TOWARDS HYSTERETIC POWER MICROSWITCHES FOR EFFICIENT VIBRATION ENERGY HARVESTING SENSOR SYSTEMS

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Abstract: Interest in vibration energy harvesting technologies has increased significantly in the last decade, primarily due to the possibility of realizing ultra-low power sensor and communication circuits. In such low-power applications, it is paramount to maximize the efficiency of the harvesting system. Here, we propose the use of a simple MEMS cantilever as a power regulating hysteretic switch that allows discharge of the collected voltage within a predetermined range through pull-in and pull-out. This approach enables voltage regulation of the load circuit without the need for any external fixed sources and minimizes losses. We have developed a model to characterize the motion of the beam and verified it by comparing to existing experimental and calculated results. The beam is designed to be immune against possible environmental shock forces; immunity may be increased by deliberately introducing squeeze-film damping. However, there is a tradeoff between shock force immunity and switching time.

Key Words: Microswitch, cantilever, shock loading, pull-in, pull-out

1. INTRODUCTION

Due to the stochastic nature of ambient vibrations, most vibration energy harvesting systems collect electrical charge on a small storage capacitor or a rechargeable battery for use when needed by an associated sensor, control or communication circuitry [1, 2]. Ensuring that enough voltage has accumulated prior to powering a sensor unit is necessary for the correct operation of the integrated circuit elements comprising the system, as well as the reliability of the measurements. Many different power control circuit designs have been proposed in the literature for this purpose [2- 5]; yet, some of them rely on external power sources, or consume too much power themselves to be practical in the microwatt range [5].

Micromechanical beams have already been demonstrated as microswitches, especially in the RF field. They offer to high electrical isolation, low transmission loss [6]. Such devices usually feature the ‘pull-in’ phenomenon, in which the beam gets to rapidly contact the substrate above a critical electrical field. For some devices, this might mean one of the failure mechanisms to be avoided; however, electrostatic microswitches make positive use of this phenomenon. There exists a vast literature that attempts to quantify and estimate the pull-in voltage for a given geometry under static conditions[7,8]. There is also recent work trying to predict dynamic behavior of beams under electrostatic and shock loading [9-11]. It was pointed out that static pull-in voltage can be smaller than the static calculations have predicted. Other studies have focused on characterizing and predicting the behavior of microbeams beyond pull-in [12, 13].

Here, we propose a mechanical alternative for power control in a vibration energy harvesting system – a hysteretic power switch based on an electrostatically actuated cantilever beam. We have developed a computationally efficient model for the behavior of cantilever beams under electrostatic and shock loading. By using this model, we have designed hysteretic microswitches that close and open at voltage levels that ensure correct transistor biasing and activation conditions for a commercially available complementary metal-oxide-semiconductor (CMOS) process. Immunity of the microswitches to unexpected environmental shocks is one of the design parameters considered in this paper, with the goal of making these switches usable in power generating systems that work under high vibration or potential shock environments.

2. MODELING AND DESIGN

2.1 Theoretical Analysis

Euler-Bernoulli Beam Theory accurately describes the transverse dynamics of long, slender beams.

$$\rho A\frac{\partial^2 z(x,t)}{\partial t^2}+\alpha\frac{\partial z(x,t)}{\partial t}+\beta I\frac{\partial^5 z(x,t)}{\partial x^4\partial t}$$
$$+EI\frac{\partial^4 z(x,t)}{\partial x^4}=f(x,t)+\frac{\varepsilon_0 bV^2}{2(d-z)^2}$$
(1)

Parameter	Description
L	Beam length
b	Beam width
h	Beam thickness
d	Gap between the surfaces
A	Cross-sectional area
I	Moment of inertia of the beam cross-section
ρ	Material density
E	Young's Modulus
ε_0	Permittivity of free space
V	Applied Voltage
α,β	Damping constants

Table 1: Description of parameters.

One computationally efficient way of solving this equation is through eigenfunction expansion. It assumes that solution has spatial and temporal parts. Spatial solutions form the modes of the system and can be solved analytically. However, nonlinear temporal part needs to be solved numerically. We used MATLAB Simulink to find the solutions and combine the results with the spatial solutions at each time step. Seven modes are found to be enough to capture the behavior of cantilever beams.

2.1 Simulation and Comparison

In order to ensure that the model has enough accuracy, we compared the results with those from COMSOL Multiphysics' finite element analysis, as well as experimental and calculated results available in the literature. In COMSOL simulations, the electrostatic equation is solved in the air domain around the beam and the associated electrostatic forces are coupled with the structural domain. Arbitrary Lagrangian-Eulerian (ALE) method is used to handle the geometry changes associated with the movement of beams. Figure 2 shows the behavior of a cantilever beam under a

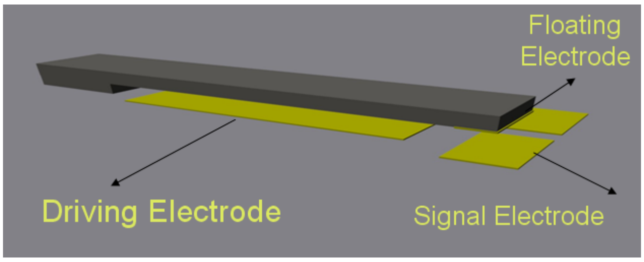

Figure 1: Microswitch geometry.

0.95 V electrostatic load and a 30 g shock. Here, the beam parameters (as defined in Table 1) are *L* = 275 µm, *b* = 30 µm, *h* = 1 µm, *d* = 1 µm. It is designed to statically pull in at 1 V; the maximum shock loading that the beam can tolerate before pull-in at 95% of the designed actuation voltage is used as a benchmark to quantify its shock tolerance. Pulse width is chosen to be almost ten times larger than natural period of the beam.

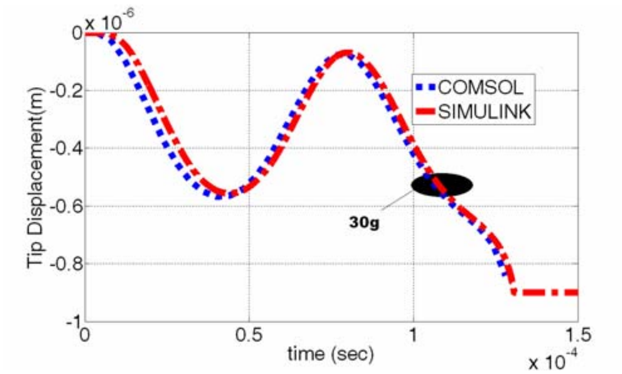

Figure 2: Cantilever tip deflection under 0.95 V and 30g shock loading (zero damping).

Table 2 depicts a comparison between our model and experimental and analytical results available in the literature for specific beam geometry.

E = 169 GPa, b = 50 µm, h = 3 µm, d = 1 µm		
Beam Length [µm]	100	150
Poisson Ratio	0.32	0.06
V_{pi} (Experimental) [8][V]	39.9	16.8
V_{pi} (Analytical) [7] [V]	39.86	16.83
V_{pi} SIMULINK [V]	40.12	16.94
COMSOL (FEM) [V]	40.02	16.87

Table 2: Comparison of Pull-in Voltages for different cantilever beams.

2.1 Design

After confirming the accuracy of our model, we set out to design a mechanical microswitch for micro-power applications. Given the microwatt power range expected from MEMS vibration energy harvesters, the beam is designed to actuate under a low electrostatic potential (1 V). In Figure 3, the microswitch is subjected to a quasistatic ramp up and down in voltage; the beam pulls in at 1 V and pulls out at approximately 0.55 V. As you can see agreement is very good between the two independent solvers. Pull-out voltage is a function of stopping layer. In this example floating electrodes (50 nm) and signal electrodes (50nm) realize this. By increasing electrodes thicknesses to, for example, 125 nm, pull-out voltage can be increased as high as to 0.935 V. Therefore, it is design issue that needs to be considered.

Circuit components in a vibration energy harvesting system need to have enough immunity against large-amplitude vibrations or sudden impacts. The cantilever microswitch can be built to have a very large first resonance frequency – well over the frequency range of ambient vibrations (typically less than a few kHz). Hence, we focused on minimizing the effects of sudden impacts on the operation of the microswitch. We have determined that the simple cantilever microswitch architecture allows significant shock force immunity during the charging of a storage capacitor, and that the immunity gets even better for increasing squeeze-film damping. Figure 4 shows the relationship between the shock load that the system can withstand at 95% of the designed actuation voltage, and the corresponding squeeze-film damping constant. Squeeze-film damping is related to the velocity of the beam and inversely proportional to the cube of gap between electrodes [14]; it is also determined by the surrounding geometry. In Figure 4, the increase in damping is attributed to the surrounding structures progressively providing more resistance to air flow.

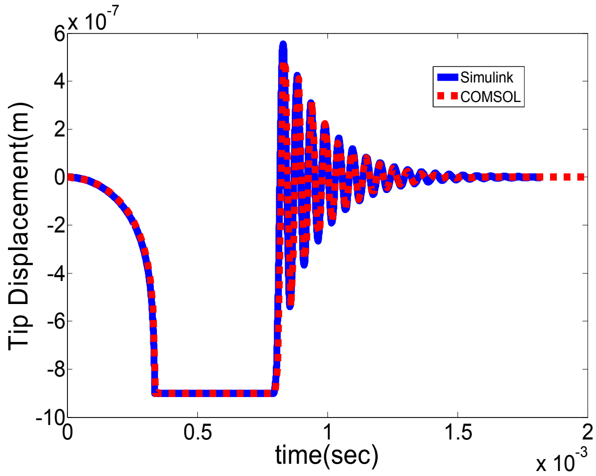

Figure 3: Pull-in and Pull-out of the cantilever beam

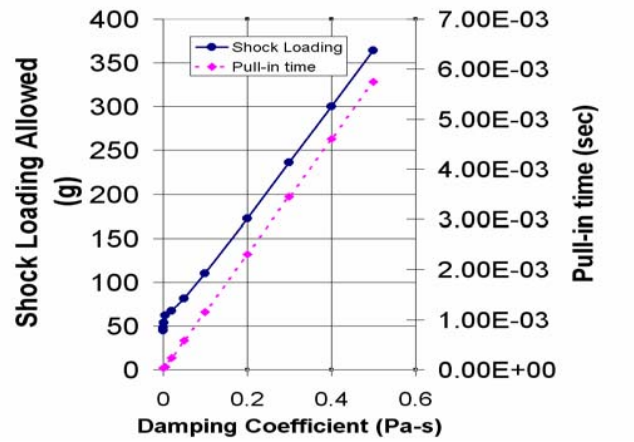

Figure 4: Threshold shock loading and pull-in time as a function damping coefficient

3. DISCUSSION

Different geometries might be considered to increase shock load immunity. There is, however, a tradeoff between high immunity and switching time (Figure 4). For most sensor nodes powered by MEMS-scale vibration energy harvesters, storage capacitance charging times will dominate over the actuation speed of the power switch. Intermittent powering every few seconds to minutes will be the normal operation mode, and the short delay of several milliseconds in power switch operation is unlikely to cause problems.

4. CONCLUSION

In this study, we have developed a model for a cantilever-based hysteretic power switch for use in vibration energy harvesting systems. We have demonstrated that the switch could be designed to accommodate significant shock loads from the environment through making use of the squeeze-film damping. A tradeoff exists between shock immunity and switch actuation time. Slower switch actuation in favor of higher shock immunity may be easily tolerated in this context, as micro-scale harvesters typically require long periods in which to charge their storage elements.

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