Control of Undesirable Modal Vibrations of a MEMS-Based Micro-cantilever with Piezoelectric Actuator

By

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FINAL PROJECT REPORT

Submitted to the Electrical & Electronics Engineering Programme
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(Electrical & Electronics Engineering)

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CERTIFICATION OF APPROVAL

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Approved:

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UNIVERSITI TEKNOLOGI PETRONAS
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May 2011

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

Nur Fatih binti Zulkarnain

ABSTRACT

The project proposes that the undesirable modal of a MEMS-based-micro-cantilever can be controlled with the existence of piezoelectric actuator. By adding a piezoelectric layer, which is PZT at the near end of the fixed micro-cantilever beam, we are able to eliminate the unwanted vibrations of the micro-cantilever, and so that the cantilever will deflect accordingly to the desired mode of vibration. The design and the lumped parameter modeling of the micro-cantilever are derived in order to obtain its axial and bending resonant frequency. Thus this will enables the first modal frequency to be obtained. Simulations by using CoventorWare are included in this project in order to further display the design scheme.

ACKNOWLEDGEMENTS

With my sincere appreciation, I would like to express my utmost gratitude to my supervisor, Dr. John Ojur Dennis for her detailed and constructive comments along with continuous help, support, motivation and guidance from the initial to the final level of the project.

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CHAPTER 1
INTRODUCTION

1.1 Background of Study

The wide usage of MEMS (micro-electro-mechanical systems) based devices in the modern technology, whether it is in the biological or non-biological applications. One of the basic MEMS devices is micro-cantilever which has been used in Atomic Force Microscopy. Even though the device is widely used nowadays, there are still some issues with the micro-cantilever. One of them is unequal bending of the beam. Frank [1] stated that it is important to study the active vibration control for micro-cantilever that produced undesirable vibrations. He found that these undesirable vibrations will certainly limit the performance of the atomic force microscope. Piezoelectric elements attached to micro-cantilever will received the applied vibrating signal in order to reduce the unwanted vibrations. Piezoelectric actuators have the ability to convert electrical energy into mechanical energy efficiently. Egusa et al [2] proposed in the journal that PZT films and ZnO films is to be considered under micron magnitude.

1.2 Problem Statement

To investigate the vibrations of the micro-cantilever beam in order to improve its performance and to be able to control or at least to reduce the undesirable modal vibrations of MEMS based micro-cantilever by adding piezoelectric actuator layers at in the micro-cantilever.

1.3 Objectives and Scope of Study

The main objectives of this study are to:

- Derive the lumped parameter modeling equation
- Study the vibration of micro-cantilever beam in MEMS and minimizes the undesirable vibration.
- Obtaining the micro-cantilever bending resonance frequency.
- Simulate the control effects of the piezoelectric actuator with CoventorWare

In this research, the scope of study will be focused on controlling the micro-cantilever at the desired modal, either in the first mode or in the second mode. It is done by the help of CoventorWare to simulate its control effects

CHAPTER 2
LITERATURE REVIEW

2.1 Material Selections for Micro-Cantilever and Piezoelectric Actuator

Zhang [3] implemented S_iO_2 with 500μm length as the cantilever beam and PZT (Lead Zirconate Titanate) as the piezoelectric actuator in order to show that active vibration control of cantilever beam can be done with the addition of piezoelectric actuator sandwiched at the near fixed end of the cantilever beam. Under micron magnitude, Cunningham et al [4, 10] considered that PZT is more suitable material for piezoelectric actuator. He shows that the equivalent bending moment of the piezoelectric layer is approximately 160 times greater using PZT compared with PVDF. And this is because of PZT has higher piezoelectric charge constant and Young's modulus of piezoelectric. Mahmoodi et al [5] studied the nonlinear vibration of microcantilever beams actuated by the piezoelectric layer for surface stress sensing of a biological layer deposited on top of the microcantilever. With the addition of a piezoelectric layer of ZnO with the same width, length and half the thickness of silicon microcantilever on its surface, it will produces both parametrically and directly-excited vibrations in the microcantilever. Another two layers of 0.25μm Ti/Au is added on top and beneath of ZnO layer acting as electrodes [6]. And this time, the piezoelectric layer does not cover the entire Si beam and the tip has a smaller width than the rest of the beam. Jian Lu et al [7] comes out with the structure of PZT cantilever which is composed of a SiO_2 structural layer, Platinum/Titanium (Pt/Ti) bottom electrode (Ti was used as adhesion layer between SiO_2 and Pt), PZT film, Ti/Pt/Ti top electrode and a SiO_2 electric passivation layer. The detailed fabrication process can be found in [7]. Takeshi et al [8] fabricated piezoelectric microcantilever using $LaNiO_3$ buffered PZT thin film through MEMS micro fabrication process. They have found that the PZT thin films without $LaNiO_3$ were degraded through the MEMS micro fabrication process. And they managed to come out with the material that can be used to avoid the degradation such as RuO_2, IrO_2, $La_{0.5}Sr_{0.5}CoO_3$, $SrRuO_3$, and $LaNiO_3$ (LNO). Based on the result gained, it proves that the composition in the micro-cantilever beam remained compared to without $LaNiO_3$. It also shows that the piezoelectric transverse constant LNO buffered PZT films are higher than PZT films without LNO.

2.2 Micro-cantilever Beam Design and Mathematical Modeling

Zhang et al [3] design the microcantilever beam using SiO_2 with dimension of 500μm (Length) x 30 μm (Width) x 3 μm (Thick). The material used as the construction for the beam has a Young's modulus value of 107GPa and has a density of 2330kg/m^3. In the research, piezoelectric is made of PZT with dimension of 30 μm (Length) x 30 μm (Width) x 0.5 μm (Thick) and the Young's modulus for the material is 139GPa. The density of the material is 7500kg/m^3 and piezoelectric constant for the material is 123 x 10^{-12} m/V.

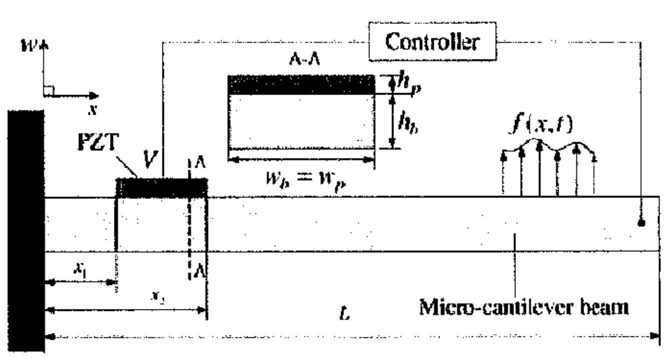


Figure 1: Microcantilever beam model

In this research, the beam is tested with a few different modes which will be at different frequencies to observe the vibration motion of the beam. The position of the piezoelectric on the beam also varies to observe how it can affect the vibration of the beam.

However, in other research done by Cunningham et al [4, 10], they used stainless steel for the cantilever beam and PZT for the piezoelectric. The dimension that been used for the beam is 16mm (Length) x 2mm (Width) x 0.7mm (Thick). At the end of the beam is attached a mirror which is used for optical vibration sensor. In this case, the cantilever is forced into periodic motion at the drive frequency. The strain induced in the cantilever beam will be dependent on the applied frequency.

Figure 2: Design model of cantilever beam

Mahmoodi et al [5, 6] also did a design for microcantilever beam with piezoelectric. The design dimension for the beam is 500 μm (Length) x 55 μm (Width) x 4μm (Thick) and the material used is Silicon. The Young's modulus for the material is 105GPa and the density of the material is 2330kg/m^3. The dimension for piezoelectric is of 375 μm (Length) x 130 μm (Width) x 4 μm (Thick). The material used for the piezoelectric is Zinc Oxide (ZnO). The value for Young's modulus is 104GPa and density of the material is 6390kg/m^3.

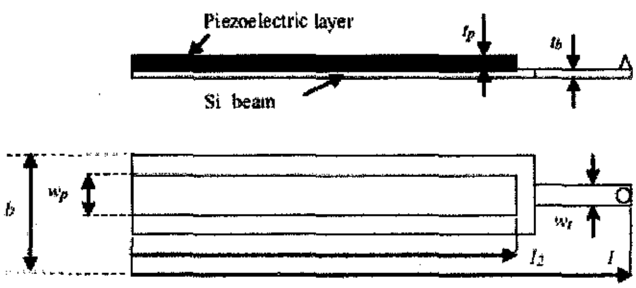


Figure 3: Geometry of the microcantilever beam

For mathematical modeling, Nicolae E. Lobontiu [9] had developed the equation based on each common design that normally used in application. One of the beam configurations that have been developed the mathematical modeling is paddle microcantilever beam.

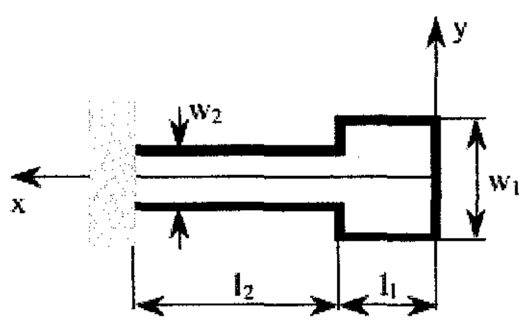


Figure 4: Top view of paddle microcantilever beam

Based on the design shown, they developed the mathematical modeling for yielding and stiffness of the design.

The axial stiffness of the microcantilever is

$$k_{a,e} = \frac{Etw_1w_2}{w_1l_1 + w_2l_1} \tag{1}$$

The lumped mass which is equivalent to the distributed inertia of the axially vibrating microrod is

$$m_{a,e} = \frac{\rho t[w_2 l_2^3 + w_1 l_1 (3l_2^2 + 3l_1 l_2 + l_1^2)]}{3(l_1 + l_2)^2} \tag{2}$$

The axial resonant frequency is

$$w_{a,e} = 1.73(l_1 + l_2)\sqrt{\frac{E(w_1 + w_2)}{\rho(w_1 l_2 + w_2 l_1)[w_2 l_2^3 + w_1 l_1 (3l_2^2 + 3l_1 l_2 + l_1^2)]}} \tag{3}$$

The mechanical moment of inertia, which is equivalent to the inertia corresponding to free torsional vibrations is

$$J_{t,e} = \frac{\rho t[w_2 l_2^3 (w_2^2 + t^2) + w_1 l_1 (w_1^2 + t^2)(3l_2^2 + 3l_1 l_2 + l_1^2)]}{36(l_1 + l_2)^2} \tag{4}$$

The torsional resonant frequency is found to be

$$w_{t,e} = 3.464(l_1 + l_2)t\sqrt{\frac{w_1 w_2 G}{\rho[(w_1 l_2 + w_2 l_1)[w_2 l_2^3 (w_2^2 + t^2) + w_1 l_1 (w_1^2 + t^2)(3l_2^2 + 3l_1 l_2 + l_1^2)]}} \tag{5}$$

The bending stiffness is

$$k_{b,e} = \frac{Et^3 w_1 w_2}{4[w_2 l_1^3 + w_1 l_2 (3l_2^2 + 3l_1 l_2 + l_1^2)} \tag{6}$$

The lumped mass which is located at the free tip is dynamically equivalent to the distribted inertia of the bending vibrating microcantilever is

$$m_{b,e} = \frac{\rho t[w_1 l_1^3(33l_1^4 + 231l_1^3 l_2) + 693l_1^2 l_2^2 + 1155l_1 l_2^3 + 1155l_2^4 + 63(10w_1 + w_2)l_1^2 l_2^5 + 7(20w_1 + 13w_2)l_1 l_2^6 + 33w_2 l_2^7}{140(l_1 + l_2)^6} \tag{7}$$

The bending-related resonant frequency is

$$w_{b,e} = \frac{5.92(l_1 + l_2)^3 t \sqrt{\dfrac{Ew_1 w_2}{\rho[w_2 l_1^3 + w_1 l_2(3l_2^2 + 3l_1 l_2 + l_1^2)}}}{\sqrt{w_1 l_1^3(33l_1^4 + 231l_1^3 l_2) + 693l_1^2 l_2^2 + 1155l_1 l_2^3 + 1155l_2^4 + 63(10w_1 + w_2)l_1^2 l_2^5 + 7(20w_1 + 13w_2)l_1 l_2^6 + 33w_2 l_2^7}} \tag{8}$$

2.3 Adaptive Vibration Control

Zhang et al [3] stated in their research that to control the displacement of microcantilever beam, they design the control system based on the modeling error compensation method by a high gain observer. From there, they can obtain a linearization feedback control for microcantilever beam system with piezoelectric actuator.

Cunningham et al [4, 10] suggest that the vibration can be controlled by covering the entire length of the beam with piezoelectric material and therefore they can make assumption that the effect of the bonding layer is negligible. The bending moment applied to the beam by the actuator is given by:

$$M_{\text{equivalent}} = \frac{h_p h_b (1 + h_p / h_b)}{2\left(1 + \frac{E_p h_p}{E_b h_b}\right)} d_{31} w E_p \Lambda$$

where

$$\Lambda = V / h_p$$

h_p = Piezoelectric height (thickness)

h_b = Microcantilever beam height (thickness)

Ep = Piezoelectric Young's modulus

Eb = Microcantilever Young's modulus

d_{31} = Piezoelectric charge constant

V = Voltage applied

The end displacement of a series may be determined from its physical properties and the exciting voltage [4,10]:

$$\Delta x = \frac{3 d_{31} L^2}{2 h_b^2} V, \quad (9)$$

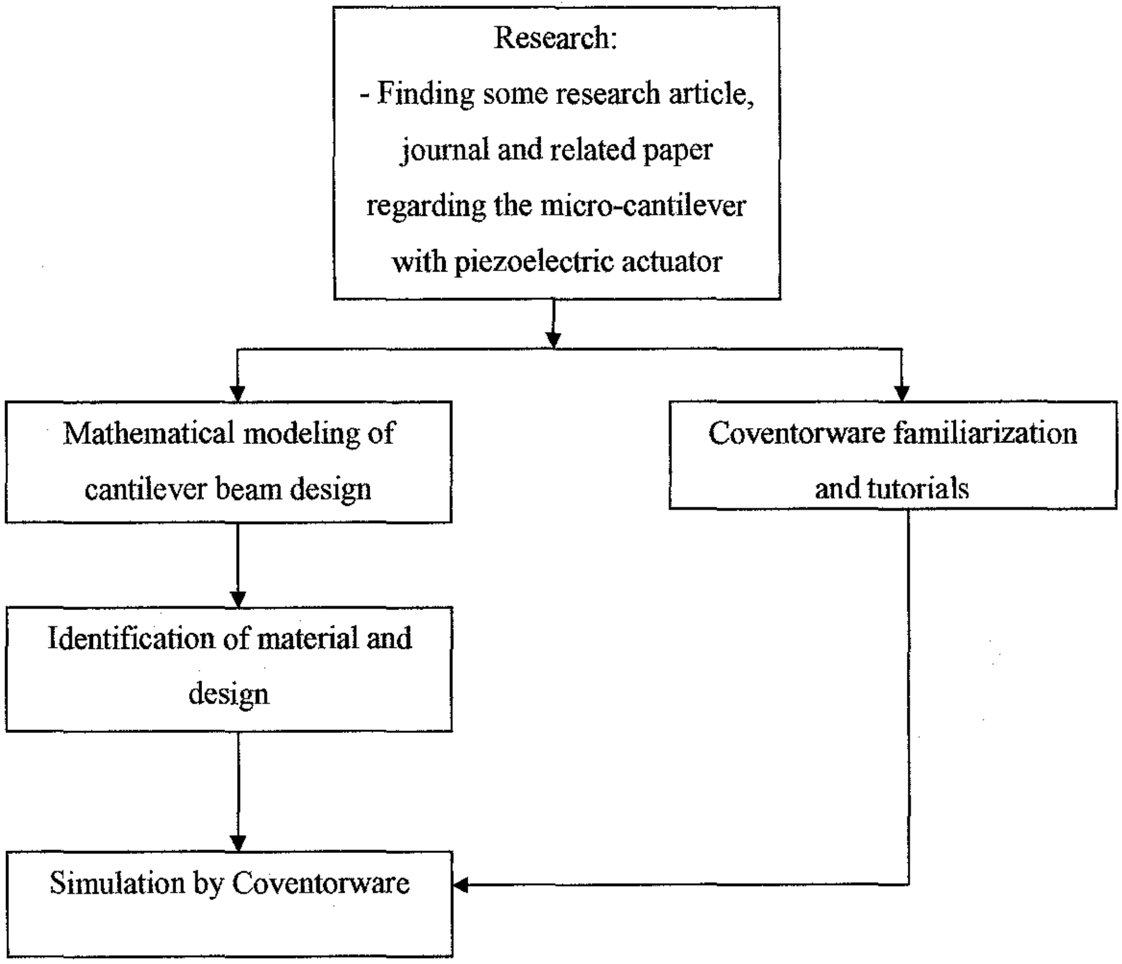
(9)

In their research, they also stated that using analogue signal processing is possible to cancel the dominant induced vibration at the first and second modal of frequencies.

In research done by DFL Jenkins et al [4, 10], they used optical vibration sensing to remove or cancelled the unwanted vibration of the beam while maintaining the ability to deflect the cantilever statically or dynamically as required. There is much type of vibration control strategies to control the vibration of the beam. The simple techniques can be constant gain or variable gain feedback [4, 10]. In this work constant gain feedback was used to control the cantilever's first two transverse modes. When a positioning signal is applied to the piezoelectric film the cantilever is forced into periodic motion at the drive frequency. The strain induced in the cantilever is dependent on the magnitude and frequency of the applied voltage. To monitor the cantilever end displacement, the optical lever effect was used.

CHAPTER 3
METHODOLOGY

3.1 Procedure Identification



3.2 Research Methodology

A further research is done in order to have a better understanding of technology in designing microcantilever beam. Paper and article from other researcher will be studied in order to find all of the option that available to design and choose the right material for the beam and piezoelectric actuator. Once all the data needed from the paper have been collected, this project is preceded to a few steps that need to be done in order to simulate a microcantilever beam with piezoelectric actuator. The process is divided into 4 steps which are:

1. Material selection for microcantilever beam and piezoelectric actuator
2. Design & Dimension of the microcantilever beam
3. Mathematical Modeling
4. CoventorWare software

The progress of this project will follow as the above steps.

3.2.1 Material Selection for Microcantilever beam and Piezoelectric Actuator

Firstly, from the data that has been collected from the research papers. A suitable material will be chosen for the microcantilever beam and piezoelectric. The decision made on the selection is based on the results and the conclusion in research papers. In this project, polysilicon, silica and platinum is selected to be the material for the microcantilever beam and ZnO (Zinc Oxide) will be used for piezoelectric actuator. Once the materials for the beam and the piezoelectric have been selected, the material properties of the selected materials are determined. Then, the project is preceded to selecting design and dimension for the microcantilever beam.

Table 1: Characteristic of the beam material

Materials	Characteristics
Polysilicon	Works as an elastic component for the microcantilever beam bending
Silica	Added as an insulating layer for the beam
ZnO (Zinc Oxide)	Piezoelectric layer. Is a very good material that can convert electrical energy to mechanical energy
Platinum	Acts as an electrode

3.2.2 Design & Dimension of the Microcantilever beam and Piezoelectric Actuator

In this step, the design and the dimension of the beam and also the position of the piezoelectric on the beam is decided. Figure below is the top view of the finalized design.

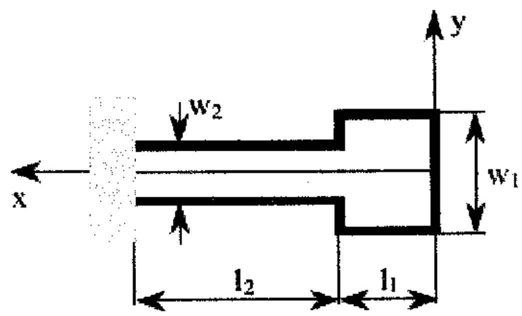


Figure 5: Top view of paddle microcantilever beam

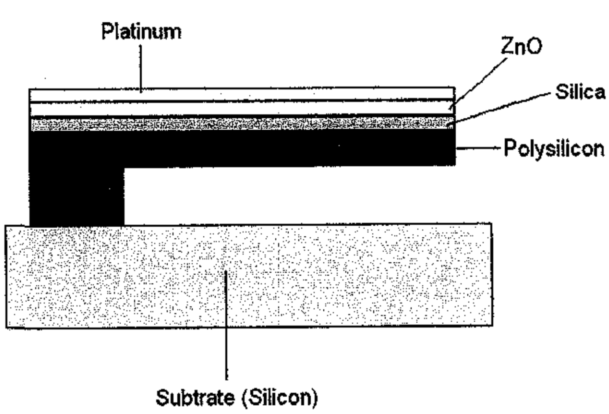


Figure 6: Layer of Microcantilever beam with Piezoelectric actuator

Table 2: Dimensions of Microcantilever Beam and Piezoelectric Actuator

Materials	Length (μm)		Width (μm)		Thickness(μm)
	L1	L2	W1	W2	
ZnO	40		40		1.64
Polysilicon	50	500	100	40	2
Silica	50	500	100	40	2
Platinum	20	500	100	40	0.3
Silicon	550		180		100

Table 3: Density and Young's Modulus for Beam Materials

Property	Polysilicon	Silica	ZnO	Platinum
Young's Modulus E, (GPa)	160	75	104	170
Density (kg/m^3)	2330	2330	6390	21400

Then the finalized design will be transferred to the CoventorWare software in order to simulate the design and observe the performance or vibration of the beam when certain mode is applied on it. Once the designing process is done, the project is moved to the next step which is developing mathematical model.

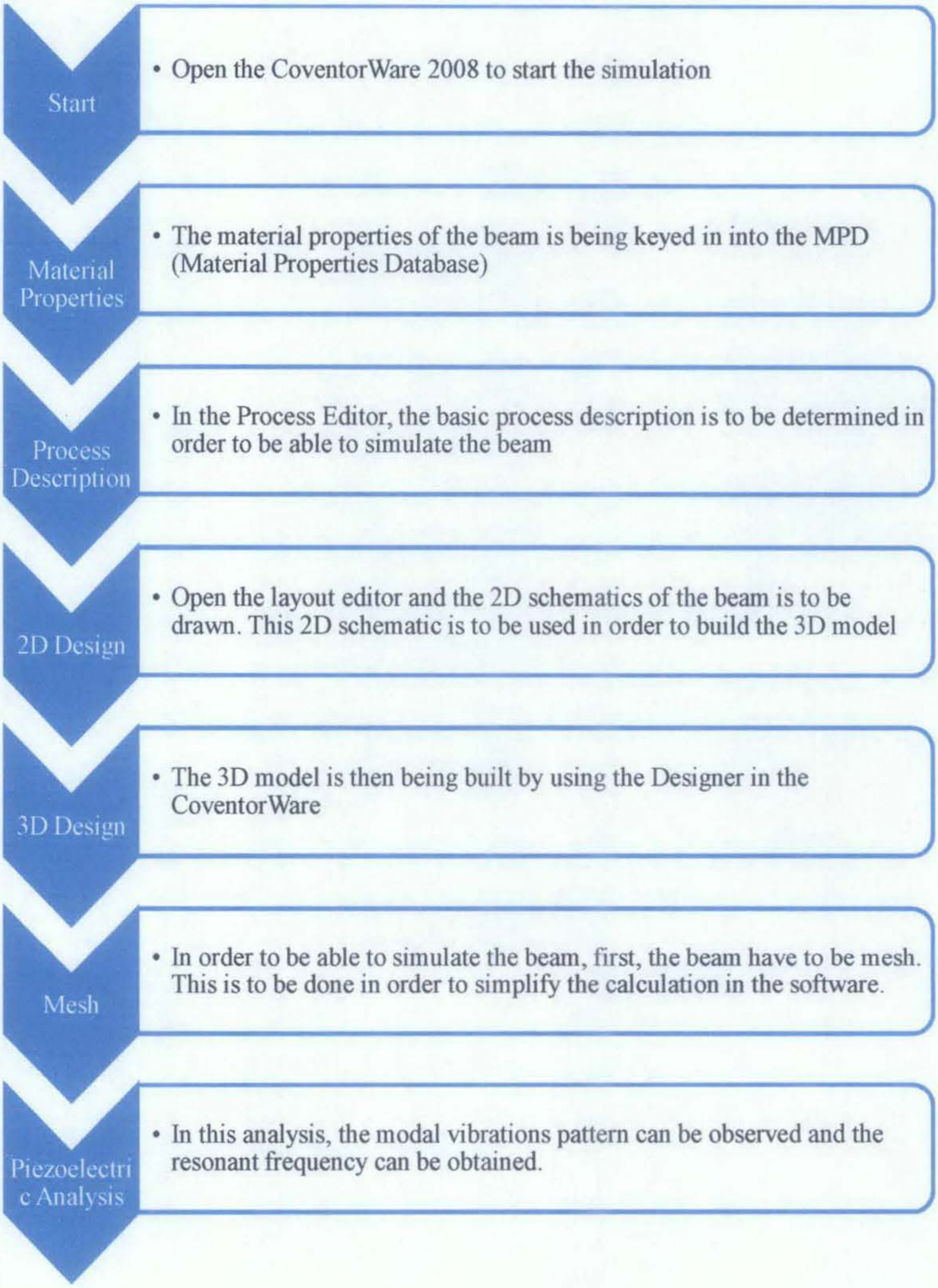
3.2.3 Mathematical Modeling

In order to further investigate the cantilever modeling and design, it is better to recalculate the bending stiffness and getting the bending-related resonant frequency with the aid of MATLAB. Equation (6) and (8) are therefore being used and the MATLAB script can be referred in Appendix I

All the important parameters that are to obtained in equation (6) and (8) can be obtained from Table 2 and Table 3.

Other than that, the end displacement is also being calculated by using equation (9).

3.2.4 Design Simulation in CoventorWare Software



The detail fabrication processes are as follow:

- On the wafer substrate (Silicon), the BPSG is deposited and then small part of it is being etched in order to allow Polysilicon to be deposited. This polusilicon acts as an achor.
- After that, the polysilicon layer is being deposited as the cantilever beam. Then the process follows with Silica, ZnO and lastly the Platinum layer.
- Then the BPSG layer underneath the Polysilicon layer is being removed and the desired model for the cantilever beam is obtained.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 CoventorWare Simulations

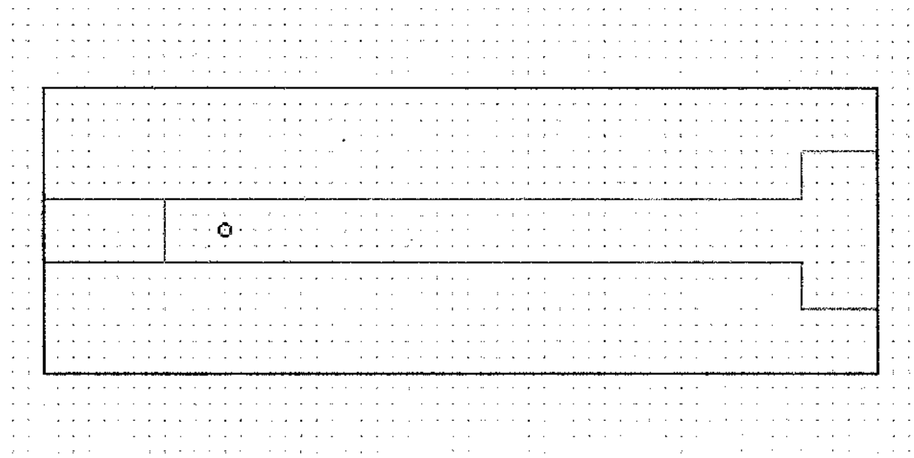


Figure 7: Layout of the Microcantilever Beam

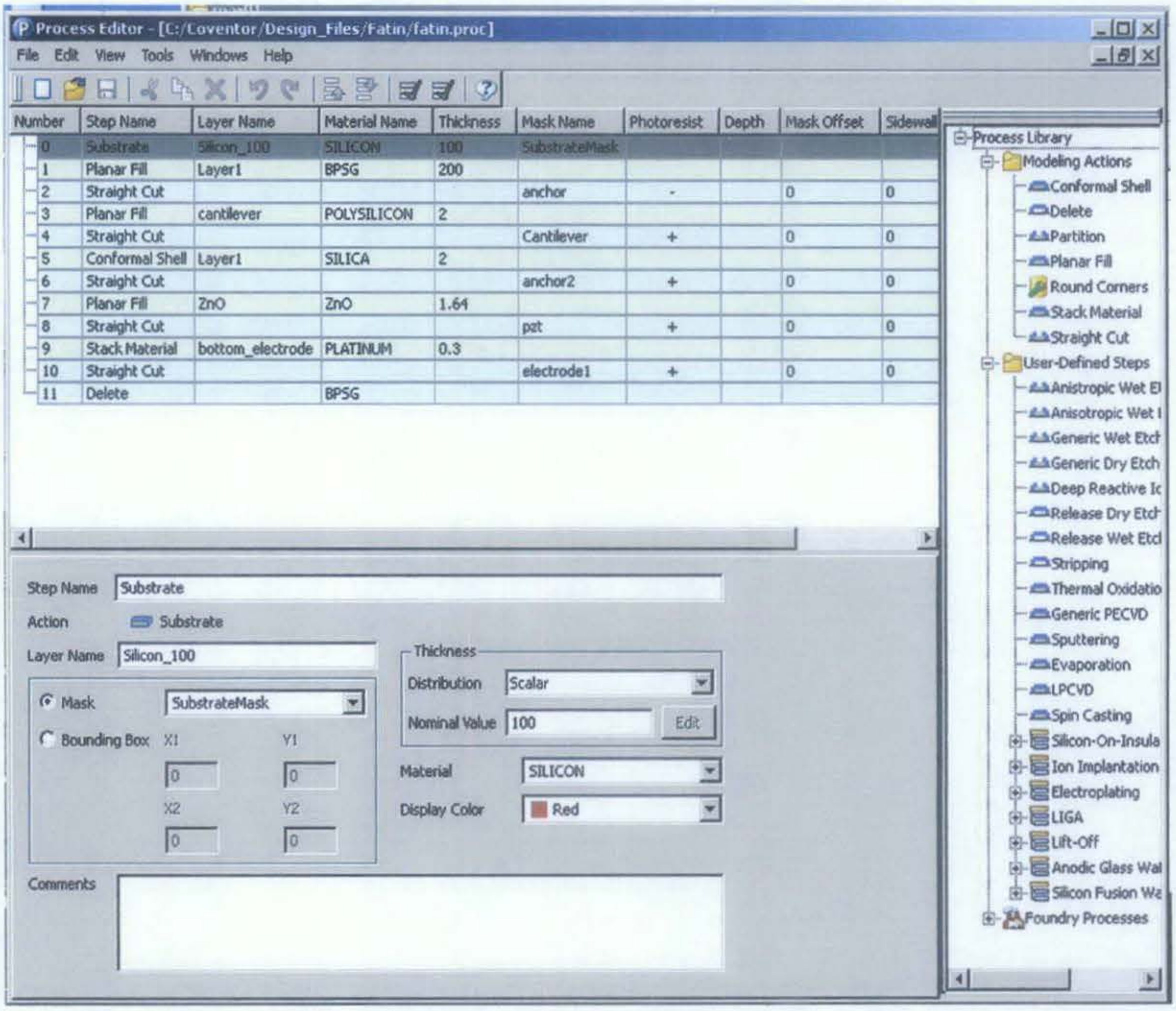


Figure 8: Process Editor for Fabrication Process

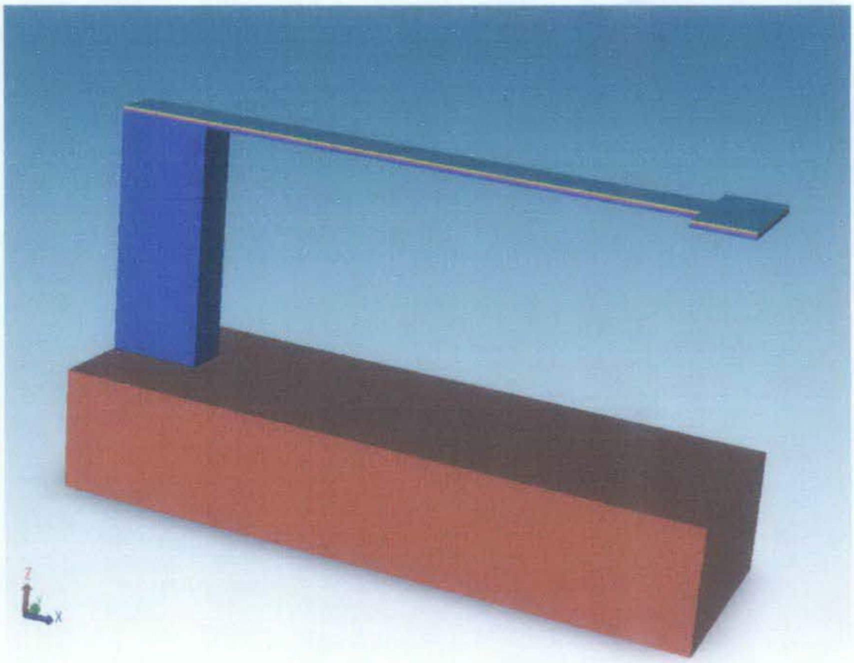


Figure 9: 3D Model of Microcantilever Beam in CoventorWare

Figure 10: 3D Model Showing Layers of Cantilever Beam

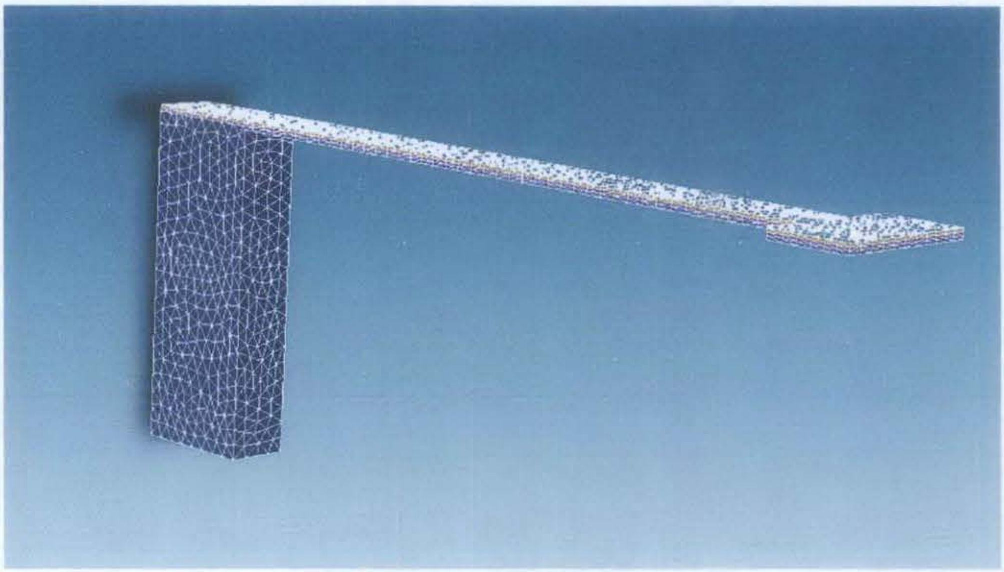


Figure 11: 3D Mesh Model

The meshing is being done by using Tetrahedrons as the mesh type and the element size is chosen to be 10. It is easier to use Tetrahedron meshing type due to it can be used for most of the calculation in CoventorWare.

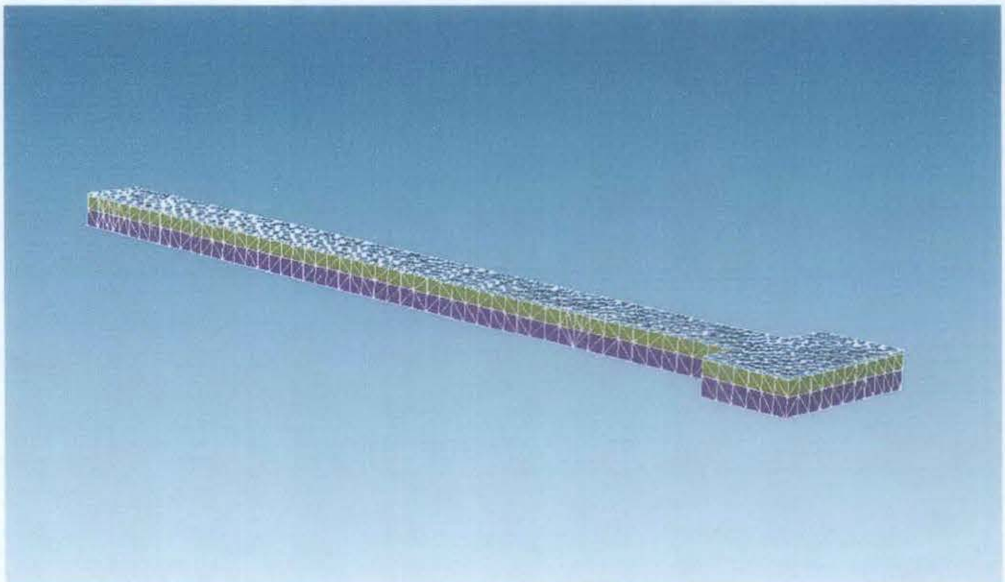
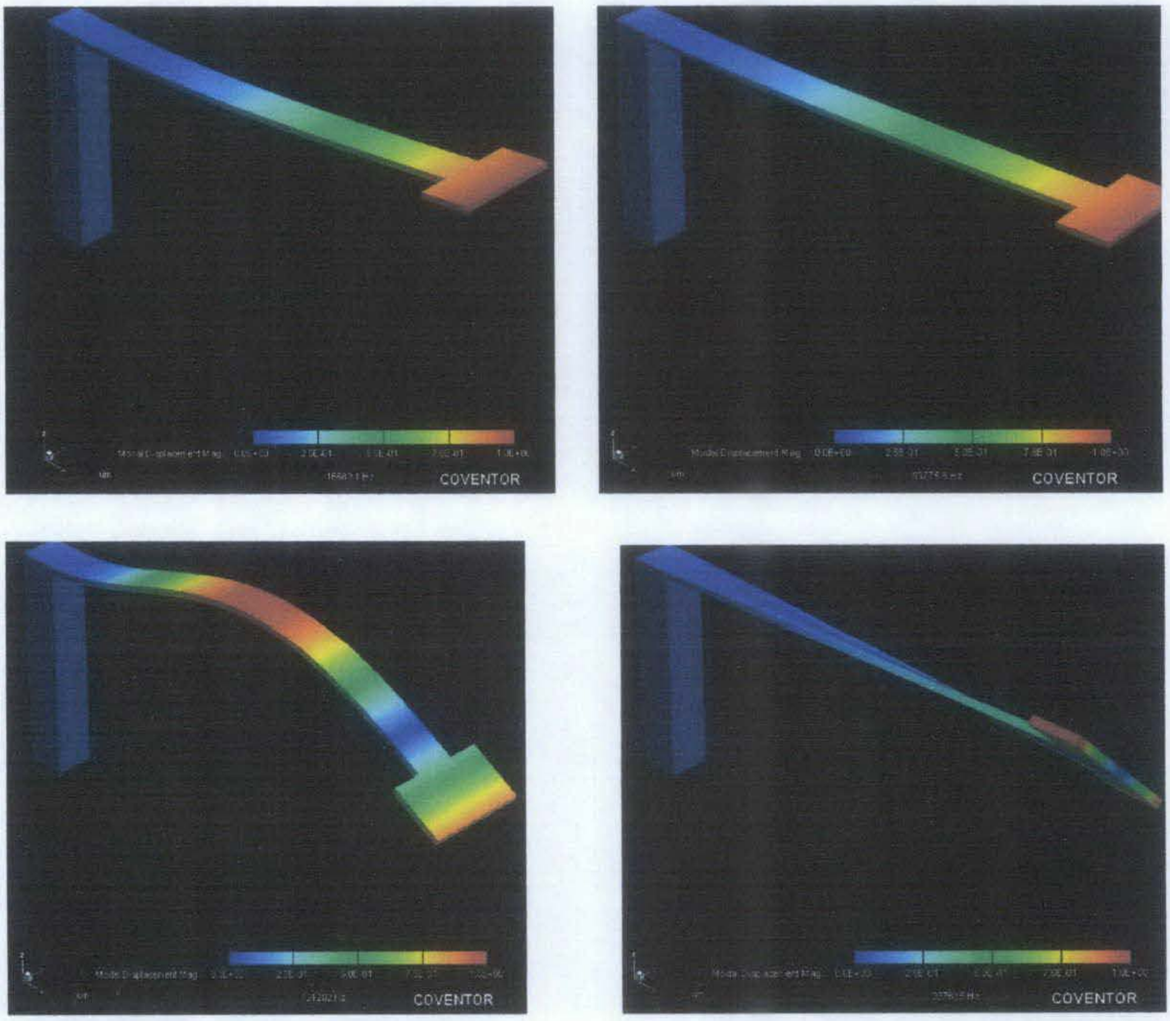


Figure 12: 3D Mesh Model with Scala 5

Table 4: Displacement of the Cantilever Beam in Piezoelectric Analysis

	Max	Min
Node displacement	0.229335	3.13E-45
Node displacement X	0.004305292	-0.000900666
Node displacement Y	0.00036264	-0.000470077
Node displacement Z	1.77768E-05	-0.2292951

Table 4 shows all the displacement type there is in the piezoelectric analysis. The CoventorWare is capable of calculating all type of node displacement. Later, the percentage difference between the simulation node displacement x and the calculated x-displacement will be calculated and compared.



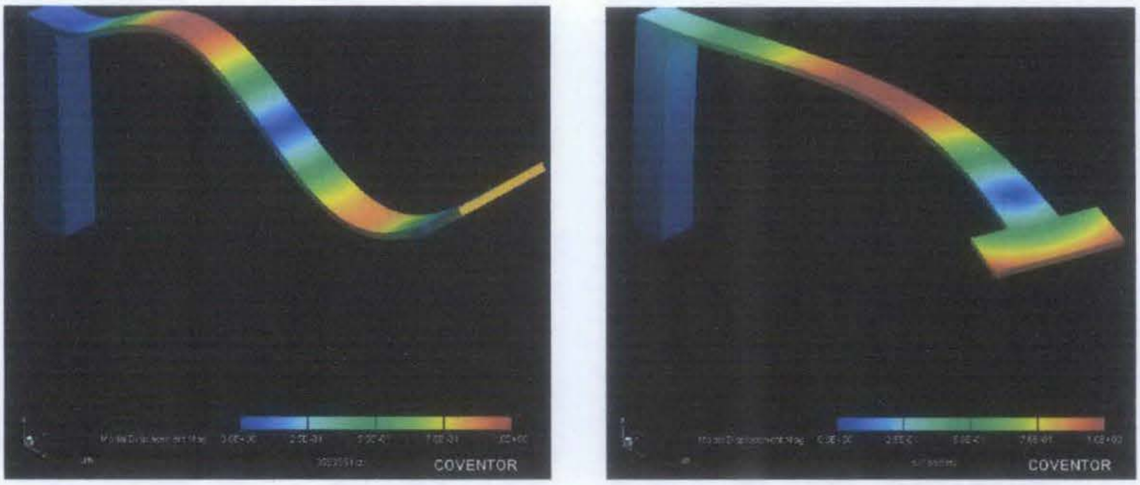


Figure 13: 6-Modes of Piezoelectric Modal Analysis

Table 5: Node Displacement for Different Voltage Applied to Piezoelectric

Voltage	Node Dis Max	Node Dis Min	Node X Dis Max	Node X Dis Min	Node Y Dis Max	Node Y Dis Min	Node Z Dis Max	Node Z Dis Min
0	0	0	0	0	0	0	0	0
3	0.2293358	3.1334E-45	0.004305292	-0.000900666	0.00036264	-0.000470077	1.77768E-05	-0.2292951
30	2.294049	1.46053E-42	0.03706606	-0.01513442	0.0036564	-0.00464909	0.000177777	-2.293748

From Table 5, we will plot the graph that is shown in Figure 14. The graph shows that when there is no voltage applied to the piezoelectric actuator, node displacement will not occur. And as we increase the voltage, the higher the node displacement will be.

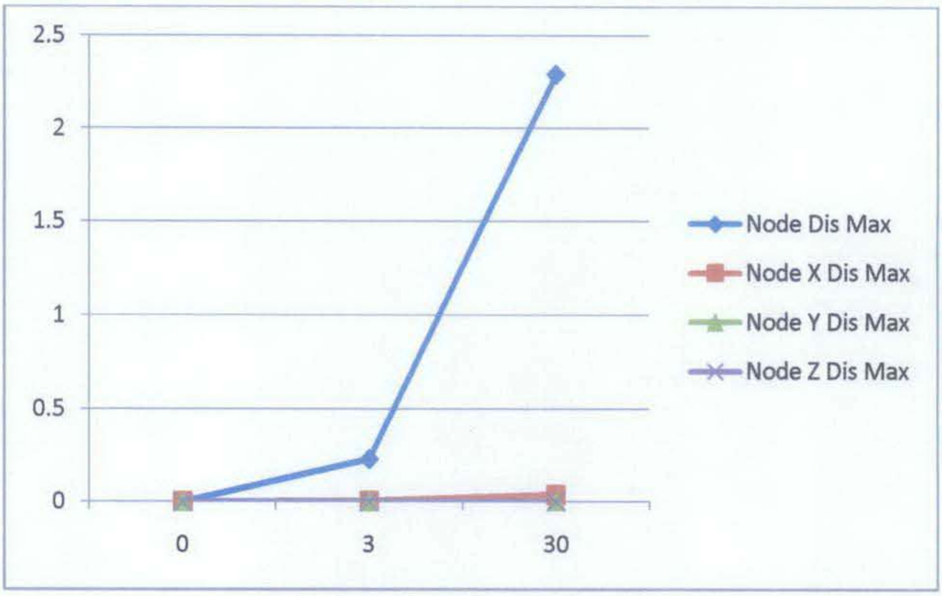


Figure 14: Graph Voltage vs Maximum Displacement

Table 6: Mode 1 and Mode 2 Resonant Frequency with Different Applied Voltage

Voltage	Mode 1 Frequency	Mode 1 Generalized Mass	Mode 2 Frequency	Mode 2 Generalized Mass
0	1.77E+04	1.89258E-10	9.35E+04	0.000935426
3	1.67E+03	1.87665E-10	9.38E+04	0.000937758
30	-1	-1	9.25E+04	0.000925095

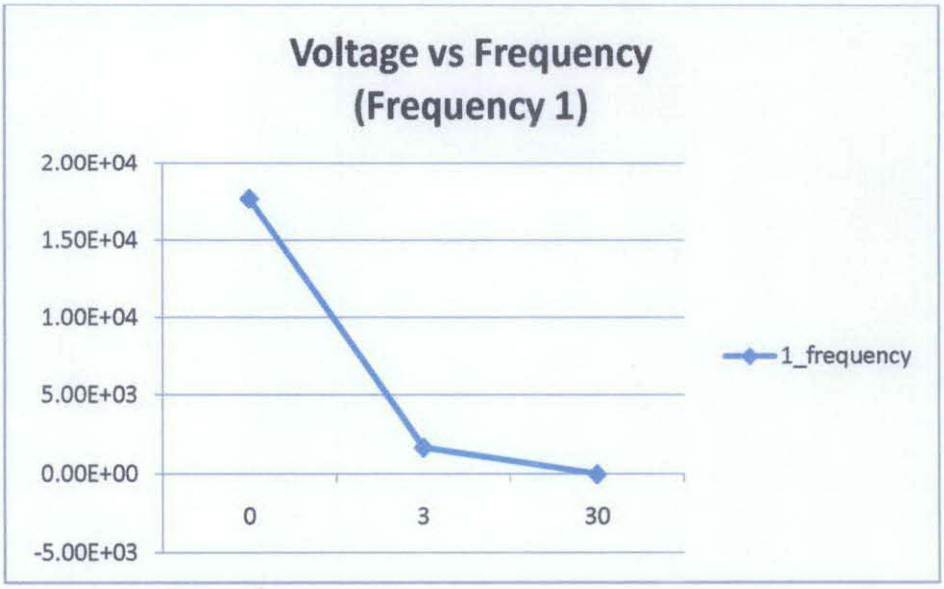


Figure 15: Graph Voltage vs Frequency for Mode 1

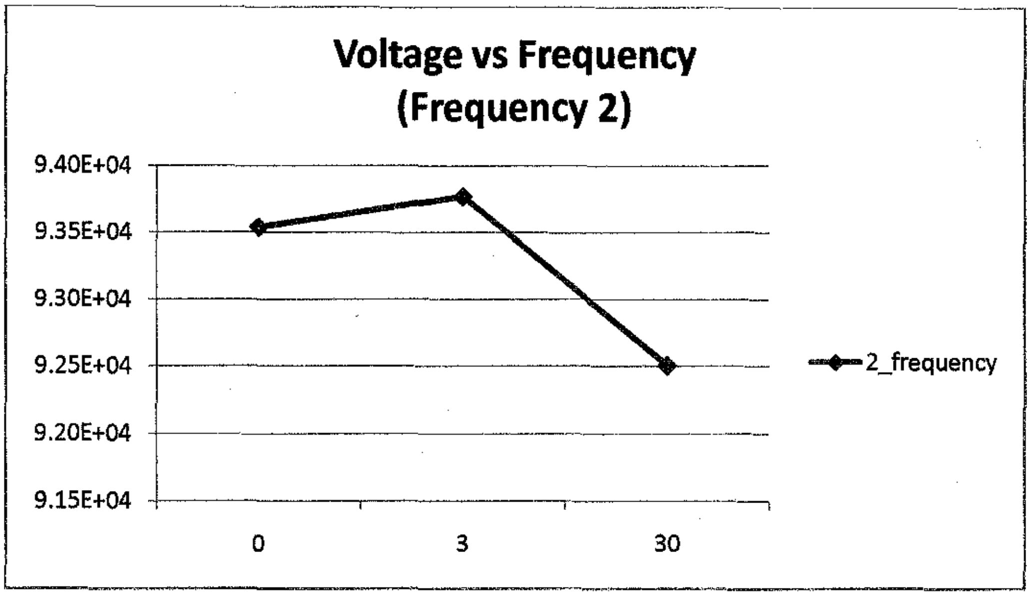


Figure 16: Graph Voltage vs Frequency for Mode 2

4.2 Mathematical Modeling

To further investigate on the cantilever beam modeling, the stiffness of the beam, the bending resonant frequency and also the end displacement is being calculated with the aid of MATLAB. And the MATLAB script is included in the Appendix I.

4.2.1 Stiffness of the Beam

Based on the equation provided above, which is equation (6), the stiffness of the beam can be calculated. And the beam stiffness is found to be k = 0.7969

4.2.2 Bending Resonant Frequency

After being calculated, the bending resonant frequency obtain is 1500 Hz

4.2.3 The End Displacement

For the end displacement, we are calculating the x-axis end displacement. Therefore the value is 4.2×10^{-3}

Table 7: Percentage Difference between Simulated Resonant Frequency and Calculated Resonant Frequency

Simulated Values	Calculated Values	Percentage Difference
1668 Hz	1500 Hz	11.2 %

Table 8: Percentage Difference between Simulated Displacement and Calculated Displacement

Simulated Values	Calculated Values	Percentage Difference
4.305×10^{-3}	4.2×10^{-3}	2.5 %

CHAPTER 5
CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This research is important in context of improving the stability of the MEMS devices which in this case is the micro-cantilever beam. By using the simulation software, the resonant frequency will be obtained and the factors that control the vibration of the beam can be known. Therefore, a better control of the MEMS based micro-cantilever beam can be produced in the future.

In order to complete this project, my main priority was to do more on research work to get to understand my project. The research was being done to learn more on the MEMS micro-cantilever beam, piezoelectric actuator, the derivation of the mathematical modeling and also the effect of different beam design on this specific project. Other than that, it is also vital to get familiarized with Coventorware software on the beam design in analyzer. Later, the finalized design for the beam and its mathematical modeling will be derived. Finally, the design is being simulate with the aid of CoventorWare.

From the results obtain by both the CoventorWare simulation and also MATLAB, it is possible to get the resonant frequency for Mode 1. By getting the resonant frequency and calculating the end displacement of the cantilever, it is possible to control the mode 1 vibration of the cantilever. The resonant frequency is 1500Hz.

5.2 Recommendations

Due to the limitations of time, not all the desired design is able to be obtained. A few recommendations that can be taken into consideration in order to proceed with this project:

- Further derivation of the mathematical modeling, in order to get Mode 2 calculated resonant frequency and end displacement, so that it is possible to compare with the simulation result
- Variation of the cantilever length and also the voltage applied to the piezoelectric actuator can be done in order to get the most suitable resonant frequency for both the mode 1 and mode 2.

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APPENDICES

APPENDIX I

MATLAB SCRIPT

```
%dimension

L1=50;
L2=500;
W1=100;
W2=40;

t_Poly=2e-6;

d_Poly=2330;

e_Poly=160;

piezo_charge=160e-12;

voltage_applied=3;

%Stiffness of Beam

Top=e_Poly*t_Poly^3*W1*W2
Bottom1=(3*L1^2)+(3*L1*L2)+(L1^2)
Bottom2=W1*L2*Bottom1
Bottom3=(W2*L1^3)+Bottom2
Bottom=4*Bottom3
k=Top/Bottom


%Bending related resonant frequency

a=sqrt((t_Poly*W1*W2)/(d_Poly*Bottom3))
a1=5.92*(L1+L2)^3*t_Poly*a
b1=(W1*L1^3)*((33*L1^4)+(231*L1^3*L2))
b2=693*L1^2*L2^2
b3=1155*L1*L2^3
b4=1155*L2^4
b5=63*((10*W1)+W2)*(L1^2*L2^5)
b6=7*((20*W1)+(13*W2))*(L1*L2^6)
b7=33*W2*L2^7
b=sqrt(b1+b2+b3+b4+b5+b6+b7)
bending_freq=a1/b

%displacement

x=3*piezo_charge*L^2
y=2*t_Poly^2
displacement=(x/y)*voltage_applied
```

APPENDIX II

GANTT CHART FOR FYP 1

	Detail\Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Selection of Project Topic								Mid Semester Break							
2	Preliminary Research Work															
3	Submission of Preliminary Report															
4	CoventorWare Familiarization															
5	Project Work															
6	Dynamical Model and Governing Equations															
7	Submission of Progress Report															
8	Seminar 2 (compulsory)															
9	Submission of Interim Report Final Draft															
10	Oral Presentation															

APPENDIX III

GANTT CHART FOR FYP 2

	Detail/Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	**15**
1	Simulation work using CoventorWare															
2	Matlab															
3	Progress Report submission															
4	Pre EDX/Electrex															
5	Draft report submission															
6	Viva															
7	Hardbound submission															