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3-D Modelling of Mems Based Micro-Cantilever Vibration Sensor

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Abstract: A micro-cantilever is a form of active, chemical, or biological sensor that detects subtle changes in parameters including frequency, load, stress, and strain. Cantilever behaviour varies subtly with even the tiniest changes in its parameters, making it highly significant in the field of sensors. The vibration sensor is an epitome of a cantilever application. Every instrument has its own natural frequency, and deviation from this frequency causes changes in the cantilever's characteristics. This resonance frequency is determined by simulations, for a certain cantilever beam design and piezo-electric material (PZT-lead zirconate titanate). To achieve a resonance frequency, micro-cantilever modelling and simulation are used. The piezoelectric cantilever beam was made of PZT material, which was subsequently covered with Cr-Au IDE (inter-digitated-electrodes).The mechanical and electrical properties of the cantilever beam were examined during the analysis. The simulation results obtained for the micro-cantilever with a dimension of 35 mm length, 6mm width and 0.5 µm thickness showed resonance frequency of 310Hz and voltage output of nearly 48mV, for a dimension of 40mm length, 6mm breadth, and 0.5m thickness, the resonance frequency of 273Hz and voltage of 38.2mV were obtained, and the resulting simulated values form a bell-shaped curve, which gives us the resonant frequency of the proposed cantilever construction.

Keywords*: Vibration sensor, Cantilever beam, PZT (lead zirconate titanate), Resonant frequency*

1. Introduction

MEMS-based devices have been used in a wide range of technologies in recent years. Including inertial navigation systems, Wireless connectivity, medical devices, pressure sensors such as accelerometers and other piezoelectric devices are used. Inorganic piezoelectric materials, such as most prevalent piezoelectric materials are Lead Zirconate Titanate (PZT3). During the last few decades, many micro-cantilever-beam-based MEMS (micro-electromechanical systems) devices such as, sequence-specific DNA sensing, the atomic force microscope (AFM), single electron spin detection, mass sensors, chemical sensors and pressure sensors, have become commonplace in modern technologies. Scanning probe instruments, detection instruments, force measurements, magnetic spin detection, and heat measurement all mainly depends on micro-cantilever rays are deflection [1, 2]. Tension, compression, torsion, and bending are examples of simple stress states which are commonly utilized to compute strain and stress observable forces and displacements in the study of mechanical behaviour of materials. However, because of the difficulties in structural dimensions, manufacturing and maintaining small weights and displacements required in such conditions, such a method cannot be applied in MEMS, as a result, designers prefer to use design calculations before spending in expensive fabrication techniques [2, 3, and 4]. Synthesizing a durable MEMS device, ensuring that the vibration sources resonate with the structure. Tackling unpredictable ambient vibrations are an issue, and satisfying the minimum electrical energy required are only a few of the problems. In order to generate usable electrical energy for powering Microsystems, it is important to optimize the performance [3], if an electric field is applied across the sensor, one plate will expand and the other will contract. As a result, stress develops in both plates, causing bending deformation throughout the structure. Also, if the applied force or a pressure to the cantilever's tip, the upper plate develops compressive strain while the bottom plate develops costly strain. Therefore, negative charge develops on the upper plate and a positive charge develops on the bottom plate. due to their capacity to generate a wide range of sensors, cantilever sensors have steadily gained favour in many scientific applications in modern years [4]. Electrical energy can be generated from ambient mechanical vibration, Wireless sensor networks, chemical sensors, and health monitoring are all examples of applications where vibration energy is utilized effectively and converted into electrical energy. Three electromechanical transduction techniques are used to convert energy piezoelectric, electrostatic, and electromagnetic, because of the ease of design and increased conversion efficiency, piezoelectric sensors have influenced a lot of

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attention among these transduction technologies [5]. The inherent frequency, displacement, stress, and strain parameters of a cantilever-based piezoelectric sensor construction are discussed in this article. The dynamic response is used to evaluate performance over a wide modal frequency range. The structure is also put through its paces in a real-world industrial setting with a variety of vibration sources. Because of their very low natural frequency, increased stress, and ease of utilize, cantilever-based sensors get more applications than others [4, 5].

2. Literature Survey

Micro-cantilever generates its highest power production when vibration reaches is at its resonance frequency, it is one of the most critical design characteristics. The frequency of the match is the same as the resonant frequency hence the power output from the piezoelectric micro-cantilever will vary when the vibration frequency changes, it is gradually reduced from the natural frequency of the device. The frequency of a micro-cantilever is determined by its size as well as the material constants. Cantilevers also have a number of advantages, vibration modes with varying resonance frequencies [1, 2, 3]. Depending on the functional requirement, different architectures play distinct roles in MEMS sensors or actuators. The boundary conditions of the cantilever result in a lower spring constant, which improves sensitivity while lowering driving voltage needs (for actuators). Both sensor and actuator applications can benefit from this**.** Electrostatic loading in the form of uniform loading along the length of the beam with varying loading spans can be termed [2]. Special circumstances for compression and tensile loads, as well as other elements, have been examined in the fundamental pull-in voltage. The observations are based on Hook's law, which assumes that load and deflection have a linear connection and that the load-to-deflection ratio is equal to the spring constant [3, 4]. Designing a cantilever sensor from ambient frequencies requires consideration of physical limits such as maximum stress and deflection. Two different modes of operation have been used with the cantilever sensor. The first mode is static, the amount of deflection is proportional to the kind of loading, modulus of elasticity, spring constant, and dimensions when a force is applied to the cantilever tip in this mode. It also relies on whether or not the system parameters have changed. As a result, the presence of an external load or residue masses on the cantilever beam modifies its capacity, resulting in extremely slight but noticeable variations in deflection. Another way of cantilever functioning is when the natural frequency of the cantilever is used as a sensing element as a result of the aforementioned factors [5, 6, 7, 8]. An induced electrical field is created when a piezoelectric material is physically distorted by pressure, vibration, or force, when electrical energy is provided, however, mechanical deformation occurs. The piezoelectric cantilever generates an electrical charge [9, 10, 11, 12, 13]

In this work, a micro-cantilever-based vibration sensor with PZT material has been built and simulated to achieve a resonant frequency that is matched with the device frequency in order to gauge the deviation. For the fluctuation in frequency of the device, a specific voltage is monitored, from which the deviation and, in turn, frequency are computed. In this simulation work, a voltage of about 48mV is detected with a resonance frequency of 310Hz.

3. Design & Simulation

A micro-cantilever is a device with one side anchored and the other unattached. It gives high strain responses for low stress forces since it is unbound at one end. Its natural frequency is mostly determined by its dimensions, which include length, width, thickness, and the material's spring constant. As a result, selecting the ideal polymer can lead to the development of a micro-cantilever with low frequencies. The most considerable parameter for the designing of micro-cantilever is resonant frequency. When the frequency of vibration equals the piezoelectric micro-resonant cantilever's frequency, the micro-cantilever produces its maximum output power and the output power will decrease eventually as its vibration frequency differs from the device's resonance frequency. The resonant frequency of the micro-cantilever always depends on the material constants and its physical dimensions. The cantilevers have certain number of vibration modes with various resonant frequencies.

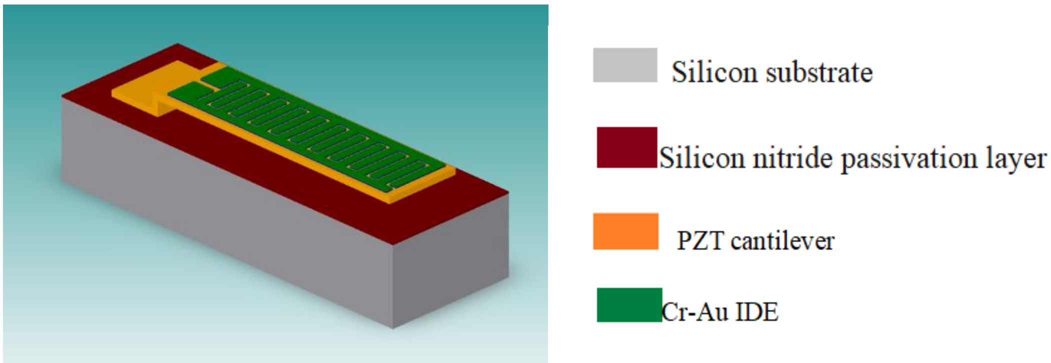

Fig 1: Designed cantilever structure with inter-digitated-electrodes

4. Results & Discussions

The impact of cantilever beam length on mechanical frequency, Pull-in voltage and displacement is factored in the computation, these parameters were determined through simulations. Conditions of mechanical frequency with respect to length and frequency are discussed, where one is varied with respect to length and the other is taken with respect to voltage.

Table (1): The various length values and their variations along frequency have been columned.

Length (mm)	**Thickness (um)**	**Frequency (Hz)**	**Displacement (mm)**	**Voltage (mV)**
15	0.3	582.36	1.1971	2.4056
20	0.3	470.28	1.1007	9.6450
25	0.3	411.32	0.9585	16.5074
30	0.3	382.76	0.8044	24.4938
35	0.5	310.39	0.6547	48.3105
40	0.5	273.64	0.4458	38.2284
45	0.8	248.02	0.1474	11.362
50	0.8	155.88	0.0742	3.0465

4.1 Effect of Frequency with respect to length

A vibration energy harvester's resonance frequency is one of the most critical design considerations in characteristics because the highest output voltage may be achieved when the frequency of vibration equals the resonant frequency. When the driving vibration frequency differs from the device's resonance frequency, the output voltage is stated to be drastically lowered. Thus, increasing the load on the beam tends to approach the compression buckling limit. Furthermore, it is demonstrated that maximum resonant frequency significantly reduce voltage to near-margin levels. Resonant frequency was solved for the material i.e., PZT with the length of cantilever beam. When the length of the micro-cantilever is changed, the variation in frequency can be studied with the help of following equation:

$$f = \frac{k_{eq}}{m} \qquad (1)$$

Where k_{eq} is the equivalent stiffness of the cantilever beam given by equation (2) and m is the effective mass on the cantilever beam.

$$k_{eq} = \frac{3EI}{L^3} \qquad (2)$$

Where E is the elastic modulus, I is the rational inertia and L is the length of the cantilever beam.

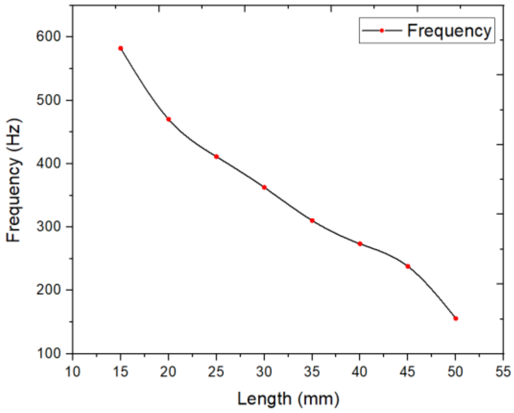

Fig 2: Variation of frequency with respect to length of the micro-cantilever beam

4.2. Effect of voltage with respect to frequency of cantilever

Due to the piezoelectric effect, a voltage output can be generated since the piezoelectric cantilever beam was driven under vibration force. In a frequency domain investigation of 150 Hz – 200 Hz, the generation of voltage output was examined. The resonant frequency of various PZT cantilever is examined as a function of variable length and thickness. The resonant frequency and pull-in voltage are measured. Fig 3 shows that the amplitude of several natural frequency modes is significantly higher than that of other higher modes. The frequency values, particularly for cantilevers of shorter length, are shown to be deviated. There is a large variation in voltages at low frequencies, and this variation is greater near the pull-in voltage. The cantilever's effective length and effective rigidity, in turn, create frequency deviation. The voltage value continuously improved until it reached a maximum of 50 mV at a resonance frequency of 310 Hz. Following that, at a frequency of 580 Hz, the voltage generation reduced until it was around 5mV-10mV.

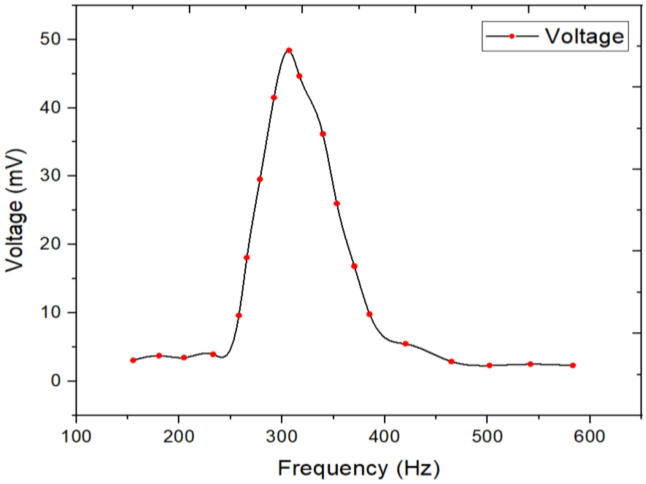

Fig 3: Variation of voltage for different frequencies of micro-cantilever beam

The Increase in beam length have been shown to increase self-frequency, whereas increase in beam width and thickness have been found to diminish self-frequency. However, the beam length has the greatest affect, whereas the beam width has a smaller impact. Despite the fact that the curves reflected the effect of a single parameter, such as length, on the frequency, the pattern remains valid when other parameters are changed.

4.3. Effect of voltage with respect to displacement

Fig 4 depicts the effect of displacement on pull-in voltage. As the displacement rises, the voltage appears to rise. At first, voltage rises more quickly as displacement rises. The rate of increase becomes practically constant as the displacement increases. Furthermore, the pull-in voltage increase linearly as the beam thickness increases as seen in Table (1). It's worth noting that the electrostatic forces and cantilever displacement have positive feedback loops. As a result, the electrostatic forces cause the beam to bend towards the grounded electrode. It is found that the voltage range can be broken down into 2 regions while the voltage is less than 50mV, the device remains stable however, once the displacement increases the device narrows due to the stress forces being overcome by electrostatic forces, causing the gap to collapse. This narrowed voltage is called as pull-in voltage.

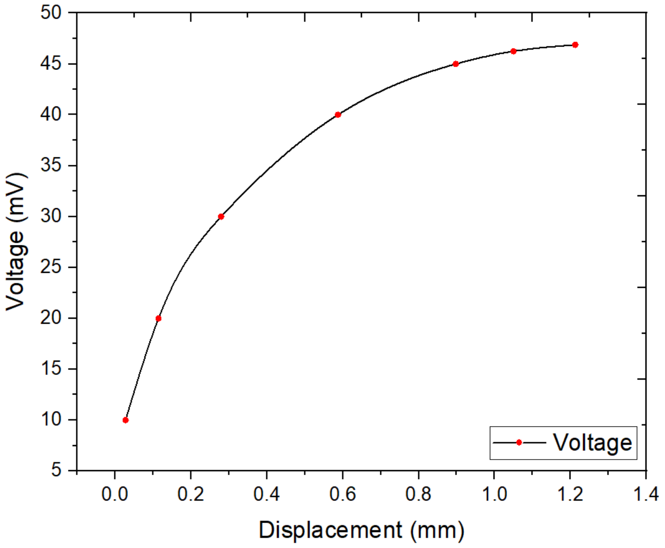

Fig 4*:* Variation of voltage with respect to displacement of micro-cantilever beam

When different loads are applied to the PZT based micro-cantilever beam, the cantilever beam's displacement fluctuates dramatically. As a result of the displacement change, the electrodes emit charge. Pull-in voltage is influenced not only by displacement but also by differences in length and thickness. To achieve a piezoelectric material based cantilever with a resonance frequency in the 160Hz range, the beam dimensions should be inversely proportional to its width. Due to the additional stress on the end, the size of the piezoelectric cantilever beam can only be determined via a theoretical solution.

5. Conclusion

Variations in cantilever properties were detected as parameters such as frequency, load, stress, and strain were changed of a MEMS-based micro-cantilever structure that was designed and simulated. It was identified that changing the length of the cantilever beam causes a change in displacement, which results in a voltage, however this variation is dependent not only on length but also on thickness. The length of the frequency should be increased inversely with the breadth to produce resonance frequency in the required range. The simulation of several dimensions of cantilever beams revealed a resonant frequency of 310Hz with a maximum output voltage of 48mV for 35mm length, 6mm width, and 0.5um thickness. These simulation results were collated and shown for various contrasts, as shown in Table 1. Fig 2 depicts the change in frequency for various lengths, which appears to be a falling curve. Fig 3, an inverted V-shaped curve, depicts voltage values for various frequencies, while Fig 4 depicts displacement fluctuation for various cantilever beam dimensions.

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