PARAMETRICAL STUDY OF MINIATURE GENERATORS FOR LARGE MOTION APPLICATIONS

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Abstract: *Designing a generator for large amplitude motion has lead to an energy-consistent model that also considers the finite dimensions of the device. Using SPICE software we have studied the influence of several design parameters on the output of the generator, including the limited motion of the seismic mass imposed by small system dimensions. Three different types of load circuits are presented, as well as their optimization towards output voltage and power.*

Keywords: micro generator, SPICE, scavenger

INTRODUCTION

Ambient intelligence has become the utopia that drives engineers towards miniaturizing complete systems into millimeter scale network nodes. Meanwhile they further increase functionality by adding precise sensors, powerful on-board calculation units and wireless communication facilities [1]. Triggered by this drive a large effort was put into low power design and efficient energy storage devices, while the idea of local energy generation has lead to the new field of Power MEMS.

This work focuses on the design of a micromachined generator for applications subjected to large amplitude motions. The generator is part of the class of seismic scavengers: these extract energy from motion in the environment of the device. They typically consist of a suspended seismic mass, connected to the moving package by a mechanical construction; this suspension is modeled by the set of springs and dampers in Fig. 1. The kinetic energy of the moving mass is then partly converted to electrical energy, based on one of the following conversion principles: electromagnetic conversion [2], electrostatic conversion [3] or piezo-electric conversion [4].

The spring-like behavior of the suspension allows the use of resonance to enhance the motion of the mass. This strategy allows the design of generators for extracting the energy from vibrations with small amplitudes and high frequencies.

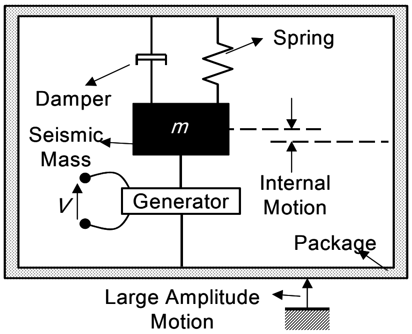

Fig. 1. Overview scheme for mechanical energy scavengers

The energy is typically extracted during the motion of the mass (velocity damped resonator) [3]. If however the amplitude of the motion is larger than the characteristic dimensions of the device, the resonance phenomenon cannot be used. In those cases the energy can either be extracted during the motion (parametric generation [5]) or during the impact of the mass onto the package (impact generation [6]). In this paper we study the effect of impact, travel length and mass on the energy output of the generator. Three types of load circuits are compared and optimized towards output voltage and power generation.

MODELING

A model that is used to study a motion-based generator should be capable to deal with the flow of energy from the mechanical domain to the electrical domain (and vice-versa). One way to achieve this energy-consistent model is by constructing an electrical circuit for all mechanical components, based on the equivalences in the behavior of masses and inductances, of springs and capacitors and of dashpot dampers and ohmic resistors. In this circuit, voltages and currents represent forces on and velocities of the mechanical components. The input motion is then represented by a current source; in this paper we apply only sinusoidal motion.

The equivalent circuit is connected to an electronic load circuit by an equivalent electrical model of the transducer, which is constructed out of its behavioral relations between force, displacement, voltage and charge. The advantage of using the electrical equivalent circuit is the ease of simulating the full electromechanical device in SPICE, as shown in Fig. 2. An additional switch mimics the impact of the mass into the package: opening the switch results in fixing the motion of the mass to the motion of the wall of the generator. This wall is modeled as a combination of a very stiff spring with a large damping. The switch closes again as soon as the acceleration of the mass changes sign; the mass is released.

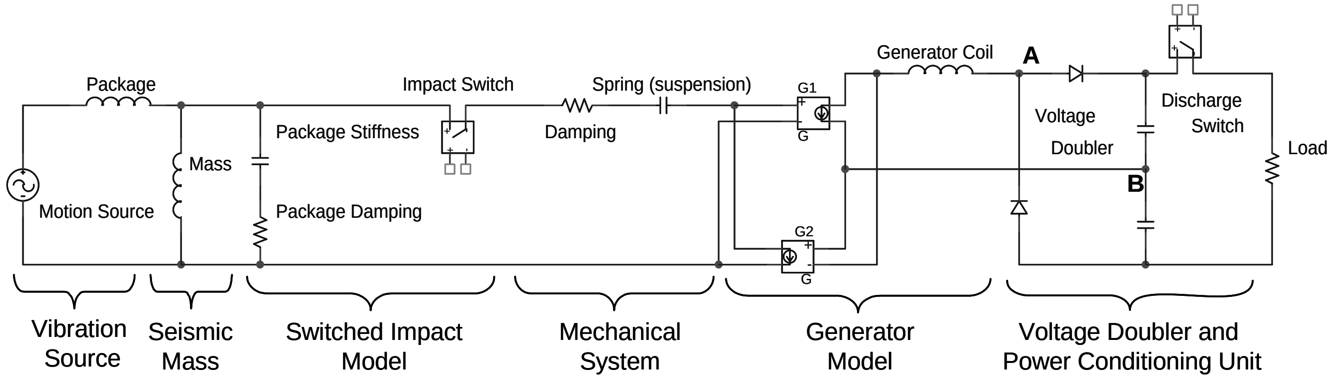

Fig. 2. Implementation of the model in PSPICE, illustrating the modeling of the different components of the system.

In Fig. 2 the generated voltage is rectified and doubled by the two diodes and capacitors, which are discharged every cycle. Any other load circuit could replace this small power conditioning circuit by simply connecting the load to the clamps (A, B). The given model of the transducer corresponds to an electromagnetic generator, however a similar model holds for electrostatic and piezoelectric generators [7].

SIMULATIONS AND RESULTS

The graphs and numbers presented in this section were obtained by simulating the electromagnetic model of Fig. 2, where a generator with a seismic mass of 1 gram was moved over a fixed displacement Y of 0.5 m at frequencies between 1 and 15 Hz. This situation can be found in industrial environments. In the low frequency limit it is also applicable to human limb motion. Unwanted damping is initially neglected, while the package only allows inelastic impact (all kinetic energy is absorbed). In Fig. 3 the motion of the mass is shown with a maximum travel of 10 mm at 10 Hz, as well as the generated voltage over the capacitors of the voltage doubling circuit.

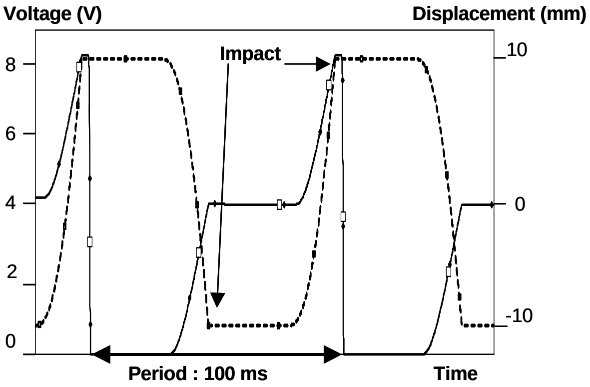

Fig. 3. Simulation of the system: movement and impact of the mass (dotted), rectified and doubled output voltage (full)

The spring constant was adjusted to obtain resonance at the used frequency. The generator is characterized by a transformation factor Γ of 1 Vs/m. This value corresponds to permanent magnet of 1T moving through a coil with a surface of 1 cm^2, constructed by a wire with a diameter of 100 μm (10 turns per mm). The transformation factor Γ represents the relationship between the generated voltages at a given speed.

Electrical parameters The load circuit that is used influences both the mechanical and the electrical behavior. We applied three types of load to the model:

- an ohmic resistor
- a voltage doubling circuit with buffer capacitors that are discharged once per cycle (discrete discharge as in Fig. 2)
- a voltage doubling circuit with buffer capacitors, directly connected to a load resistance.

A different load circuit results in a different voltage pattern, as illustrated in *Fig. 4*.

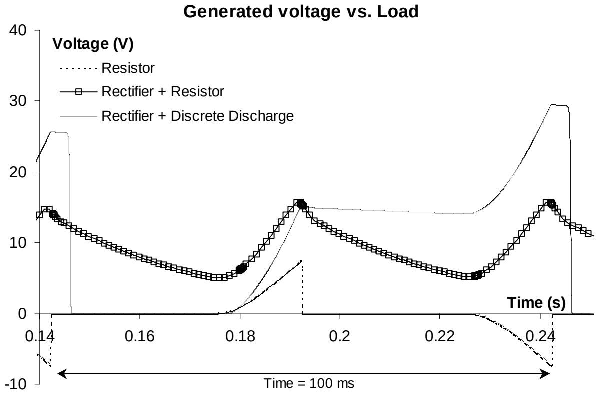

Fig. 4. A higher voltage is obtained by discharging a buffer capacitor at discrete times (maximum displacement = 5 cm)

Resistive load

For electromagnetic generators the electromechanical damping is inversely proportional to the applied resistive load: a bigger load will result in a higher power at a larger voltage, but the amplitude of the motion of the mass will also increase. There exists an optimum value [7]:

$$R = \frac{\Gamma^2 X_{\max}}{m\omega Y}$$

at which the amplitude of the mass *m* reaches the maximum allowable displacement x_{max}, at the angular frequency ω. A higher resistance leads to the impact of the mass onto the package (arrows in Fig. 5). The generated power decreases, while the generated voltage still increases but saturates. Note that the decrease of the power is linked to the saturation of the voltage by $P = V^2 / R$.

Discrete discharge buffer

The discharge switch that is shown in Fig. 2 discharges the buffer capacitors completely once every cycle. The charge on the capacitors is then transferred to the load or to a power-conditioning unit at a doubled voltage.

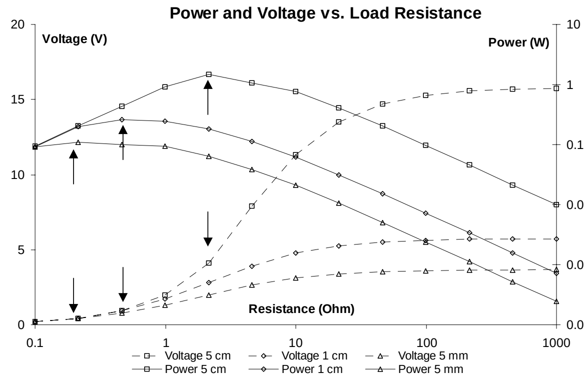

Fig. 5. Effect of the applied resistive load on the power and on the voltage.

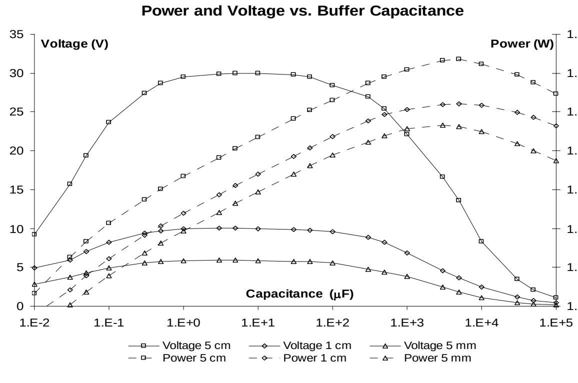

Fig. 6. Output power and voltage as a function of buffer capacitances.

Small buffer capacitances will charge and discharge very fast, but will only store a limited amount of energy. Large capacitances can store more energy, however the voltage is proportional with the amount of charge on the capacitor: the generated amount of energy might not be sufficient to achieve the desired voltage. We conclude that:

- the optimal capacitance for high power does not coincide with the optimum for high voltages, as was the case for a resistive load.
- the optimum is reached at an very high load capacitance.
- the optimized power is slightly higher than the power achieved with a resistive load.

Voltage doubling circuit with resistive load

This type of load is constructed by removing the discharge circuit from Fig. 2 and replacing it by a resistive load. Depending on the ratio between the used buffer capacitances and the applied load resistor the load will change its behavior. A small load resistance will continuously discharge the buffer capacitances; the load behaves as a resistive load, while the voltage is not doubled. If the load resistance is larger the capacitors will not discharge completely, and the average voltage will rise, as illustrated by *Fig. 4*. The optimum power is reached at a higher load resistance than the purely resistive load, although the power level is lower.

The impact of impact

In the following paragraphs we assume a resistive load. As mentioned before, the optimum power is reached if the load resistance is tuned to allow the maximum mass displacement without the occurrence of impact. It is however not always possible to optimally tune the load, e.g. due to parasitic impedances such as the series resistance of the coil. If the electro-mechanical damping is further decreased (a higher load is applied), then the mass will reach a higher speed in between two impacts. This speed is translated directly into a higher voltage (Fig. 5). The optimum load resistor is now equal to the unwanted series resistance (matched output). In Fig. 7 we compare this situation to the situation where *mechanical* damping has been increased to avoid the impact of the mass. By allowing impact, we obtain a much higher voltage.

Mechanical parameters

The simulation exercise of Fig. 7 also illustrates the importance of the travel length when optimizing the converted power and voltage. A larger maximum displacement will allow the mass to gain more speed, and therefore generate a higher voltage. This trend saturates however to the case where the mass moves harmonically. Closely linked to this observation is the influence of the *mass* on the generated voltage and energy. The generated power increases monotonically with mass (Fig. 8). For small masses the curve is steep: in this region the mass does not impact. As soon as the mass impacts, the gain saturates. Note that the obtained power is large at higher frequencies. Still, the power level is about 10 μW at 1Hz.

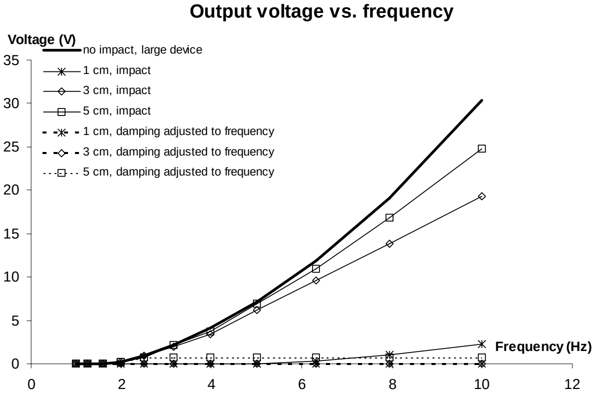

Fig. 7. Impact vs. no impact, if the motion of the mass is mechanically damped

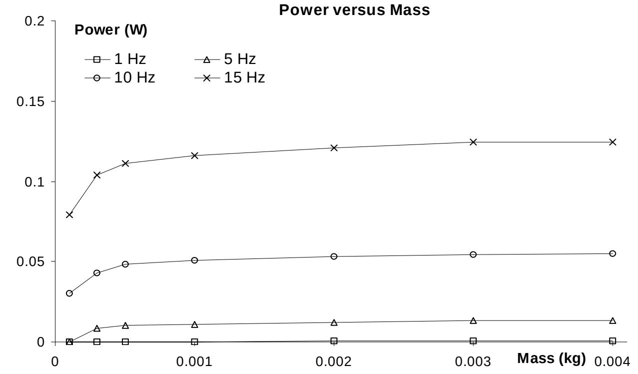

Fig. 8. The generated power saturates with increasing mass

CONCLUSIONS

In this paper we have demonstrated the power of equivalent electrical circuits for analysis and design of large motion generators. The influence of electrical and mechanical parameters was studied using a SPICE simulator. The model allows dimensioning of important parameters such as mass and maximum travel, and the effect of impact. This approach was also used to study the impact of power conditioning electronics on the behavior of the generator. We conclude that the occurrence of impact is beneficial in terms of voltage and power, especially if the appropriate type of load is used.

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