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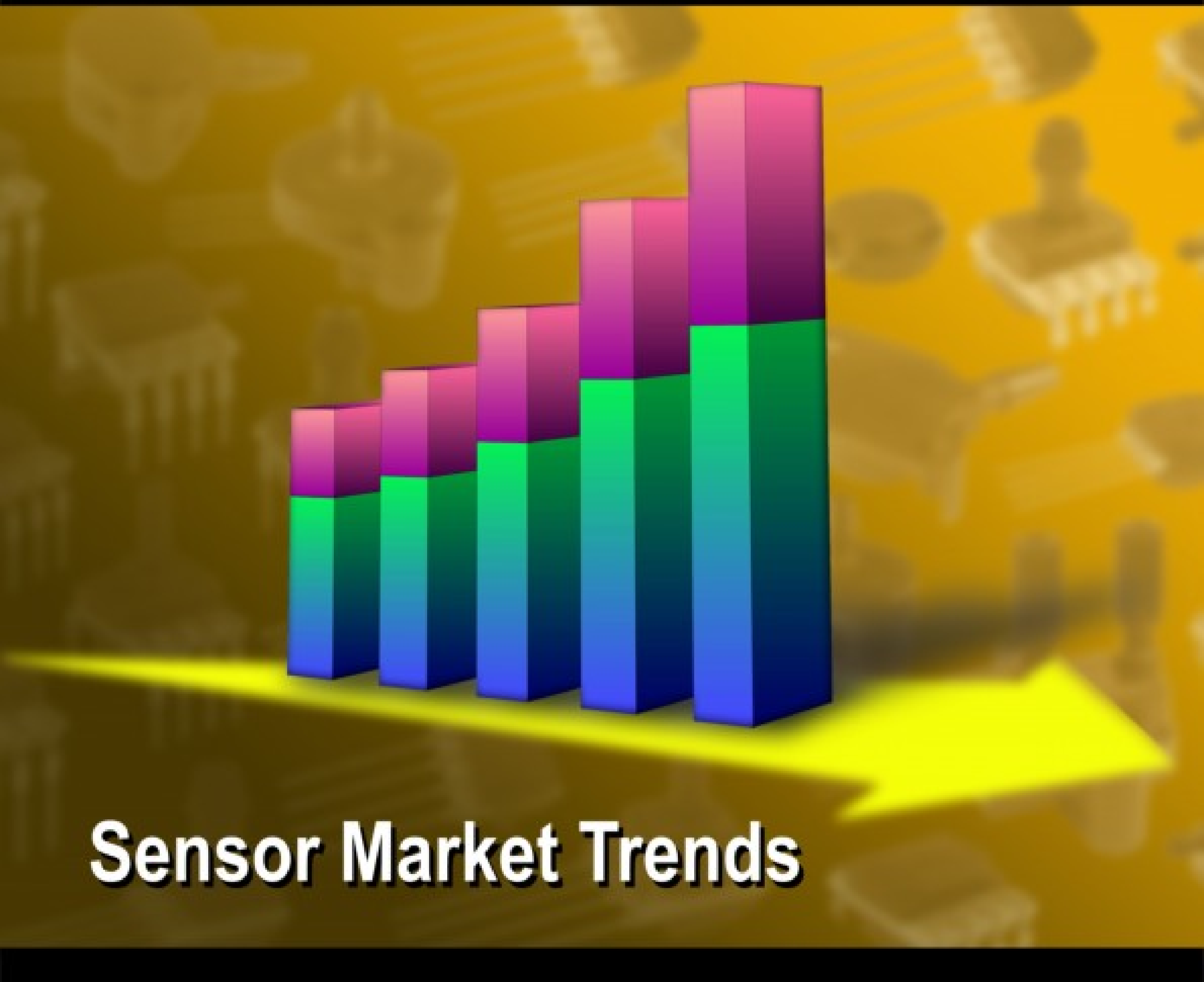

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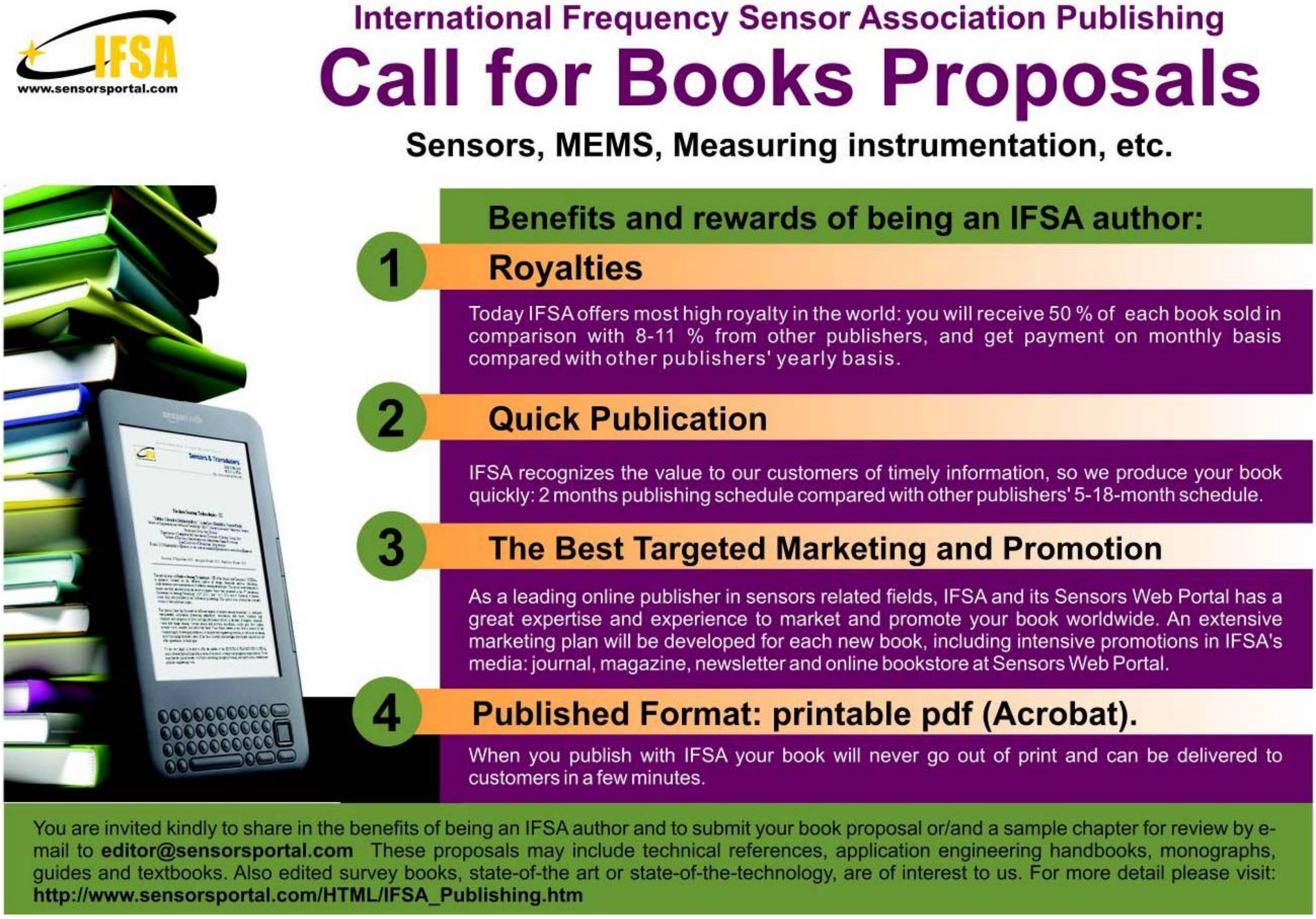

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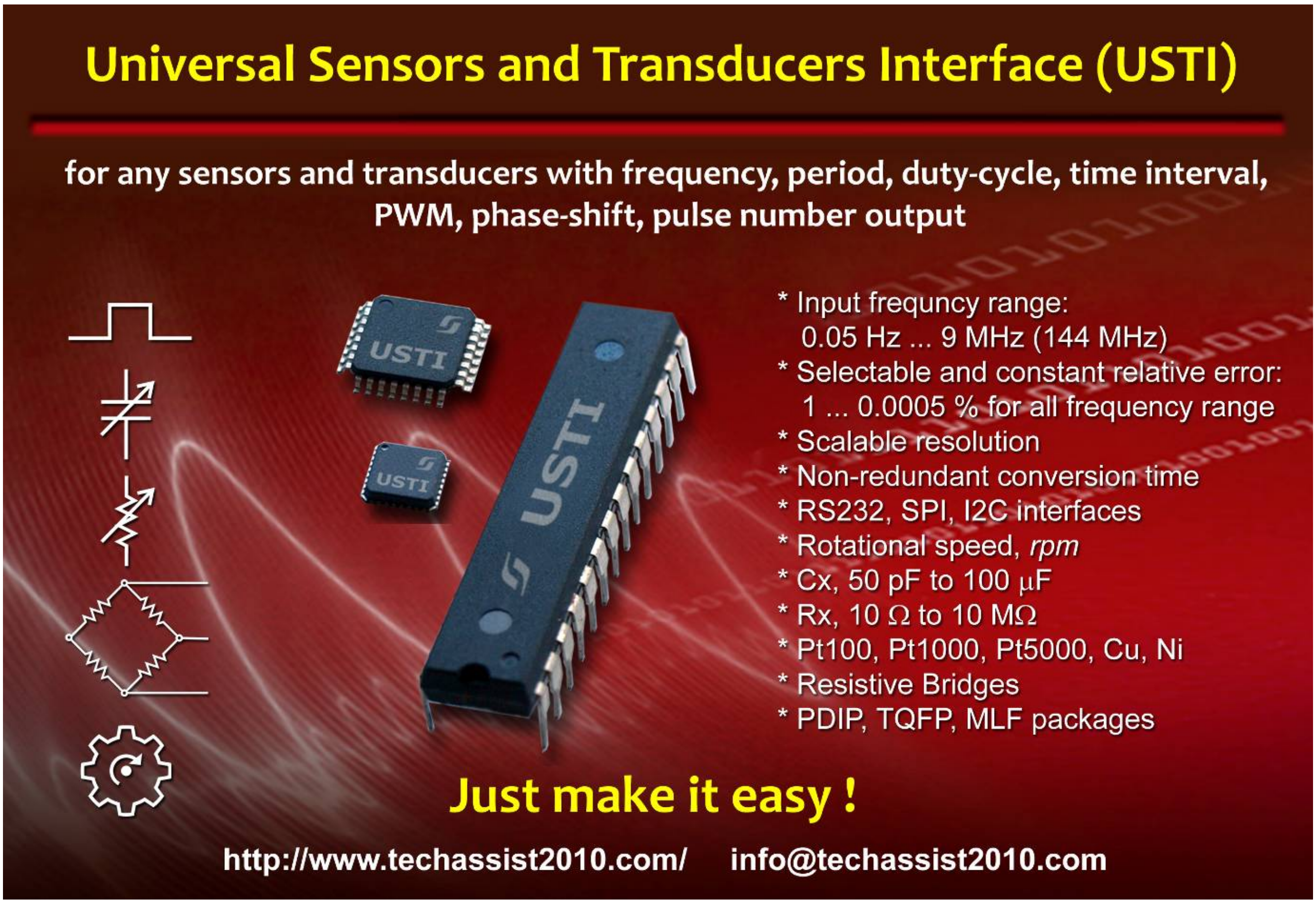
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Modeling of Spring Constant and Pull-in Voltage of T-Shaped Radio Frequency Microelectromechanical (RF-MEMS) Cantilever Switch

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Abstract: This paper presents the design and simulation of a low actuation voltage microelectromechanical system (MEMS) switch for high-frequency applications. Low pull-in voltage and low spring constant of the switch were achieved by using T-shape microcantilever of specific dimension. The modelling indicated that increased area of actuation at a distance from the fixed end reduced the pull-in voltage. Increasing the length of the cantilever was also observed to decrease the pull-in voltage to an even greater extent than increasing the actuation area did. It has been observed that switches using this design and actuation mechanism, the minimum pull-in voltage of 5-8 V can be achieved. Finally, both theoretical and simulated data for the dynamic behaviour of the device is presented. *Copyright © 2011 IFSA.*

Keywords: Microelectromechanical system (MEMS), Pull-in voltage, Spring constant, Cantilever.

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1. Introduction

Microelectromechanical Systems (MEMS) is a technology in which micro-fabrication techniques are used to construct miniaturized mechanical and electro-mechanical devices and structures. The functional elements of the devices and structures are predominantly sensors and actuators (transducers). These transducers have found numerous applications in fields such as biotechnology, medicine and inertial sensing [1, 2]. These switches are key elements for the performance of wireless applications operating in the high-frequency bandwidth [3]. RF MEMS (Radio Frequency) finds application in phased arrays and reconfigurable apertures for defence and telecommunication systems, switching networks for satellite communications and single-pole N-throw switches for wireless applications [4-8].

A particular structure of vital importance in RF MEMS is the switch. RF MEMS switch is superior than its solid-state counterparts (PIN diodes and FET switches) like near-zero power consumption, very high isolation, very low insertion loss, linearity, low cost potential. They also have their share of impediments, such as relatively low speeds, high voltage or high current drive, power handling and reliability [1]. It also has much smaller volume and weight than a conventional mechanical switch does [9]. These switches can be categorized as either dc switches or capacitive switches depending upon the contact interface. DC or metal-to-metal contact switches exhibit superior low-frequency operation as compared to capacitive switches. Of the numerous methods of switch actuation available [10], the electrostatic method of actuation is most common due to its lowest power consumption and fastest switching speed [11].

The operating principle of an electrostatic RF MEMS switch is quite simple. A beam (bridge or cantilever) is suspended from the anchor with an actuation electrode placed underneath. When a DC voltage is applied between the beam and actuation electrode, the beam is pulled down due to induced electrostatic force. The DC actuation voltage, at which the beam collapses onto the electrode, is called the pull-in voltage.

Pull-in voltage can be reduced in three different ways: by increasing the area of actuation, by decreasing the gap between the switch and the bottom electrode, and by designing the structure with a low spring constant. The first option is not feasible due to the need for a miniature structure; the second is also not desirable as it increases return loss. Thus, the structure must be modified to lower the spring constant which in turn, lowers the pull-in voltage. In order to reduce the pull-in voltage for RF MEMS switches, techniques like folded spring, narrower beam close to the anchor than actuation electrode were used [12]. In this paper, we propose a new design of a cantilever using non-uniform width that result in reduction in pull-in voltage. Spring constant and pull-in voltage of this cantilever are modelled for a uniformly distributed load on part of the surface of the cantilever. The structure is essentially a modified T-shaped cantilever as is shown in Fig. 1. Though many researchers [13-15] had proposed earlier a model for spring constant and pull-in voltage but the structure proposed here is an improved structure because, to improve the dc contact on the transmission line, the cantilever extends beyond the wide electrode. This extended area makes contact with the transmission line. The electrodes make minimum contact, however, this helps reduction of stiction problem.

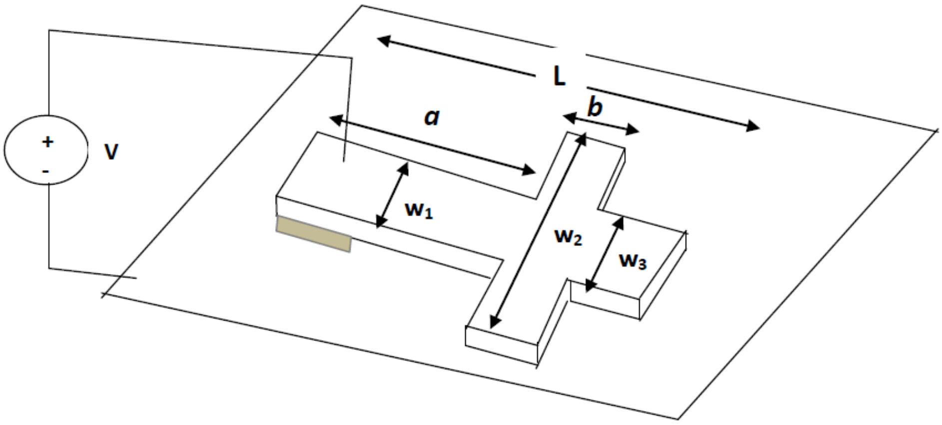

Fig. 1. Schematic view of proposed cantilever beam of non-uniform width.

2. Structure Design and Spring Constant

In order to obtain the pull-in voltage for this cantilever structure, the spring constant for the cantilever must be calculated first. Fig. 2 shows the side view of the proposed cantilever structure which consists of three segments of different widths and lengths as illustrated in Table 1. The thickness of all the segments is taken to be same.

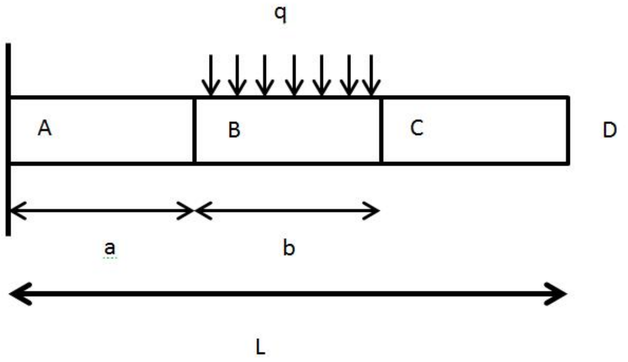

Fig. 2. Side View of the proposed cantilever beam.

Table 1. Length and width of three segments of cantilever.

Segment	Width	Length
AB	w_1	a
BC	w_2	b
CD	w_3	(L-(a+b))

The reaction and moment at the support are R_A and M_A respectively. Their values are calculated, from the equilibrium of the cantilever, to be:

$$R_A = qb$$

$$M_A = qb\left(a + \frac{b}{2}\right)$$

For Segment AB$(0 \leq x \leq a)$:

$$V = -R_A$$

$$M = -qbx + qb\left(a + \frac{b}{2}\right)$$

$$EI_1\left(\frac{d^2v}{dx^2}\right) = M \quad ,$$

where $I_1 = \frac{w_1 t^3}{12}$ is the moment of inertia for Segment AB.

$$At\ x = 0, v = 0, \frac{dv}{dx} = 0$$

$$\therefore \frac{dv}{dx} = \left(\frac{1}{EI_1}\right)\left[\frac{qbx^2}{2} - qb\left(a + \frac{b}{2}\right)x\right] \tag{1}$$

$$\therefore v = \left(\frac{1}{EI_1}\right)\left[\frac{qbx^3}{6} - \frac{qb\left(a+\frac{b}{2}\right)x^2}{2}\right] \tag{2}$$

For Segment BC$(a \leq x \leq a + b)$:

$$V = q(x - a) + qb$$

$$M = \frac{q(x^2 - a^2)}{2} + qbx - qb\left(a + \frac{b}{2}\right)$$

$$\frac{dv}{dx} = \left(\frac{1}{EI_2}\right)\left[\frac{qx^3}{6} - \frac{qbx^2}{2} - \frac{q(a+b)^2x}{2} + c_1\right], \tag{3}$$

where $I_2 = \frac{w_2t^3}{12}$is the moment of inertia for Segment BC.

$$\frac{dv}{dx}|x = a \textit{ is the same by both equations}$$

$$\therefore c_1 = \left[\frac{qba^2}{2} - qb\left(a + \frac{b}{2}\right)a\right]\left(\frac{w_2}{w_1}\right) - \frac{qa^3}{6} - \frac{qba^2}{2} + \frac{q(a+b)^2a}{2}$$

$$v = \left(\frac{1}{EI_2}\right)\left[\frac{qx^4}{24} + \frac{qbx^3}{6} - \frac{q(a+b)^2x^2}{4} + c_1x + c_2\right] \tag{4}$$

$$v|x = a \textit{ is the same by both equations}$$

$$\therefore c_2 = \left[\frac{qba^3}{6} - \frac{qb\left(a + \frac{b}{2}\right)a^2}{2}\right]\left(\frac{w_2}{w_1}\right) - \left[\frac{qa^4}{24} + \frac{qba^3}{6} - \frac{q(a+b)^2a^2}{4} + c_1a\right]$$

For Segment CD$((a + b) \leq x \leq L)$

$$V = 0$$

$$M = 0$$

$$\therefore v = \left(\frac{1}{EI_3}\right)[c_3x + c_4],$$

where $I_3 = \frac{w_3t^3}{12}$is the moment of inertia for Segment CD.

$$v(L) = \left(\frac{1}{EI_3}\right)[c_3L + c_4]$$

The spring constant of the cantilever is given by:

$$k = -\left(\frac{P}{v(L)}\right)$$

$$\therefore k = -\frac{qb}{v(L)}$$

Thus, a model of the spring constant of the cantilever structure has been obtained. Given the material and dimensions of the cantilever, its spring constant can be calculated.

A widely cited formula for the pull-in voltage of the cantilever is as follows [16]:

$$V_p = \sqrt{\frac{8kg_0^3}{27\varepsilon_0 L_e w_y}} \tag{5}$$

where k is the spring constant of the moving structure in the direction of desired motion, g_0 is the gap between the electrodes when no potential is applied between the electrodes, L_e is the length of the electrode and w_y is the width of the electrode.

3. Results and Discussions

Using the value for spring constant calculated above, the cantilever was modelled for varying widths and varying lengths. Fig. 3 shows the variation of spring constant as a function of width of electrode. The length of the beam is taken as 300 µm and the thickness as 2 µm. The width of the beam at the anchor is taken as 100 µm and the length of the electrode is taken as 100 µm and the width of the electrode (w_2) is varied from 100 µm to 300 µm. For calculation of spring constant, the material of the beam is chosen as aluminium. It was observed from the graph that the spring constant actually increases with an increase in area but increase in spring constant is undesirable. However corresponding pull-in voltage for above mentioned dimensions shown in Fig. 4 against width of the electrode, indicates that although the spring constant does increase, the pull-in voltage still falls with increasing electrode width. This is attributed to the fact that pull-in voltage is inversely proportional to area of actuation. This value is observed to increase in direct proportion with increase in electrode width, whereas the spring constant increases at a comparatively lower rate. The pull-in voltage is observed to approximately halve when the width of the electrode quadruples.

Fig. 5 shows the variation of spring constant as a function of width of electrode of length 250 µm keeping other dimensions same as before. The variation in the spring constant at lower beam length is observed to be lower. The value of spring constant is also higher. This indicates that longer beams have lower spring constants. Corresponding pull-in voltage for above mentioned dimensions is shown in Fig. 6 against width of the electrode. It is observed that with increasing width of the electrode, the pull-in voltage decreases. The voltage is again observed to decrease by approximately half with quadrupling of the electrode width, as in the previous case. However, with decreasing beam length, the pull-in voltage is observed to increase drastically.

Fig. 7 shows the variation of spring constant and corresponding pull-in voltage as a function of length of the beam. The beam width is taken as 200 µm and the thickness of the beam as 2 um. The width of the beam at the anchor is 100 µm and the length of the electrode is taken as 100 µm.

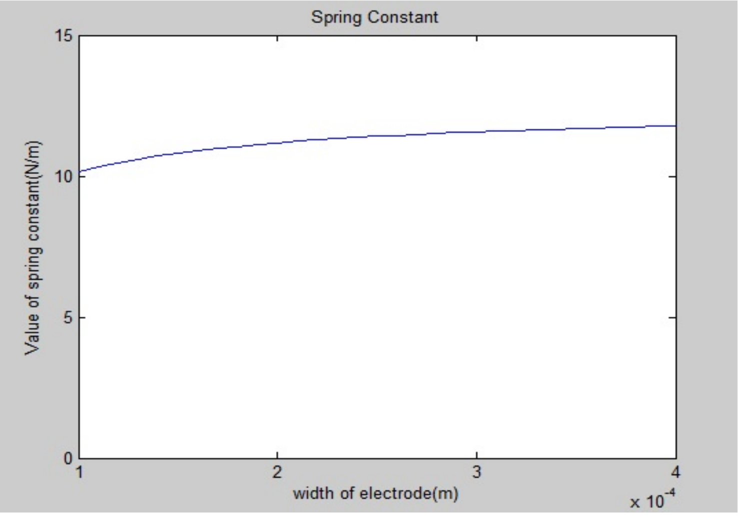

Fig. 3. Spring Constant variation with increase in electrode width.

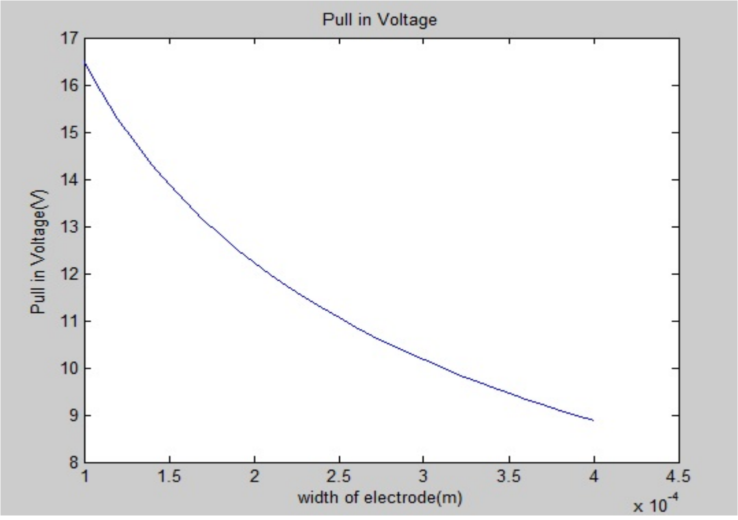

Fig. 4. Pull-in Voltage variation with increase in electrode width.

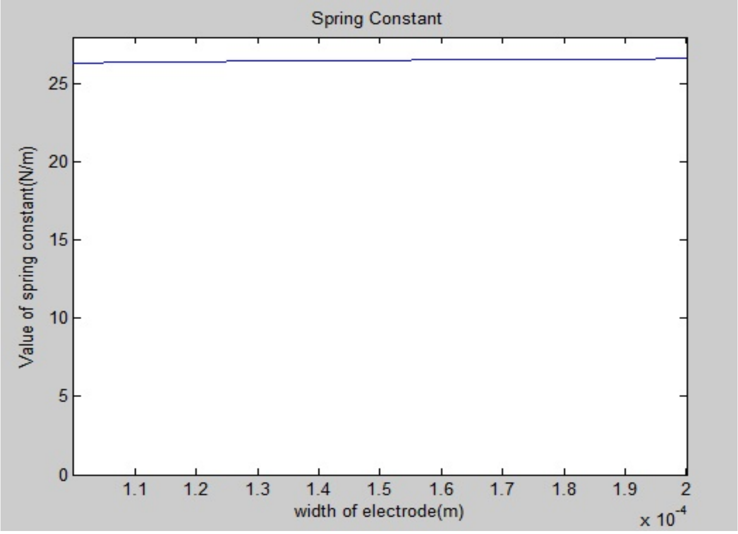

Fig. 5. Spring Constant variation with increase in electrode width.

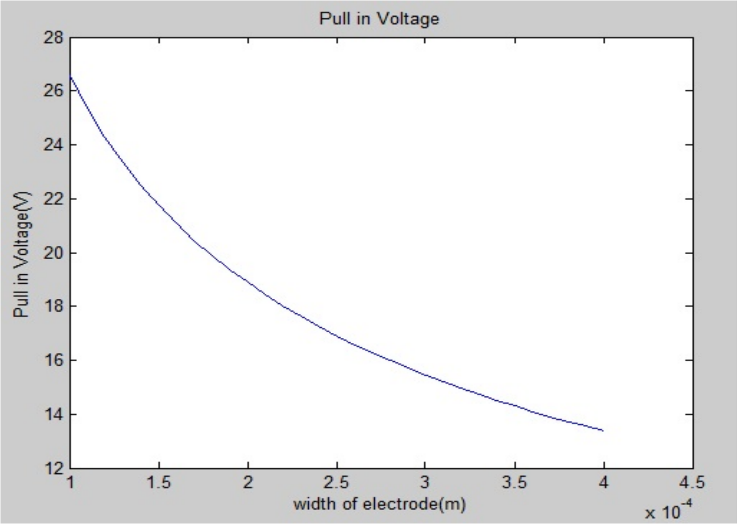

Fig. 6. Pull-in Voltage variation with increase in electrode width.

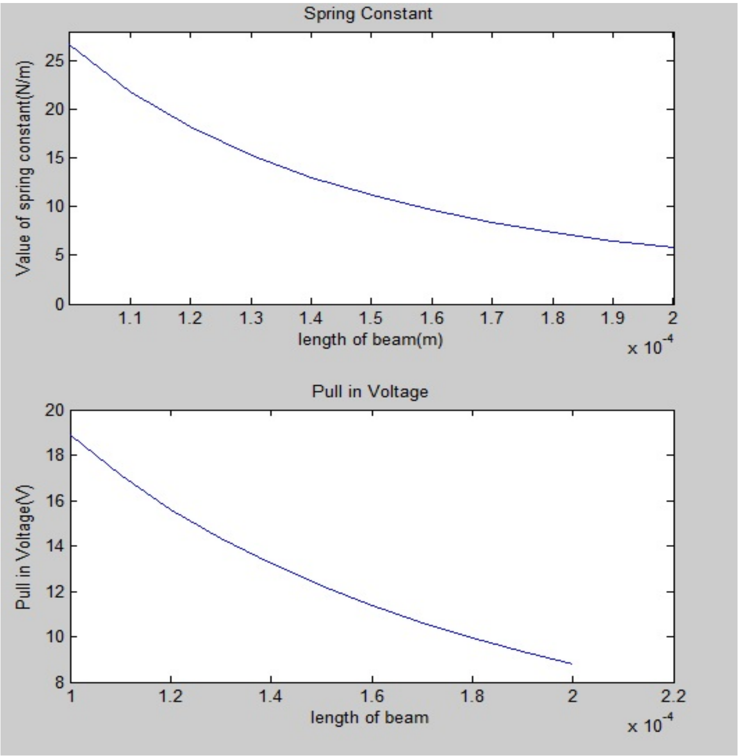

Fig. 7. Spring Constant and Pull-in Voltage variation with increase in length of the beam.

As is evident from the graph shown in Fig. 7, the pull-in voltage decreases quite rapidly with increase in beam length. There is an even more drastic drop in the spring constant value. The spring constant value is observed to drop by a factor of five with the doubling of the beam length.

4. Simulation Results from SUGAR Simulator

Sugar is free MEMS simulation software developed at UC Berkeley. This software may be used to provide a swift, approximate solution for MEMS structure simulations [17]. The structure simulated was of the following dimensions (see Fig. 8): a = 150 µm, b = 100 µm, L = 300 µm, t = 2 µm, w_1 =

100 µm, w_2 = 300 µm, w_3 = 100 µm.

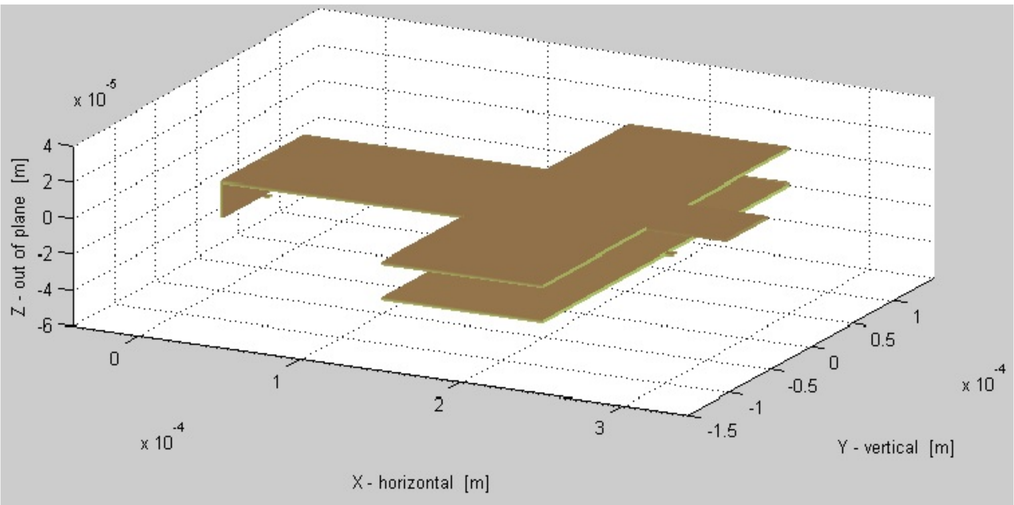

Fig. 8. The Sugar Model of the Cantilever Structure.

Simulations were carried out by gradually increasing the voltage until the simulator began to specify that the results were inaccurate. The value of the voltage just before the simulator began to produce inaccurate results was taken to be the pull-in voltage. This was done assuming that this voltage was close enough to the pull-in voltage to be approximated as the pull-in voltage. This voltage did not correspond to a deflection of 1/3 g_0, corresponding to a greater deflection. Table 2 shows the voltage applied and the deflection observed.

Table 2. Voltage and corresponding Deflection.

Voltage(V)	**Deflection (µm)**
4	0.26267
5	0.47574
5.5	0.6624
5.8	0.8858

The voltage at which SUGAR begins to provide inaccurate results, which was taken to be the pull-in voltage, is 5.8 V. However, the corresponding value obtained by the mathematical model is approximately 10.16 V. The corresponding regression curve is shown in Fig. 9.

Similarly, for different dimensions:
a = 100 µm, b = 100µm, L = 250µm t = 2µm, w_1 = 100µm, w_2 = 300µm, w_3 = 100µm.
The deflections at voltages are shown in Table 3.

The corresponding regression curve is shown in Fig. 10.

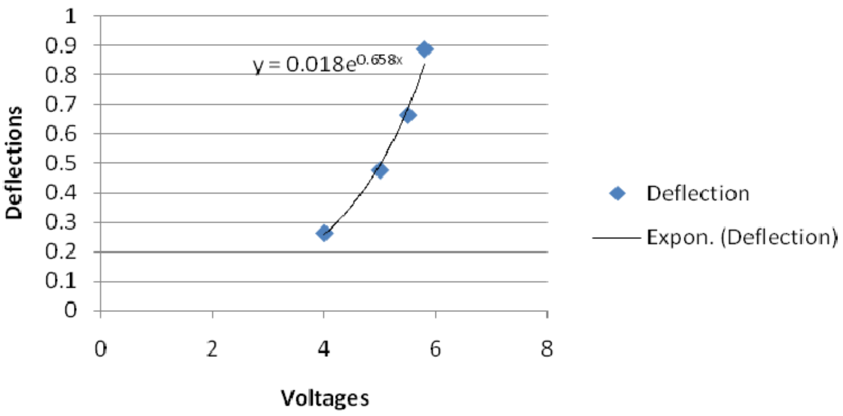

Fig. 9. Deflections and Corresponding Voltages (model 1).

Table 3. Voltages and their corresponding deflections.

Voltage(V)	Deflection (μm)
4	0.11155
5	0.18154
6	0.27674
7	0.40908
8	0.61115
8.5	0.77736
8.8	0.96145

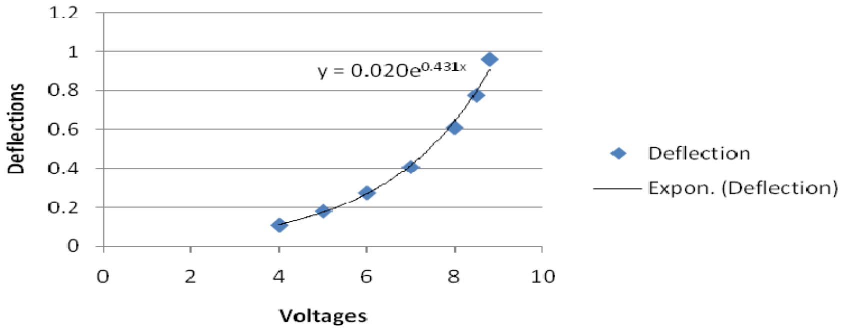

Fig. 10. Deflections and Corresponding Voltages (model 2).

This graph gives us a pull-in voltage of 8.8V however the mathematical model gives us a pull-in voltage of 15.45V for the same structure. Table 4 compare the pull-in voltage calculated using SUGAR simulator and mathematical model. The ratio between the pull-in voltages obtained for 2 methods are 1.751, 1.75 respectively which indicate proper correlation between the two values.

Table 4. Comparison of Sugar and Model Results.

	Pull-in Voltage (Sugar) (V)	Pull-in Voltage (Model) (V)
Model 1	5.8	10.16
Model 2	8.8	15.45

5. Conclusions

In this paper, a DC switch cantilever structure was modelled, using the principles of solid mechanics. The modelling indicated that increased area of actuation at a distance from the fixed end reduced the pull-in voltage. Increasing the length of the cantilever was also observed to decrease the pull-in voltage to an even greater extent than increasing the actuation area did. SUGAR simulation provided a value for the pull-in voltage that was of the order of the value obtained by the mathematical model. There also appears to be a constant ratio (modelling coefficient) between the model pull-in voltage and that obtained by SUGAR. Hence, the model provides a computationally inexpensive method of calculating the pull-in voltage to the correct order, as per the Sugar simulation.

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