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Dynamic Simulation of a MEMS Cantilever Switch

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Abstract

The dynamic behavior of a micro-electro-mechanical-system (MEMS) cantilever switch is investigated. Over-actuation of the switch can degrade bounce characteristics and reduce the lifetime of the contacts. This work concerns the development of a control system that limits the number of switch bounces and reduces the impact force on the beam tip. A limited mass-spring analysis of the tip-position is given and an associated control approach is applied. Input limiting, state-feedback, and adaptive control methods are compared. All results demonstrate improved switch bounce characteristics for the simplified beam model with the adaptive showing the best performance improvement. A comprehensive finite element analysis is shown that predicts the dynamic beam behavior along the entire length. This approach produces a realistic model of the beam during switching, especially the tip displacement. A versatile control system is proposed that uses finite-element-analysis simulation and adaptive control. The feasibility of this dynamic control system is also discussed.

Index Terms—**MEMS, Micro-Relay, Adaptive Control, Finite Element Analysis.**

1. Introduction

Micro-electro-mechanical-systems (MEMS) technology has demonstrated the ability to miniaturize currently large systems to silicon-level designs, or Systems on a Chip (SoC). SoC designs allow for instrumentation to be reduced in size for portable and low-power devices. Use of the micro-cantilever has demonstrated usefulness in several applications. Applications including accelerometers [1], atomic microscopy [2], pressure sensors, and micro-relays have been shown. In this work a discussion of the micro-relay system is given. This application can allow the reduction of a large discrete part with a micro part that allows for weight and power reduction for relay dependent systems.

A description of a MEMS switch in terms of mechanical properties and results for switching time simulation has been previously presented [3-5]. In the presentation of the MEMS relay a description of the physical model and experimental

results are presented. The paper does not provide control to the switch but does address the bouncing of the contact of the system. In consideration of the system dynamics it would be a favorable trait of a controller to limit the number of tip bounces, or to limit energy imparted to the tip during switching.

Controllers developed in this work center on minimization of tip contact energy during switching. In limiting bounces, or imparted energy, the relay's life-span can be extended. The trade-off for this control is that the settling time of the switching is increased. A system that may operate at several switching speeds can be useful in systems that will be task at different priorities during their life-cycle. Long term installations, and remote applications, can benefit from this advancement. Satellite systems are one type of system that may operate for long durations in a low-priority state, but may be tasked heavily during other times.

In this paper a method for controlling a MEMS micro-relay model is presented. A description of the device and its operation is shown. Approximation of the system with a simplified mass-spring-damper (MSD) system is shown. Control of the MSD system is shown for using limiting control, pole-placement control, and adaptive control methods. It is shown that an adaptive control method is to be the most effective for the MSD system. Next, a finite-element analysis (FEA) model is used to simulate the micro-relay system in a more accurate manner. For this method the adaptive control method is used for the FEA model and results are shown.

2. MEMS Cantilever Switch

In this section an overview of the MEMS cantilever switch is given. A description of the basic geometry, operation, and performance criteria are shown. Work previously done in this area has shown the simulation of a MEMS cantilever switch to characterize bounce in the switching process [5].

The MEMS micro-relay is a metallic switch on a silicon-substrate with the relay contacts residing on the metallic beam and substrate. An example of the micro-relay geometry can be seen in Figure 1. Figure 1 shows the metallic beam adhered to the silicon-substrate with contacts and the gate area below the beam. The gate area supplies electrostatic control-force input for the beam. Electrostatic actuation has been covered in MEMS texts [6]. By energizing the gate area with a control voltage the beam can be made to move towards the substrate by electrostatic actuation completing a conducting path as the contacts meet.
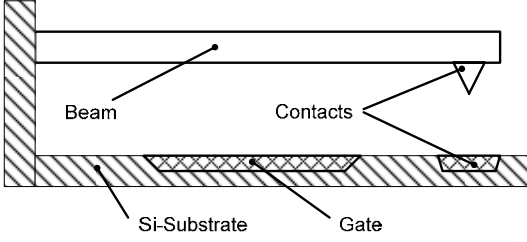
Figure 1. MEMS micro-relay geometry

3. Mass-Spring-Damper Analysis and Control

The MEMS cantilever can be approximated as a MSD system for reduced accuracy simulations. The use of the MSD model allows for a simplified simulation model for testing dynamic behavior using differing controllers. In this section a treatment of the MEMS cantilever as a MSD system will be shown along with simulation results to demonstrate open loop performance of the micro-relay.

The approximation of the micro-relay through a MSD system is shown in (1); where m is mass, k is the stiffness, b is the damping coefficient, and y is the tip-position. In the simulation tip contact is accounted for by a saturation function that emulates the tip impact. The electrostatic force, f_e, is simulated in (2) where ε_o is the permittivity of free space, w is the width of the beam, V is the input voltage, and d_t is the original height of the beam above the substrate. The system is then simplified using a state-space system model to prepare for simulation. The resulting system is presented in (3), (4), and (5). Finally in (6) the calculation of the mass-normalized momentum is calculated for use as a figure of merit for the simulations, where v_{tip} is the tip velocity of the beam. Figure 2(a) shows a block diagram representation of the open loop system is shown, Figure 2(b) is a closed loop version of a controlled beam system. Figure 3 and Figure 4 show the open loop characteristics of the MEMS micro-relay approximated as a MSD system.
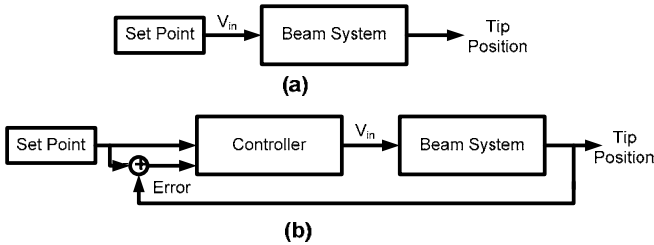

(a)

(b)

Figure 2. Block Diagram of: (a) Open Loop Beam System, (b) Closed Loop Controlled System

$$m\ddot{y} = -kx - b\dot{y} - f_e \tag{1}$$

$$f_e = \frac{\varepsilon_o w V^2}{\left(d_t - y\right)^2} \tag{2}$$

$$y_1 = y \tag{3}$$

$$\dot{y}_1 = y_2 \tag{4}$$

$$m\dot{y}_2 = -kx - by_2 + f_e \tag{5}$$

$$M_N = \frac{1}{2}\int_0^{t_f} v_{tip}^2\, dt \tag{6}$$
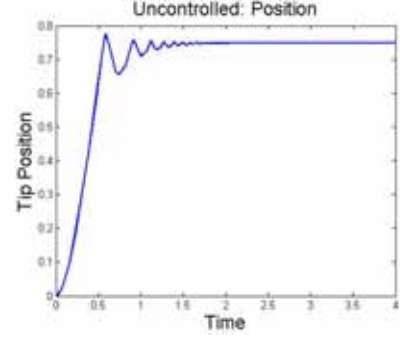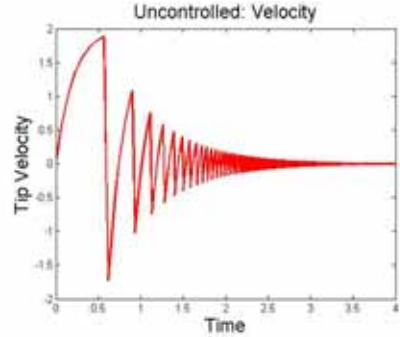

Figure 3. Open Loop MSD Position

Figure 4. Open Loop MSD Velocity

TABLE I
OPEN LOOP PERFORMANCE OF MSD MODEL

First Tip Impact [sec]	Normalized Momentum [m²/sec²]
0.59	0.6558

4. Proposed dynamic MSD controllers

Dynamic control of the MEMS cantilever switch is provided using three methods in this paper. The proposed controller types are force limiting, pole-placement, and adaptive control. Force limiting control limits the actuation force in a manner as to not over accelerate the switch. This type of control allows for limiting the momentum of the tip during the impact and subsequent bounces during actuation. Pole placement control is also used to demonstrate a known technique that is commonly used in state-space control. This controller type provides the ability to tune the dynamics of the switch actuation to a determined performance. Finally an adaptive control scheme was formulated and designed to minimize energy in the actuation to minimize impact momentum of the tip during actuation.

4.1. Force limiting control of MSD system

Use of a force, or acceleration, limiting control is explored in this section for the MSD system. Use of a saturation function in simulation, or a diode in hardware, can facilitate this type of control. The basic model is modified with a limiting function on the acceleration input of the device. This corresponds to effectively limiting the actuation forces along the micro-beam. By limiting these forces the overall energy input to the system can be limited to reduce the momentum of the tip during the impacts. Table II shows the results of the limiting controller for several cases with a maximum energy decrease of 38.21%.

TABLE II
LIMITING CONTROL PERFORMANCE OF MSD SYSTEM

Limit [Volts]	First Tip Impact [sec]	Normalized Momentum $[m^2/sec^2]$	Energy Decrease [%]
1.75	0.60	0.6363	2.9735
1.50	0.63	0.5989	8.6764
1.25	0.70	0.5614	14.3946
1.00	0.80	0.5240	20.0976
0.75	1.00	0.4861	25.8768
0.50	1.50	0.4486	31.5950
0.25	3.00	0.4052	38.2129

4.2. Pole-placement control of MSD system

In this section results for the pole-placement controller for the MSD system is shown. The controller is calculated using Ackerman's formula for pole-placement. Use of pole-placement control allows for a way to tune the performance of the switching to differing criteria. Table III shows the performance calculations for the pole-placement method. Several pole-placements where tried. It can be seen that increased time to first impact allows for more energy decrease in the system, but this makes for a slower switching system. Pole-placement control can be used for adjustment of performance of the system to suit the needs of the task at hand. The best performance of the pole-placement is shown at a 18% decrease in tip energy.

TABLE III
POLE-PLACEMENT CONTROL PERFORMANCE OF MSD SYSTEM

Poles	First Tip Impact [sec]	Normalized Momentum $[m^2/sec^2]$	Energy Decrease [%]
-.1, -.2	0.265	0.5357	18.3135
-.5, -.1	0.250	0.6016	8.2647
-1, -2	0.240	0.6718	-2.4398
-2, -4	0.220	0.8956	-36.5660
-1-j, -1+j	0.260	0.5329	18.7405
-3-j, -3+j	0.220	0.8937	-36.2763

4.3. Adaptive control of MSD system

In this section the formulation for an adaptive controller for minimizing the energy of impact of the tip of the micro-relay during switching is shown. Adaptive methods using Lyapunov formulation is formulated. The results of the formulation are shown in (7). The equation shows that the updates of the input signal are calculated by integrating the error, e, multiplied with the tip position, y, where v is the input voltage of the relay actuation system. Simulations are shown for the adaptive controller on the MSD system and show the performance improvements for the specified criteria. The adaptive control of the MSD system shows a 40.28% decrease in tip energy over the open loop system. This comes at the compromise of an increase of switching time of a factor of 8.5. This fits the trend seen with the other controller types that the decrease of switching energy will result in an increase of switching time. The results of the adaptive controller are presented in Table IV. Figure 5 and Figure 6 show the tip position and velocity respectively for the adaptive controller applied to the MSD model.
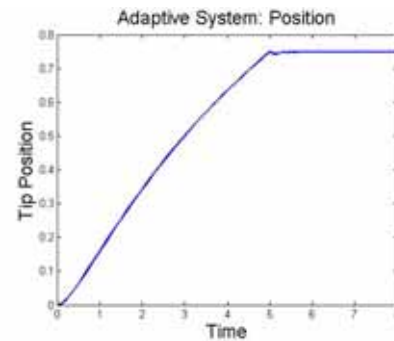
$$\dot{v} = e \cdot y \tag{7}$$

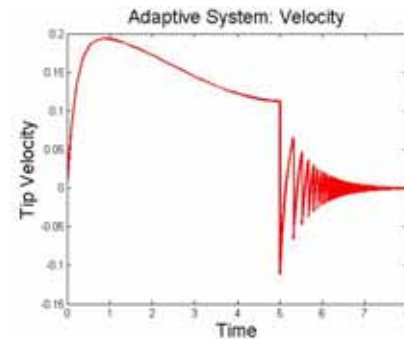
Figure 5. Adaptive Controller MSD Position

Figure 6. Adaptive Controller MSD Velocity

TABLE IV
ADAPTIVE CONTROLLER PERFORMANCE OF MSD MODEL

First Tip Impact [sec]	Normalized Momentum [m²/sec²]	Energy Decrease [%]
5.0	0.3916	40.28

5. FEA analysis of the micro-cantilever

FEA allows for a problem to be numerically simulated and retain the structural constraints that are found in analytical analysis of traditional problems. The micro-relay simulation was investigated with an FEA method. System dynamics were computed with methods found in standard FEA texts [7-9]. FEA of the micro-relay was done using a two-degree of freedom analysis broken into 30-segments. System simulations where done based on (8). The simulation is a matrix based simulation that relies on state-space system design for simulation and control methods. The use of a state-space setup allows for a flexible system model that can be simulated and controlled in many ways. Use of Matlab and Simulink for simulation also allows for rapid prototyping of control schemes for the beam system.

$$M\vec{\ddot{y}} = -K\vec{y} - B\vec{\dot{y}} + \vec{f}_e \tag{8}$$

After construction of the system equations the system can be understood from (8), where M, K, and B are square 2N+2 matrices. In (8) the system dynamic components include the mass, M, stiffness, K, damping, B, and the electrostatic actuation force, f_e. Use of the MSD system is still prevalent in this simulation; however the relationship of the states is now vector driven and allows for a greater degree of accuracy than the scalar case. Use of state-vectors, $\vec{y}$, allows for each unit-length of the beam to be simulated in its interaction to neighboring elements.

While (8) gives some intuitive description to the behavior of the beam from a systems point of view it must be noted that the K-matrix is a banded matrix as derived in Reddy [4]. This banded stiffness matrix supplies the coupling between beam elements. This coupling includes the distribution of applied shear and moment forces that propagate through the beam to other neighboring elements. Figure 7 and Figure 8 illustrate the open-loop FEA results for tip position and the velocity.

TABLE V
OPEN LOOP PERFORMANCE OF FEA MODEL

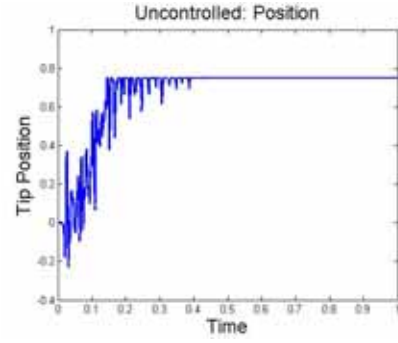| First Tip Impact [sec]	Normalized Momentum [m²/sec²]
0.15	34.17

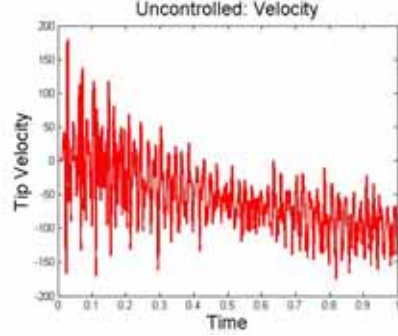**Figure 7. Uncontrolled FEA Position**

Figure 8. Uncontrolled FEA Velocity

6. Adaptive control of FEA system

The adaptive controller developed for the MSD model was next tested on the FEA system. Formulation stays the same for the FEA system adaptive controller using (7) as the adaptive update control law. Results for the adaptive control of the FEA system do not approach the results seen for the simplified MSD model. The main difference can be seen in the amount of tip movement. This extra tip movement increases the tip energy throughout the switching cycle and accounts for the disparity between the two models. The FEA model does give a more realistic representation of the actual beam problem that would be encountered on the device. The performance increase above open-loop for the FEA case is only 3.7% as seen in Table VI. Figure 9 and Figure 10 show the tip position and velocity respectively for the adaptive controller on the FEA model.
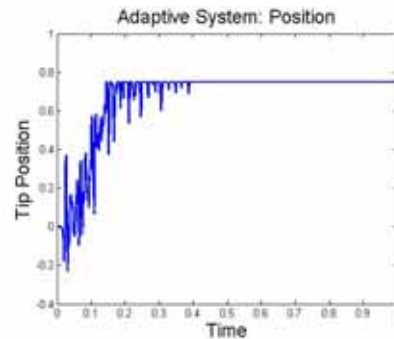

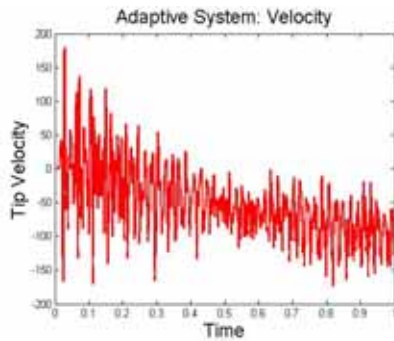**Figure 9. Adaptive Controller FEA Position**

Figure 10. Adaptive Controller FEA Velocity

TABLE VI
ADAPTIVE CONTROLLER PERFORMANCE OF FEA MODEL

First Tip Impact [sec]	Normalized Momentum [m^2/sec^2]	Energy Decrease [%]
0.15	32.91	3.6870

7. Conclusions

A controlled switching method for the MEMS micro-relay has been demonstrated in a simulation environment. Use of different control methodologies can allow for tuning of the switching action of the relay system to accommodate different uses. In a low-speed switching scenario one can use an adaptive controller to minimize the impact of the tips to preserve the contacts for longer life-span and more switching cycles before switch failure. The use of a pole-placement control can allow for tuning of the switch to different performance criteria by selecting where the poles of the system lie to accommodate a trade-off between switching speed and tip wear due to impact momentum. Also considered was a simple acceleration, or force, limiting control that allows for the momentum of the tip impact to be constrained.

Simulation results show that for an MSD approximated model the adaptive methods results in significant energy reduction in the tip impact. For the FEA results of the same controller adaptive methods reduce the energy only slightly. While the results do not show much improvement for the adaptive controller for the FEA method, the use of a more advanced controller may result in a more significant increase in performance.

In general a trade-off exists between switching time and impact minimization. The MSD model using adaptive control has been shown to decrease tip energy as much as 40% with an increase of switching time to 5 seconds. It is noted that the MSD model is not an accurate model of the system and for this reason FEA methods where employed. The FEA model allows for a simulation of the entire beam along its length. Results for the adaptive methods using the FEA model allow for only a 3.69% energy improvement, but the switching time was not increased. Simulations shown in this work demonstrate the ability of controller methods to be applied to MEMS micro-relay systems to achieve system performance enhancements. Future work in this area should include development of other controller types for energy conservation in MEMS technology to improve performance, life-span, and adaptability of devices to different situations.

8. References

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Dr. Steve E. Watkins (S'80-M'90-SM'98) is Director of the Applied Optics Laboratory and Professor of Electrical and Computer Engineering at the University of Missouri-Rolla. His interdisciplinary research includes projects that address educational innovation, structural health monitoring, and intelligent transportation applications. He is a senior member of the Institute of Electrical and Electronics Engineers (IEEE), a 2004 IEEE-USA Congressional Fellow, the 2000 recipient of the IEEE Region 5 Outstanding Engineering Educator Award, a 1993 finalist in the Eta Kappa Nu Outstanding Young Engineer Award Program, and recipient of a National Science Foundation Fellowship. He is on the Board of Governors for Eta Kappa Nu and the IEEE Intelligent Transportation Society. He received a Ph.D. from the University of Texas at Austin in 1989.