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TECHNICAL PAPER

Design and analysis of bio-mimicking tactile sensor for upper limb prosthesis

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Abstract

Tactile sensing is crucial sensory feedback that helps humans and robots to perceive their surroundings in a better way. The performance of a prosthetic hand is severely restricted by the scant tactile information provided by their sensors in contrast to the extensive tactile feedback of the human hand which has mechanoreceptors and capable of detecting both static and dynamic stimulus. Previous studies were mostly limited to detecting static stimulus and low frequency dynamic stimulus. However, some are capable of measuring both static and dynamic stimulus, but they are costly and unable to measure stimulus in frequency range of mechanoreceptors. A novel bio-mimicking tactile sensor with the ability to detect both static and dynamic forces in the frequency range of mechanoreceptors is presented in this paper. Proposed sensor design is inspired by human touch sensing receptors and targeted for use in upper limb prosthetics. A piezoelectric material is used for measuring dynamic stimulus in the sensor, whereas for evaluating static stimulus, principle of differential capacitance is utilized. A mathematical model is developed, and finite element analysis is performed using COMSOL, so that natural frequency of the sensor lies in the range of Ruffini endings (slow adapting receptor) and Pacinian corpuscles (fast adapting receptor). Results show that the first frequency of the beam is 324 Hz, which lies in the sensing range of Ruffini endings and Pacinian corpuscles. Sensor shows more than 99% agreement when results are validated by comparing eigenfrequency analysis and analytical model. The present research offers design of a bio-mimicking tactile sensor for a prosthetic hand, which is expected to incorporate prosthetic hand with touch sensing capabilities closer to that of a human hand.

1 Introduction

Tactile sensing is an important area in the field of robotics (Kappassov et al. 2015; Silvera-Tawil et al. 2015; Yousef et al. 2011) and prosthetics as it gives the sense of touch to a prosthetic arm. Human and robots utilize tactile sensing to interact with the environment. When a human hand grasps something, tactile feedback helps a human to grasp objects with precise control. Without feedback signal from the tactile sensor, it is exceedingly difficult to manipulate different types of fragile object with precise control.

In order to equip robots with better tactile sensing capabilities, researchers have built different types of tactile sensors using the transduction techniques such as thermoresistive, inductive, piezoelectric, capacitive, magnetic, and optical (Yousef et al. 2011; Najarian et al. 2009; Wei

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and Xu 2015; Zou et al. 2017). Among these transduction techniques, some have the ability to detect static stimuli (Pan et al. 2014), whereas some have the ability to detect dynamic stimulus (Cutkosky and Ulmen 2014; Howe and Cutkosky 1993). For example, the capacitive transduction technique can detect static stimulus (Ko et al. 2006) and piezoelectric materials can identify dynamic stimulus (Qasaimeh et al. 2009; Tiwana et al. 2016). MEMS-based capacitive tactile sensor developed using bulk micromachining also got much attention due to its spatial resolution and its diminished size. However, the cost associated with the fabrication process makes it uneconomical for the low volumes (Chu et al. 1996). Table 1 summarizes tactile sensors with different transduction technique.

In our experimental work (Tiwana et al. 2011) we proposed a state of art cantilever based tactile sensor design which works on the principle of differential capacitance and can measure the shear forces. The fabricated sensor has a good sensitivity and most salient feature is that it can be manufactured at very low cost for both low and high volumes. The fabricated sensor can be used in robotics and prosthetics field. However, the limitation is that it can only detect static forces or low-frequency dynamic forces in the range of 100 Hz.

To make a prosthetic arm that works effectively, it must be able to imitate the tactile sensing capabilities of human hand. Human touch receptors have the ability to detect both static and dynamic forces. In human glabrous skin, there are sensory receptors which respond to mechanical deformation, these receptors are known as mechanoreceptors (Dahiya et al. 2010; Johansson and Vallbo 1979; Dario et al. 2003), which transduce the magnitude and direction of forces, these sensors provide feedback to the brain. Without feedback from the tactile interface related to the amount of incipient slip and shear force present, it is difficult, firstly, to approximate the required amount of grip force and, secondly, to control the magnitude of the applied grip force to safely manipulate a given object (Tiwana et al. 2012).

There are basically four kind of different tactile sensors in the human body, which are the Merkel cells, Meissner corpuscles, Ruffini endings and Pacinian corpuscles (Girão et al. 2013; Johnson 2001). These four types of tactile sensor can be grouped further into two groups, static stimulus and dynamic stimulus (Romano et al. 2011). Merkel cells and Ruffini endings are sensitive to low vibrations or static load, Meissner corpuscles are very effective for spotting light touch, for identifying high-frequency vibration Pacinian corpuscles are used. Merkel cells and Ruffini endings lie in the group of slow adapting receptors, whereas, Meissner corpuscles and Pacinian corpuscles lie in the group of fast adapting receptors, frequency range of Ruffini endings and Pacinian corpuscles is discussed in Table 2.

Here, we report design of a multimodal bio-mimicking tactile sensor, which endeavors to overcome these limitations, sensor utilizes differential capacitance to detect static stimulus and piezoelectric material to detect high-frequency dynamic stimulus, sensor is mimicking the functionality of human touch receptors in terms of frequency.

2 Methods

2.1 Design

The proposed model is the improved shape of our experimental model (Tiwana et al. 2011), proposed sensor as shown in Fig. 1, consists of a trilayer cantilever beam, in which center layer is of ZnO, which is a piezoelectric material, whereas, the layers along both sides are copper layers. There is a base plate on which cantilever is fixed.

Table 1 A summary of previously reported tactile sensors exhibiting different transduction techniques along with their pros and cons

Sr no	Author name	Transduction technique	Advantages	Shortcomings
1	Muhammad et al. (2011)	Capacitive Transduction (Array)	Good static sensing	Costly Low dynamic sensing
2	Liu et al. (2006)	Piezoelectric (PVDF)	Flexible Sensitive High dynamic range	Dynamic sensing only
3	Qasaimeh et al. (2008)	Piezoelectric (PVDF)	Flexible Sensitive High dynamic range	Dynamic sensing only
4	Yahud, et al. (2010)	Multi Modal PVDF + strain gauges (multiple)	Static and dynamic sensing	Bigger size
5	Ahmad Ridzuan and Miki (2019)	Strain gauges (multiple)	Static sensing	Static sensing only

Copper pads are placed at some distance from the cantilever beam on both sides, which forms a differential capacitor. The dimensions of the sensor are optimized with the help of the parametric sweep function in the COMSOL, both the length and width of the sensor are swept to get the optimized geometry so that the response of the sensor remains in the desired frequency range. The dimensions of the proposed sensor are as follows: The cantilever beam has a length of 40 mm and width of 3 mm, whereas, the thickness of copper layer is 0.2 mm and of the piezoelectric layer is 0.4 mm.

For a better perspective, two-dimensional view of the model is shown in Fig. 1b, so that all the features can be viewed distinctly. Top view of the sensor is shown in Fig. 2, the dimension of various aspects are a = 20 mm, b = 5 mm, d_1 = 4.6 mm, d_2 = 4.6 mm and w = 3 mm. A bio-mimicking sensor should vibrate on the same frequency as that of mechanoreceptor to replicate it, for this purpose, eigenfrequency analysis is performed. In order to verify the results, three different methods are used i.e., analytical approach, harmonic analysis approach and FEM modeling using COMSOL.

It is also proposed that the trilayer beam has to be covered with a polydimethylsiloxane (PDMS) based addition curing silicone elastomer, this will increase the dynamic range of the sensor as an addition of a PDMS layer will increase the flexibility of copper ribbon (Ryspayeva et al. 2019). One of the ways to enhance the capacitance of a capacitive sensor is to increase the value of the dielectric constant (Qin et al. 2021), the PDMS layer on the sensor will enhance the capacitance of the sensor as its dielectric constant is much higher than air, In addition the PDMS layer also helps the copper beam to damp the frequency whereas the magnitude of damping depends on the hardness of the elastomer layer, the sensor with elastomer on the beam is shown in Fig. 3.

2.2 Working principle

Whenever a mechanical stimulus is applied on the trilayer cantilever beam it deflects due to the applied force, if the applied force is a static force it can identified by a change in differential capacitance, whereas, if the applied stimulus is dynamic then it can be detected through the piezoelectric material. Piezoelectric material is a material which produces a voltage when experiences a mechanical deflection. It is very popular in tactile sensing application as it is capable of identifying high-frequency dynamic stimulus and due to its stability and workability (Flanagan and Wing 1993), mathematical expression for measuring voltage is given below in Eq. 1.

$$\mathrm{V} = \frac{\mathrm{Fl}^3}{3\mathrm{EI}} \tag{1}$$

A cantilever-based sensor of length l, young modulus E and moment of inertia of cantilever I, will experience a voltage v upon the application of a force F on the cantilever.

3 Calculation

3.1 Analytical model

An analytical model has been developed and verified using COMSOL model. Eigenfrequency analysis is performed to find out the natural frequencies of the sensing beam. The mathematical expression for finding eigenfrequency is given in Eq. 2.

$$\mathrm{f_n} = \frac{\mathrm{v_n}^2}{2\pi}\sqrt{\frac{\mathrm{EI}}{\mathrm{ml}^3}} \tag{2}$$

where l is the length and m represent mass, EI is flexural modulus, V_n is the fundamental mode of frequency whose value varies for different modes of frequency, which are 1.875, 4.694, 7.853, 10.995, 14.137, and 17.279. All the six fundamental modes of frequencies can be calculated using the Eq. 2.

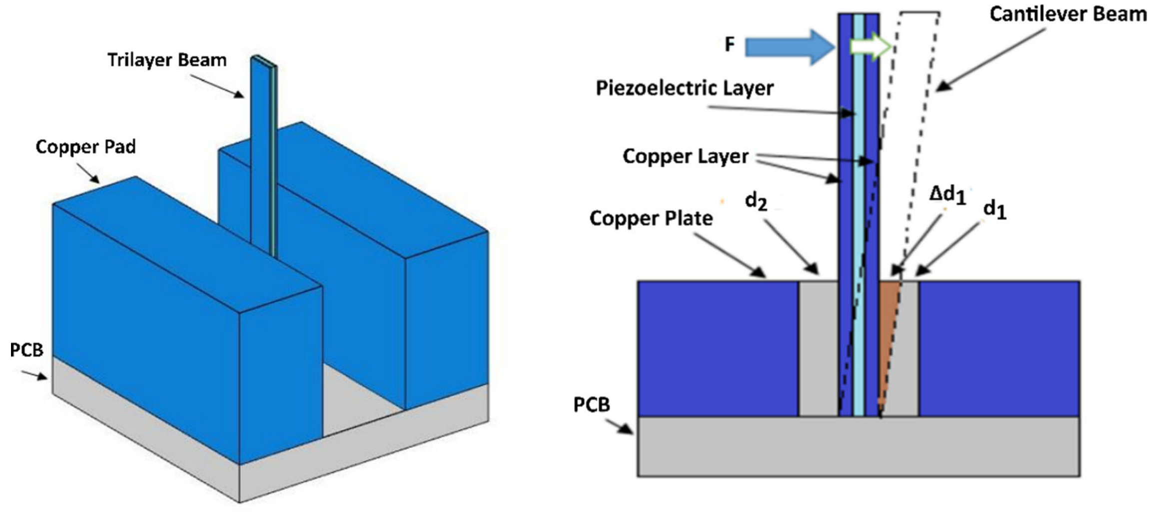
For finding flexural modulus of a multi-layer composite, classic beam theory is applied (Du et al. 2010; Lee et al. 2005), derived from Timoshenko equation (Timoshenko and Young 1968), flexural modulus for tri layer cantilever beam is given in Eq. 3.

$$EI_{eff} = E_1 b h_1^3 \frac{(1 + Y_2 + Y_3 + Y_{23})}{12(1 + m_2 n_2 + m_3 n_3)} \tag{3}$$

where m_2 is height ratio of piezoelectric material to copper and n_2 is Young's modulus ratio of piezoelectric material and copper.

Table 2 The frequency range of mimicked receptors and mimicking sensor is also described below

Sr no	Receptors name	Properties	Frequency range	Mimicking sensor
1	Ruffini endings Joo et al. (2019)	Slowly adapting	100–500 Hz	Differential capacitor
2	Pacinian corpuscles Joo et al. (2019)	High-frequency vibration (Fast adapting receptors)	40–500 Hz	Piezoelectric



(a) (b)

Fig. 1 a 3D model of the sensor consisting of trilayer cantilever beam at center and copper pads on both sides. b Two-dimensional model of the sensor showing all three layers and displacement changes on both sides as the force applied to tri layer cantilever beam

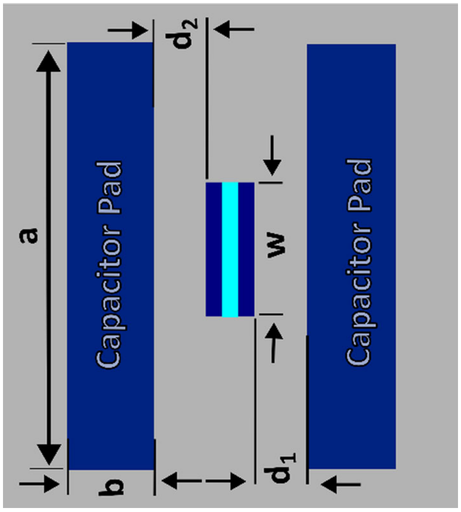


Fig. 2 Top View of the sensor

$$Y_2 = 4m_2n_2 + 6m_2^2n_2 + 4m_2^3n_2 + m_2^4n_2^2 \tag{4}$$

m_3 is height ratio of copper to copper and n_3 is Young's modulus ratio of copper material and copper.

$$Y_3 = 4m_3n_3 + 6m_3^2n_3 + 4m_3^3n_3 + m_3^4n_3^2 \tag{5}$$

$$Y_{23} = m_2m_3n_3[(4m_2^2 + 6m_2m_3 + 4m_3^2)n_2 + 12(1 + m_2 + m_3)] \tag{6}$$

where m is the equivalent mass of all layers of trilayer cantilever beam.

$$m = 2lbh_1\rho_{ZnO} + 2lbh_1\rho_{Cu} \tag{7}$$

All the material properties required for finding the flexural modulus of a tri-layer cantilever beam are provided in Table 3.

The differential capacitance technique is used for measuring static stimulus because of its effectiveness and ability to find the direction of applied stimulus.

A be the area of the beam, r is the separation between the plates, $\in_0$ is absolute permittivity, $\in_r$ is relative permittivity, w is width and H is the height of the beam,Δd_1 and Δd_2 are displacements on both sides.

$$C = A\frac{\in_0\in_r}{r} \tag{8}$$

where dC_1 and dC_2 are small differential capacitance.

$$dC_1 = \in_0\in_r wH\frac{dh}{Hd_1 - \Delta d_1 h} \tag{9}$$

$$dC_2 = \in_0\in_r wH\frac{dh}{Hd_2 + \Delta d_1 h} \tag{10}$$

Hence, for both capacitors, capacitances are C_1 and C_2.

$$C_1 = -\in_0\in_r wH\left[\frac{\ln(Hd_1 - \Delta d_1 h)}{\Delta d_1}\right] \tag{11}$$

$$C_2 = \in_0\in_r wH\left[\frac{\ln(Hd_2 + \Delta d_1 h)}{\Delta d_1}\right] \tag{12}$$

Equation below represents the differential capacitance.

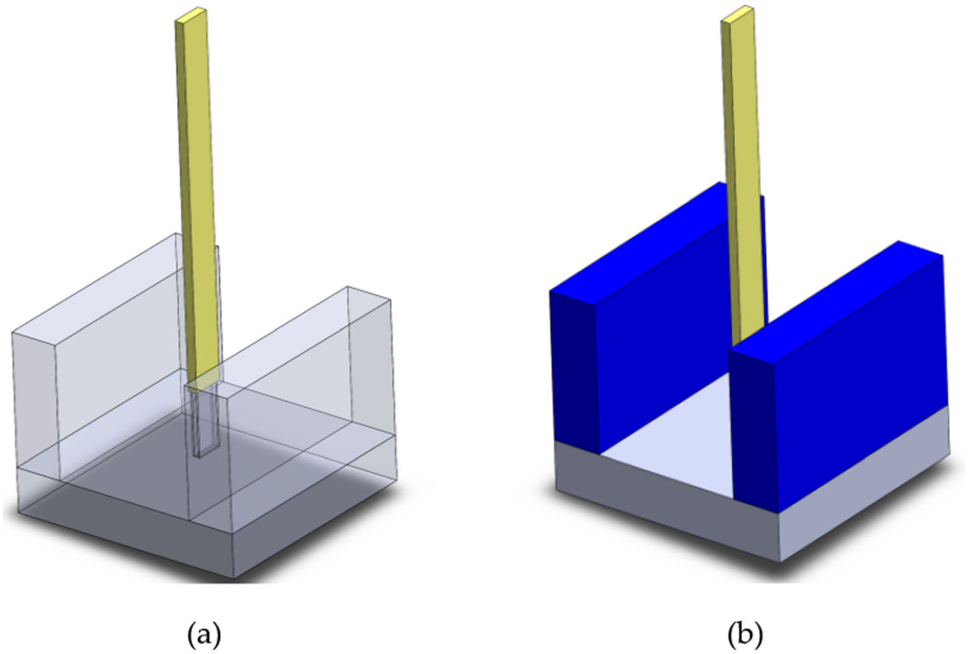


Fig. 3 a Transparent view of the sensor with elastomer on the trilayer beam. b Three dimensional view of the sensor with elastomer on the trilayer beam

Table 3 Provides the detailed properties and ratios which are required for finding out the flexural modulus of a trilayer cantilever beam

Layer no i	Material	Thickness h_i (mm)	$m_i = h_i/h_1$	Young's modulus E_i (GPa)	$n_i{=}E_i/E_1$
1	Copper	0.2	1	110	1
2	ZnO	0.4	2	140	1.27
3	Copper	0.2	1	110	1

$$\Delta C = \quad C_1 - C_2 = \in_0 \in_r \, wH \left[\frac{\ln\left[\frac{(d_1)(d_2)}{(d_1-\Delta d_1)(d_2+\Delta d_1)}\right]}{\Delta d_1} \right] \tag{13}$$

3.2 Finite element method COMSOL model

A finite element model of the system is established using COMSOL. Analysis is performed using eigenfrequency study. A mesh is created with 41,401 domain tetrahedral elements and 194,259 number of degrees of freedom for the COMSOL model as shown in Fig. 4. First six fundamental frequencies of the trilayer cantilever beam are found using the eigenfrequency analysis.

4 Results

The eigenfrequency analysis (Muthalif and Nordin 2015), of trilayer cantilever beam is performed using COMSOL. All the six fundamental modes of the tri-layer cantilever beam are shown in the Fig. 5 with their modal frequencies.

Harmonic analysis of the tri-layer cantilever beam is performed using COMSOL by plotting frequency against displacement. It is good for determining the eigenfrequency and to verify whether these frequencies are resonant or anti-resonant. Six resonant frequencies (Beatty 2006), are represented by the positive peaks in Fig. 6.

A comparative analysis is performed in which the results of eigenfrequency analysis of the trilayer cantilever beam are verified using analytical model and harmonic analysis,

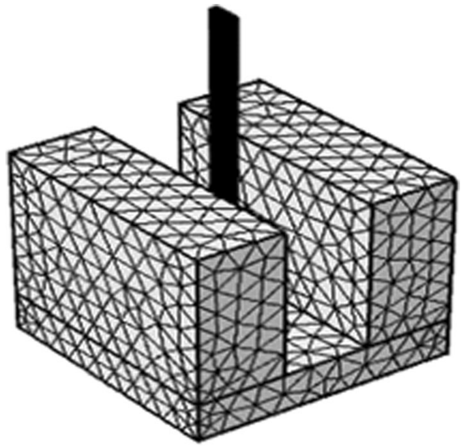


Fig. 4 FEA Analysis of the sensor model is carried out using COMSOL and meshing is performed using tetrahedral mesh

which shows a good match, there is a small difference in the analytical and COMSOL results, this is because COMSOL caters for bonding between the layers, damping and temperature effects, whereas, analytical model does not cater for these things. A comparison between the COMSOL, analytical and harmonic analysis results is given below in Table 4 along with their relative error.

A comparison between the COMSOL, analytical and harmonic analysis results is shown in Fig. 7.

The capacitance of the sensor as shown in Fig. 8, is predicted through mathematical expression for differential capacitance.

The first eigenfrequency of the beam is below 400 Hz, which lies in the sensing range of Ruffini endings (Büscher et al. 2015; Chorley, et al. 2009) (slow adapting receptor) and Pacinian corpuscles (Büscher et al. 2015; Chorley, et al. 2009) (fast adapting receptor), so both sensing parts of the proposed sensor can detect stimulus in the frequency range of mechanoreceptors.

To check the feasibility of the proposed sensor, the stress analysis has been performed by using the parametric sweep function in COMSOL, a range of forces has been applied to the sensor, and from the results it was found that ± 2 N force range is safe to apply on the structure, as the stresses generated in the structure in that range are less than the yield strength of both copper and ZnO, which depicts that this magnitude of the force is safe and it will not damage the structure. The Yield strength of Copper is 333.4 MPa and that of ZnO is 0.412 ± 0.05 GPa (Ong et al. 2003).Results of stress analysis are shown in Fig. 9.

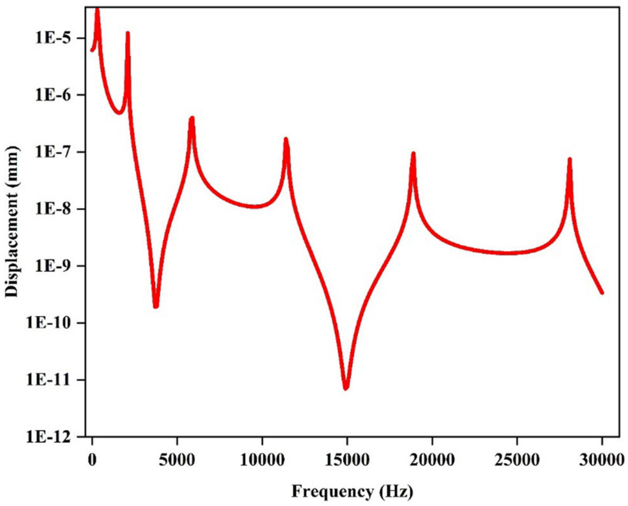


Fig. 6 Harmonic analysis of cantilever beam is performed using COMSOL, which shows peaks of resonant and anti-resonant frequencies and their frequency values

5 Discussion

5.1 Benefits

The purpose of this research is to improve the design of a previously stated sensor (Tiwana et al. 2011), which have the advantage of detecting static stimulus (Muhammad et al. 2011; Restagno et al. 2001; Dargahi et al. 2006) and low frequency dynamic stimulus (Tiwana et al. 2011]. The aforementioned sensor utilizes differential capacitance technique (Tiwana et al. 2011) and can be fabricated at low

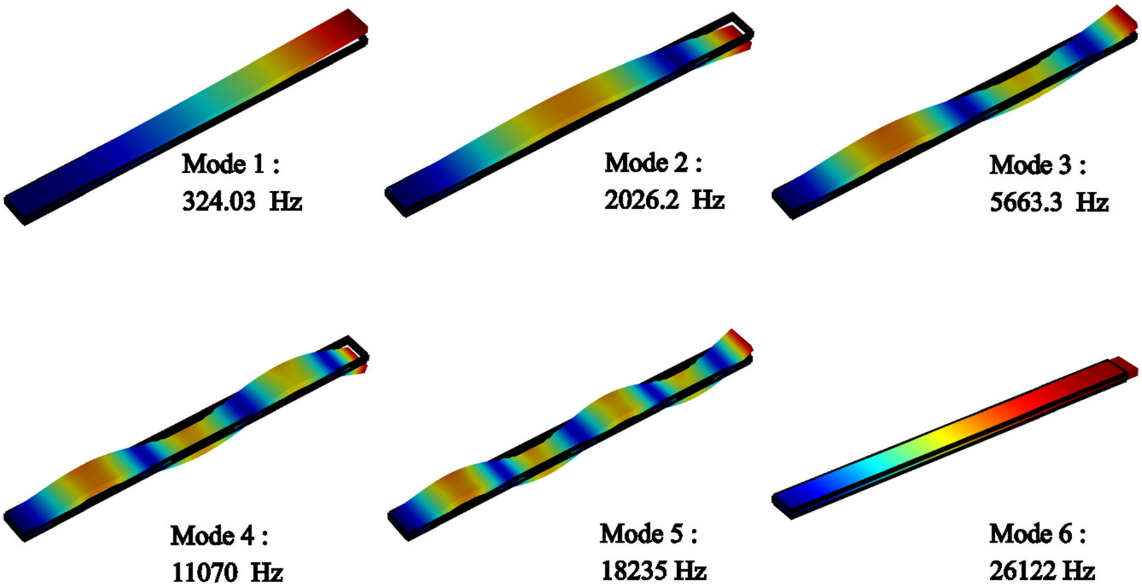


Fig. 5 First six eigenfrequency and eigenmodes are shown in the figure. The eigenfrequency analysis is carried out using COMSOL. The first eigenfrequency is 324.03 Hz which lies in the range of Ruffini endings and Pacinian corpuscles

Table 4 Comparison of eigenfrequencies of COMSOL, analytical and harmonic analysis

Mode no	COMSOL (Hz)	Analytical (Hz)	Harmonic analysis (Hz)	Relative error (%)
1	324.03	321.4	323.9	0.8
2	2026.2	2014.2	2026	0.6
3	5663.3	5638.7	5662.8	0.4
4	11,070	11,052	11,069	0.2
5	18,235	18,270	18,234	0.2
6	26,122	27,293	26,122	4.4

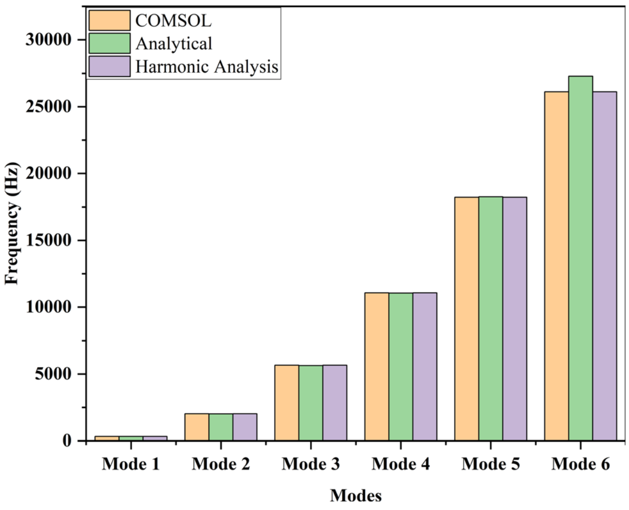


Fig. 7 Comparison of eigenfrequencies of COMSOL, analytical and harmonic analysis

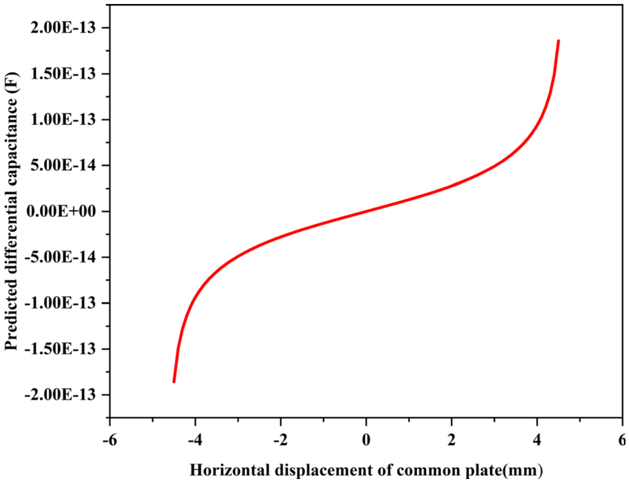


Fig. 8 The predicted differential capacitance of the sensor on different displacements of the trilayer cantilever beam

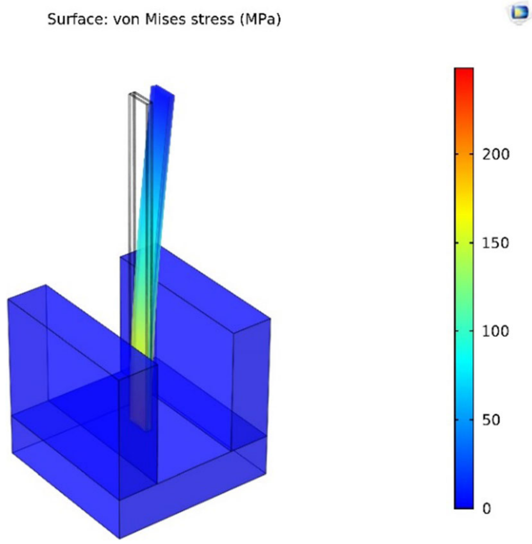


Fig. 9 Stress analysis of the sensor

cost for both low and high volumes but the inadequacy of the design is that it caters for only low dynamic frequencies (Restagno et al. 2001), whereas, the proposed design is capable of detecting both the static and high dynamic frequency (Cutkosky and Ulmen 2014; Son et al. 1994; Dargahi and Najarian 2004), which is its advantage over previously reported sensor (Tiwana et al. 2011).

5.2 Limitations

The sensor uses a single trilayer cantilever beam as a sensing element which can mimic only one resonant frequency of the biological counterpart, whereas, cantilevers of different lengths can be utilized so that output can be used from different cantilever beams depending upon the resonant frequency in the range.

6 Conclusions

The proposed sensor has outperformed cantilever-based state of the art tactile sensor by achieving an improvement in sensing frequency range from 100 to 324 Hz by incorporating piezoelectric layer in the beam for measuring high frequency dynamic stimulus. The eigenfrequency analysis of the trilayer cantilever beam matches well with the analytical and harmonic analysis. Model of the bio mimicking tactile sensor is presented in the paper so that researchers related to prosthetics field can use it for further fabrication of the sensor using MEMS techniques.

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Data availability All data generated or analyzed during the study is included in this published article.

Declarations

Conflict of interest The authors declare that they have no conflicts of interest concerning this article.

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