Literature Review: Characterization of the Resonant Frequencies of Carbon Fibre Composites

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Abstract

This report outlines a sample of the key research pertaining to the project mentioned above. The study that will be undertaken looks to ascertain the resonant frequency of carbon fibre rods; then using these frequencies to determine the elastic moduli of the rods. Initially the details of the production and use of carbon rods is reviewed, so as to provide background knowledge of the composition of rods, also the conditions that they will undergo. Because of its importance, the consequences and causes of resonance are also discussed to provide insight into the research. There are several methodologies of determining resonance and the elastic modulus of materials; a selection are detailed here, though the focus is predominately aimed at non-destructive testing. From this research, the authors of this study will proceed to use mechanical stimulation to excite the specimens and thus measure the resonance, determine the elastic modulus from the resonance, then to compare the elastic modulus obtained with values supplied by the manufacturer to assess the accuracy of this method.

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Introduction

Carbon fibre reinforced polymers consist of a large range of carbon and epoxy based products, they are relatively new materials that have been developed in the last 50 years since the discovery of carbon fibre. These products offer unique properties to a wide range of industries and varied use has prompted a large amount of research, the manufacturing methods have vastly improved. When it was discovered, fibres had a 20% carbon content (Bacon, 1960), then when Shindo developed the use of a new precursor (PAN) in (1961) producing 55% carbon and now with a carbon content of>85%. This has been done by improving oxidization methods and the use of different precursors. The discovery of the resonant frequencies and their relationship to young's modulus is important in industries such as construction and music.

This study will test the resonant frequencies of Carbon Fibre Rods of varying thicknesses to find a relationship between the resonant frequencies of the different thickness of rods. Using a mathematical method derived from Hooke's law acting on a loaded beam and the knowledge of resonant frequencies, determine Young's modulus. The proposed study will compare these values of Young's modulus obtained to values found using other means or using manufacturer supplied values, thus testing both the accuracy of the obtained resonant frequencies of the rod, and the methods to measure it. The study also aims to develop the use of resonance to calculate the elastic modulus.

This review aims to both provide some background information to carbon fibre, resonance and young's modulus. It also aims to analyse methods of determining the resonant frequencies and young's modulus, so as to provide the reader an understanding of the various aspects of the field.

Carbon Fibre

Carbon fibres are long thin strands of material that mostly consist of carbon atoms, they have diameter 0.005-0.1mm (Cantwell & Morton., 1991). It is made using a precursor that is drawn into long fibres and heated to very high temperatures in an oxygen free environment. This oxygen free environment stops the fibre burning and causes the atoms in the fibre to vibrate until all the non-carbon atoms are expelled. Machines such as the one shown in figure 1 feed long precursor fibres into the areas where they are oxidised, then the carbon fibres may be treated or wound onto spools for later use.


PAN fiber going through oxidation oven

Figure 1: Image shows the precursor being oxidized to become carbon fibre (Zoltek, No Date)

Once the precursor has been carbonised, it is then treated in a variety of ways so its surface reacts better to epoxies and other important chemicals used for constructing composites (Zoltek, No Date). The carbon fibres are then woven into mats of different structures depending on what they will be used for, or even moulded into carbon rods. The structures that it may be woven into are adapted as to whether the material will be used for its ability to be moulded into tight corners thus using a less dense weave, or for strength and rigidity a denser weave is used.

There are several different types of precursor available for making carbon fibre, Polyacrylonitrile (PAN) is the most common, but petroleum pitch and rayon have also been used (Cogswell, 1992, p. 34). These precursors are all organic fibres and are chosen for their influence upon the properties of the final product, with some of the organic fibres chosen to increase the Young's modulus, others to have high tensile strength.

The modulus of the fibres is a measure of how much force can be applied before the fibres deform. High modulus carbon fibres will have a modulus of up to 900GPa (Naito, et al., 2008), whereas the modulus for steel is approximately 200GPa (MatWeb, No date). It can be seen that the modulus of carbon fibres can be up to almost 4.5 times that of steel.

Composites are made out of reinforcement, such as carbon fibres, woven and shaped and mixed with a matrix such as epoxy resin. Epoxy consists of a resin and a hardener and is mixed together then applied to the fibres and allowed to cure, thus allowing the carbon to be moulded to almost any shape. The epoxies used are a class of polymers which contain epoxide groups, most epoxies are petroleum based, although some organic ones exist. (BOLON, 1995)

Carbon fibre products are used in many industries, some of the most common being in aerospace and commercial aircraft for example the Boeing Airbus A350XWB frame being made out of composites supplied by the company Hexcel (Hexcel, No date). Other industries include; Sporting goods, Construction, Music and Automotive (Liu, et al., 2012). It's often chosen due to its high strength to weight ratios and its aesthetically pleasing look.

Understanding the mechanical properties of composites such as carbon fibre is very important because of its wide usage and its importance in many industries. The intention of this study is to understand more about the elastic moduli and the resonant properties of carbon fibre products, specifically carbon fibre rods.

Resonance

Resonance, in physics, is defined as the state of a system in which a forcing frequency from an external stimulus is the same, or nearly the same, as the natural frequency of the specimen. This creates vibrations of greater amplitude than measured at forcing frequencies different to the natural frequency (Timoshenko, 1955, p. 42). This is shown in Figure 2 where a graph of frequency against amplitude is plotted. There is a significant peak in amplitude at the resonant frequency.

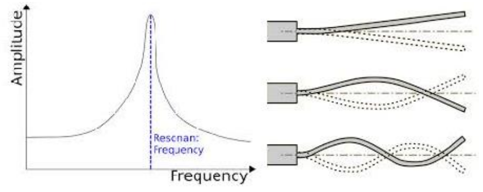

Figure 2: (right): Resonant nodes in a clamped bar, the top being the fundamental node and the ones below the subsequent nodes. (HyperPhysics, No date) *(left): A graph that demonstrates how amplitude behaves near resonant frequencies (left)* (Wikibooks, 2013).

Examples of resonance are: Waves causing sea based structures to move, wind acting on tall buildings and bridges, earthquakes on rock formations, someone strumming a guitar, or a beam vibrating, as shown on the right in Figure 2. Resonance can be a useful phenomenon, such as in generation of tidal electricity, harmonics in musical theory, or pushing a swing. Other times it can be destructive, as in the incident of the Tacoma Narrows Bridge, where the bridge was destroyed on the 7th of November 1940 due to high winds, these induced a forcing frequency that was similar enough to the resonant frequency of the bridge and causing it to collapse. (Bülah & Scanlan, 1991)

It is of interest how resonance relates to the elastic modulus and flexural strength of Carbon rods. In building and other applications, the knowledge of resonant frequencies of materials is important for safety reasons, such as the case of buildings built upon fault lines or tall buildings. In countries such as Taiwan, building materials are often chosen so their resonant frequencies do not match those frequencies that can be induced by earthquakes and high winds, such as the Taipei 101. The Taipei 101 utilises tuned mass dampers to damp the vibration of the building caused by high winds. (Chien-Liang Leea, et al., 2006)

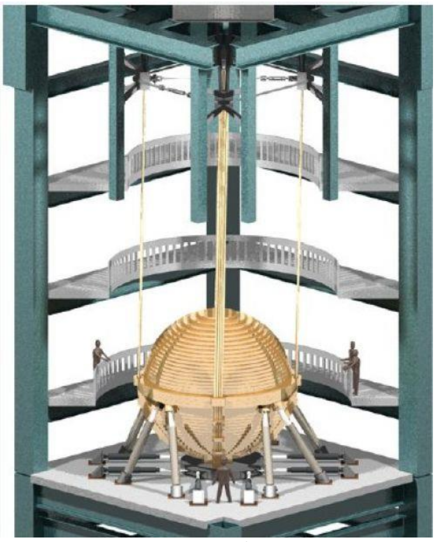

Figure 3: This image shows one of the tuned mass dampers in the Taipei 101, it is several stories high and the 660 metric ton weight sits upon hydraulic arms that damp the motion of the tower swaying. (probyte2u, 2011)

The study that will be undertaken proposes to use this knowledge of resonance to discover the elastic moduli of carbon rods, to do this the study will employ a method derived from Hooke's law and the geometry of the sample to calculate the elastic modulus. As the samples are carbon rods, their geometry will be that of a cantilever beam, fixed at one end and the other free.

Cantilever Beams

Cantilever definition: A projecting structure, such as a beam, that is supported at one end and carries a load at the other end or along its length. (Timoshenko, 1947)

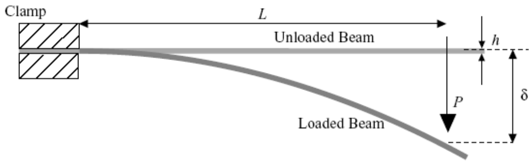

Figure 4: A simple sketch of a cantilever setup, unloaded and loaded beam (University of Cambridge, No date)

Figure 4 shows a simple cantilever setup of a clamped beam in two positions, one loaded and one unloaded. From knowing the dimensions on the beam and the forces exerted upon the beam, it is possible to determine the Young's Modulus using Hooke's law.

Cantilevers are often used in buildings, for example, when a building 'steps out' on the second floor and extends outside the base of the first floor walls; they are supported by a cantilever. This information on cantilevers pertains to the current research; we will be using the knowledge of the physics of a cantilever to test for the elastic modulus of carbon rods.

Methodology for testing Resonance

For this experiment we will be using different diameters of carbon rods, this will be done to find the resonant frequencies of various thicknesses of the samples, and to find a relationship between the geometric shape and the resonance.

There are several ways to test for resonance such as measuring peaks in acoustic emission from a stimulated sample (Martin, 2013). Measuring maximal displacement in a stimulated beam (Perrin, et al., 2007), or resonant ultrasonic spectroscopy (Farzbod, 2013). The latter two of these methods are used extensively in materials testing in some form or other, with the changes to the method being predominately differences in boundary conditions of the specimen; the test that is used often depends on the specimen to be tested and the funding available.

In his paper *'Characterisation of the resonant waveforms of Carbon Fibre Composites'*, Alex Martin looks to model the waveforms for different layers of a carbon composite using a mechanical oscillator to stimulate one side of rectangular sheets of composite whilst the other end is clamped. Then a piezo-electric sensor was placed close to the sample to find the acoustic maximums generated by the specimen. However, when using a piezo-electric sensor to detect resonant frequencies, it will pick up interference from other vibrating equipment, such as; mechanical vibrator holding the sample, the clamp for the sample and other surrounding equipment. Also, modelling waveforms in a layered composite requires a more detailed technique, such as using ultrasonic waves (Wilkinson & Reynolds, 1974). The technique employed in this paper is aimed at finding the velocity of waves in composite materials, and thus models the propagation of waves along different axis.

A method employed by Didier Perrin *et al.* in the report *'A novel method for the measurement of elastic moduli of fibres'* (Perrin, et al., 2007) negates the possibility of acoustic interference by measuring the displacement instead of acoustic maximums. The sample fibres were fixed at one end onto a support and then oscillated. At maximum displacements of the free end of the fibres, the resonant frequency was noted and then used to calculate the elastic moduli.

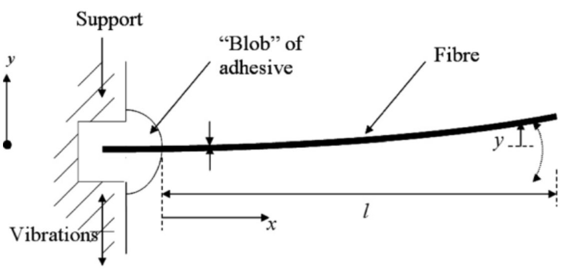

Figure 5: Fibres used by Perrin et al. were fixed into a support which was then vibrated. The free end of the fibre oscillated at varying displacements dependent upon frequency of vibration (Perrin, et al., 2007)

This was done because of the size of the samples used; Perrin *et al.* measured the elastic moduli of fibres of lengths 1.77-12.79mm, it is difficult to fix both ends of fibres of this size accurately. This method is innovative because the difficulty of usual tensile testing on a small scale has been circumvented by only fixing one end of the sample, and performing non-destructive testing to a high degree of accuracy. The results obtained differed only 5% from accepted values when testing the first resonant mode.

Ultrasonic waves are often used in testing the properties of materials, though not often to test for resonance. Ultrasonic waves are sound waves that have frequencies 10kHz up to 172kHz (Farzbod, 2013). They are used to detect different boundaries in materials and can be used for imaging aswell as discovering elastic constants. There are other methods of spectroscopy that use compression waves although their primary purpose is not for discovering resonance, but other material qualities and as such are not relevant to this study.

From this research into the methodologies for testing resonance, it can be seen that an efficient and cost effective method would be to use a method similar to that of Didier Perrin *et al.* This investigation will measure the maximal displacement of oscillating rods to find the resonant mode of the carbon samples. Then using analysis demonstrated by the aforementioned authors to endeavour to ascertain a pattern in the resonance.

Young's Modulus

Young's modulus is a measure of the stiffness of an elastic material that is used to characterize materials. It is defined as the ratio of the stress over the strain along an axis (McNaught & Wilkinson, 1997, p. 12). It is only applicable in the range of stress in which Hooke's law applies. A material with a high Young's modulus, e.g. Diamond, with a Young's modulus of 1220GPa (Spear & Dismukes, 1994), is described as rigid. As Young's modulus is a ratio of stress over strain its units are units of pressure, e.g. [GPa]. (Spear & Dismukes, 1994)

Young's modulus was first used by Leonard Euler, but was named after the later user, Thomas Young, but the first experiments that used Young's modulus as we know it today were performed by Giordano Riccati in 1782 (Truesdell & Euler, 1960). Young's modulus enables the calculation of the change in dimension of a bar under tensile or compressive loads, e.g. how much a bar shortens under compression (Southwell, 1936). The Young's modulus represents the factor of proportionality in Hooke's law, but any real material will eventually fail and break when stretched over a large distance or with a large force, however, all materials will display Hookean behaviour for small values. Materials are called linear when they obey Hooke's law, and so carbon fibre is said to be linear for small values.

Anisotropic materials have varying mechanical properties depending upon orientation and thus the Young's modulus in not the same in all directions. Most materials are isotropic, meaning their mechanical properties are the same in all orientations of the material. Composites though, are anisotropic and in carbon fibre the Young's modulus is higher when force is loaded parallel to the fibres. (Boyd & Uttamchandani, 2012)

Hooke's law is the principle that states the force needed to extend or compress a material by some distance x is given by:

$F=kx$ (SOKOLNIKOFF, 1956)

where k is a constant factor characterising the material.

As stated, the Young's modulus is a measure of rigidity, as such it is important for any material that is considered when building or in construction as some materials are chosen to be more rigid (e.g. Steel reinforcement bars) and some less rigid (e.g. expansion joints), so the materials what are chosen to be more rigid will be chosen because of a high Young's modulus. This study aims to characterize the elastic moduli for various carbon rods, and as such, it is important to investigate different techniques for its measurement.

Methodology for testing Young's Modulus

When considering properties of a material for a specific usage, the Young's modulus is an important property to consider, it is a measure of rigidity. One of the key aims of this study is to assess the experimental methods for measurement of the elastic modulus.

There are many ways to measure the elastic moduli. They can be categorised as destructive tests and non-destructive tests. Examples of destructive testing are tensile testing or crash testing. Some examples of non-destructive testing are ultrasonic, radiographic and infrared testing. (EngineeringToolbox, No date)

Tensile testing is a test in which a sample is subjected to a controlled, measured, tension until failure. This test is used for discovering properties aswell as quality control. For anisotropic materials such as composites and fabrics biaxial testing is required. (ATSM, No date)

A typical specimen for a tensile test is a bar that has two shoulders for griping and a gage section where failure is most likely to occur. This is shown in figure 6.

Figure 6: The figure shows typical tensile testing specimens. They have a thinner gage length between two gripping ends that are held by the testing machine. (Materials Evaluation and Engineering, Inc, 2009)

The machine that is used most often is a universal testing machine, as shown in figure 7. The machine must be able to control the quantity and speed of applied tension; this is because it needs to be able to mimic the applications of force that the material is most likely to experience. The universal testing machine will generate a stress-strain curve that can be analysed to obtain: elastic modulus, yield strength and maximal elongation or compression. (Bruce, 1938)

Figure 7: This figure shows an example of a universal testing machine. There is a fixed head at the bottom and an adjustable one above. This is used for applying tensions and stress's to samples. If plugged into correct software, it may generate a stress-strain curve. (Advanced Universal & Force Testing Technologies, No date)

When testing samples of materials produced by a manufacturer, the tensile test is favourable due to its relative low cost and it adheres to industry standards. It also provides information on many properties with each test, but it also damages or destroys the sample. When testing a material that is already in use and therefore cannot be destroyed, or does not have the correct dimensions to be tested by the universal testing machine, then another sort of testing is required, a non-destructive test.

An example of a non-destructive test is one that has already been mentioned; ultrasound. Ultrasonic testing is a technique that is becoming more popular due to its abilities as a non-destructive test (Marzani & De Marchi, 2012). It has been used in such tests as: checking pipe welds for imperfections, failure mechanisms in materials and characterizing material properties.

An ultrasound spectroscopy test typically consists of using an ultrasound transducer that is placed over the specimen separated by a couplant; the transmitter then sends an ultrasonic pulse into the material. There are two methods of measurement of the ultrasonic pulse, once sent into the material; the transducer will detect any pulse reflections from imperfections in the specimen. Also, if a receiver is placed the other side of the surface is will pick up the intensity of the pulse after travelling through the material. This allows the transducer operator to detect flaws in the material aswell as calculate the materials properties from the time taken for the wave to propagate (Wilkinson & Reynolds, 1974). Therefore ultrasonic spectroscopy is a very useful technique, although this type of testing is very expensive as it uses modern technology. It also requires a skilled technician to operate to interpret the data received from the transducer and receiver, as described in the techniques patent. (Mcnulty, 1966)

Acoustic emission testing is a form of testing that also uses sound waves but of a lower frequency than ultrasonic. It works in a similar way, waves are stimulated in a specimen and the reflections and intensity of the waves are measured to build up a picture of the interior of the sample. This type of testing is often used to test for failure mechanisms such as: matrix cracking, fibre pull-out, breakage and delamination. (Liu, et al., 2012). The disadvantages of this type of testing include the expense and the 'noise', the acoustic interference that the machinery can detect. Its advantages lie in its ability to detect failure mechanisms and its repeatability (JALILI, et al., 2010). The experiment done by JALILI *et al.* was to find the elastic modulus using acoustic emission, the set up they used is shown in figure 8.

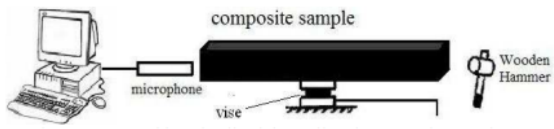

Figure 8: In the experimental setup shown by JALILI et al. A sample was held in a vice and then stimulated using a wooden hammer. The acoustic waves travelling through the sample were then measured using a microphone. (JALILI, et al., 2010)

They succeeded in successfully measuring the elastic modulus to a reasonably high degree of accuracy in comparison to mechanical methods. (JALILI, et al., 2010)

The technique that will be used to measure elastic modulus in this study utilises the phenomena of resonance. Once the frequencies are found in which resonance occurs, the elastic modulus can be found using the method described by Didier Perrin *et al.* A formula is derived using assumptions made about an oscillating beam and the boundary conditions of a cantilever to discover the Young's modulus of fibres. This formula will apply to the carbon fibre rods being used in this study. Thus using resonance discovered from the rods as described above, elastic modulus can be discovered using this formula. (Perrin, et al., 2007)

In this study we will be assessing the accuracy of this non-destructive testing on carbon rods and its advantages and inaccuracies. Through using this method of testing we find both the resonance and the elastic modulus, providing two pieces of key data when considering materials for particular uses.

Conclusion

The literature reviewed from the three areas of research focused upon (background of carbon fibre, resonance and elastic modulus) has shown itself to be important to the undertaken study. The evaluation of carbon fibre production has shown that the use of carbon fibre is becoming more widespread, also that the calculation of its elastic modulus is essential, although sometimes difficult due to its composite nature. This shows that we need to apply different methods to calculate its modulus. The research into resonance demonstrated its uses aswell as the different methods to calculate it and each methods shortcoming, such as interference and problems with the dimensions of specimens. The literature on tensile testing is well documented and there are many standards that industries must adhere to, as shown by reading the literature by ATSM.

There were sometimes issues finding literature that linked these areas of research although there has been cases where the research converged, as in the paper by Perrin *et al.* This study aims to develop on these links and continue to link these fields, also to develop the use of resonance to calculate the elastic modulus.

Acknowledgements

The authors would like to thank Mr Ben Reed and Mr Nathan Davis for their useful advice, also to thank the researchers whose papers have been mentioned in this document for making their research available.

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Project Plan: Characterization of the Resonant Frequencies of Carbon Fibre Composites

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Project Outline

This project plan is designed to organise experimental proceedings throughout the remainder of the project; this study will be supervised by Dr Martin Wilding. The aim of the study is to demonstrate the relationship between resonant frequencies and elastic constants of materials; and ascertain the accuracy of methods used to measure Young's modulus. In particular this study will measure the resonant frequencies of mechanically stimulated Carbon rods and use the data found to calculate the elastic constants, the calculation will involve an application of Hooke's law. The experimental data required will be the resonant frequencies of different diameter carbon rods; this will be obtained using a high speed camera to capture the maximal vibration at the free end of the beam, thus identifying resonance. A clamp will also need to be created to attach the samples onto the mechanical oscillator (a diagram is shown below).

The experimental time taken is not expected to be longer than two weeks, the initial week for preliminary testing and the second week to successfully capture the resonance on the high speed camera. The samples are simple to prepare with only needing to be cut to a specific length depending upon diameter. The work area required in the laboratories is minimal.

External Resources Required

- Carbon Rods for testing required from 17/02/2014 (Already received)
  Ordered from: http://www.easycomposites.co.uk/Category/carbon-fibre-rod-1m.aspx

The samples ordered consisted of the 1m carbon rods of varying thickness's from 0.28-4mm

- Clamp required to be made before 17/02/2014 (This has been requested for construction)
- Equipment for sizing rods *(scissors and a junior hacksaw)* before 17/02/2014 (Already obtained)

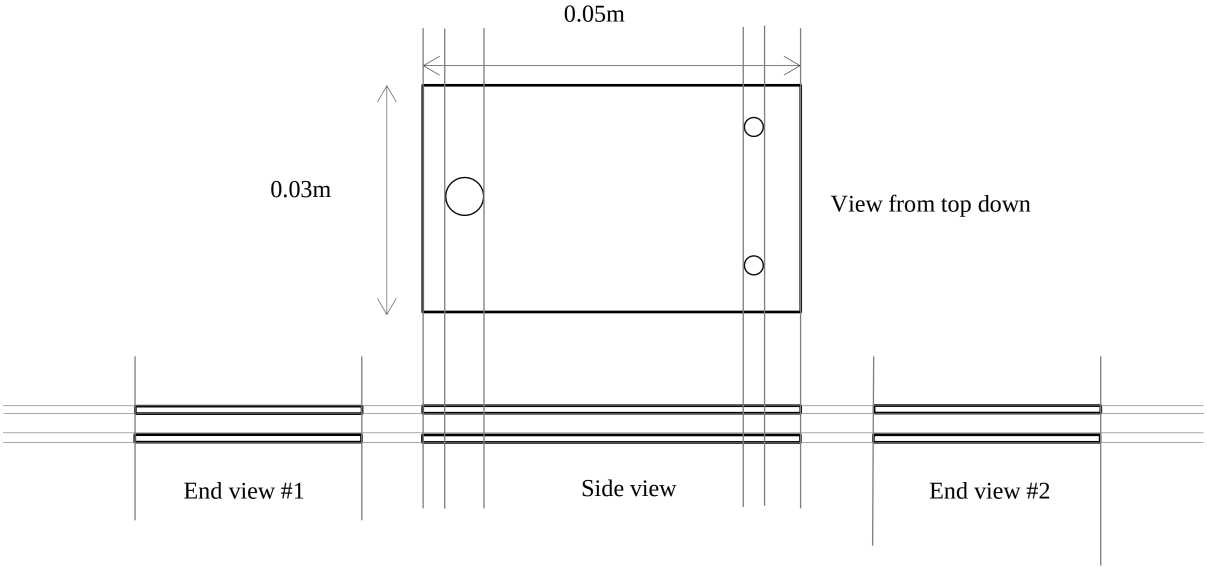
Internal Resources for experimental procedure (required from 17/02/2014)

- Mechanical Vibrator SG-9324 (Oscillator)
- Function Generator TF810 200MHz
- Signal Generator A.F Type J2
- Oscilloscope OS-5020 20Mhz
- Clamp Stand
- Ruler
- High Speed Camera
- Strobes
- Screen
- Work area (Part 1 lab/ Optics lab)

Project Milestones

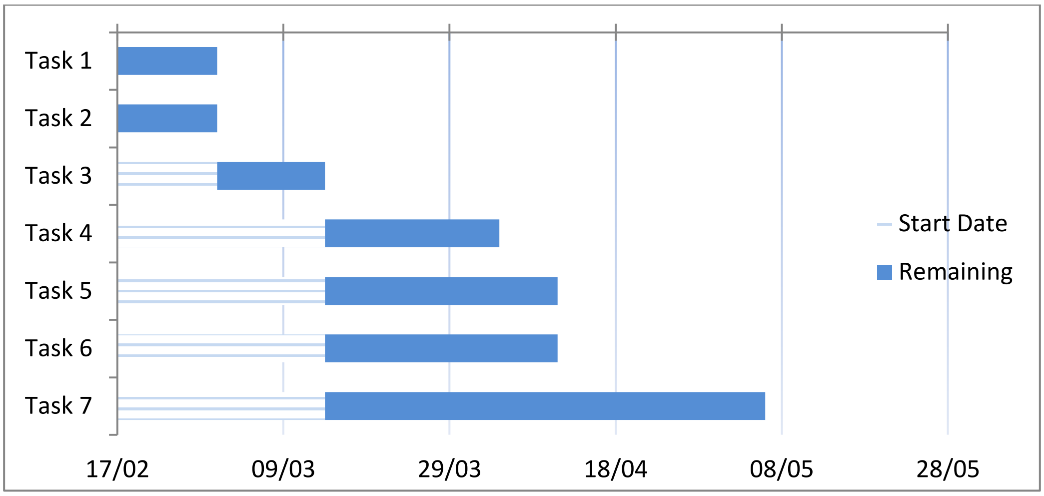
Number	Task	Target date	Completed
1	Cut carbon samples to size	1st of March	
2	Perform initial experiments to test setup of procedure and requirements for lighting and high speed camera	1st of March	
3	Experimentation on Carbon Rods to gather results – Use of high speed camera to capture video of oscillating rods.	Week beginning 10th of March	
4	Draft of topics for presentation so that the two presentations are discussed.	Week beginning 31st of March	
5	Presentation	Week beginning 7th of April	
6	1st draft of final report for inspection	Week beginning 7th of April	
7	Submission of final report	Tuesday the 6th of May	

Design plan of Clamp



The above diagram shows a design of the clamp that is to be made for holding the samples to be tested. It shows two metal plates with three holes drilled through them; the larger hole is to attach the clamp to the mechanical oscillator, the sample will be held between the plates at the opposing end to the oscillator. It's will be tightened into the clamp with nuts and bolts through the two remaining holes. Dimensions may vary dependent upon the materials available to the technician manufacturing the clamp.

Gantt chart for timescale



The above chart displays the tasks categorised in the table above and shows the sequence in which they must be done and the date they must be completed by.