International Journal of Technical Innovation in Modern Engineering & Science (IJTIMES)
Impact Factor: 5.22 (SJIF-2017), e-ISSN: 2455-2585
Volume 5, Issue 2, February-2019

Effect of the damping and stiffness on the switching time of a micro-cantilever based RF MEMS Switch.

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Abstract

Dynamic Analysis of a micro-cantilever based MEMS (Micro-electro-mechanical systems) RF Switch using lumped parameter based modeling. The switching time of a RF (Radio frequency) switch is modeled based on the simple spring mass model. The resulting switching time is then compared for various parameters of modeling like stiffness, equivalent mass and damping that are obtained using various approaches. As the switching or actuation time for a MEMS based RF switch should be as small as possible; it was observed that the trade-off between the stiffness and damping is necessary and an optimal switching time should be one that leads to decrease in the vibrations of the beam and this can be achieved by increasing damping of the system. However that leads to the increase in the switching time. This is then compensated by increasing the stiffness which will lead to the increase in vibrations that is not desirable.

Keywords: Micro-cantilever; MEMS RF Switch; switching time; Stiffness; Damping

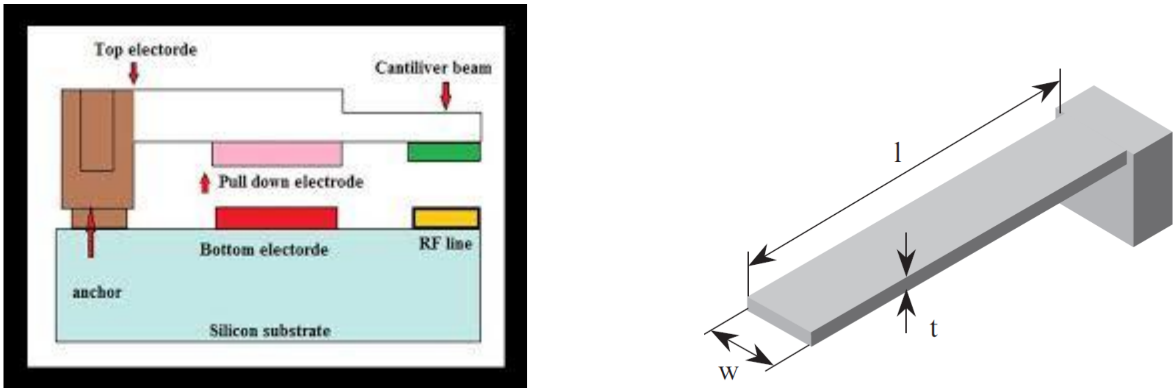
Introduction

A switch is a device for making or breaking an electric circuit . Switches can be made by various technologies, for example using semiconductors, transistors, and diodes. They can be purely mechanical, electrical, or a combination. A special category of switches that have gained a great deal of attention in recent years is RF (radio frequency) MEMS switches. MEMS switches can be defined as miniature devices that use a mechanical movement to achieve a short circuit or an open circuit in a transmissions line. Most MEMS switches rely on electrostatic forces to actuate a moveable electrode or a microstructure with a voltage load beyond pull-in to achieve large stroke in a short time. The actuation mainly is achieved by a step-input voltage that is applied repeatedly at a certain frequency (a periodic square signal). The duration of time a microstructure takes to travel from the un-actuated state (the “off” state) to pull-in (the “on” state) is called the pull-in time. It plays a vital role in determining the capability and range of applications of the switch. The shorter the pull-in time the better the switch is. Besides the common known advantages of MEMS and electrostatic actuation, especially the low-power consumption and the batch-fabrication, capacitive switches feature many other advantages. These include high isolation (isolation is the amount of output signal when the switch is off), low insertion loss (insertion is characterized by the amount of losses in the signal output line when the switch is on), high on-off capacitance ratio, and a much broader operating temperature range than silicon electronic devices. Their major disadvantages however are their relatively high driving voltage and low switching speed. Applications of capacitive micro-switches are in the domain of wireless communications and radar systems. Transmit/receive switches in a cellular phone are one example of such uses. Also, these devices are excellent candidates to be used in phase shifting and time-delay circuits, such as in phased-array radars and communications antennas.

In this paper we present the effect of various parameters like stiffness, mass and damping on the actuation time of the RF switch. The fundamental equation of motion is used to model a micro-cantilever beam that is actuated by the electrostatic force. The electrostatic force is inherently nonlinear and it is a coupled field problem. The governing equation is solved in the simulink software MATLAB. The various parameters in the modeling like stiffness, equivalent mass, damping are calculated using the standard procedures.

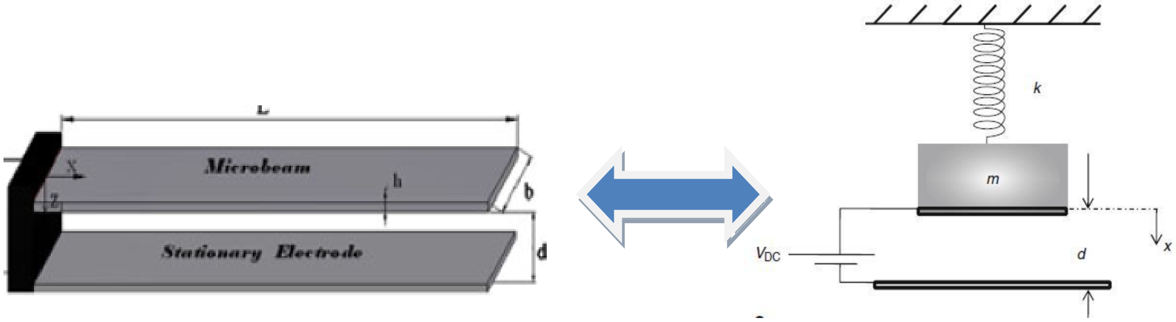
2. Modeling and Simulation.

The micro-cantilever is modeled using the lumped parameters as a spring mass system. The lumped parameters are then used in the governing equation. These parameters include the equivalent stiffness, mass and damping. The use of a micro-cantilever as a switch is shown in the figure1 (a).The micro-cantilever to be modeled is shown in figure1 (b).The micro-beam is actuated by the electrostatic force that is provided by the external voltage. Thus the micro-cantilever shown in figure 1(b) is modeled as a spring mass system shown in figure (2).The basis for modeling the micro-switch will be the one shown in figure 2.The mechanical properties of the cantilever beam of figure1(b) are shown in table 1



(a) (b)

Fig1:(a)A micro beam based RF MEMS switch, (b) A micro-cantilever beam as an actuator.



(b

Fig 2: Micro-cantilever modeled as spring mass model based on lumped parameters. K represents equivalent stiffness, m represents equivalent mass.

Table 1: Mechanical properties of the cantilever beam

Density ρ	2332 kg/m^3
Young's modulus E	160.0 GPa
Length l	100.0 µm
Breadth w	10 .0 µm
Height t	1.0 µm
Gap d_o	1.0 µm

The fundamental equation of motion is written for the spring mass system shown in figure2 as

$$m\ddot{x} + c\dot{x} + kx = \frac{\mathcal{E}_o A V^2}{2(d-x)^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

The dot on x represents differentiation with respect to time. Equation is inherently nonlinear in terms of forcing function and no closed form solution is available to this differential equation. The above equation can be non dimensionalized by making the following substitutions

x' =x/d, t'=t/d, u'=c/$\sqrt{mk}$

T is the natural time period of the system

$T = \sqrt{\frac{m}{k}}$ and $\beta = \frac{\mathcal{E}_o A}{2kd^3}$

When the above parameters are substituted in equation 1,the resulting non-dimensional equation becomes

$$\ddot{x} + u'\dot{x} + x = \frac{\beta V^2}{(1-x)^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

Equation 2 is the non-dimensionalized so that the subsequent simulations are both easy to perform and interpret. The above equation for various values of damping and stiffness and obtain the results for displacement versus time for a range of voltages. It is observed that the electrostatic force is inherently non linear and hence no closed form solution is available for this equation. A Simulink model is developed for the above equation and the resulting switching time (the time when the mass strikes the lower electrode) is calculated. This switching time is important in case of RF MEMS switches where a low switching time is desirable.

2.1Calculation of Lumped system parameters

2.1.1Stifness

We will only use computational methods to calculate the stiffness of the micro-cantilever. Since the micro-cantilever under consideration is actuated by the nonlinear electrostatic force, the calculation of stiffness on the basis of this type of loading may prove to be a cumber- some process. We however assume a uniform load acting on the cantilever and then calculate the stiffness of this structure based upon the tip deflection, and average deflection. It is observed that the stiffness estimated on the basis of tip deflection is lower than that obtained by the average deflection method. We will also calculate the stiffness of the micro-cantilever assuming a point load acting at the end.

Table2: Effective stiffness calculated by different methods

Type of load	Value of k
Uniform load based on the tip deflection	1.15 N/m
Uniform load based on the average deflection	2.67 N/m
Point load at the tip	0.40 N/m

2.1.2 Effective mass

The effective mass refers to the fact that for a flexible microstructure of distributed mass, not all of its portions may participate in a particular mode of motion nor do they necessarily participate in the same proportion. For example, in the case of a cantilever beam, the mass near the support almost does not contribute to the motion. The effective mass calculated on the basis of various methods is indicated in table2.

Table3: Calculation of effective mass by different methods

Method employed	Effective mass
Galarken method(load at tip)	5.4e^{-13}kg
Galarken method(distributed load)	1.51e^{-12}kg
Rayleigh method(load at tip)	5.13e^{-13}kg
Rayleigh method(distributed load)	1.52e^{-12}kg

2.1.3 Damping

Squeeze-film damping (SQFD) is considered the most common and dominant dissipation mechanism in MEMS. Many devices employ microstructures of big surface-to-volume ratio, such as micro beams and micro plates and hence an appreciable amount of damping is present within the system. When the upper plate moves down the air caught in between is squeezed out and hence resists the downward motion of the plate. The empirical relation for viscosity given by vijoola[4] is used to find the damping constant to model the lumped parameter system. The effective damping coefficient that is obtained for the chosen parameters is obtained as

C=1.21e-6 Nms-1.

3. Results of the simulation

The equation (1) is solved by employing the simulink model shown in figure 3 to find the required time that it takes for the micro-cantilever to strike the plate that is below it. This time is called the switching time.

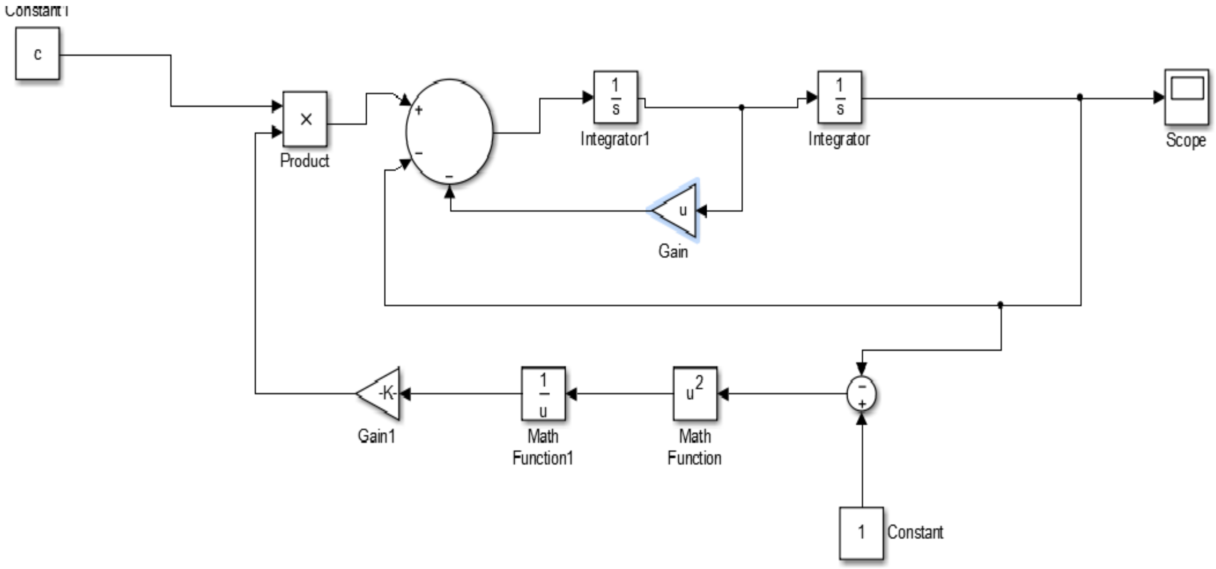


Fig3: Simulink model to solve equation

The results of the above simulink model are presented in the table 4.The table gives the switching time in microseconds of the micro-cantilever beam for various parameters

Table4. Value of pull in time for various parameters

u'	β	V	T	Switching time(μs)
0	0.0042	9.6	1.9	2.27
0.5	0.0023	9.6	2.9	4.12
0.98	0.0023	9.6	4.9	8.82
0.98	0.0023	12	2.9	5.80
0	0.0042	12	2.2	4.18
0	0.0023	12	1.5	3.10
0.98	0.0042	12	1.8	2.17

From the table it is clear the increase in damping(u') leads to the increasing switching time.Also when the stiffness(β) is increased,switching time decreases and hence a trade-off between the damping and stiffness is necessary to obtain the optimum switching time.

Conclusion

The switching time of a RF MEMS based switch is the important parameter of its effeciency.In this paper,we have presented the effect of damping and the stiffness calculated on the switching time of a micro-cantilever based RF switch.These parameters are calculated for the lumped parameter modeling using the spring mass system.It has been observed that the switching time increases with the increase in the damping.However the vibrations of the switch after the removal of the external voltage decrease as damping increases which is a desirable aspect.We have also established that the with increase in the stiffness ,the switching time increases ,but the vibrations of the switch also increase which lead to the unstability of the system.The parameters should be choosen so as to obtain the optimum switching time using the trade-off between damping and the stiffness.

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