

Design and Fabrication of MEMS Area Changed Capacitive Accelerometer Using FDM 3D Printing Technique and Vibration Test based Mechanical Characterization

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Abstract:

This work presents the design, fabrication and testing of a MEMS (Microelectronics and Mechanical Systems) area-change capacitive type accelerometer. The need for rapid production of mechanical components and replacements has become increasingly important, driving the growth of fast prototyping and additive manufacturing across various industries, including sensor manufacturing. Authors used the FDM 3D Printing Technology for the design. A key requirement for FDM 3D printing is that all material dimensions must be in millimeters. Authors developed the area changed capacitive accelerometer and performed several simulation analyses. The fabricated device produced a displacement=2.13mm along X-axis, natural frequency=19.292 Hz, noise floor = 0.063 Hzng / and voltage outline=1.417 Volts for g=50. The cross axis sensitivity is 7.01% only even for very high acceleration range (0-50g).The simulation analysis are performed using COMSOL multiphysics software. The authors tested the 3D-printed device for frequency and displacement across all three axes using a vibration shaker, and most of the results showed close agreement with the theoretical values.

Index Terms—MEMS, Accelerometer, Displacement, Frequency, 3D Printing, noise, vibration shaker

I Introduction

Recently, the fused deposition modelling (FDM) technology has revolutionized the fabrication of unique polymer-based composite components. Understanding the fundamental mechanical properties of FDM-printed components is critical for engineering applications. FDM has been widely utilized in additive manufacturing (AM) because of its ability to manufacture complicated items at a lower cost and with precise dimensions [1].

Fabrication is the process of creating or constructing anything with conventional tools like hammers, saws, welding, and machining [2]. 3D printing, also known as additive manufacturing, is a process of building a three-dimensional item layer by layer from a computer-generated design [3].3D printing enables the creation and fabrication of more complicated designs than traditional manufacturing procedures. More conventional techniques have design constraints that can be eliminated by 3D printing. The printing time is

determined by several factors, including the part's size and the printing parameters. The quality of the completed product is also significant when considering printing time, as higher-grade goods take longer to manufacture [3]. 3D printing can take anything from a few minutes to many hours or days, depending on the pace, resolution, and volume of material used. It is very much complicated to design capacitive accelerometers with dimensions in the range of mm [4]

There are Different types of 3D printing Processes namely Polyjet technology, Fused Deposition Modelling (FDM), Stereo lithography (SLA), Selective Laser Sintering (SLS), Direct Metal Laser Sintering (DMLS), Electron Beam Melting (EBM), Digital Light Process (DLP) and Multi Jet Fusion (MJF). Among these methods FDM technology is known for its accuracy, dependability, and reproducibility [5-7]. It is one of the easiest 3D printing technologies to understand and use, with printers that can be used in the office as well as industrial-grade platforms on the factory floor. Material variety expands your application field by linking engineering-grade plastics and high-performance polymers. Fused deposition modelling (FDM) is a manufacturing technique in which a moving nozzle extrudes fibers of polymeric material layer by layer to create a structural design [8]. FDM is mostly utilized for mechanical system modelling, fabrication, and manufacturing. FDM technology use the melt extrusion technique to create a structural design from a thermoplastic polymer [9]. When a layer in the x-y plane is finished, the base platform (z axis) is lowered, and the technique is repeated until the entire structure is created [10].

Unlike traditional techniques, 3D printing has fewer stages, allowing you to print more easily. In general, there are four phases involved in creating a model using 3D printing: modelling, slicing, printing, and post-processing. FDM uses a variety of materials, although PLA is the most popular among residential and industrial 3D printer users [11] due to the following reasons.

Polylactic acid (PLA) is a bioplastic, which means it is ecologically friendly and safe for both people and animals. PLA's glass transition temperature varies from 50°C to 70°C, while its melting point temperature ranges from 180°C to 220°C. PLA plastics are biodegradable and degrade fast when disposed off, as opposed to other plastics, which have created significant disposal issues. PLA, like other biopolymers, degrades to natural and non-toxic gases, water, biomass, and inorganic salts when subjected to natural conditions, hydrolysis, or burning. Most 3D printer users use PLA since it does not necessarily require a heated bed to guarantee that the print adheres to the platform. However, graphene-doped PLA has a significant disadvantage for non-heated bed printers since it cannot generate high-quality prints on non-heated build plates.

This paper reports test results on an area change capacitive accelerometer fabrication using FDM technique. Capacitive accelerometers, also known as vibration sensors, work by measuring changes in electrical capacitance in response to acceleration. These devices have been used in a variety of commercial applications, including automotive air bags, navigation, and instrumentation. These devices have been used in these and many other applications because they usually offer better sensitivity (V/g) and resolution than comparable piezo

resistive accelerometers [11]. Area changed capacitive accelerometers use the characteristics of an opposing plate capacitor, in which the overlapping area between the plates varies proportionately to the applied acceleration, hence changing capacitance. Area changed capacitive accelerometers have been extensively studied because of their great resolution, wide dynamic range, outstanding linearity, and low power consumption [12].

It is learnt from the latest research that the cross axis sensitivity is increases whenever the size of the device is increases. When cross axis sensitivity increases then voltage sensitivity is decreased [13-19]. Further the area changed capacitive accelerometers suffer with parasitic capacitance and stray capacitance. To limit the impacts of parasitic and stray capacitance while maintaining high sensitivity, the capacitance should be substantial. This may be accomplished by making the space between the moveable and fixed electrodes minimal.

In this work authors concentrated to achieve better cross axis sensitivity and voltage sensitivity. From the past research in capacitive accelerometers when parasitic capacitance is large voltage sensitivity is decreases. Voltage sensitivity is dependent on parasitic capacitance. So while designing the area changed capacitive accelerometers authors follow the guide lines prepared by Kannan solai and Joseph Daniel .They designed the guide lines for achieving better voltage sensitivity and high linearity and minimal cross axis displacement for area changed capacitive accelerometers.

Past research by the authors showed that parasitic effects don't cause major issues in area changed capacitive accelerometers [20]. Here authors designed the new structure for area changed capacitive accelerometer for 20Hz frequency and several simulation analyses are performed. Finally, the 3D printed device was tested using vibration measurement. There are various methods for testing the vibration performance of accelerometers, each tailored to specific objectives such as evaluating frequency response, sensitivity, or displacement. The following are some widely-used techniques [21-22].

1. Shaker Table Testing (Vibration Shaker) 2. Laser Doppler Vibrometry 3. Drop Table Testing 4. Electrodynamic Shakers with Sweep Frequency Testing 5. Piezoelectric Actuation.

When testing the vibration performance of polymaterials, shaker table testing and laser Doppler Vibrometry are particularly suitable methods:

1. Shaker Table Testing: Advantages: Controlled Environment: Provides a consistent and controlled environment for testing, allowing for precise manipulation of frequency and amplitude. Versatile: Suitable for a wide range of applications and can test multiple devices simultaneously. Repeatability: Offers repeatable test conditions, which is crucial for comparative studies and reliability assessments. Disadvantages: Physical Limitations: May not accurately represent real-world conditions, especially if the device experiences complex vibration modes. Equipment Costs: High initial investment for shaker table systems and associated infrastructure. Physical Contact: The device must be mounted on the shaker, which can introduce stresses that may affect the results. [23]

2. Laser Doppler Vibrometry: Advantages: Non-Contact Measurement: Allows for high-precision measurements without physical interference, making it ideal for sensitive devices. High Sensitivity: Capable of detecting small displacements and velocities, this is critical for evaluating MEMS devices. Detailed Data: Provides detailed spatial and temporal vibration data, enhancing analysis capabilities. Disadvantages: Setup Complexity: Requires careful alignment and setup, which can be time-consuming. Cost: Equipment can be expensive, and operational costs may also be higher due to maintenance and calibration needs. Environmental Sensitivity: Results can be affected by environmental factors like air turbulence or vibrations from external sources[24]. These methods each have their own strengths and weaknesses, making them suitable for different aspects of vibration testing. When combined, they can provide a comprehensive understanding of the vibrational behavior of devices like accelerometers and MEMS sensors.

Shaker Table Testing: Shaker tables can typically operate at frequencies starting from 1 Hz, allowing for the assessment of low-frequency responses in accelerometers and MEMS devices [25]. Laser Doppler Vibrometry: This method is capable of measuring frequencies down to approximately 0.1 Hz. It is particularly advantageous for applications requiring high precision without contact, which could interfere with the vibration measurements[26]. Due to the advantages of flexibility, range of frequency authors used Shaker Table Testing for testing the 3D Printed accelerometer structure in this work.

2. Structure of area changed capacitive accelerometer

2.1 Suitable structure for folded beam and lateral beam capacitive accelerometer for area changed structure

The structure shown below is suitable for normal folded beam and lateral beam capacitive accelerometer area changed structure. The structure consists of proof mass with folded and lateral beams. Seismic mass is suspended with the help of elastic folded beams and lateral beams. Whenever the proof mass is subjected to force with the help of acceleration then the proof mass moves along X, Y, Z directions. Some fixed electrodes are placed over the mass due to force capacitance is generated between the parallel plates. In Fig. 1 l_f, l_l, w_f, w_l are widths and length of folded and lateral beams. The proposed area-changing capacitive type accelerometer will be built as a near-optimal single-axis accelerometer, high displacement is produced in X-axis direction and low displacement is generated in remaining two Y, Z axis. Change in the length is caused because of Y-axis displacement so that change in area is produced. The gap between the plates is altered because of Z-axis direction displacement. Here authors concentrated on low cross axis sensitivity for getting better displacement in principal axis direction. To validate this author performed simulation studies for getting low cross axis sensitivity.

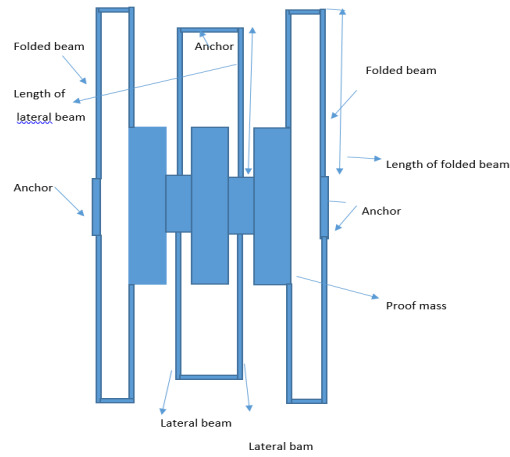


Fig.1: MEMS capacitive accelerometer with folded and lateral beams

Fig. 2 represents the generation of capacitance for single electrode. Whenever there are two parallel plates there will be capacitance generated. When there is no force that is in rest case capacitance $C_1 = C_2$. When the force is applied there is a change in capacitance. Depending on the displacement direction C_1 increases and C_2 decreases and vice-versa. This basic principle is suitable for area changed capacitive accelerometer capacitive analysis.

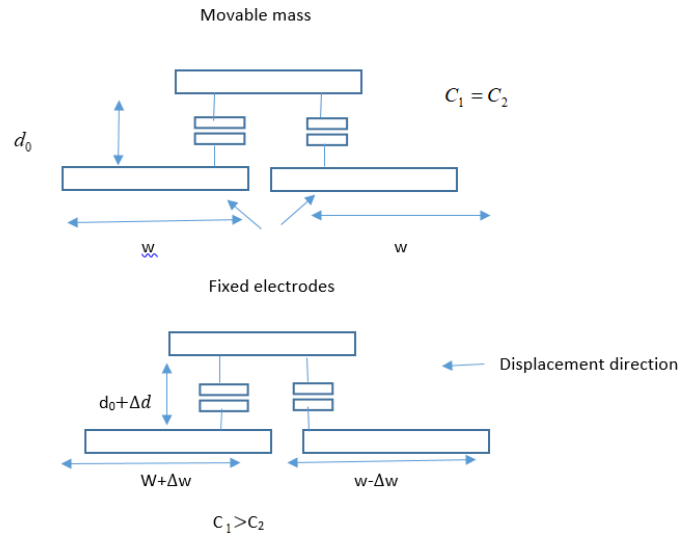


Fig. 2 a) When $g = 0$, a cross sectional picture along the X-axis of a single unit parallel plate capacitor setup is produced. b) When the acceleration is $g > 0$, a cross sectional image of a single unit parallel plate capacitor arrangement is obtained along the X-axis.

3. Structural model of capacitive accelerometer

3.1 Theoretical analysis for displacement, sensing mass, and frequency

Authors first validate the results before fabricating the structure. Authors used the theoretical models to design various geometries like W_{lb} is the width of lateral beam, W_{fb}

width of the folded beam, l_{fb} length of the folded beam, l_{lb} is the length of the lateral beam. The material chosen for designing the structure is Poly lactic acid.

$K_{x,lateral}$ is the stiffness constant of lateral beam, $k_{x,folded}$ is the stiffness constant of the folded beam. These values are calculated by using Eq. (2), Eq. (3). The total stiffness constant is calculated by using Eq.(4).

The frequency of the structure is calculated by using Eq. (5). The displacement is calculated on X-axis is by using Eq. (6).

m_s is the sensing mass. E is Young's modules of PLA and it is 4.107 G.pa

The stiffness constant of the lateral beam [13] is expressed as

$$k_{x,lateral} = 8Et_{lb} \left(\frac{w_{lb}}{l_{lb}} \right)^3 \quad (1)$$

The stiffness constant of folded beam [13] is expressed as

$$k_{x,folded} = 2Et_{fb} \left(\frac{w_{fb}}{l_{fb}} \right)^3 \quad (2)$$

Total stiffness constant is expressed as

$$k_{x,total} = k_{x,folded} + k_{x,lateral} \quad (3)$$

The frequency of the structure is calculated as [13]

$$f = \frac{1}{2\Pi} \sqrt{\frac{k_{x,total}}{m_s}} \quad (4)$$

The principal axis displacement is [16] expressed as

$$\delta_x = \frac{F}{k_{x,total}} \quad (5)$$

The sensing mass of the structure [16] is expressed as

$$m_s = \rho [w_m l_m h + N_s w_s l_s h] \quad (6)$$

ρ is the density of PLA=1240 kg/m³

h=thickness

N_s = Number of sensing electrodes

W_s = Width of the electrode

l_s = length of the electrode

h =height of the electrode

By using the above equations authors calculated the theoretical frequency which is equal to 23.462 Hz, displacement of X-axis is 2.13 mm for $g=50$

3.2 Simulation Studies on Folded and Lateral beam supported area differentiated capacitive accelerometer

Authors designed new area changed capacitive accelerometer by using COMSOL Multiphysics software. While designing the new structure authors followed the guide lines prepared by Joseph Daniel [16]. The new area changed capacitive accelerometer has low noise floor, high voltage sensitivity and less cross axis sensitivity. The new structure has additional lateral beams with folded beams it leads to achieve better cross axis performance without restricting the proof mass displacement. Close look at the structure the lateral beam length is high than the proof mass, so it could not restrict the principle axis displacement

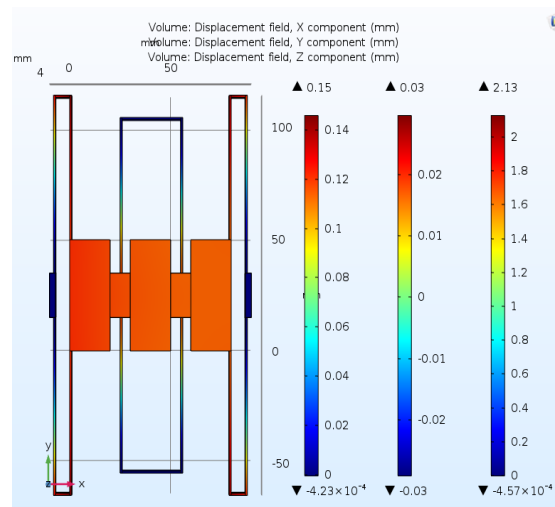


Fig. 3 Simulation results of folded beam and lateral beam area changes capacitive accelerometer

Fig. 3 shows simulation results for area changed capacitive accelerometer for acceleration $g=50$. The displacement in principle X- axis direction is 2.13 mm and other two minor axis displacements in Y,Z are 0.03 mm, 0.15 mm. The cross axis sensitivity is less than 7.01% in major axis. From the past research [12] the cross axis sensitivity is less for very high acceleration $g=50$. The natural frequency obtained is 19.292 Hz and the principal axis displacement is 2.13 mm for $g=50$. All the theoretical values are nearly equal to the simulated values. The geometrical parameters for the designed devices are given in Table 1.

Table 1 Geometries for proposed area changed accelerometer

Symbol	Parameter	Value
$W_f b$	Folded Beam width	1mm
$L_f b$	Folded Beam length	80 mm
t_{fb}	Beam thickness	5 mm
W_m	Mass width	80 mm
L_m	Mass length	50 mm
do	Air gap between proof mass and substrate	1 mm
W_{lb}	Lateral Beam width	1 mm
L_{lb}	Lateral beam length	70mm
t_{lb}	Lateral beam thickness	5mm

For the required frequency authors just use COMSOL multiphysics software after those authors validate the results with theoretical values also.

3.3 Displacement Analysis

By Applying the force on parallel plates the displacement is obtained in X, Y, Z-axis. The range of acceleration is from [0g-50g] .Top plate is fixed, bottom surface is movable. Whenever we apply the force on the structure bottom surface is moved. Depending on the applied forces for various accelerations from [0g-50g] various displacements are generated. Whenever the force is varied there is change in displacement on 3 axes but the frequency is not changed.

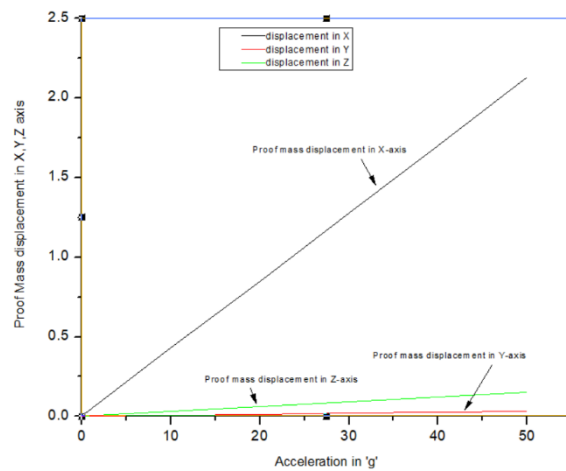


Fig. 4 Acceleration vs Displacement of Proof mass

The Fig. 4 is plotted between the acceleration and proof mass displacement . The acceleration range is [0g-50g]. From the figure 4 it is clear that the principal axis displacement is high when compared to minor axes displacement. The Displacement in Y-axis is 1.40% of X-axis axis displacement and in Z-axis is 7.04% of X- axis displacement. When the acceleration is increases the displacement of Proof mass is increased in Major axis direction

3.4 Capacitive Analysis

The capacitance is generated between the parallel plates. In the proposed structure the bottom surface is movable and top electrodes are fixed. Upon the application of force the bottom surface is moved then the capacitance is generated .Calculation of capacitance depends on overlapping length, width and gap between the electrodes .When two plates are nearer to each other even if there is no acceleration between the plates the capacitance is generated which is called Parasitic capacitance. In this work authors concentrated the parasitic capacitance also when calculated the capacitive analysis.

The ideal capacitance [16] is expressed as

$$C_{ideal} = N\epsilon l \left[\frac{w}{d_0} \right] \quad (7)$$

d_0 is the Primary gap between the plates.

Eq. (8) represents the ideal capacitance means we should not consider any acceleration. Generally the capacitance is formed between the plates even if there is no acceleration. For ideal case $C_1=C_2$ because there is no acceleration in ideal case.

The ideal parasitic capacitance is [16] is expressed as

$$C_{p,ideal} = N\epsilon l \left[0.77 + 1.06 \left(\frac{w}{d_0} \right)^{0.25} + \left(\frac{h}{d_0} \right)^{0.50} \right] \quad (8)$$

Eq. (9) represents the ideal parasitic capacitance .when there is a capacitance no doubt the parasitic capacitance is also generated. For ideal case $C_{p1}=C_{p2}$.

All the below capacitance values are calculated whenever the force applied for different accelerations.

$$C_1 = N\epsilon l \left[\frac{w + \Delta w}{d_0 - \Delta d} \right] \quad (9)$$

$$C_2 = N\epsilon l \left[\frac{w - \Delta w}{d_0 - \Delta d} \right] \quad (10)$$

$$C_{p1} = N\epsilon l \left[0.77 + 1.06 \left(\frac{w + \Delta w}{d_0 - \Delta d} \right)^{0.25} + \left(\frac{h}{d_0 - \Delta d} \right)^{0.50} \right] \quad (11)$$

$$C_{p2} = N\epsilon l \left[0.77 + 1.06 \left(\frac{w - \Delta w}{d_0 - \Delta d} \right)^{0.25} + \left(\frac{h}{d_0 - \Delta d} \right)^{0.50} \right] \quad (12)$$

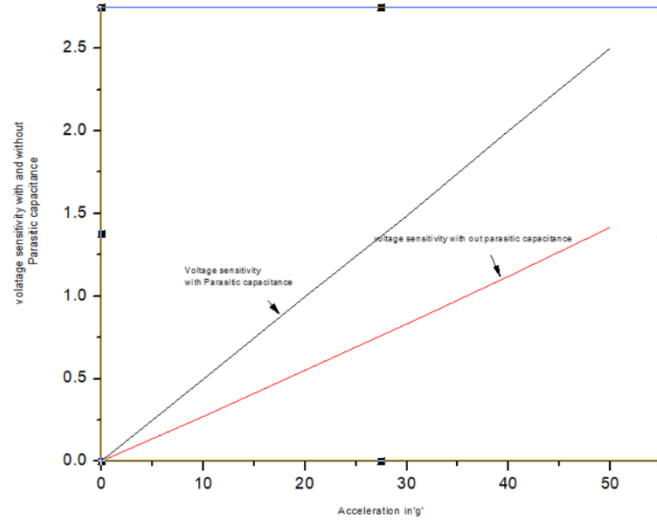


Fig. 5 Acceleration Vs V_0 with and without parasitic effect

Eq. (10), Eq. (11), Eq. (12), Eq. (13) Represents the capacitance

C_1 , C_2 , C_{p1} , C_{p2} . Whenever there is an acceleration then all the above capacitances are generated with different values.

The total capacitance [16] is expressed as

$$C_{total1} = C_{p1} + C_1 \quad (13)$$

$$C_{total2} = C_{p2} + C_2 \quad (14)$$

$$C_{total1,ideal} = C_{p1,ideal} + C_{1,ideal} \quad (15)$$

L =length of the electrode

ϵ =Permittivity of air

N =Number of electrodes

Δw =displacement of the principal axis

Δd =displacement of Z-axis

The above equations represents the total capacitance with and

Without ideal conditions.

The second term in eq.(11- 12) that is

$$\left[\frac{w \pm \Delta w}{d_0 - \Delta d} \right]^{0.5}$$

produces non-linear effect but its effect is very less in case of area changed capacitive accelerometer.

In this work, the authors also present voltage sensitivity, which requires capacitive analysis. Using equations (8-9), authors calculated the ideal capacitance and ideal parasitic capacitance, yielding values of 23.895 pF and 25.209 pF, respectively. Similarly, by applying equations (10-15), authors determined the values of C_1 , C_2 , C_{p1} , C_{p2} , C_{t1} , and C_{t2} , which were found to be 39.825 pF, 13.275 pF, 27.152 pF, 24.118 pF, 66.977 pF, and 37.393 pF, respectively, for $g = 50$. The authors also performed similar calculations for other acceleration values.

3.5 Output voltage sensitivity

The output voltage sensitivity [16] is expressed as

$$V_0 = V_n \left[\frac{(C_1 - C_2) + (C_{p1} - C_{p2})}{(C_1 + C_2) + (C_{p1} + C_{p2})} \right] \quad (16)$$

V_n is applied voltage=5v

$$V_0 = V_n \left[\frac{\Delta C}{\varepsilon C} \right] \quad \text{For ideal case} \quad (17)$$

Authors calculated the output voltage sensitivity by using Eq. (17),Eq. (18) for Normal case and also voltage sensitivity for ideal case . In ideal case parasitic capacitance is not consider.

Output voltage Sensitivity is calculated for different accelerations. By using the capacitance, parasitic capacitance and total capacitance values authors calculated the output voltage sensitivity. For $g=50$ the output voltage sensitivity is 1.417 V .which is very high value for the proposed area changed accelerometer.

The Fig.5 represents the acceleration vs output voltage sensitivity with and without parasitic capacitance. The output voltage sensitivity with parasitic capacitance is 2.5V. The difference of output voltage sensitivity is small for with and without parasitic capacitance.

3.6 Noise and temperature analysis

Noise plays an important role in smaller devices. To get the required frequency in accelerometers the noise should be as low as possible. The noise depends on several factors like air, liquid molecules etc. The Brownian noise equivalent acceleration (T) in kelvin and damping coefficient (D) are given as [14].

$$\begin{aligned} \text{BNEA} &= \frac{\text{Damping force}}{\text{mass}} \text{ ms}^{-2} / \sqrt{\text{Hz}} \\ &= \frac{\sqrt{4K_bTD}}{9.8 * M_s} \text{ g} / \sqrt{\text{Hz}} \end{aligned} \quad (18)$$

4. Fabrication using Fused deposition modeling (FDM)

Fused deposition modelling (FDM) is influenced by numerous factors. The parameters are separated into two categories: machine and material parameters. The machine parameters are the values that the 3D printer user inserts into the slicing software when creating STL binary files, and the material parameters are the qualities of the filament or materials that will be expelled via the nozzle. The selection of these elements determines the quality and performance of the printed objects. It is important to note that not all printers have a heated bed, and all other materials, including PLA, require heating to connect to the platform. When utilizing a non-heated bed with specified

Where K^b is the Boltzmann constant and M_s is the sensing mass in kg and $K^b = 1.38 * 10^{-23} \text{ m}^2 \text{ kg s}^{-2} \text{ K}^{-1}$

The proposed area changed accelerometer BNEA noise = $0.063 \text{ ng} / \sqrt{\text{Hz}}$. The temperature fluctuations are produced because of thermal stress and Young's modulus of the material. The effect is very low because the structure is like frame structure. Authors using PLA material for capacitive accelerometers. The temperature has no effect up to 170°C materials, it is customary to utilize sticking fluids such as office glue to boost the adhesion of the initial layer of the print. Fig.6 represents the FDM parameters. During printing, set the extrusion temperature to the filament's melting point. During 3D printing it is very much necessary to know the Machine and Material parameters

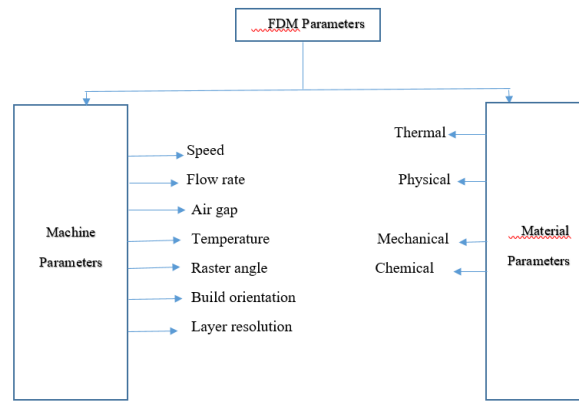


Fig.6 FDM Process parameters

4.1. Flow chart for main stages of FDM

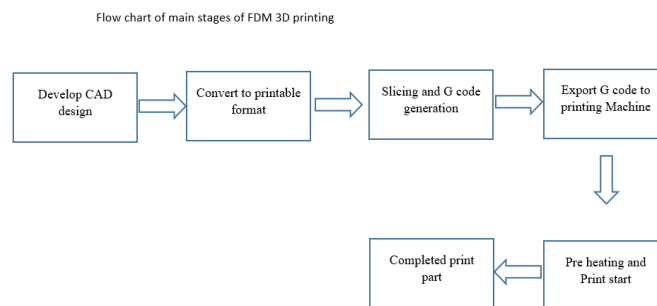


Fig. 7 Flow chart of main stages of FDM 3D printing

The main stages of FDM 3D printing is represented in the above flow chart.

STEP 1: Develop the CAD design [Ex: solid works,Mol 3D,3DX Max etc.]

STEP 2: Convert to the printable format [Ex:STL,OBJ,3MF etc.]

STEP 3: Slicing and G code generation [Ex:Cura,slic3r,123D catch etc.]

STEP 4: Export G-code to Printing Machine

[G-code is the generic name for a control language understandable by the printer]

STEP 5: Pre heating and print start

[Nozzle temperatures PLA=180 to 230 c]

In this structure authors used PLA material and the parameters of the machine and Material are represented in the below tables. For designing any 3D structures these are the first important parameters in FDM technique.Fig.6 represents the Flow chart for main stages

of FDM. Above 5 steps clearly explain the FDM process. Table 2 and Table 3 represents the machine and material parameters.

Table 2: Machine Parameters

S.No	Parameter	Values/Materials
1	Filament diameter	1.75 mm
2	Layer Thickness	0.4 mm
3	Supported Printed Materials	PLA, WOOD, COPPER
4	Build Volume	300 mm×300 mm×400 mm
5	Nozzle diameter	0.2 mm, 0.3 mm, 0.6 mm, 0.8 mm, 1 mm
6	3D printer speed Max	180 mm/s
7	Input voltage VAC	240 V
8	Power	240 W
9.	File input formats	OBJ, STL, G-CODE
10	Printer software	Crealiti 3D
11	Product range	CR series

Table 3 Material Parameters

Property, Test condition	Standard (ASTM)	unit	values
Melt flow index	D1238	gms/10 min	7
Tensile Yield strength	ISO 527-1	psi (MPa)	45

Tensile Modulus	D638	psi(MPa)	3,500
Melting point	D3418	⁰ c	155-170
Glass Transition Teperature	D3418	⁰ c	60
Specific gravity	D792	g/cc	1.24

Authors fabricated the area changed capacitive accelerometer structure using FDM 3D Printing technique. The material used to construct the design is Polylacticacid (PLA).During the printing processes the machine and material parameters are properly chosen. The pictures of the proposed structure in 2 different stages of fabrication namely initial stage and final stage are shown in Fig 8 and Fig 9.While fabricating the structure using FDM technique initially the model is formed in X-Y mode later on in the Z-axis mode to add layer by layer until the desired structure is achieved.

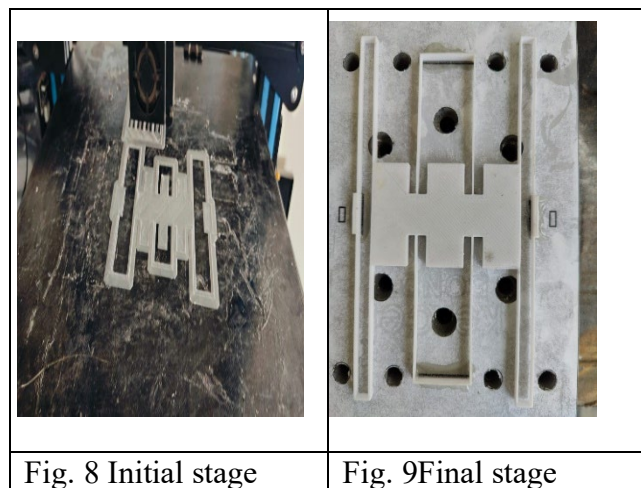


Fig. 8 Initial stage

Fig. 9Final stage

5. Test for Frequency and displacement



Fig.10 Vibration shaker Model :i220 SamsAct Testing Services

Table 4 Vibration shaker Details

Make:IMV,Japan
 Vibration shaker MODEL :i220
 Freq.Range: DC to 3000Hz
 Max.Payload:200kg
 Specimen Mounting Screw Arrangement: M8*16mm (17 no's)
 Rated Force SINE : 8 KN
 Freq.Range: 5Hz to 3000 Hz
 Max.Accln.:1159m/sec² (118 g)
 Max. velocity: 2.2m/sec
 Max.displacement: 51 mm P-P
 Special Specifications with Head Expander (TBV-630S-i20-A,38 Kg):
 Freq.range: 5Hz to 700Hz
 Special Specifications with slip Table (TBH-6-i20-A,45 Kg):
 Freq.range: 5Hz to 2000Hz

Rated Force:8 KN
 Armature Mass: 6.9Kg
 Armature Table Dia:190 mm
 Random: 5.6 KN
 Max. Accln:178 m/sec² (18g)
 Max. Accln:154 m/sec² (15g)

Table 5 Accelerometer Details

SamsAct TestLab Accelerometer details

S.No	Modal No.	Serial No.	Charge sensitivity		Calibrated By	Calibrated Date	Next cal.Due Date	Valid For	Remarks
1	VP-32	1596U	2.94 pC/(m/s ²)	28.76 pC/g	SSPL Cal.Lab	17-Jan-23	16-Jan-25	2 Years	-----
2	VP-32	1597U	2.91pC/(m/s ²)	28.48pC/g	SSPL Cal.Lab	17-Jan-23	16-Jan-25	2 Years	-----

Using the vibration shaker and fabricated accelerometers sample mentioned in the previous section, the authors tested the device for measuring the natural frequency and displacement. The authors used the shaker Table method to assess the performance of the device. Here is the step-by-step procedure followed to measure the frequency and displacement of the structure placed on a vibration shaker:

1. Setup the Experiment: Mount the Structure: Securely place the structure to be tested on the vibration shaker. Attach Accelerometers: Attach accelerometers at appropriate locations on the structure to measure the vibration response (acceleration).

2. Calibrate the equipment: Shaker Calibration: Ensure the vibration shaker is calibrated to apply controlled sinusoidal input at different frequencies.

3. Input Desired Frequency Range: Set the vibration shaker to operate over a specific frequency range (e.g., 15 Hz to 25 Hz). Define the increments at which you will increase the frequency during testing (e.g., increase by 0.1 Hz or 0.2 Hz).

4. Start the Test: Begin vibrating the structure at a low starting frequency. Gradually increase the frequency to span the entire range you want to test. Allow the structure to reach steady-state vibration at each frequency before recording data.

5. Measure Acceleration: As the structure vibrates, the accelerometers will record the acceleration at each frequency step. Use a data acquisition system to capture the acceleration readings.

6. Calculate Displacement: Frequency-Domain Method: Using the relationship between acceleration and displacement in the frequency domain

7. Document Results: Plot the frequency vs. displacement graph to visualize how the structure responds to the vibration. Use the data to draw conclusions about the structure's natural frequency and behavior under vibration.

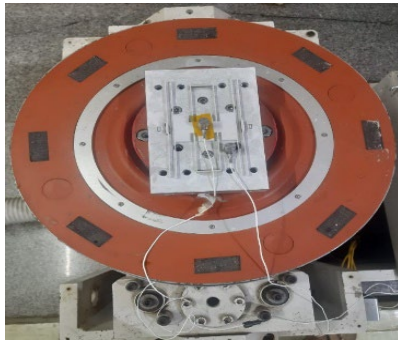


Fig.11 Position of X-axis vibration on the Shaker



Fig.12 Position of Y-axis vibration on the Shaker



Fig.13 Position of Z-axis vibration on the Shaker

Follow the outlined steps to measure and record the frequency-displacement graph along all three axes. The authors applied acceleration ranging from 10g to 50g. Document the results for each axis accordingly. Figures represent the various positions of structure on the shaker during Vibration Process. The 1597U accelerometer serves as the control sensor, while the 1596U acts as the monitoring sensor. The control sensor is connected to the shaker based on the vibration position, while the monitoring sensor is placed on the device. During the experiment, control signals are sent to the shaker from the system, causing it to vibrate. Simultaneously, the monitoring sensor detects variations on the device, and all the measured

values are plotted. Table 4 and Table 5 represents the specifications of vibration shaker and accelerometers. The authors tested the 3D-printed device to determine the natural frequency and displacement across all three axes. The figures 14-24 present the corresponding values and graphs. The frequency and displacement values in the principal axis direction showed an exact match. During the Y-axis test, the shaker was unable to detect movement due to the very low displacement. The shaker can detect displacement up to 0.045 mm, but it is unable to detect any displacement below that threshold. The authors conducted tests within a frequency range of 15 Hz to 25 Hz along the X-axis. A total of 600 cycles were applied for total acceleration level, ranging from 10g to 50g. Figures 14 to 18 illustrate the tested frequency and displacement values along with corresponding graphs. The tested values closely match the simulation results. Fig. 19 represents the frequency and displacement values for $g=50$ on Y-axis direction. The value is almost equal to simulation result values. For the remaining accelerations due to very low displacements the shaker cannot detect the displacement values for the prescribed frequency. Figures 20 to 24 present the tested frequency and displacement values, along with corresponding graphs, for vibration in the Z-direction. The tests were conducted within a frequency range of 18 Hz to 25 Hz, with a total of 420 cycles applied for total acceleration level, ranging from 10g to 50g. The tested values closely match the simulation results. In the figures below, the authors have highlighted the required range for both frequency and displacement using yellow colour.

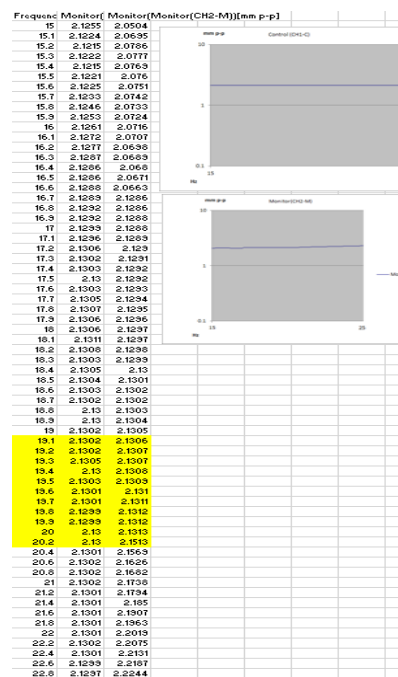


Fig. 14 Frequency vs displacement for $g=50$ on X-axis direction

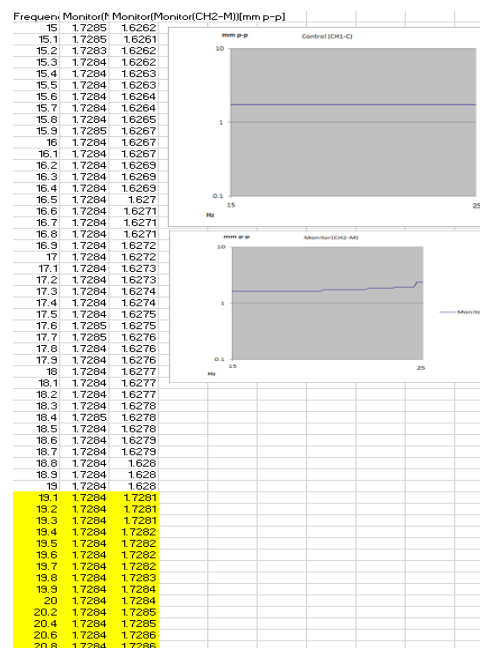


Fig. 15 Frequency vs displacement for $g=40$ on X-axis direction

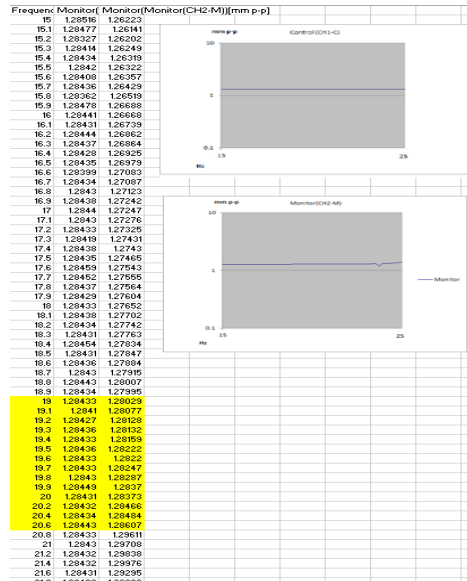


Fig. 16 Frequency Vs displacement for g=30 on X-axis direction

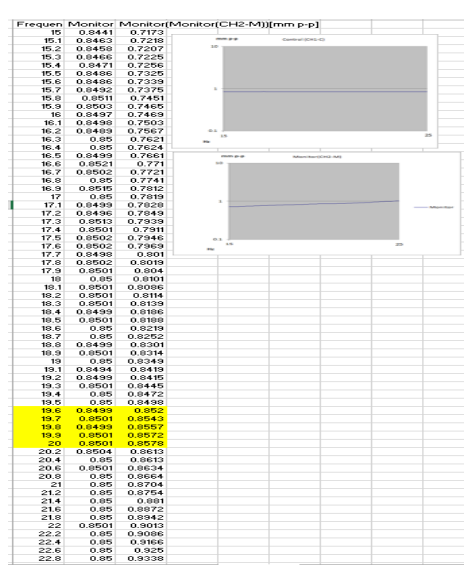


Fig. 17 Frequency Vs displacement for g=20 on X-axis direction

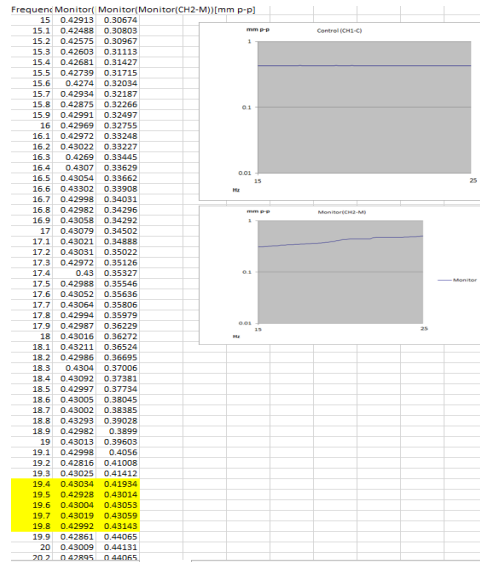


Fig. 18 Frequency Vs displacement for g=10 on X-axis direction

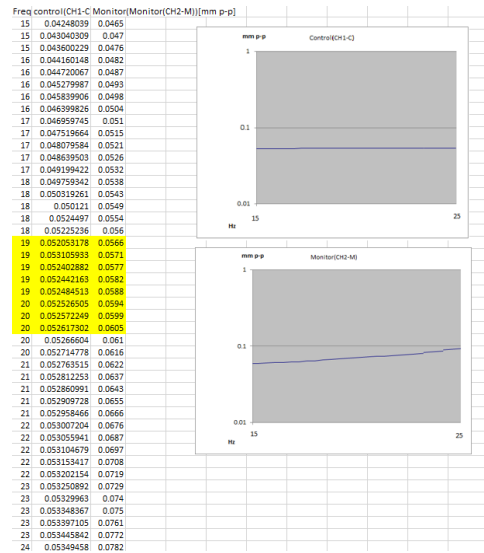


Fig. 19 Frequency Vs displacement for g=50 on Y-axis direction

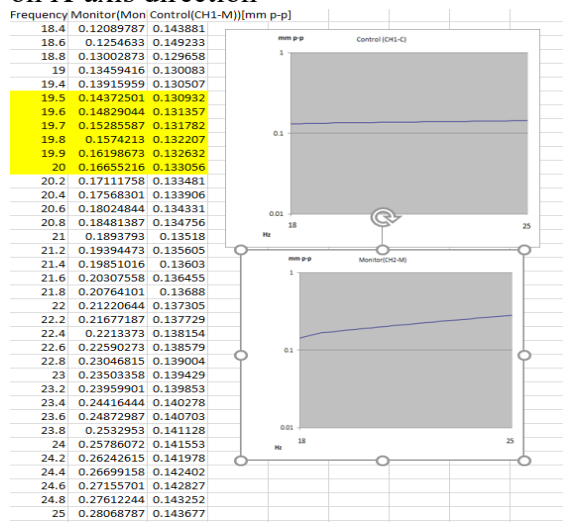


Fig. 20 Frequency Vs displacement for g=50 on Z-axis direction

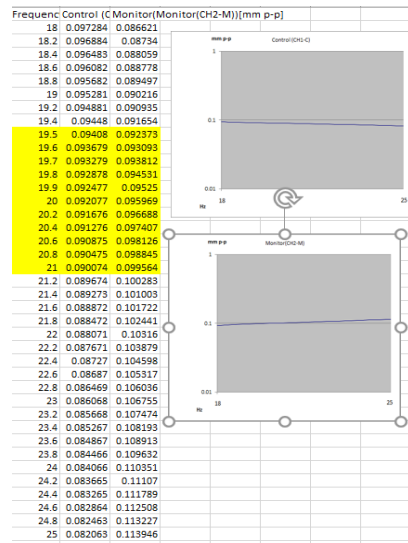


Fig. 21 Frequency Vs displacement for g=40 on Z-axis direction

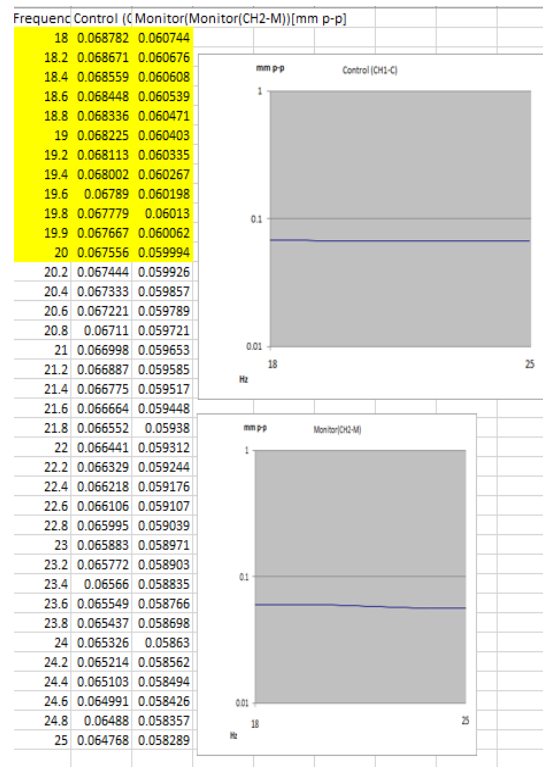


Fig. 22 Frequency Vs displacement for g=30 on Z-axis direction

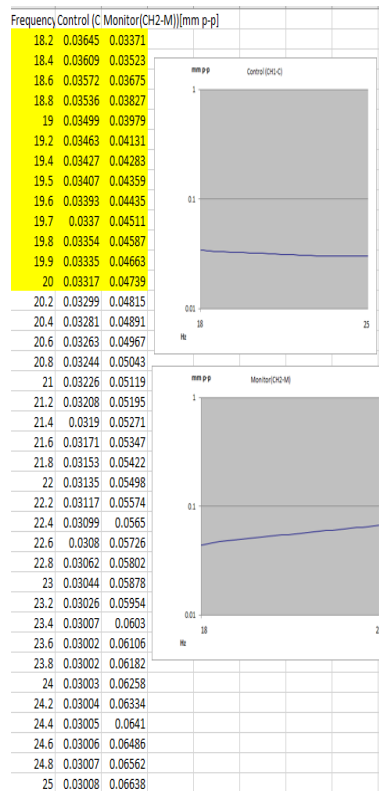


Fig. 23 Frequency Vs displacement for g=20 on Z-axis direction

Fig. 24 Frequency Vs displacement for g=10 on Z-axis direction

6. Conclusions

In this research the authors mainly concentrated to fabricate area changed capacitive accelerometer using FDM 3D printing Technique. FDM is cheap, highly reliable and eco-friendly. The complex structures are also designed very easily. The major requirement for 3D printing technique is each device dimension should be in millimeters. So Authors chose the parameters in millimeters to design the area changed capacitive accelerometer and performed some analysis using COMSOL multiphysics. The results obtained at 50g is as follows displacement=2.13 mm, natural frequency=19.292 Hz, Noise= $0.63 \text{ ng} / \sqrt{\text{Hz}}$, and voltage =1.417 V. Less cross axis displacements were very small over the acceleration range of (0g-50g). The device was initially analysed for frequency and displacement using FEA simulation technique in all the three directions and later using the shaker table method for 3D printed device. The results closely matched with the simulation outcomes. All the vibrations tests are conducted at Sams Advanced Climatic Technologies Pvt. Ltd. IDA Patancheru, Hyderabad

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