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Mechanical Modeling Issues in Optimization of Dynamic Behavior of RF MEMS Switches

Suhas K and Sripadaraja K

***Abstract*—**This paper details few mechanical modeling and design issues of RF MEMS switches. We concentrate on an electrostatically actuated broad side series switch; surface micromachined with a crab leg membrane. The same results are extended to any complex structure. With available experimental data and fabrication results, we present the variation in dynamic performance and compliance of the switch with reference to few design issues, which we find are critical in deciding the dynamic behavior of the switch, without compromise on the RF characteristics. The optimization of pull in voltage, transient time and resonant frequency with regard to these critical design parameters are also presented.

***Abstract*—**Microelectromechanical Systems (MEMS), Radio Frequency MEMS, Modeling, Actuators

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I. Introduction

MEMS actuators have assumed great importance because of the critical advantages they pose over the conventional methods of actuations. Notwithstanding the tradeoffs and compromises with enhanced functionality in terms of a few parameters, MEMS actuators have been very successful in capturing the market where these particular parameters are the most valued [1]. Radio frequency MEMS (RF MEMS), among the many actuators are one of the important subsystems in many electronic circuitry [2]. RF MEMS switches are the most basic and the most mature of all the RF MEMS devices [3].

RF MEMS switches, when weighed against conventional MOS switches, stand out in terms of isolation, insertion losses, return losses, repeatability, quality factor, parasitic effects and frequency response. Although these may sometimes suffer from unfavourably higher actuation voltages, longer actuation times and complexity of fabrication (bulk production is very easy though), they do find various applications where the advantages weigh out the disadvantages [3]. It's also noted that integration with microelectronics becomes easy with the advent of micromachining compatible with current IC trends. With a proper combination of these micromechanical structures and conventional MOS devices, we can easily achieve the desired numbers in terms of the performance of the system [4].

This paper deals with optimizing the various parameters of RF MEMS switches that determine the dynamic response of the structure. Also, many seemingly trivial parameters are explored and their effect on the dynamic response is evaluated.

Suhas K is with the Electronics and Communication Engineering Department, BMS College of Engineering, Bull Temple Road, Basavanagudi, Bangalore-19, India (phone: +91 80 22425433; e-mail: suhas.asulikeit@gmail.com)

Sripadaraja K is with the Electrical Communication Engineering Department, Indian Institute of Science, Bangalore-12, India (e-mail: sripadaraja@gmail.com)

II. Background

A. Description of the switch

We consider a 'crab leg' membrane structure for many of the analysis carried out in this work. The geometry considered is quite a complex one for intuitive analysis or even analysis with closed loop formulae. Meandering legs are introduced to bring down the pull in voltage. Perforations are introduced to check the air damping. This is a trade off since introduction of perforations reduce the effective electrode area and hence increase the pull in voltage. The overall geometric design can be completely explained with consideration of the RF characteristics of the device [1] [5]. The geometry of the structure is discussed in detail in [6]. This switch was fabricated using SOI (Silicon On Insulator) approach. Figure 1 depicts he switch.

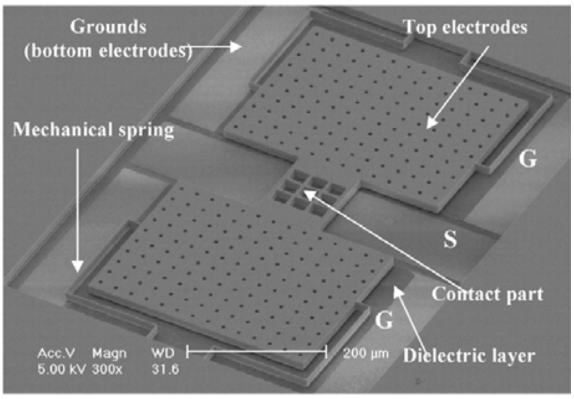

Fig. 1 The structure of the crab leg membrane

B. Overview of the work

Given the surface micromachined broad side series switch discussed above, we discuss briefly the well documented effects of variation of actuation voltage, resonant frequency and related dynamic parameters with variation in thickness of the system, variation in the geometries of the anchoring legs and effect of altering the meander sections.

We also discuss few design parameters, which are many a times overlooked because of their seemingly trivial nature, which contribute a lot [1] [7]. When many of these parameters are overlooked, it renders the effective variation in stiffness and pull in voltage very high. This is best explained with the available experimental data. Here, one switch is shown to actuate at 15V [6], while another [8], with a bit of compromise on the precision of geometry because of fabrication constraints, is expected to actuate at about 100V on paper. But it is a sad story of the latter, where it fails repeated trails and iterations even for voltages much higher than the expected values and is shown to actuate at about 190V on simulations. This paper would attempt to exhume many of the unnoticed design variations, in the two seemingly similar structures, that contribute to the very bad performance of one of the latter.

IntelliSuite (3D), Synple (IntelliSuite 2D) and COMSOL Multiphysics wherever simulation was needed. Transient response, dynamic behavior and static behavior in terms of resonant frequency and actuation voltages are the core discussions of this paper.

III. Dynamic Behavior Parameters

A. Variation in actuation voltage

TABLEI VARIATION OF ACTUATION VOLTAGE WITH THICKNESS OF SYSTEM

Thickness of system (µm)	Actuation voltage (V)
5	20
10	42
15	63
20	80
25	100

The inference is that thickness does play an important role in deciding the stiffness of the structure and hence the actuation voltage. The next step would be to identify that part of the structure that contributes most to the actuation voltage [7]. An easy way would be to go for frequency response (magnitude response for a range of applied frequencies) since it is a good measure of the variance in the stiffness of the structure.

B. Variation in resonant frequency

TABLE II VARIATION OF ACTUATION VOLTAGE WITH THICKNESS OF SYSTEM

Thickness of system (µm)	Resonant frequency (kHz)
15	80
20	57
25	46
30	40
35	34
40	31

It is observed that as the thickness of system increases, the resonant frequency decreases. For variations in low values of thickness, there is a large variation of f_r and at higher values of thickness, the variation is comparatively smaller, though it is considerable. Table 3.4 shows this effect. This table is to be taken as an analogy to Table 1.

It was further probed to see which part of the structure contributed most to the variation in the resonant frequency; if at all the sensitivity was concentrated at a particular position(s). It is found that the anchoring legs play a very important role in deciding the resonant frequency. The thickness of anchoring legs seems to contribute almost entirety to the variation in resonant frequency, which hardly seems to depend on the thickness of the other parts of the structure. All this discussion needs to be seen as an analogy to the stiffness of the structure [9]. Figure 2 depicts the anchoring legs.

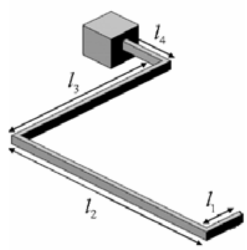

Fig. 2 The meandering legs used for anchoring

Further probing was done to investigate that part of the anchoring system, which was the culprit in being the most sensitive. It is seen that *l4* contributes to almost all the variation in the resonant frequency with variation n its thickness.

The width of the anchoring legs was also tested for sensitivity. *l4* was again found to be the culprit in terms of sensitivity. This contributed most in terms of variation in its width while the variation width of other legs hardly seemed to matter [10]. Figure 3 depicts this effect.

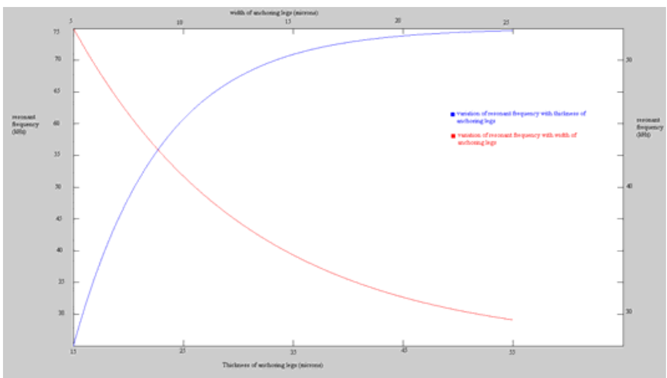

Fig. 3 Blue line is the variation of resonant frequency with width of anchoring legs and red line is the one with variation in thickness of anchoring legs

This discussion is just a short bridge of well understood effects and detailed discussions of these effects are done in [10] and [12].

IV. More Dynamic Behavior Parameters

A. Length of anchoring legs

The length of legs does matter in deciding the stiffness (or resonant frequency or actuation voltage) of the structure. Equation (1) describes this behavior [11].

$$K = \frac{1}{\frac{1}{Ewt^3}(l_1^3 + l_2^3 + l_3^3 + l_4^3) + \frac{1}{2xGtw^3}(l_1^2 l_2 + l_2^2 l_3 + l_3^2 l_4)} \quad (1)$$

Where K is the spring constant, E is Young's modulus, G is the shear modulus, t and w are the thickness and width of the spring and x is the shape constant. It can be seen that this equation is quite symmetric with respect to the lengths of all legs, but still a bit partial with respect to *l4*.

B. Position of meanders

The effect of this looks predictable only if it is detected. It went unnoticed in [8], as discussed in section II.*B*., because of the feeling that variation in length of *l1* would mean variation in the position where *l1* holds the membrane. Figure 4 is used to depict this.

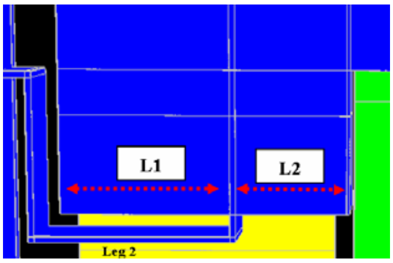

Fig. 4 A part of the crab leg membrane to depict position of meanders

Figure 3.3 makes it clear that variation in length of Leg 2 need not mean variation in *l1* and *l2*. It was also found that *l1*<*l2* is a better condition for having a more compliant membrane. This might be because mass may dominate in the region of *l1* if this is dominant over *l2*.

C. Altering the meander sections

Meander sections are added to make the system more compliant by increasing the effective aspect ratio of the membrane. This is generally done to reduce the actuation voltage. Figure 5 shows the addition of another meandering section consisting of four more legs. This was added to the structure in Figure 1. This was simulated to check for actuation voltage and resonant frequency.

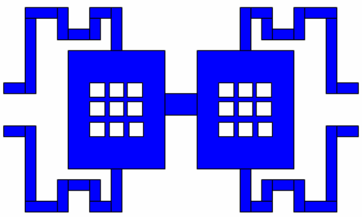

Fig. 5 An extra meander section added to the structure in Fig. 1

Simulation showed that the actuation voltage does come down quite considerably. Actuation voltage decreased from 190V to about 100V, which was much expected. The resonant frequency decreased from 46 kHz to about 27.3 kHz. This was an important result considering the comparison of the frequency response of the two structures. Figure 6 and Figure 7 show this comparison.

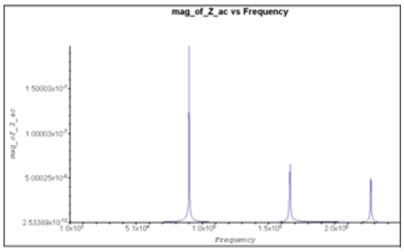

Fig. 6 Frequency response with few resonant peaks for the structure described in Fig. 1

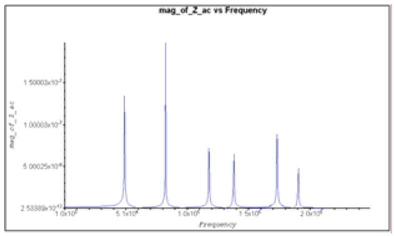

Fig. 7 Frequency response with many resonant peaks for the structure described in Fig. 5

It can be clearly seen that apart from the reduction in the frequency of the resonant peak in the first mode, there are many more resonant peaks added when there are more legs added. Even though typical operational frequencies for switches are less than that of the first mode of resonance, introduction of more legs would constrain this range. If the membrane is a part of a sensing mechanism which demands the absence of resonant peaks in its range of sensing, adding more les to make the system compliant will be a bad idea as it can be seen in Figure 7.As an implication of reduction of the frequency of first mode of operation, it can be inferred that the response time would increase in tune to the decrease in frequency [13]. So, there needs to be a tradeoff between the compliance and the response time too.

D. Area of contact pads

The area of the contact pad, which forms the top electrode during actuation, was tested for variation in stiffness (through resonant frequency). This hardly seemed to matter and this could be attributed to the high sensitivity in the area of cross section of the meandering legs, which seems to overshadow the effect of any variation in the area of any other part of the structure.

Even though this may not affect the stiffness of the structure much, it must be noted that this would very much affect the actuation voltage because of the variation in the overlapping area of the top and the bottom electrode of the actuating mechanism [1].

E. Anchoring style

Anchoring style affects the distribution of stresses in the meander legs. There is a difference in this distribution when *l4* is directly anchored and when the bottom face substrate which holds the entire structure is anchored. Figure 8 and Figure 9 show the distribution of stresses for the two cases.

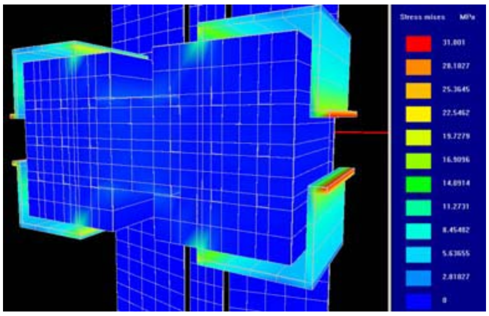

Fig. 8 Stress distribution when the meander legs are directly anchored

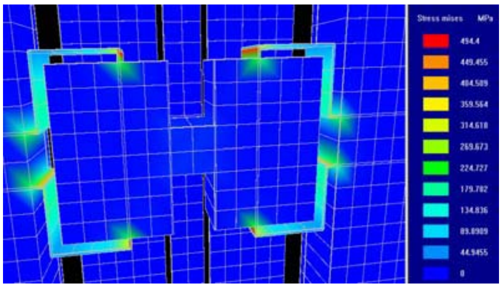

Fig. 9 Redistribution of stresses due to anchoring the bottom face of the substrate

Figure 8 and Figure 9 show that there is considerable redistribution of stress when anchored differently. When the meander legs are directly anchored, *l4* is the one which holds the key in stress management, whereas, when the bottom face of the substrate is anchored, it is found that *l1* is the most important one in determining the stiffness of the structure. Anchoring the substrate seems to yield a much more compliant structure than taking to the other anchoring method. The intuitive reason behind this might be that there is an additional torsion effect introduced when *l4* is not anchored directly. Either ways, this appears to be an authoritative effect which contributed to the high stiffness seen in [8].

The stiffness may be altered in many of the methods discussed so far. But inducing more compliance would mean a compromise with the transient response. Figure 10 shows the transient response for the structure taken with different stiffness. There can be considerable information extracted from Figure 10. It can be seen that the curve is much smoother for higher stiffness. The time required for the transients to die out is more or less 3-4 times the pull back time in this case [14]. This can be minimized by adding more damping to the beam. More damping would mean longer pull in and also pull back time. So, there needs to be a compromise.

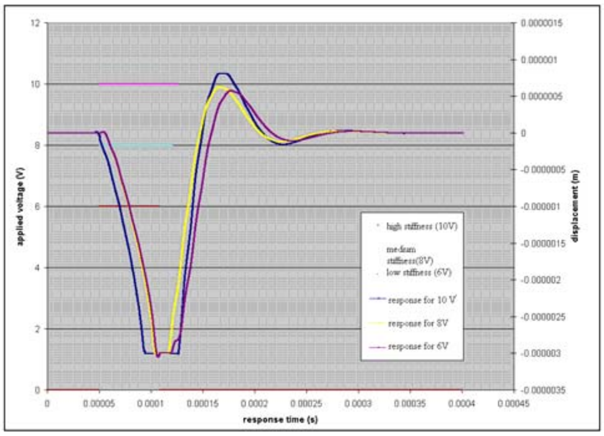

Fig. 10 Transient response for varying stiffness

V. Conclusion

Slight variations in subtle parameters may add up to alter the stiffness of a structure enormously. These variations in stiffness can be studied through resonant frequency or pull in voltage too. This work is an attempt to bring to light few of those parameters, which appear quite inconspicuous in many designs.

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References

[1] DJ Bell, TJ Lu, NA Fleck, SM Spearing, *MEMS actuators and sensors: observations on their performance and selection for purpose* - Journal of Micromechanics and Microengineering, 2005, 15 S153-S164.

[2] J Jason Yao, *RF MEMS from a device perspective,* 200J. Micromech. Microeng.1 R9-R385.

[3] E. R. Dept. of Electr. Eng., California Univ., Los Angeles, CA, *RF-MEMS switches for reconfigurable integrated circuits*, Brown,; Microwave Theory and Techniques, IEEE Transactions on, Nov 1998, Volume46,Issue11, Part 2, pp 1868-1880.

[4] Rebeiz M. Gabriel, *RF MEMS Theory, Design and Technology*, HobokenJohn Wiely and Sons, 2003.

[5] Kim Jong-Man, Sanghyo Lee, Jung-Mu Kim, Chang-Wook Baek, Youngwoo Kwon and Yong-Kweon Kim, *A Mechanically reliable digital-type single crystalline silicon (SCS) RF MEMS variable capacitor*, J. Micromechanics and Microengineering 15, pp.1854-1836, 2005.

[6] Jong-Man Kim et al, *The SiOG-Based Single-Crystalline Silicon (SCS) RF MEMS Switch With Uniform Characteristics,* Journal Of Microelectromechanical Systems, Vol. 13, No. 6, December 2004, IEEE.

[7] D. Peroulis ET AL, *Electromechanical considerations in developing low-voltage RF MEMS switches*, IEEE Trans. Microwave Theory Tech., vol. 51, pp. 259270, Jan. 2003.

[8] M.S. Giridharr et al, *Silicon-On-Glass RF MEMS switch for X band applications* Proceedings of ISSS 2008 International Conference on Smart Materials, Structures and Systems, July 2008, Bangalore, India, P35.

[9] Shishir Kumar and Rudra Pratap, *Partitioning design space for linear tuning of natural frequencies in planar dynamic MEMS structures*, Sensors and Actuators A: Physical, Vol 125, Issue 2, pp 304-312, 2006.

[10] R. Pratap, *Some issues in mechanical design of MEMS transducers*, Proceedings of the ISSS-SPIE, Bangalore, India, December 12–14, 2001, pp. 733–739.

[11] S.-W. Chung and Y.-K. Kim, *Design and fabrication of hidden spring structure type micro SLM for phase and amplitude modulation* Proc. SPIE, vol. 3513, pp. 156-163, 1998.

[12] Suhas K, *Modelling Studies and Fabrication Feasibility for Non-Conventional RF MEMS Switches*, KVPY IIT-B Report 2008, (EB2007), Thesis 2008.

[13] J. B. Muldavin and G. M. Rebeiz, *High-isolation CPW MEMS shunt switches Modeling and design*, IEEE Trans. Microwave Theory and Tech., vol. 48, no. 6, pp. 10451056, 2000

[14] P G Steeneken et al*, Dynamics and squeeze film gas damping of a capacitive RF MEMS switch*, 2005 J. Micromech. Microeng. 15 176-184.