been reported in the literature. In this paper, a PSpice based simulation tool kit for inertial micro generators has been developed. This simulation tool kit, free for download from our research group website, can be used to simulate or to optimize the micro generator system or to develop suitable power conversion circuits as per load requirements. The development of this toolkit is discussed in the rest of the paper and usage examples are presented.

2. COMBINED ELECTRO-MECHANICAL SIMULATION MODEL

A critical issue for the optimization of a micro generator is the electromechanical link between the transducer and power processing circuitry because the performance each subsystem depends on the behavior of the other. Therefore, In order to accurately simulate and optimize a micro generator system, a combined electromechanical simulation is required. An equivalent circuit approach is commonly used for combined electromechanical simulation by representing the mechanical and electrical parts in electrical circuit elements [5]. Fig. 1. shows an equivalent circuit representation of a piezoelectric bimorph [1] and this can be simulated using any standard circuit simulator. However, the representation of mechanical parts by electrical elements is often not intuitive and in the case of inertial micro generators modeling of non-linear effects such as the proof mass hitting an end stop and loosing some momentum is very difficult. A PSpice based simulation model which considers the non-linear effects and electromechanical interactions has been developed in [6] for the electrostatic parametric generator. Here, we have modularised this model and developed a complete toolkit for inertial micro generators includes Electromagnetic, Electrostatic and Piezoelectric transducer technologies.

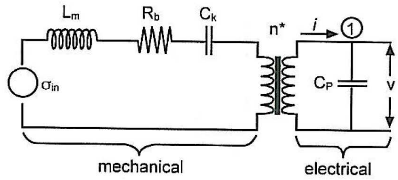

Fig. 1. Equivalent circuit representation of piezoelectric bimorph [1]

A block diagram of the generic inertial micro generator for modeling it's electromechanical behavior is shown in Fig. 2. It consists of generic mass spring damper (MSD) model with end stop dynamics, the electrical and parasitic damping directly arising from the transduction mechanism is also present.

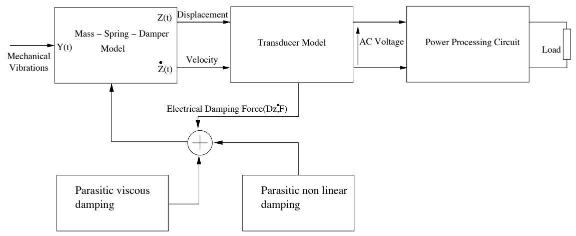

Fig. 2. Block diagram of the generic electromechanical behavior model of the inertial micro generator

The generic MSD model gives accurate position of the proof mass with reference to end stop limits and it has been realised by solving the differential equ. 1 using the PSpice Analog Behavioral Model (ABM) library.

$$m\ddot{z}(t) = -m\ddot{y}(t) - D_m\dot{z}(t) - D_e\dot{z}(t) - K_s z(t) - F_{ESD} \quad (1)$$

The terms in equ. 1 represent the force due to the linear mass, spring and damper elements except F_{ESD} which represents the non-linear end stop dynamics. The end stop dynamics are modeled in such way that whenever the proof mass hits either of end limits (i.e. $+Z_l$ or $-Z_l$) some of its kinetic energy will be dissipated as heat. The F_{ESD} force is modeled as a damped spring system and is given in equ. 2. Z_l is the end stop limit which can be varied according to desired specification and K_{ESD} and D_{ESD} are the end stop impact spring and damping coefficients respectively, which can be altered depends on the material used in the fabrication.

$$F_{ESD} = \begin{vmatrix} (|z(t)| - z_l) * K_{ESD} + \dot{z}(t) * D_{ESD} & \text{if } |Z(t)| > Z_l \\ 0 & \text{Otherwise} \end{vmatrix} \quad (2)$$

The electrical damping force D_e and the parasitic damping force D_m in equ. 1 depend on the transduction mechanism (Electromagnetic, Electrostatic and Piezoelectric) and so the MSD model must be combined with suitable transducer block to build up a full simulation. Modeling of electrical damping forces associated with EM and ES transduction mechanisms is discussed in the following section. Details of modeling of Piezoelectric electrical damping force and parasitic damping forces associated with each transduction mechanism are not provided in this paper.

3. MODELING OF EM AND ES DAMPING FORCES

Electromagnetic:

The voltage developed by an electromagnetic transducer is described by faraday's law of induction. In a micro generator, this corresponds to a velocity dependent voltage source. The magnitude of the voltage source is given by

$$V_{coil}(t) = (N_c * B_m * L_c)V(t) \quad (3)$$

where L_c is active length of the coil in the magnetic flux cutting region, N_c is no of the coil turns, B_m is change in flux density and $V(t)$ is velocity of the proof mass. The inductance and resistance of the coil are then added in series with the voltage source.

The PSpice model of the electromagnetic transduction mechanism is shown in Fig. 3. The relative mass velocity is multiplied with the factor $N_c * B_m * L_c$ to represent the rate of change of flux linkage using a gain block and a voltage dependent voltage source (E) is used to represent velocity dependent voltage source. The electrical damping force (BIL force) is calculated by multiplying the current through the coil L_m with $N_c * B_m * L_c$. This force can be used as electrical damping input to the generic MSD model. The two terminals *Load_pos* and *Load_neg* are then used to connect the electrical load.

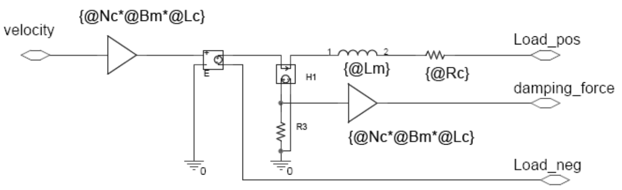

Fig. 3. EM transduction PSpice simulation model

The case study simulation results of electromagnetic transduction mechanism are given in section 4.

Electrostatic:

A capacitor can be thought of as a charge controlled voltage source. A time varying capacitor is a charge controlled voltage source with variable gain. To represent this kind of variable gain voltage sources, a generic variable capacitor is realised using a fixed capacitor and a multiplier as shown in Fig. 4.

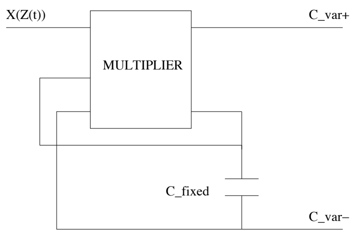

Fig. 4. Generic Variable Capacitor realisation

The fixed capacitor voltage is multiplied with a position dependent factor X(z(t)), therefore the variable capacitor voltage is given by:

$$V_{C_{var}} = (1 + X(z(t)))V_{C_{fixed}} \tag{4}$$

where $V_{C_{var}}$ and $V_{C_{fixed}}$ are voltages across the variable capacitor and the fixed capacitor respectively, which are referenced to C_var-, so that the variable capacitor can be realised as a fully floating component (i.e. it is not ground referenced). The X(z(t))value is derived based on the principle that the current flowing through the variable capacitor and fixed capacitor is the same and is given by

$$I = C_{fixed}\frac{d}{dt}V_{C_{fixed}} \tag{5}$$

from voltage relation equ. 4, substituting the V_{fixed} value

$$I = \frac{C_{fixed}}{(1 + X(z(t)))}\frac{d}{dt}V_{C_{var}} \tag{6}$$

Any time varying capacitance can be simulated using this generic variable capacitor model shown in Fig. 4, if its capacitance can be written of the form $\frac{C_{fixed}}{1+X(z(t))}$. Different types of variable capacitor's C_{fixed} and X(z(t)) values are given in Table. I.

Variable capacitor type	C_{fixed}	X (z(t))	ES Force
Inplane gap Closing	$\frac{2N_g\varepsilon L_f h}{d}$	$-\left(\frac{z(t)}{d}\right)^2$	$\frac{Q^2 z(t)}{2N_g\varepsilon L_f hd}$
Inplane overlap	$\frac{\varepsilon L_f h}{d}$	$\frac{-z(t)}{L_f+Z(t)}$	$\frac{Q^2 d}{2Ng\varepsilon h}\frac{1}{(L_f+z(t))^2}$
Out of plane gap closing	$\frac{\varepsilon A}{d_{min}}$	$\frac{(Zl+z(t)-d_{min})}{d_{min}}$	$\frac{Q^2}{2\varepsilon A}$

TABLE I

PARAMETERS OF VARIOUS VARIABLE CAPACITORS

Different variable capacitors are modeled in PSpice by realising appropriate $X(z(t))$ in the generic variable capacitor equ. 4. For example, the PSpice model for inplane gap closing comb drive structure is shown in Fig. 5. Computation of electrostatic force given in Table I is also provided in the model using ABM library. This can be used as the electrical damping force input to the generic MSD model. Simulation results of inplane gap closing type variable capacitor are discussed in the following section.

4. SIMULATION RESULTS

Complete micro generator systems are modeled by interfacing various PSpice models such as generic MSD model and electrical and parasitic damping force models according to Fig. 2.

The electromagnetic micro generator is simulated for given input amplitude Y_o= 22.3μm, frequency F= 50 Hz, inductance L_m= 2mH, No of

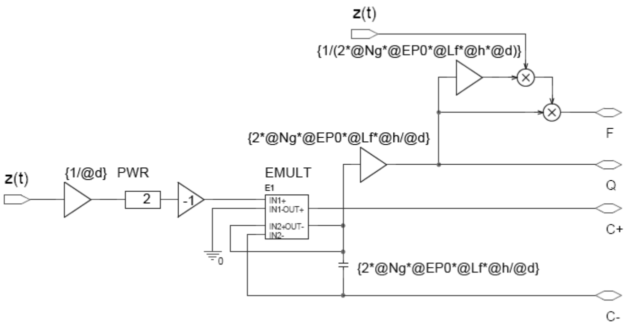

Fig. 5. PSpice model of an inplane gap closing comb drive variable capacitor

turns N_c=1000, active coil length L_c=2 mm, flux density B_m= 0.8T, coil resistance R_c=25Ω, load resistance R_l= 2310Ω, proof mass=1g, parasitic damping coefficient (assumed) D_m=0.001 and end stop limit being set at $100\mu m$.

The simulation results of the proof mass displacement and velocity are shown in Fig. 6. It can be seen that there is a plateau portion at the peak of the inertial mass displacement, which occurs when the mass hits the end stop limit. Sudden change in the velocity of the mass on hitting the end stop represents the loss of its momentum.

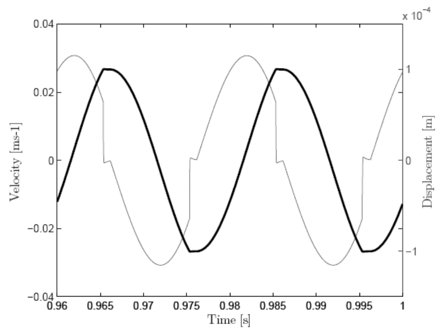

Fig. 6. Proof mass relative velocity and displacement

In order to validate the PSpice model of the inplane gap closing variable capacitor, it has been interfaced with the generic MSD PSpice model and also with external circuit elements, which are used to charge and discharge the variable capacitor at specific points of mass travel. The variable capacitor is charged when it is in the maximum capacitance position i.e. at $z(t) = Z_l$ and $z(t) = -Z_l$ and is discharged when it is in the minimum capacitance position i.e. at z(t)=0. Fig. 7. shows the simulation results of the position of the comb fingers, the voltage across the variable capacitor and the associated electrostatic force.

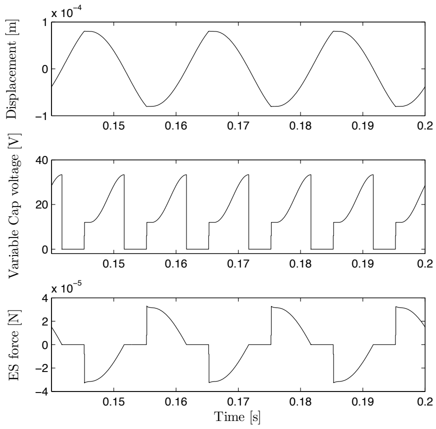

Fig. 7. Inplane gap closing comb drive displacement,variable capacitor voltage and electrostatic force

5. CONCLUSIONS

A combined electromechanical simulation tool kit has been developed for inertial micro generators. Case study simulation results of Electromagnetic and Electrostatic micro generator systems have been presented to verify the operation of the models. In this paper, micro generator systems are simulated with the load being a simple resistor. However, designing and interfacing of suitable power conversion circuits needs to be addressed, and the flexibility of our simulation toolkit allows such simulations to be achieved by simply drawing the circuits in PSpice. The toolkit for download along with installation instructions can be found at http://www.imperial.ac.uk/controlandpower/powermems.

REFERENCES

[1] S. Roundy, P. K. Wright, and J. M. Rabaey, *Energy Scavenging for Wireless Sensor Networks*, 1st ed. Boston, Massachusetts: Kluwer Academic Publishers, 2003.
[2] P. D. Mitcheson, E. K. Reilly, T. Toh, P. K. Wright, and E. M. Yeatman, "Transduction mechanisms and power density for mems inertial energy scavengers," in *Proceedings of Power MEMS 06*, Berkeley, USA, 2006, pp. 275 – 278.
[3] Serre.C, Pe'rez-Rodriguez.A, Fondevilla.N, Martincic.E, Morante.J.R, Montserrat.J, and Esteve.J, "Optimization keys for vibrational electromagnetic generators," in *32nd International Conference on Micro and Nano Engineering*, Barcelona,Spain, September 2006.
[4] C. Saha, T. O'Donnell, H. Loder, S. P. Beeby, and M. J. Tudor, "Optimization of an electromagnetic energy harvesting device," *Magnetics, IEEE Transactions on*, vol. 42, no. 10, pp. 3509–3511, 2006.
[5] S. D. Senturia, *Microsystem Design*, 1st ed. Boston, Massachussets, USA: Klewer Academic Publishers, 2001.
[6] P. D. Mitcheson, "Analysis and optimization of energy harvesting micro generator systems," Ph.D. dissertation, Department of Electrical Engineering, Imperial College London, 2005.