Vibration Analysis of Carbon Nanotube Based Bio-Sensors

By

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Universiti Teknologi PETRONAS
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Perak

CERTIFICATION OF APRROVAL

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A project dissertation submitted to the
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Universiti Teknologi PETRONAS
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(MECHANICAL ENGINEERING)

Approved by,

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(DR. TADIMALLA VVLN RAO)

UNIVERSITI TEKNOLOGI PETRONAS
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JANUARY 2016

CERTIFICATION OF ORIGINALITY

This is to certify that all of the work submitted in this project report regarding this has been undertaken by me and therefore I am wholly responsible for the content of report. Exception applies to acknowledgements and also and also to those of which has been stated in references. The contents of this report has not been conducted by any other unmentioned sources or individuals.

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(SHAATIESH A/L THANARAJEE)

ABSTRACT

This project paper has developed an ANSYS model for structural analysis of Carbon Nanotube (CNT). The vibration pattern response are simulated for six different vibration modes. The change in its mass components are modelled as an added mass that when simulated acts as a unified mass of the nanotube itself. The current researches have studied the response vibration pattern of nanotubes for varying masses at zeptogram level. This is limited as the nanotubes have an astounding range of material properties in relation to its size and if practical application were to be made, it can implemented for uses in masses of higher order. This project emphasizes the vibrational pattern when subjected to loads of different range specifically higher order of mass. To date there is no analysis data for masses above zeptogram. In order to address this issue the paper stresses on the mass order of picogram and slightly higher than that and the response frequency of the nanotubes. The materials necessary for the literature are researched and compiled. This includes the material properties of the carbon nanotubes to be implemented into data for the simulation process. The model is constructed in two different configurations namely cantilevered and bridged. Results are obtained by modelling the nanotube and running structural analysis with the pre-determined properties using the ANSYS software. The vibration of both the configurations are obtained for six different vibration modes which are plotted separately for each mode to determine the pattern of the vibrational behavior of the nanotubes.

ACKNOWLEDGEMENT

First and foremost I would like to express my gratitude to God almighty for his blessings and never ending guidance. Currently I am now at the end of my Final Year Project (FYP) and could not have sailed easily without the spiritual strength I have blessed upon.

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My family has always been my pillar of support since the dawn of my life journey and it has not differed ever since. Without their support and prayers I would not be who I am at this moment.

Last but least, I would like to put it in black and white the appreciation I have for my friends, colleagues, and well-wishers who was always there when I seek them in my needy times. Without their support even the easiest of my times would have been lonely and a tough journey to embark on. Their encouragement has made me sail unaffected through the rough times.

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CHAPTER 1:

INTRODUCTION

1.1 Background Study

The progress regarding mankind over decades has been contributing nothing but a deeper and deeper revelation and understanding of the world which we live. Technological advancements due contribution by great thinkers and scientific minds has enabled mankind to bridge the gap between science and nature and further shorten it over the years. The complex systems that exist as a part of nature and creation which has always made scientist curious are now within our analytical capabilities for us to study and comprehend. Responses in nature (biological forms) can be transmitted into mathematical expressions for the betterment of life quality.

Bio-sensors are devices which can be used to obtain an electrical response from a biological response. Since the discovery of Carbon Nano Tubes (CNT) in 1991 [1], the possibilities of fabricating bio-sensors based on CNT has been an interest scientific minds. This is because of their special structural, electronic and mechanical properties that make them an exceptionally appealing material for an extensive variety of applications [2]. CNTs are basically graphene sheets which are rolled up to a cylindrical from. Cylinders can be chambers of single sheet producing single-walled carbon nanotubes (SWCNT), or distinctive axial barrels of expanding width around a fundamental hub isolated by 0.34 nm as shown in Figure 1. This structure is classified as Multi Walled Carbon Nanotube. [2].

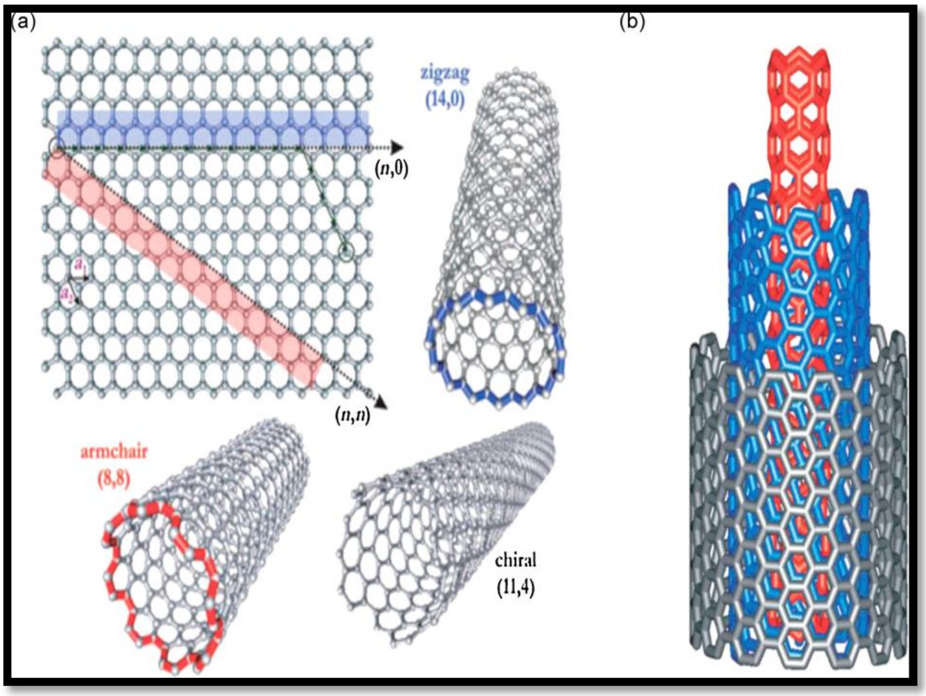


Figure 1: a) Roll up of graphene sheets b) multi walled nanotube structure

The study of the properties and applications of CNTs has tremendously increased [2]. Sensors based on CNTs and graphene have shown incredible performance in electrochemical discovery of metal ions, pesticides and other pollutants. The properties of CNTs, such as fast electron transportation, high thermal conductivity, great mechanical adaptability and great biocompatibility, make it a potential in the creation of sensitive electrochemical biosensor [2].

1.2 Problem Statement

In applications of carbon nanotube based bio-sensors, the sensors function by giving out a resonance frequency as a single unit together with the attached mass. To understand further the principles of these carbon nanotube based bio-sensor, detailed analysis has to be done. In previous studies, analysis has been conducted using the elastic continuum model [3]. This model has been preferred by researchers to study the vibrational behaviour of Carbon Nano Tubes (CNT). The reason being that in order to avoid the complications involving experimental characterizations of nanotubes and also considering the nature of computational atomistic simulation which requires a lot of time [3].

A complete understanding of the behaviours of CNT can only be obtained conducting various experimental an analysis based studies by applying various factors as a variable unit and vice versa.

The existence of Single Wall Carbon Nano Tube (SWCNT), Double Walled Carbon Nano Tube (DWCNT) or Multi Wall Carbon Nano Tube (MWCNT) branches out further. Previous studies on SWCNT focused deriving a non-complex linear estimation for all of non-linear sensor equations. This equation later used used to derive an expression in which the mass of the attached object can be calculated based on shift in the frequency when compared with natural frequency prior to the presence of an attached mass [4].

Whereas for DWCNT, research has been conducted to study the effect in the frequency shift when the length of the outer layer of the DWCNT is kept as a manipulate variable and the inner length as a constant [3]. Other than that, study the shift on the resonance frequency when subjected to attached mass of various size and mass.

The SWCNT has been proved showing a change in frequency when subjected to change in mass by implementing the complex equations that has been derived from previous studies as stated above. This behaviour has been seen when subjected to smaller order of masses. The mechanical properties of these materials allow them to be subjected to a mass at a magnitude higher than the body mass of the tubes. Hence the, frequency pattern needs to studied when subjected to mass change of higher order

1.3 Objective of Study

The main objectives of this project is to:-

- To study the vibrational characteristics of Single Walled Carbon Nanotube when is configured in cantilevered position.
- To study the vibrational characteristics of Single Walled Carbon Nanotube in when is configured in bridged position.

1.4 Scope of Study

This study involves developing a model of Single Wall Carbon Nano Tube in two different configurations. The models will be constructed in cantilevered and bridged configuration using a simulation software. Based on the availability in the institution, ANSYS software will be used for the generating the model and running a simulation. Prior to that necessary material properties will be gathered to be inserted a new material. The results will be later tabulated and analysed in graph to obtain the pattern for of resonance frequency shift. The results serve as reference in zeroing down on the vibrational characteristics of the Carbon Nano Tube based bio-sensor

CHAPTER 2:

LITERATURE REVIEW

2.1 Carbon Nano-Tube

Discovered in 1991, carbon nanotubes successfully created huge movement in various extents of science fields and also fields involving engineering out by virtue of their uncommon physical along with fabricated properties. The unique combination of mechanical, thermal and electronic properties has not been documented as a property of any previous material. All of these together make them perfect for a wide grouping of uses furthermore as an exhibiting ground for central science. Specifically, this blend of properties put together is why they are flawless hopefuls as cutting edge materials as candidate for composite filling. Experts have envisioned investigating their conductivity and high perspective degree to pass on conductive plastics exhibiting extremely low pervasion edges. Meanwhile on a separate domain, researchers feel that their extreme thermal conductivity can be harnessed to produce composites which are heat conductive. Regardless, evidently the most consoling district of composites examination fuses, is the mechanical upgrade where carbon nanotube act as fillers in production of plastics. The considered utilizing pseudo one-dimensional fillers as a propping experts is regardless old thing new. Along with time straw has been utilized to manage mud pieces resulting to around 4000 BC. Moving down the timeline, strands of fibres conveyed materials of relatively high usage, for occasion, alumina, glass, boron, silicon carbide and particularly carbon have been utilized as fillers as a part of composites. On the other hand, these standard strands have estimations on the meso-scale with breadths of numerous microns and lengths of sales of millimetres. Their mechanical properties are preeminent, particularly carbon strands reliably showing solidness and quality in the reaches 230–725 GPa and 1.5–4.8 GPa, independently. Later carbon Nano fibres saw fabrication from vapour stage showing breadths of sales of 100 nm lengths some spot around 20 and 100 lm. These little estimations mean that the carbon nanotubes possess higher surface degree per unit mass compared to routine Carbon strands permitting considerably more obvious correspondence with composite grids.[1]

They additionally incline towards possessing amazing mechanical properties with Young's modulus in the compass 100–1000 GPa. Meanwhile their strengths ranges some place around 2.5 and 3.5 GPa. Despite all of this being said, a conclusive material to be used as mechanical filler has to be carbon nanotubes. Nanotubes' external properties shows widths going from 1 to 100 nm. As for their lengths it can range up to millimetres. As for their densities, stoops as low as 1.3 g/cm3 along with Young's moduli which are better than the existing carbon filaments showing values more conspicuous comparatively to 1 TPa. In any case, their quality is the thing that genuinely sets them isolated. 63Gpa is the highest ever strength quality ever recorded for a carbon nanotube. This is a solicitation of degree more grounded compared to good quality carbon filaments. For sure, even if the selected kind is the weakest among the types of carbon nanotubes, the qualities will range up to a few Gpa. But a great deal of work has to be carried out prior to utilizing the advantages regarded with the unique properties that the material possess. [1] Figure 2 shows the applications of it.

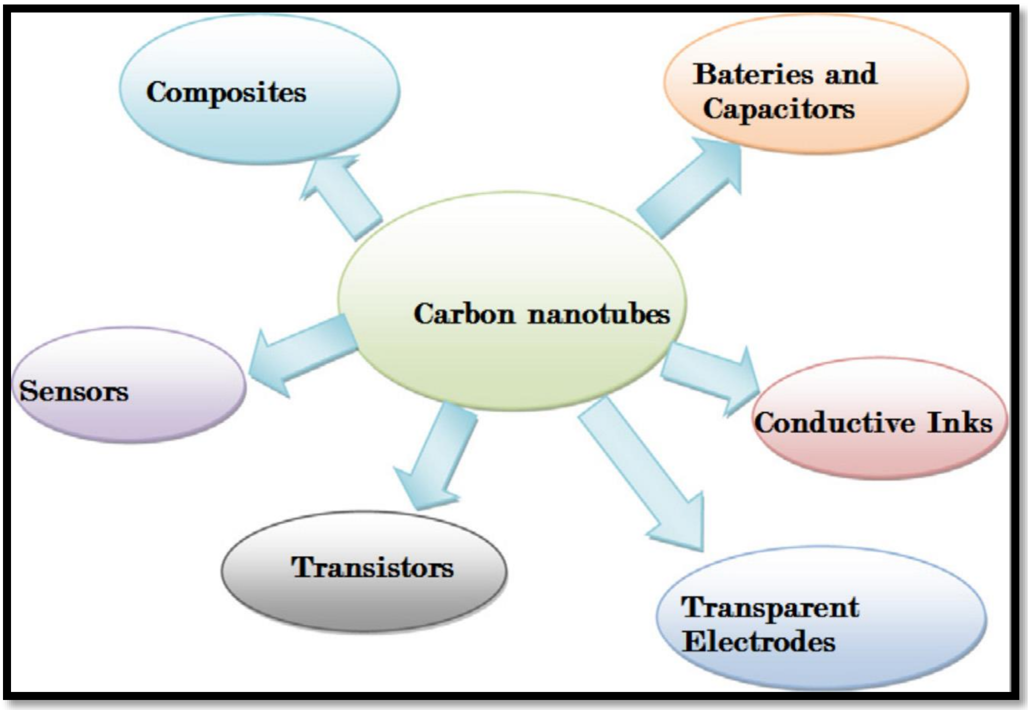


Figure 2: Applications of Carbon Nano-Tubes

2.2 Potential of SWCNT as A Mass Sensor

In this research conducted by, the potential of SWCNT to function as Nano mechanical resonator in nano sized mass sensor was studied. Operating within two assumptions namely, cantilevered and bridged configuration only, continuum mechanics approach was used to develop simple formulas for analysing CNT based Nano resonators. The mass of the biological objects attached were detected using closed wall expression derived from the frequency shift. Following that linear approximations were done for the non-linear sensor equations which were then tested for validity under various cases using finite element (FE) software. Results indicated the sensor equation derived earlier can be used [1].

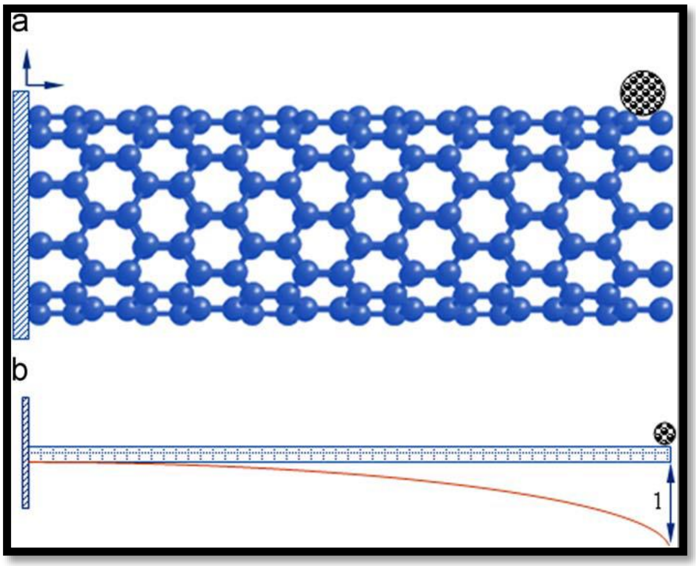


Figure 3: a)Cantilevered nano tube with additional mass at tip. b) Deflection mathematical representation

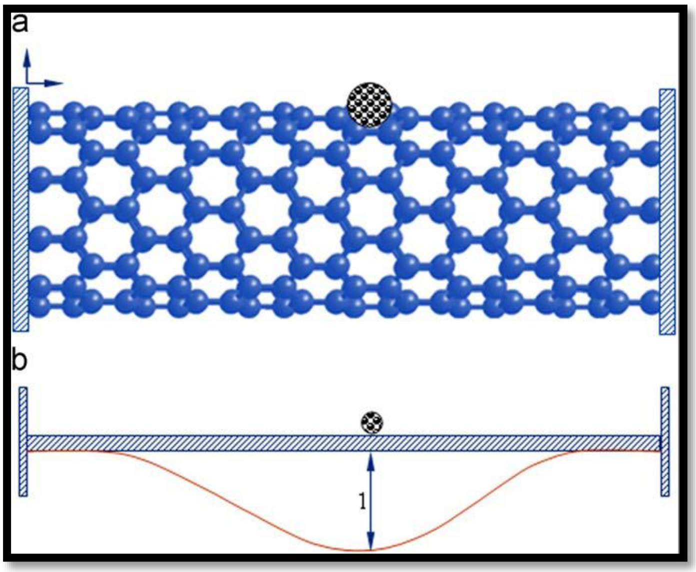


Figure 4: a)Bridged nanotube with additional mass at center. b)Deflection mathematical representation.

Figure 3 and Figure 4 shows the modelling of the tubes in two different configurations namely bridged and cantilevered and the mathematical representation of the respective model.

2.3 Vibrational Characteristics of Double Walled Carbon Nanotubes

In this study, the vibrational characteristics of DWCNT was studied using lumped masses and spring element method. The model developed exhibited the inner and outer wall as two separate beams. The beams were elastic by nature on construction with interaction only by the means of Van Der Walls Forces. The spring elements afore mentioned were incorporated to simulate interlayer interactions. By keeping the length of the inner layer as a constant variable, the length of the outer layer was manipulated and the effects were studied. The shift in resonant frequencies were analysed using analytical and finite element procedure [3]. Figure 5 shows the model of double walled carbon nanotube with the representation of spring element.

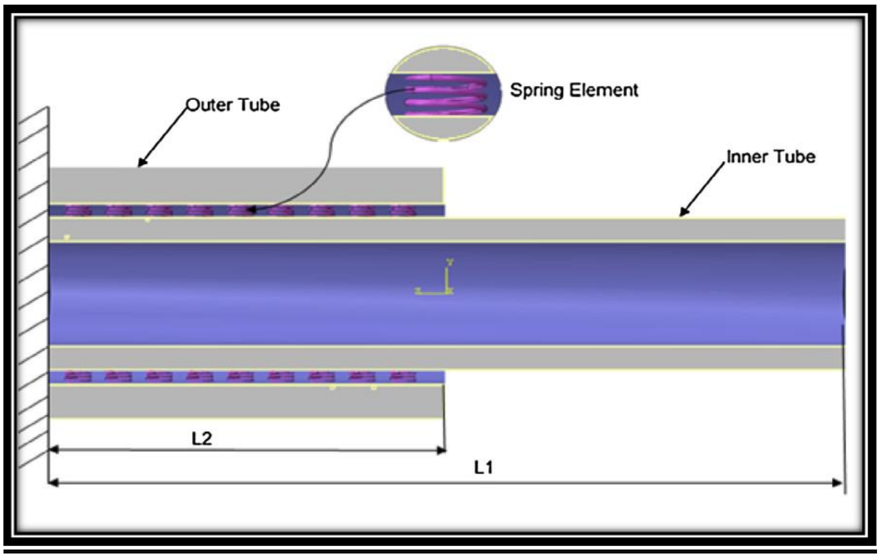


Figure 5: Cantilevered model of Double Wall Carbon Nano Tube

Both cantilevered and bridged models were simulated under the same conditions. The results obtained showed minimum variance when compared with previous researches [3].

2.4 The Characteristics of Mass Sensing Of Double Walled Carbon Nanotubes

This study focussed on analysing the mass sensing characteristics of DWCNT. The interlayer detachment as Van der Waals cooperation is displayed utilizing trademark spring component. The nanotubes internal and external dividers were displayed like adaptable bars comprising of spring segment associating the two layers. For the purpose of investigation to condition were considered namely bridged and cantilever. The study investigates the resounding recurrence movement of Double walled Carbon Nanotubes brought on due to the adjustments in the size as far as length along with the masses. Outcomes demonstrated how the dynamic attributes were affected by the manipulation of length and in addition masses connected with the inside and also at the nanotubes' tip. Results additionally demonstrated the mass sensing abilities ranging till 0.1 Zeptogram basing on Nano equalizations. Moreover, this study also proved fruitful in the applications comprising oscillators along with sensors taking into account Nano electromechanical gadgets with high frequency vibrations up to order of THz. [5].

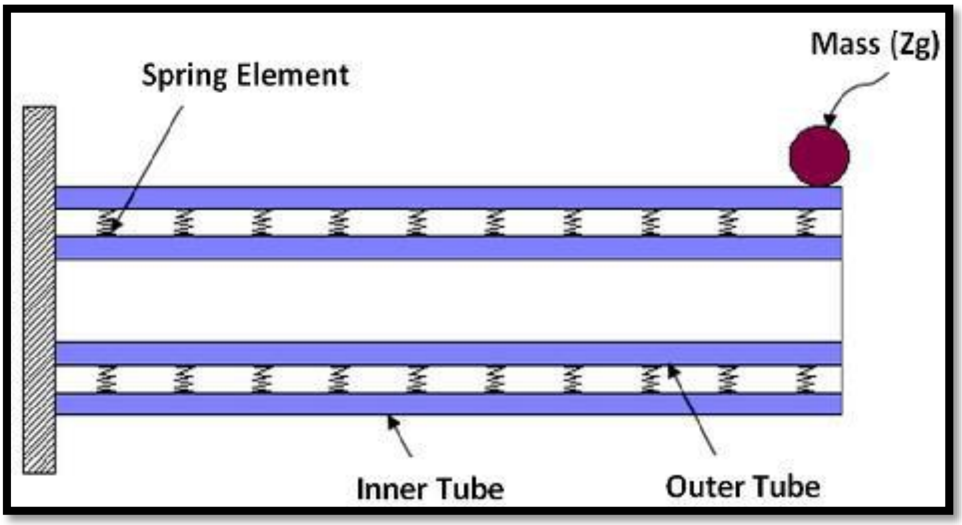


Figure 6: Cantilevered model of Double Wall Carbon Nano Tube

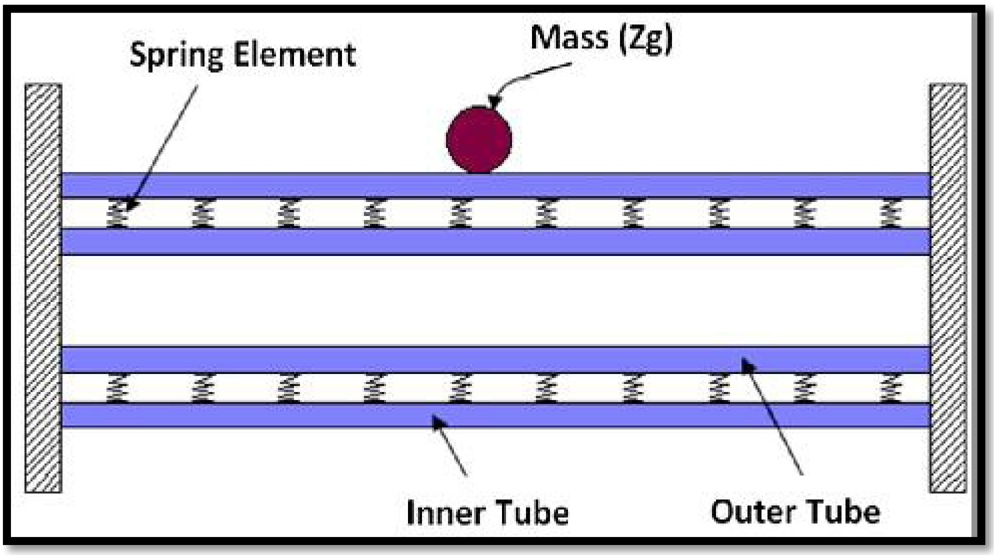


Figure 7: Bridged with the mass attached in the middle

Figure 6 above shows the cantilevered configuration of the double walled carbon nanotube with the additional mass at the tip of the tube. Meanwhile Figure 7 shows the double walled carbon nanotube with the attached additional mass at the centre of the tube symmetrically from both ends.

CHAPTER 3:

METHODOLOGY

3.1 FYP I and FYP II Methodology

The methodology used in this project is computer simulation with a new set of material properties. A computer model of Carbon Nano Tube using ANSYS software will be first created. The necessary parameters will be listed down before being entered into the software. The results of the simulation will be tabulated and corresponding graphs will be generated and analysed. Finally, the results will be discussed.

As for FYP 1, practice to familiarize the finite element software will be taken. The simulation will be carried out during FYP 2.

3.2 Overall Process Flow

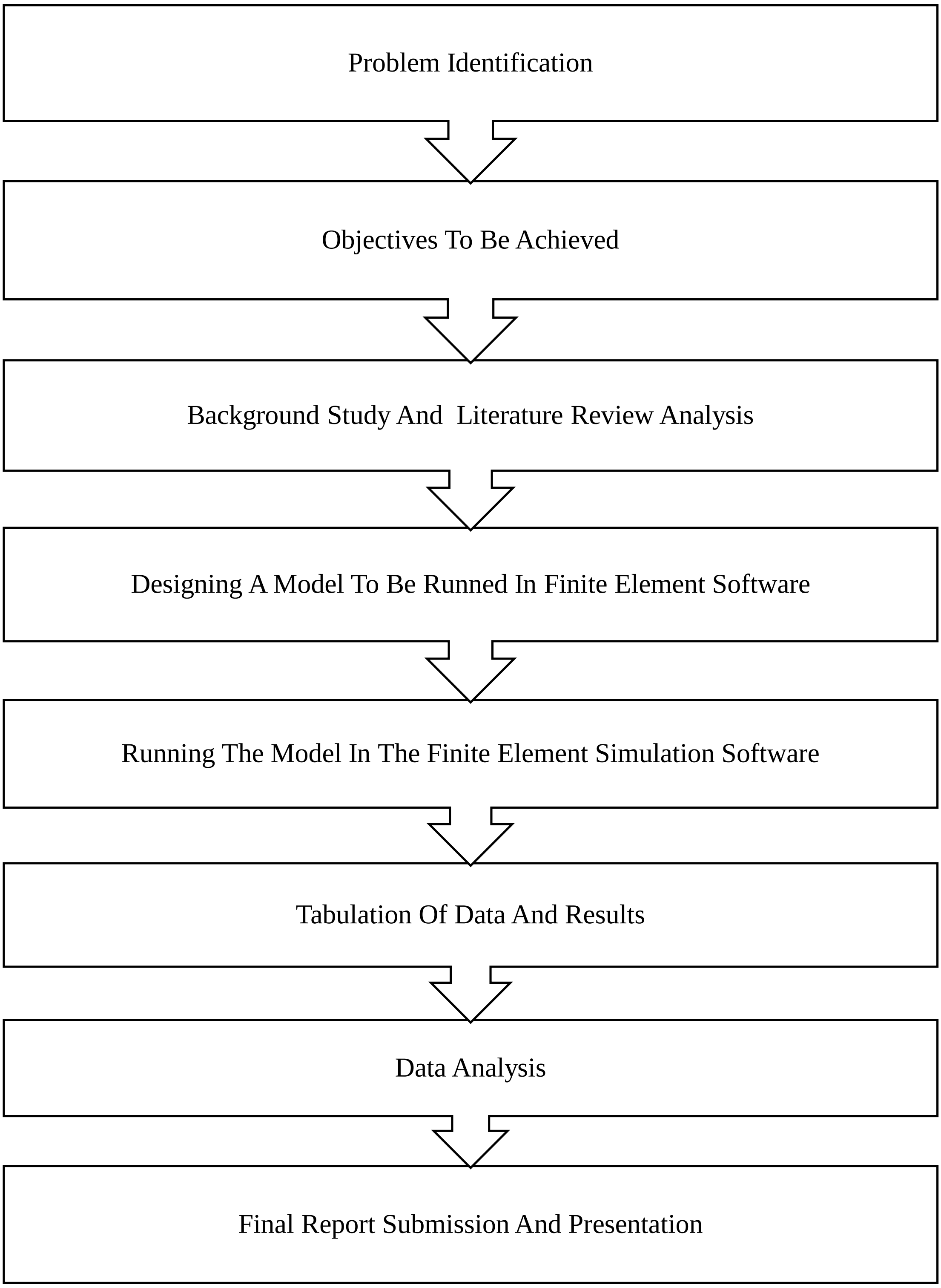


Figure 8: Methodology Flow Chart

Figure 8 shows the overall process flow of the project inclusive of FYP I and FYP II.

i) Confirmation of Project topic

This is the first where the project topic is chosen based on the list of topics available for Final Year Project September 2015 given by the project coordinator. Topic is later verified by the course coordinator and a supervisor is allocated.

ii) Consultation with Supervisor

As soon as the project is confirmed by the coordinator and the supervisor is assigned. Appointment with supervisor is made for consultation. The purpose is to get guidance and a clearer picture of the topic of study. Throughout the two semesters meetings are done with dependence on lecturer’s availability and the urgency of the topic to be discussed. Updates and clarifications are done in this process.

iii) Problem Identification

The following step is identifying the problem to be solved. This step is a crucial part of the process flow as it identifies the problem statement which will be based in the zeroing down objective of study.

iv) Objectives and Scope of Study

Based on the problem that has been identified in the previous step, objective of the study is chosen. Scope is later determined as follow up from that. It was crucial to make sure that the scope was not too extensive as in real world applications or involves technical support that was beyond the students reach and availability. Moreover it was also made sure that the project was feasible within the time scope.

v) Literature Review

A thorough background study on the title and the previous studies that has been conducted revolving the topic was conducted. What are the material properties that are crucial in the study of this material was determined and obtained from the available and legitimate sources such as conference papers and journals.

vi) Data Collection

Necessary properties that are part of the engineering data needed in order for the simulation to run is gathered through research.

vii) Computer Model Development And Simulation

A development of a model that is to be run in the ANSYS is started as soon as the necessary material properties are obtained.

viii) Results

Results from the end process of the simulation are gathered. Based on the results the graph is plotted. This enabled to study the pattern of the response by analysing the curve.

ix) Documentation

All the steps that is undertaken are documented completely and with reference to the standardised format. The documentation is written in a complete report format for reference. At the end of the report conclusions are made based the objective of the study and the results. Recommendation are made for the purpose of future study of and comparatively extensive than the current project undertaken. Based on the report Powerpoint Presentation is prepared for the purpose of oral presentation to the supervisors and examiners.

3.3 Process Flow Chart

Figure 9 below shows the process flow chart of the project.

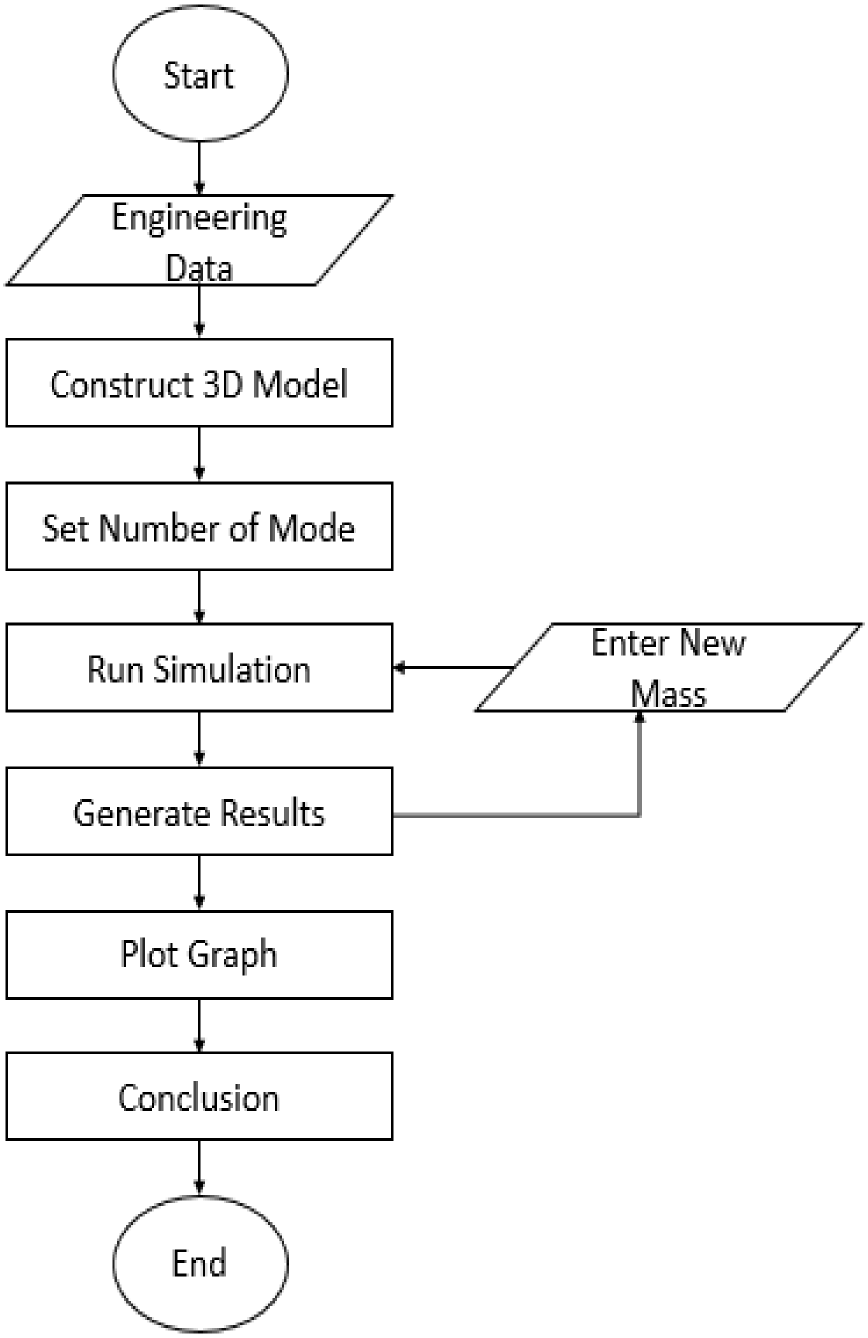


Figure 9: Process Flow Chart

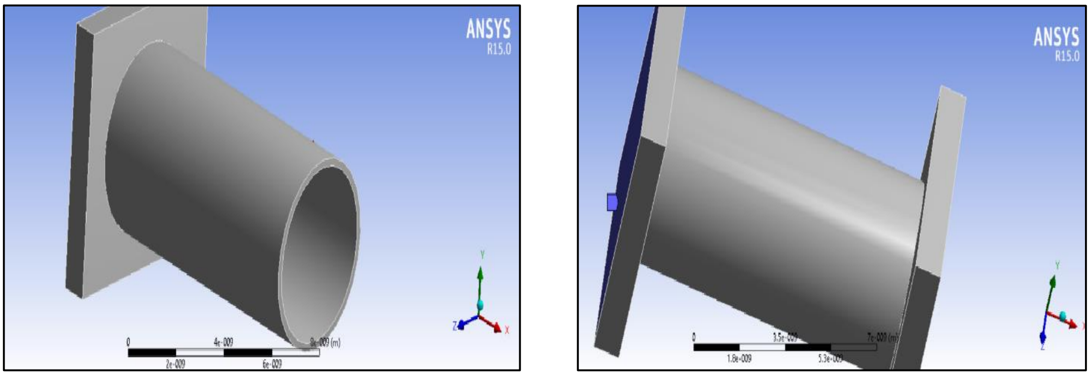
3.4 Simulation 3D Model

3.4.1 Constructing the 3D Model

The first step in preparing the 3D model was to list down the external parameters of the model for both cantilevered and bridged configurations. Table 1 shows the parameters used in designing the ANSYS model. The parameters were applied to construct the model as shown in Figure 10.

Table 1: Parameters Used for Model

Type Of Configuration	**Base Height** (ηm)	**Base Width** (ηm)	**Radius** (ηm)		**Extrude length** (ηm)
Cantilevered	7	7	Outer	Inner	1
			5	4.6	
Bridged	7	7	Outer	Inner	1
			5	4.6	



(a) (b)

Figure 10 : a) Cantilever Beam Model b) Bridged Beam Model

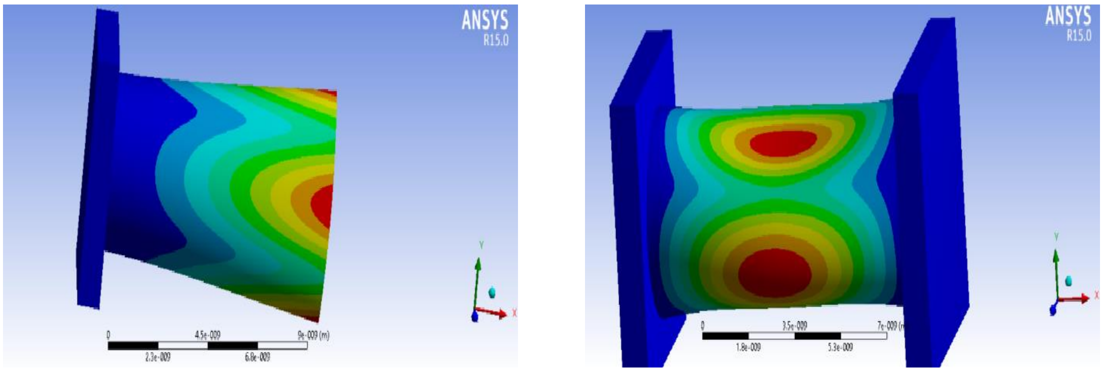
3.4.2 Engineering Data Input

The material properties of the nanotubes that were required by the simulation was inserted into the program and named as a new material. Table 2 shows the properties that were necessary for the simulation process. As soon as the necessary material properties has been applied the simulation was run as shown in Figure 11.

Table 2: Material Properties

Young's Modulus	Density	Tensile Strength	Yield Strength	Poisson's Ratio
$1.0\ TPa$	$2240\ {}^{kg}/_{m^3}$	$130\ GPa$	$20\ GPa$	0.06

3.4.3 Running the Simulation



(a) (b)

Figure 11: Simulation Running In ANSYS Software

3.4 Gantt Chart And Key Milestones

Table 3: FYP I Gantt Chart and Key Milestones

No.	Week Activities	0	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Topic Selection For Project	🟥	🟥▲												
2	Literature Review On Carbon Nanotubes			🟥	🟥	🟥	🟥								
3	Critical Analysis of Published Papers for Material Properties					🟥	🟥	🟥							
4	Extended Proposal Draft Report Submission							🟥							
4	Extended Proposal Report Submission							🟥▲							
5	Proposal Defence Presentation								🟥	🟥▲					
6	Resume Work With Construction Of The First Configuration (Cantilever)										🟥	🟥	🟥	🟥	
7	Draft Interim Report Submission													🟥	
8	Interim Report Submission														🟥▲

Table 4: FYP II Gantt Chartt and Key Milestones

No.	Week Activities	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Construction of Second Configuration (Bridged)	🟥	🟥												
2	Running Simulation for Both Cantilevered and Bridged configuration		🟥	🟥	🟥	🟥	🟥								
3	Tabulation and Analysis of Data					🟥	🟥	🟥							
4	Submission of Progress Report							🟥▲							
5	Pre-Sedex								🟥	🟥	🟥▲				
6	Draft Dissertation Submission											🟥▲			
7	Soft Bound Dissertation Submission												🟥▲		
8	Technical Paper Submission												🟥▲		
9	Dissertation Viva													🟥▲	
10	Dissertation Submission														🟥▲

CHAPTER 4:

RESULTS AND DISCUSSION

The following chapter provides the results that was generated after the simulation was complete using the ANSYS software. The simulation was run for both configuration based on the parameters that has been stated above. The tabular data that was generated by the software has been regenerated using Excel graph to portray the behavioural pattern. The following graphs are plotted for all six different modes comparing the behaviour of cantilevered Nanotube configuration and also bridged nanotube configuration under the same mass change. The direct tabular outputs of the software has been attached to the appendices for reference purposes.

4.1 Mode 1

Table 5: Frequency of Beam with Increasing Mass for Mode Number 1

Mass (kg)	Frequency of Cantilevered (Hz)	Frequency of Bridged (Hz)
2.50E-15	1.23E+07	1.55E+07
5.00E-15	8.67E+06	1.09E+07
7.50E-15	7.08E+06	8.86E+06
1.00E-14	6.13E+06	7.73E+06

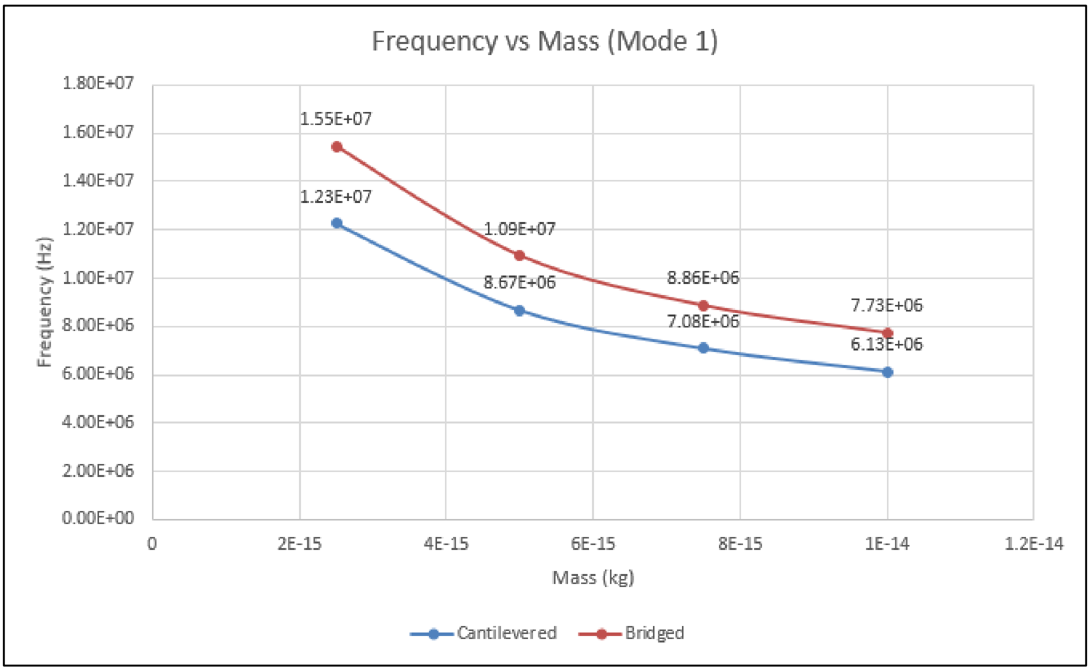


Figure 12: Frequency of Nanotube against Mass for First Vibration Mode

Based on Figure 12 above, it can be seen that the frequency of the of the nanotube experiences a reduction as the mass increases. Both the cantilevered and bridged configuration exhibits a similar pattern of decline. For cantilevered, at a mass of 2.50E-15 kg, the resonant frequency is 1.23E+07 Hz, at 5.00E-15 kg the resonant frequency is 8.67E+06 Hz, at mass of 7.50E-15 kg the resonant frequency is 7.08E+06 Hz, finally at mass of 1.00E-14 kg the resonant frequency is 6.13E+06 Hz.

Meanwhile for bridged configuration, at 2.50E-15 kg the resonant frequency is 1.55E+07 Hz, at the mass of 5.00E-15 kg the resonant frequency is 1.09E+07Hz, and at mass of 7.50E-15 kg the resonant frequency is 8.86E + 06 Hz, finally at 1.00E-14 kg the resonant frequency is 7.73E + 06 Hz.

4.2 Mode 2

Table 6: Frequency of Beam with Increasing Mass for Mode Number 2

Mass (kg)	Frequency of Cantilevered (Hz)	Frequency of Bridged (Hz)
2.50E-15	1.25E+07	3.05E+07
5.00E-15	8.85E+06	2.16E+07
7.50E-15	7.23E+06	1.71E+07
1.00E-14	6.26E+06	1.53E+07

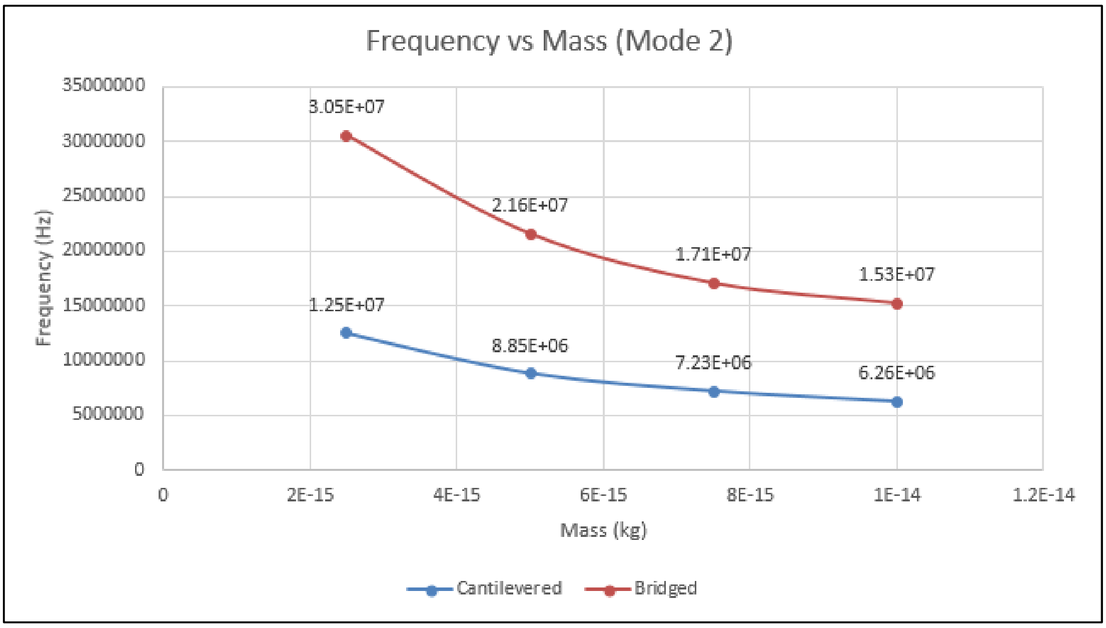


Figure 13: Frequency of Nanotube against Mass for Second Vibration Mode

Based on figure 13, it can interpreted that for the second mode the decline pattern is almost similar to the first mode, but the frequency of the cantilevered configuration is relatively lower compared to the first mode. For cantilevered, at a mass of 2.50E-15 kg the resonant frequency is 1.25E+07 Hz, at a mass of 5.00E-15 kg the resonant frequency is 8.85E+06 Hz , at a mass of 7.50E-15 kg the resonant frequency is 7.23E+06 Hz, at a mass of 1.00E-14 kg the resonant frequency is 6.26E+06 Hz.

Meanwhile for bridged configuration, at a mass of 2.50E-15 kg the resonant frequency is 3.05E+07 Hz, at a mass of 5.00E-15 kg the resonant frequency is 2.16E+07 Hz, at a mass of 7.50E-15 kg the resonant frequency is 1.71E+07 Hz, and at a mass of 1.00E-14 kg the resonant frequency is 1.53E + 07 Hz.

4.3 Mode 3

Table 7: Frequency of Beam with Increasing Mass for Mode Number 3

Mass (kg)	Frequency of Cantilevered (Hz)	Frequency of Bridged (Hz)
2.50E-15	3.75E+07	5.46E+07
5.00E-15	2.65E+07	3.86E+07
7.50E-15	2.16E+07	3.01E+07
1.00E-14	1.87E+07	2.73E+07

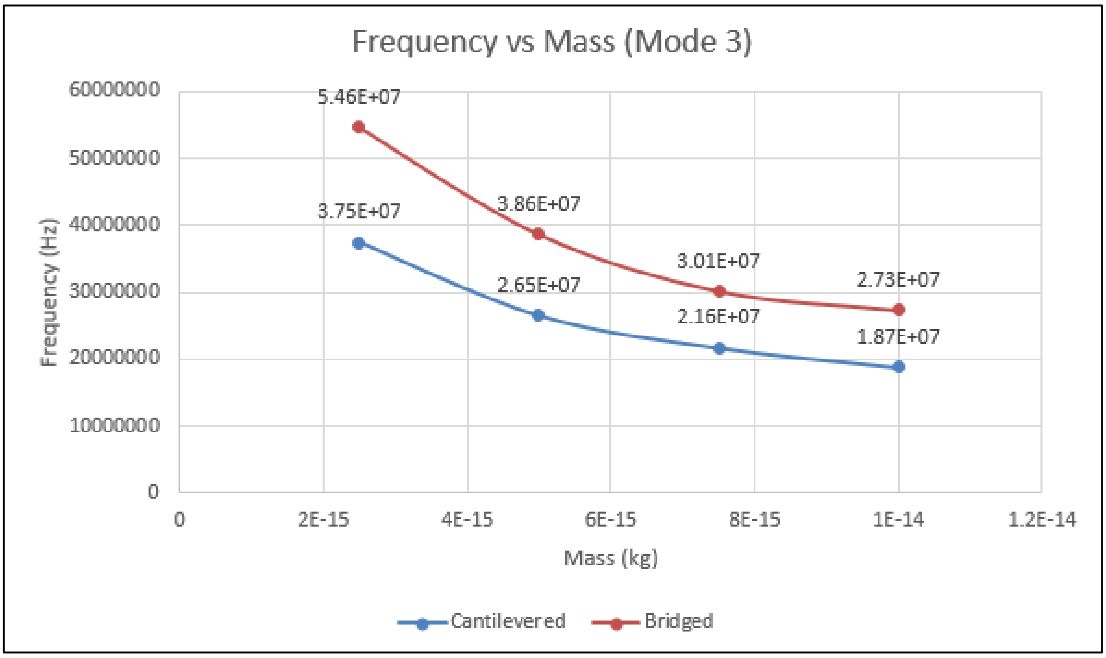


Figure 14: Frequency of Nanotube against Mass for Third Vibration Mode

Based on figure 14 above, we can strongly say that the pattern reduction has not changed. The frequency are still dropping with an increase in mass of attached particle. This pattern applies for both the cantilevered and bridged configuration. For cantilevered, at a mass of 2.50E-15 kg the resonant frequency is 3.75E+07 Hz, at a mass of 5.00E-15 kg the resonant frequency is 2.65E+07 Hz, at a mass of 7.50E-15 kg the resonant frequency is 2.16E+07 Hz, at a mass of 1.00E-14 kg the resonant frequency is 1.87E+07 Hz.

Meanwhile for bridged configuration, at a mass of 2.50E-15 kg the resonant frequency is 5.46E+07, at a mass of 5.00E-15 kg the resonant frequency is 3.86E+07 Hz at a mass of 7.50E-15 kg the resonant frequency is 3.01E+07 Hz at a mass of 1.00E-14 kg the resonant frequency is 2.73E+07 Hz.

4.4 Mode 4

Table 8: Frequency of Beam with Increasing Mass for Mode Number 4

Mass (kg)	Frequency of Cantilevered (Hz)	Frequency of Bridged (Hz)
2.50E-15	1.10E+11	2.85E+11
5.00E-15	1.10E+11	2.85E+11
7.50E-15	1.10E+11	2.85E+11
1.00E-14	1.10E+11	2.85E+11

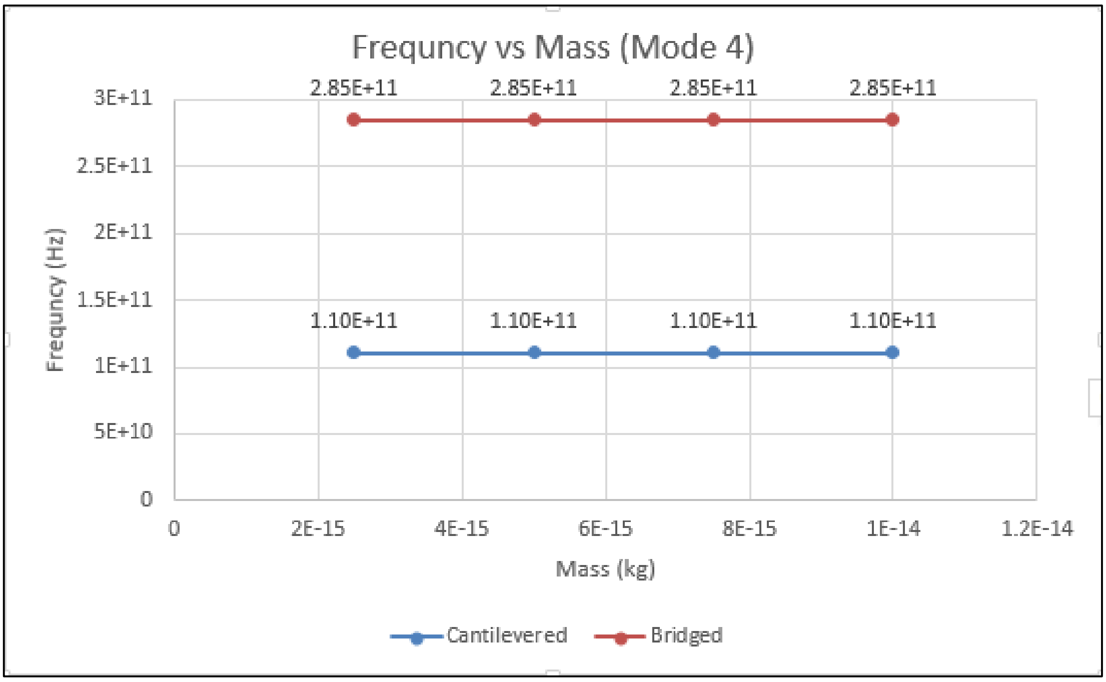


Figure 15: Frequency of Nanotube against Mass for Fourth Vibration Mode

Figure 15 above exhibits a different pattern compared to the smaller modes. At this point the change in mass does not affect the frequency of the nanotubes. Meanwhile the range of frequency remains constant with the increase in mass. For cantilevered, at a mass of 2.50E-15 kg the resonant frequency is 1.10E+11 Hz, at a mass of 5.00E-15 kg 1.10E+11 Hz, at a mass of 7.50E-15 kg the resonant frequency is 1.10E+11 Hz, at a mass of 1.00E-14 kg the resonant frequency is 1.10E+11 Hz.

Meanwhile for bridged configuration, at a mass of 2.50E-15 kg the resonant frequency is 2.85E+11 Hz, at a mass of 5.00E-15kg the resonant frequency is 2.85E+11 Hz, at a mass of 7.50E-15kg the resonant frequency is 2.85E+11 Hz, and at a mass of 1.00E-14 kg the resonant frequency is 2.85E + 11 Hz.

4.5 Mode 5

Table 9: Frequency of Beam with Increasing Mass for Mode Number 5

Mass (kg)	Frequency of Cantilevered (Hz)	Frequency of Bridged (Hz)
2.50E-15	1.10E+11	2.89E+11
5.00E-15	1.10E+11	2.89E+11
7.50E-15	1.10E+11	2.89E+11
1.00E-14	1.10E+11	2.89E+11

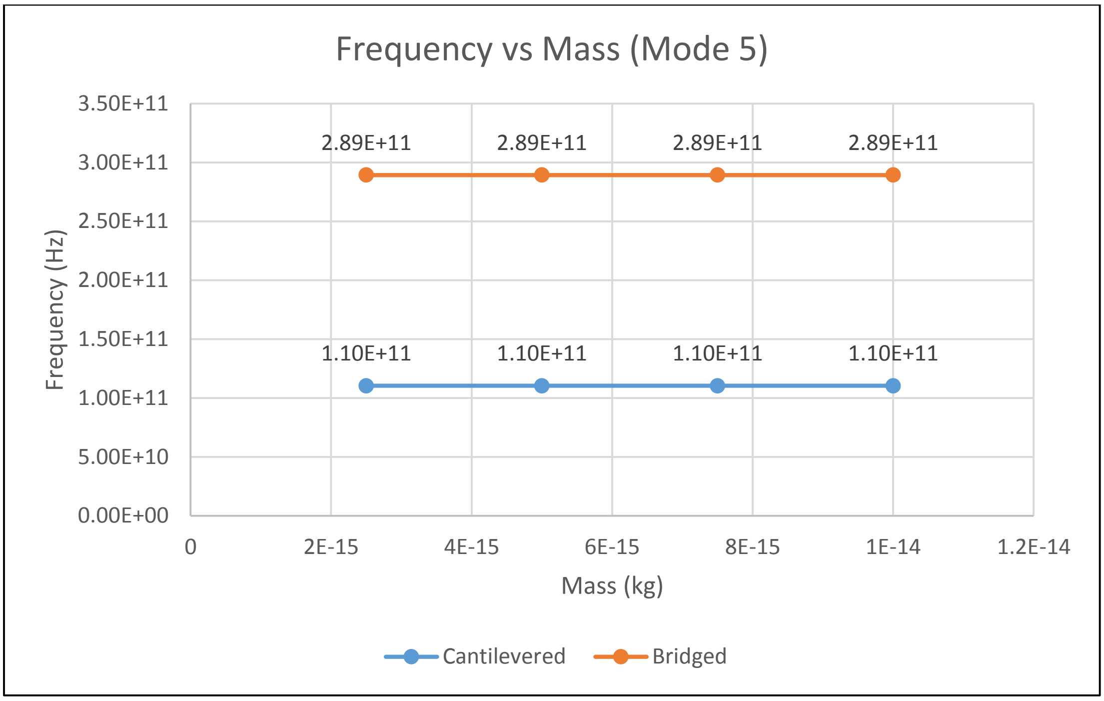


Figure 16: Frequency of Nanotube against Mass for Fifth Vibration Mode

Figure 16 shows the fifth mode of vibration. It can be seen that the behaviour is similar to that of the fourth mode. The Frequency remains constant with the increase in mass of same values as the first three modes of vibration. . For cantilevered, at a mass of 2.50E-15 kg the resonant frequency is 1.10E+11 Hz, at a mass of 5.00E-15 kg the resonant frequency 1.10E+11 Hz, at a mass of 7.50E-15 kg the resonant frequency is 1.10E+11 Hz, at a mass of 1.00E-14 kg the resonant frequency is 1.10E+11 Hz.

Meanwhile for bridged configuration, at a mass of 2.50E-15 kg the resonant frequency is 2.89E+11 Hz, at a mass of 5.00E-15kg the resonant frequency is 2.89E+11 Hz, at a mass of 7.50E-15 kg the resonant frequency is 2.89E+11 Hz, and at a mass of 1.00E-14 kg the resonant frequency is 2.89E + 11 Hz.

4.6 Mode 6

Table 10: Frequency of Beam with Increasing Mass for Mode Number 6

Mass (kg)	Frequency of Cantilevered (Hz)	Frequency of Bridged (Hz)
2.50E-15	2.61E+11	3.32E+11
5.00E-15	2.61E+11	3.32E+11
7.50E-15	2.61E+11	3.32E+11
1.00E-14	2.61E+11	3.32E+11

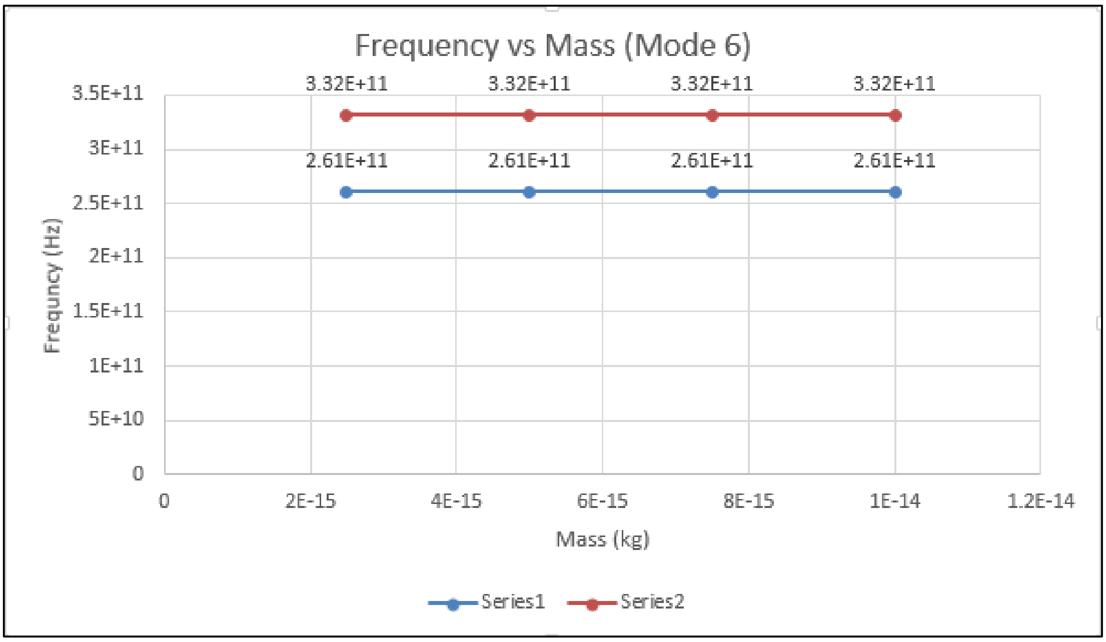


Figure 17: Frequency of Nanotube against Mass for Fifth Vibration Mode

Figure 17 above shows that the behaviour of frequency at the sixth mode is constant. This pattern is similar to that of the earlier two modes. Although the pattern is the same exhibiting a constant frequency, the range of values where the constant line remains are different. For cantilevered, at a mass of 2.50E-15 kg the resonant frequency is 2.61E+11 Hz, at a mass of 5.00E-15 kg the resonant frequency is 2.61E+11 Hz, at a mass of 7.50E-15 kg the resonant frequency is 2.61E+11 Hz, at a mass of 1.00E-14 kg the resonant frequency is 2.61E+11 Hz.

Meanwhile for bridged configuration, at a mass of 2.50E-15 kg the resonant frequency is 3.32E+11Hz, at a mass of 5.00E-15kg the resonant frequency is 3.32E+11Hz, at a mass of 7.50E-15 kg the resonant frequency is 3.32E+11Hz, and at a mass of 1.00E-14 kg the resonant frequency is 3.32E+11Hz.

CHAPTER 5:

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

The first objective of the project was to study the vibrational characteristics of single walled carbon nanotube in cantilevered configuration. The simulation was run using ANSYS software for six different modes of vibration. The mass change applied was in an incremental order. For the first three modes of vibration the pattern exhibited a decline in resonant frequency as the mass increases. For the next three nodes the resonant frequency remained constant. It can be concluded that when the cantilevered nanotube are subjected to a mass change the original frequency is changed in decreasing manner for the first three modes of vibration only.

The second objective was to study the vibrational characteristics of single walled carbon nanotube in bridged configuration. The simulation was using the same software. The mass change was applied was the same value in the same order. For the first three nodes the pattern exhibited a decline in resonant frequency as the mass increases. The following nodes remained constant irrespective of the increase in mass. It can be concluded that when the bridged nanotubes are subjected to a mass change the original frequency is changed in a decreasing manner for first three modes of vibration only.

In the whole picture it can be seen that irrespective of being in a cantilevered or bridged position the carbon nanotubes pattern of vibrational behaviour when subjected to mass order of picogram, exhibits a frequency decline for selected modes of vibration.

5.3 Recommendation

This study as stated assumes the continuum mechanics in developing the model for the vibrational analysis. Further studies can be done by conducting the same study using molecular dynamics simulation. A comparison can be derived between both the results for validation.

Besides, the study should be conducted in real time. The carbon nanotubes has to fabricated and put to test by intentionally changing the mass that is attached to the particle. The vibrational frequency should be measured. Results has to be analysed with simulation results to determine the accuracy of prediction.

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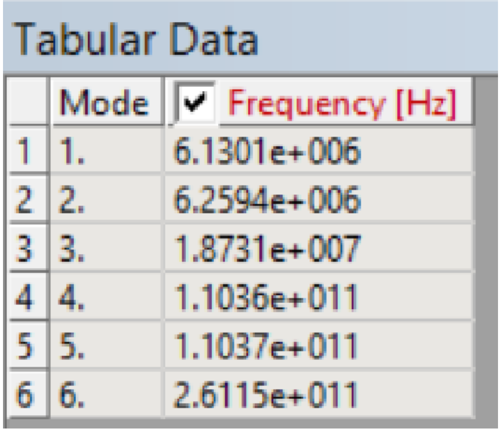
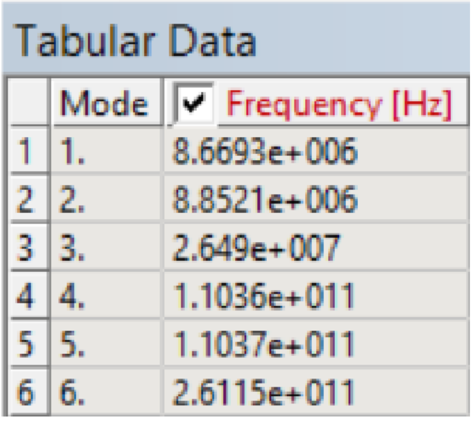
APPENDICES



Tabular Data

	Mode	☑ Frequency [Hz]
1	1.	6.1301e+006
2	2.	6.2594e+006
3	3.	1.8731e+007
4	4.	1.1036e+011
5	5.	1.1037e+011
6	6.	2.6115e+011



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	Mode	☑ Frequency [Hz]
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2	2.	8.8521e+006
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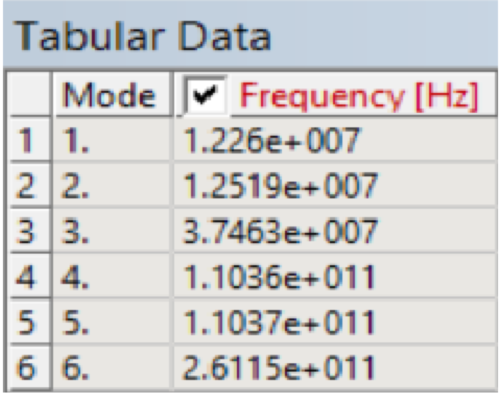
6	6.	2.6115e+011



Tabular Data

	Mode	☑ Frequency [Hz]
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2	2.	1.2519e+007
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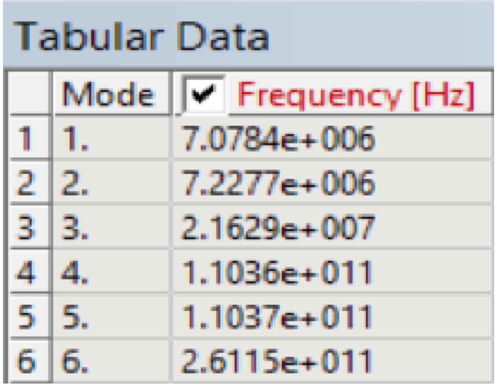
4	4.	1.1036e+011
5	5.	1.1037e+011
6	6.	2.6115e+011



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2	2.	7.2277e+006
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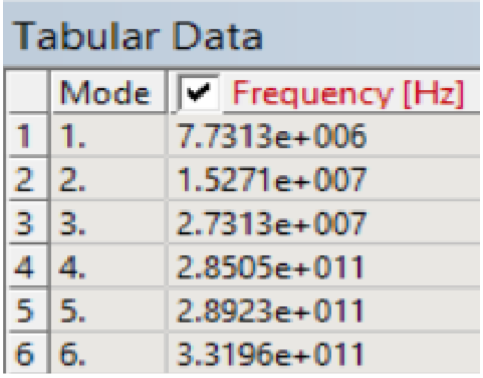
5	5.	1.1037e+011
6	6.	2.6115e+011



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2	2.	1.5271e+007
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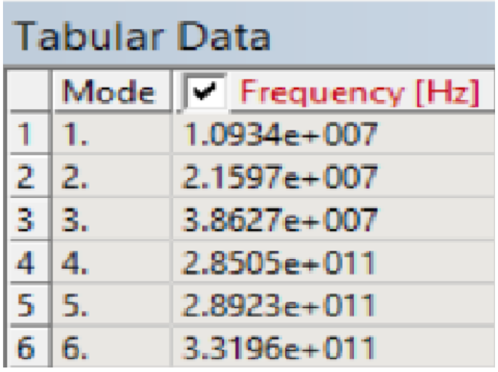
5	5.	2.8923e+011
6	6.	3.3196e+011



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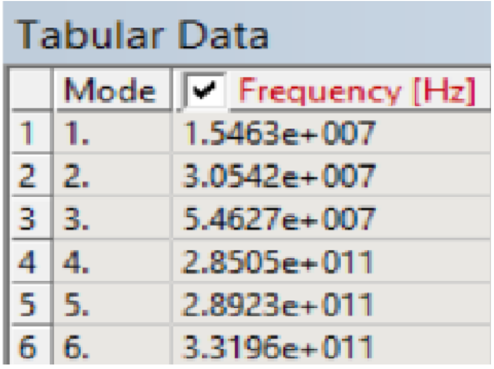
5	5.	2.8923e+011
6	6.	3.3196e+011



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6	6.	3.3196e+011