Performance analysis of a MEMS cantilever beam

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The behaviour of a cantilever beam for a capacitive accelerometer is analysed through simulations, varying the parameters of displacement, electrical capacity, and voltage. Simulation is thus demonstrated to be a very useful design accelerator.

Keywords: capacitive accelerometer, Comsol, modeling, simulation

1. Introduction

Cantilevers are beams constrained at one end and stretch freely outwards at the other. The cantilever is rigid for limited movement in most macroapplications[1]—nobody wants to step out onto a balcony and feel it curve, or look out of the window of a jet aircraft and see its wings flapping. A diving board, on the other hand, must flex under load, hence is made with more flexibility. Some cantilevers are used in microapplications, they are often more adaptable than macroscopic ones, allowing for a greater range of motion. Flexible microcantilevers are used in situations where the cantilever[2,3] is bent due to an external force or internal tension (e.g. in atomic force microscopes, diagnostic transducers, chemical sensor arrays). Needles, probes and transport systems for transducers are made of more rigid cantilevers.

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1 Padarthi Sindhuja, Vinay Sharma, Madhur Deo Upadhayay, Atul Vir Singh, K.S. Jitendra, A. Srinivasulu and B.P. Singh, Simulation and analysis of actuation voltage of electrostatically actuated RF MEMS cantilever and fixed–fixed switches with variable beam parameters. *Intl Conf. on Micro-Electronics and Telecommunication Engineering* (ICMETE), Ghaziabad, 22–23 September 2016, pp. 450–454.

2 P.V. Kasambe, A. Barwaniwala, B. Sonawane, J. Rana, N. Raykar and D.V. Bhoir, Mathematical modeling and numerical simulation of novel cantilever beam designs for ohmic RF MEMS switch application. *Intl Conf. on Advances in Computing, Communication and Control* (ICAC3), Mumbai, 20–21 December 2019, pp. 1–6.

3 S. Priyadarsini, J.K. Das and A. Dastidar, Analysis of MEMS cantilever geometry for designing of an array sensor. *Intl Conf. on Signal Processing, Communication, Power and Embedded Systems* (SCOPES), Paralakhemundi, 3–5 October 2016, pp. 625–628.

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Microcantilevers are commonly used in microsystems, including microelectromechanical systems (MEMS).[4] Their adaptability and versatility make them a common component for a wide range of uses. The fundamental properties of cantilevers[5] influence the operating characteristics of macro- and microcantilevers.[6] In terms of fabrication and operation, microcantilevers are the simplest MEMS-based devices. Applications of microcantilever sensors have gradually grown and are nowadays ubiquitous because of their success—high performance, low cost, low power consumption and fast response—and have huge further potential. Physical, chemical and biological sensing make use of microcantilevers. They can readily be multiplied in large arrays, for noise reduction, multianalyte analysis, or both. In medicine they have been used advantageously to screen for viruses, identify point mutations, monitor blood sugar levels, and detect chemical and biological warfare agents.

Modern radio frequency (RF) front-end devices (used to transfer data) frequently incorporate MEMS into their designs to take advantage of inherent MEMS properties, such as low mass, low power consumption and small size.

The objective of this paper is to develop a fast and convenient methodology for determining the optimum cantilever design for any given application. The paper is organized as follows: §2 briefly presents the state of the art; §3 describes the proposed cantilever beam design; §4 the simulation methodology, and §5 contains the performance analysis of the cantilever beam.

2. Existing cantilever systems

Mechanical deformation, i.e. deflexion of the membrane or beam structure, is the basis for MEMS cantilever sensors;[7] the cantilever deforms when it is loaded.[8] More precisely, when a disturbance or load is applied to the cantilever's free end or along the cantilever surface, deflexion occurs.[9,10] Microcantilever-based biosensors,[11,12] such as those used for medical

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[4] B. Tian, H. Li, N. Yang, H. Liu and Y. Zhao, A MEMS-based flow sensor with membrane cantilever beam array structure. *IEEE 12th International Conference on Nano/Micro Engineered and Molecular Systems* (IEEE-NEMS), Los Angeles, 9–12 April 2017, pp. 185–189.

[5] Y. Wu, J. Wang, X. Zhang, C. Zhang and G. Ding, Modeling of a bistable MEMS mechanism with torsion/cantilever beams. *IEEE 5th Intl Conf. on Nano/Micro Engineered and Molecular Systems* (IEEE-NEMS), Xiamen, 20–23 January 2010, pp. 153–156.

[6] D.K. Parsediya, Deflection and stresses of effective micro-cantilever beam designs under low mass loading. *Intl Conf. on Electrical Power and Energy Systems* (ICEPES), Bhopal, 14–16 December 2016, pp. 111–114.

[7] H.U. Rahman and R. Ramer, Supported bars novel cantilever beam design for RF MEMS series switches. *9th IEEE Conference on Nanotechnology* (IEEE-NANO), Genoa, 26-30 July 2009, pp. 255–258.

[8] After loading, the cantilever may bend;[6] more generally, the structure of the material (which may be a complex nanocomposite) from which the cantilever is made may change as a result of the deformation. Most commonly, the loading is a force or mass applied to the surface of the cantilever.

[9] Y. Liu, J. Liu, B. Yu and X. Liu, A compact single-cantilever multicontact RF-MEMS switch with enhanced reliability. *IEEE Microwave Wireless Components Lett.* **28** (2018) 191–193.

[10] C. Chu, X. Liao and C. Chen, Improved dynamic range of microwave power sensor by MEMS cantilever beam. *J. Microelectromech. Systems* **26** (2017) 1183–1185.

[11] Q. Wang, D. Mao and L. Dong, MEMS tunable photonic crystal-cantilever cavity. *J. Microelectromech. Systems* **28** (2019) 741–743.

[12] R.R. Basantkumar, B.J.H. Stadler, W.P. Robbins and E.M. Summers, Integration of thin-film galfenol with MEMS cantilevers for magnetic actuation. *IEEE Trans. Magnetics* **42** (2006) 3102–3104.

diagnostics, operate on the principle of biorecognition of an analyte being converted into some kind of nanomechanical motion (deformation). The microcantilever is coated with receptors for a particular target molecule. Microfluidic subsystems bring the analyte-containing sample in contact with the coating.[13] Due to the small size of many target analytes of medical interest, their recognition and the determination of their concentration[14] requires a high level of precision in cantilever design (including the associated electronic circuitry) and signal processing (Fig. 1).

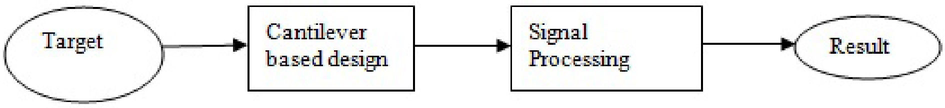

Figure 1. Block diagram of a cantilever device.

Capacitive accelerometers, also called vibration sensors, rely upon a change in electrical capacitance in response (reaction) to acceleration. Accelerometers make use of a plate condenser; the space between the plates varies proportionally to applied acceleration, therefore changing the capacitance, from which a voltage proportional to acceleration is derived with suitable circuitry. Capacitive accelerometers are able to measuring steady and sluggish as well as brief intervals of and periodic acceleration.

AC capacitive acceleration sensors essentially contain as a minimum the following components: the primary one is a stationary plate (i.e., associated with the housing) and the secondary plate is attached to an inertial mass (i.e., unfastened to allow movement within the housing), typically supported above by torsion bars. These plates constitute an electrical condenser whose capacitance is proportional to the distance d between the plates. When responding to a steady (uniform) acceleration, the capacitance change is proportional to it (also called DC or static acceleration).

3. Proposed cantilever beam

The inertial mass acts as the movable electrode (Fig. 2 and Table 1), between two fixed electrodes mounted on glass plates. The capacitance difference between the two condensers is useful to quantify the acceleration; the symmetric layout with differential sensing minimzes the influence of any thermal mismatch and linearizes the relationship between acceleration and capacitance.

To lessen the influence of parasitic and stray capacitances and to have high sensitivity, the capacitance has to be large. This may be achieved through making the distance between the movable and fixed electrodes small. To lessen the impact of air damping (which can significantly decrease the bandwidth of the accelerometer), holes should be made in the plates. The air damping impact also can be decreased through a force-balanced dimension scheme.

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[13] G. Schiavone, A.S. Bunting, M.P.Y. Desmulliez and A. J. Walton, Fabrication of electrodeposited Ni–Fe cantilevers for magnetic MEMS switch applications. *J. Microelectromech. Systems* **24** (2015) 870–879.
[14] Sometimes, it is merely necessary to indicate whether a threshold concentration is exceeded.

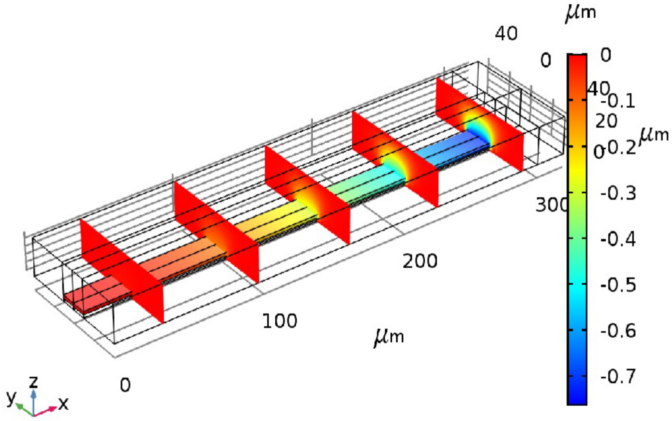

Figure 2. Geometry of the elastic cantilever beam, one of the most basic structures used in MEMS design, showing typical vertical displacement. The beam is fixed at one end (on the left), An electrostatic load (Fig. 3) is applied to the beam, which bends as shown (vertical displacement); surface displacement field and (slices) spatial mesh displacement (colour online). The coördinate system has its origin at the fixed end of the beam. The *x*-axis is perpendicular to the unbent beam's axis, while the *y*-axis is parallel to it. All dimensions in μm.

Table 1. Material and size parameters of the cantilever.

Name (symbol)	Value	Unit
Young's modulus	153	GPa
Poisson's ratio	0.23	–
Density	2330	kg/m^3
Beam length (L)	300	μm
Beam width (b)	40	μm
Beam thickness (h)	0.3	μm
Gap (d)	0.2	μm

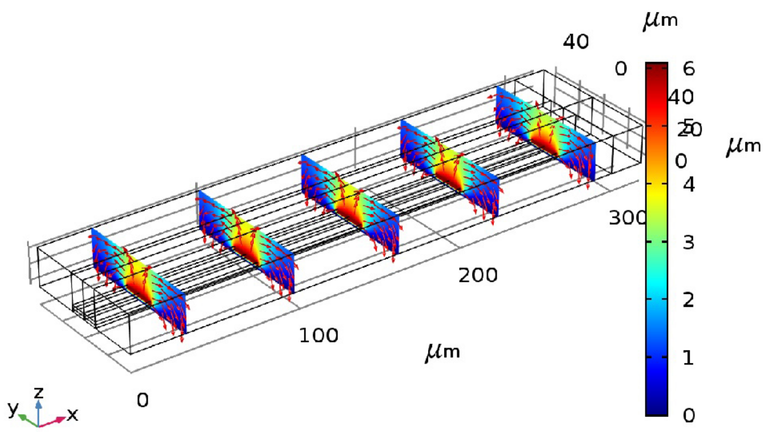

Figure 3. Electric potential (in volts, according to the scale on the left, colour onine) distribution (slices) in the cantilever (Fig. 2). Arrow volume shows electric field (V/μm).

4. Simulation method

The simulation used Comsol software. Mesh displacement is employed, since real deformations are not usually obvious to the human eye in very small devices like MEMS hardware. The cantilever movement can be visualized as a change in the device while simulating acoustic waves, vibrating mechanical hardware or fluid in a channel, to mention a few examples. COMSOL's general extrusion operator was used to generate analytic equations to allow the calculation of electrostatic forces and actuator capacitances based on the distance between elements in the model. This method is scalable to sophisticated devices with a large number of cantilevers grouped into combs. To correctly mimic the effect of manufacturing errors on the geometry, COMSOL's deformed geometry interface was used, which allows one to distort the mesh using user-defined equations, and then apply the changed geometry in a structural finite element simulation. This feature allows the designer to cycle through design variants while utilizing the same mesh, yielding information about the influence of the design variations even when changes in performance are difficult to resolve with the mesh.

5. Results

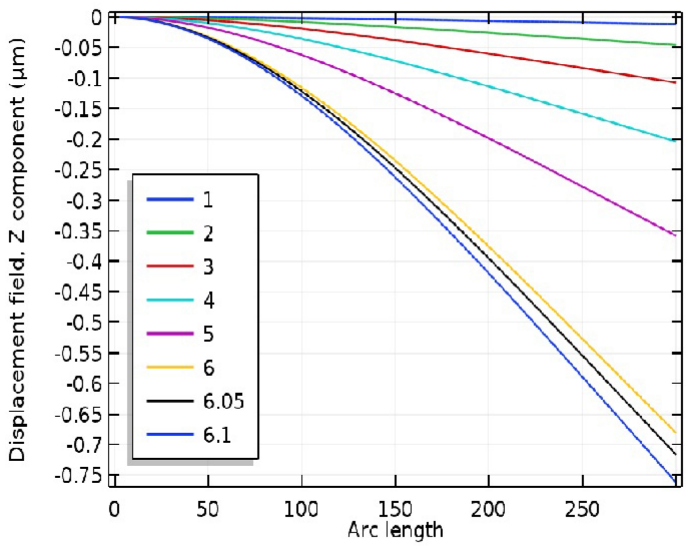

Figure 4. Cantilever tip (i.e., right end in Fig. 2) displacement field for different applied voltages/V as shown in the inset (colour online). The distance between two places along a portion of a curve is known as arc length; curve rectification is the process of determining the length of an uneven arc segment. All dimensions in µm.

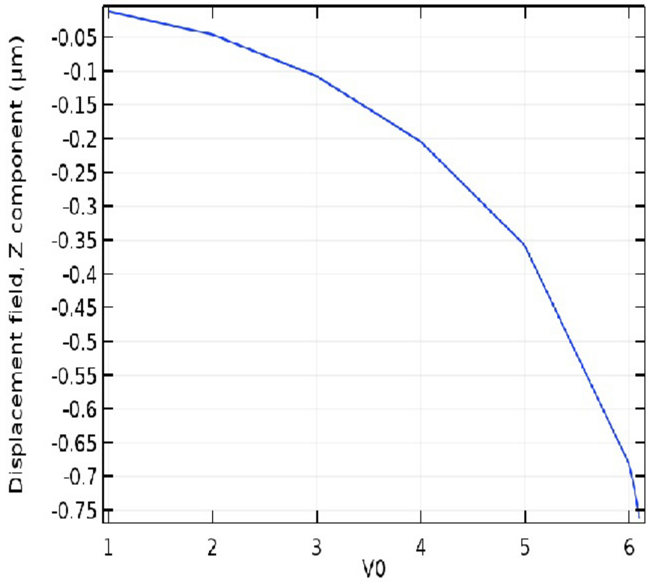

Figure 5. Cantilever tip displacement field v. applied voltage V_0. It accounts for the effects of free and bound charge; in free space, the electric displacement field is equivalent to flux density (cf. Gauss's law).

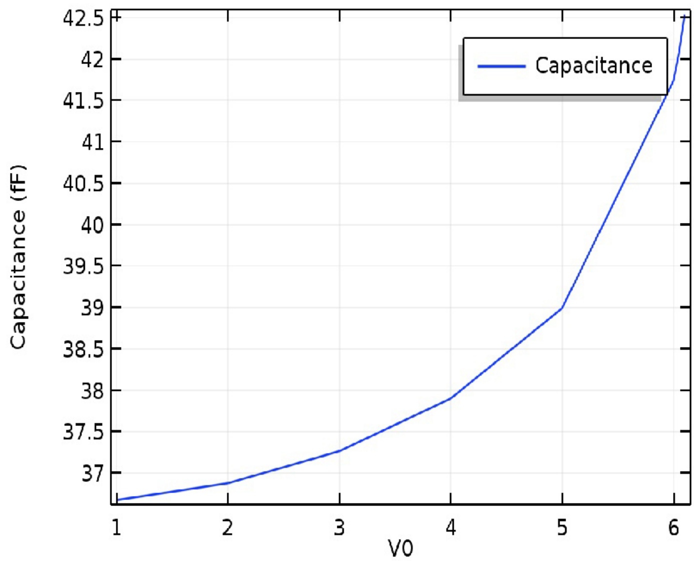

Figure 6. Capacitance/fF v. applied voltage V_0/V. Capacitance C was calculated using the equation $C = \varepsilon_0\, s/(h + d/\varepsilon)$, where ε is the relative permittivity of air and s is the space between the two beams.