Analysis of the Ultrasonic Cautery

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DECLARATION

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

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Lee Han Wei

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Abstrak

Analisis cautery ultrasonic

Cautery terma merupakan peranti yang digunakan oleh paker bedah untuk mengantikan pisau bedah untuk berhenti berdarah berlaku semasa pembedahan. Cautery yang paling popular digunakan pada masa kini ialah cautery electric. Bagi cautery elektrik, reka bentuk cautery terma pada masa kini mengalami issues kesalmatan semasa ia digunakan oleh doktor. Salah satu cara penyelasaiannya ialah dengan menganti penggunaannya dengan cautery ultrasonic. Kedua-dua jenis cautery telah dibantingkan menunjukkan cautery ultrasonic mempunyai kelebihannya dalam aspek keselamatan dan memberi kesan sampingan yang lebih rendah terhadap pesakit selepas pembedahan dijalankan walaupun cautery elektrik mempunyai kelebihan seperti harga yang lebih murah, lebih ringgan dan lebih mudah untuk penyelenggaran.

Informasi mengenali teknology cautery ultrasonic tidak dapat dicarikan dari mana-mana sumber. Oleh itu, penyelidikan atas teknologi dan prinsiple bagi cautery ultrasonic adalah penting sebelum reka cipta cautery yang lebih baik dapat dijalankan. Satu review telah pada reka ciptaan cautery ultrasonic telah dilakukan telah menunjukkan kebayakkan cautery ultrasonic perlu beroperasi pada 20kHz ke 60kHz.

Piezoelektrik digunakan sebagai actuator untuk menghasilkan kekerapan ultrasonic kerana ia lebih banyak digunakan untuk menghasilkan kekerapan ultrasonic. Sistem kawalan untuk mengawal penggerak piezoelektrik telah disediakan untuk mengawal penggerak piezoelktrik. Prinsip yang terlibat dalam penggerak piezoelectric dianalisiskan. Selepas itu, amplifikasi mekanasi untuk membesarkan jarak amplitud juga dikajikan.

Resonator dan sonotrode yang didapati sesuia untuk dijadikan mekanasi amplifikasi akan telah dikajikan dan dianalisikan dengan menggunakan finite element analisis (FEA). Resonator telah dibuktikan dapat menjadi amplifikasi mekansi. Finite element analysis (FEA) yang dilakukan juga telah membuktikan fungsinya.

Abstract

Analysis of an ultrasonic scalpel

Thermal cautery is a device used by surgeon in surgical operation to replace scalpel and to mitigate bleeding. The most popular cautery that used today is electrocautery. For the electrocautery, the current design of the thermal cautery facing safety issues while using it. One of the solution is introducing the ultrasonic technology in cautery. Both the usage of the electrocautery and ultrasonic cautery is compared show that the ultrasonic cautery has its advantages of safety features and has lower side effect to the patient after the surgery although the electrocautery has the advantages of cheaper in price, lighter and easier in maintenance.

The information on the technology and working principle on the design of ultrasonic cautery does not given in any source thus the research and analysis on the technology and working principles of an ultrasonic cautery is important before any design work or improvement can be done. A review on the current design of the ultrasonic cautery has been done and it shows that most ultrasonic cautery need to be operate between 20kHz to 60kHz.

Piezoelectric is used as the actuator to produce ultrasonic frequency due to its popularity in usage and has relative simpler usage. The control system to control the piezoelectric actuator is set up to control the piezoelectric actuator. The principles involve in a piezoelectric actuator is studied and experimented. Then amplification mechanism to amplify the amplitude of a piezoelectric actuator which has only $5\mu m$ is studied and analysed.

Resonator and sonotrode are found to be more suitable to be used as the amplification mechanism. Therefore, both the resonator and sonotrode are studied and analysed using both experiment and finite element analysis (FEA). The resonator has proved to be work as able the amplification mechanism since it will amplify the stroke or amplitude of the resonator by at least twice. The finite element analyse (FEA) on the sonotrode has been done also in order to prove its functionality.

Chapter 1: Introduction

1.1 Background study

Cauterization is a medical practice where heat is used during surgery to burn off a portion of tissues to close the blood vessel and mitigate bleeding. Thermal cautery device is the device used in thermal cauterization and it is already exist in the market. However, the current design of the thermal cautery device facing some safety issue where it will have injured both patients and the surgeon during the surgical process. They can cause burn injury and even gene mutation. Therefore, the thermal cautery need to be redesign and improve. (Peter WSoballe 1998) Therefore it essential to overcoming this shortcomings by either redesigning the cautery or introducing a new technology.

One of the easiest way to mitigate the safety issues faced by most thermal cautery especially the thermal cautery is using the ultrasonic cautery. The ultrasonic cautery has its own advantages over the other type of thermal cautery including it's safer and it has lower rate of post-operative complication compare to other types of cautery.

There are a lot of design of the ultrasonic cautery available over the market, however these designs does not provide a detailed working principle on how does the ultrasonic technology being applied in the design of the ultrasonic cautery. Therefore, a systematic study and analysis is required so that the technology and the working principles of the ultrasonic cautery can be understand and comprehended. The understanding of the technology of the ultrasonic cautery since the knowledge can be used to improve and design a better ultrasonic cautery. Furthermore, even the most contemporary and sophisticated ultrasonic cautery that is available in the market has its own disadvantages. The work on design and improving a better cautery or ultrasonic cautery should never been stop. While before any design or improving work can be done on the ultrasonic cautery, it's crucial to fully understand how it work first.

Therefore, both the pros and cons of the electrocautery and ultrasonic cautery will be reviewed in this project. Then the technolgy and working principle of an ultrasonic cautery will be studied and research using both experiment and finite element analysis (FEA). The finite element analysis will be done using ANSYS Mechanical APDL.

1.2 Problem Statement

The piezoelectric actuator is used as a device to produce ultrasonic frequency in the ultrasonic cautery. However its amplitude is too small to be apply in an ultrasonic cautery. Therfore it need an amplification system to help it to ampify the amplitude until it achieved the desired amplification. The sonotrode is an important motion amplification device for ultrasonic cautery. Therefore, it is used to

1.3 Objective

To study and analyse the technology and working principles of the sonotrode for ultrasonic cautery.

1.4 Scope of the project

Current available design of sonotrode for ultrasonic amplification together with the piezoelectric is studied. The amplification mechanism to amplify the amplitude of the piezoelectric actuator is calculated using finite element analysis (FEA). A basic experiment to measure piezo displacement is used for the control system of the piezoelectricity.

1.5 Thesis outlines

This thesis is divided into five chapters; introduction, literature review, methodology, results and discussion, and conclusion. Chapter One consists of background study, problem statement, motivation of work, objectives and scope of the research. Chapter Two describes a comprehensive literatures on the thermal cautery device over the past years. Chapter Three presents the theory and methodology of current work and the results are discussed in Chapter Four. Finally, Chapter Five describes the conclusion of this research and recommendation for future work.

Chapter 2: Literature Search

2.1 Review of current available thermal cautery devices

Ultrasonic cautery also called harmonic cautery or harmonic scalpel. One of the latest design of the ultrasonic cautery is shown in figure 2.5. It is a light, self-contained, hand held surgical scalpel with an ultrasonic power source within the housing. The ultrasonic power are provided by an ultrasonic driver and the ultrasonic vibration are moved to the blade to which result in cutting features by lateral motion as well as by reciprocating motion.

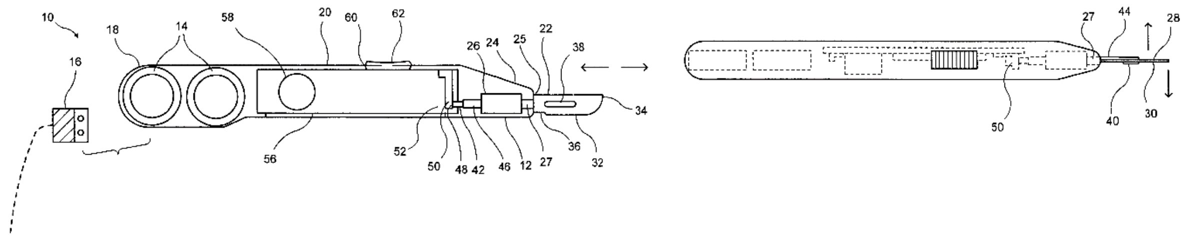


Figure 2.5: Ultrasonic scalpel. (Warren R. Jewett, 2001) (Jewett 2001)

The advantages of this ultrasonic scalpel is that it is portable and light weight but its shortcoming is that it has exposed blade which is dangerous. A most sophisticated design of the ultrasonic cautery is the cordless hand-held ultrasonic cautery cutting device (Kevin and Thomas). It has all the advantages that can overcome the aforementioned shortcoming. The cordless hand-held ultrasonic cautery has a disposable head and it has handle which will help in easier manoeuvrability. It has safety features like covering blade which will help avoid medical error. However, no matter how sophisticated and contemporary a design is, there will be some shortcoming and the major shortcoming of the cordless ultrasonic cautery is it is heavy and thus the surgeon may not handle it long enough in the surgical operation and may cause injuries. Besides, the cautery is also the most expensive in the market.

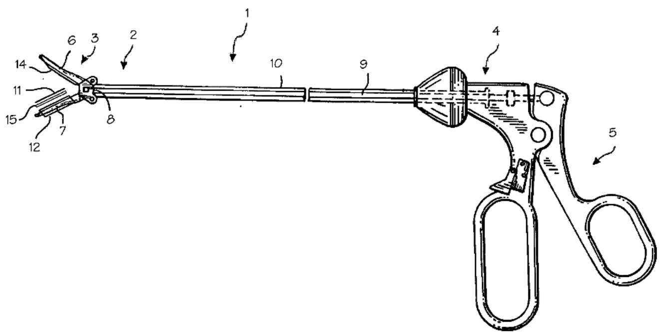


Figure 2.6: Cordless Hand-Held Ultrasonic Cautery Cutting Device (Kevin and Thomas) (Kevin W. Smith 2007)

2.3 Properties of an ultrasonic cautery

An ultrasonic cautery also called harmonic scalpel is a surgical instrument used to simultaneously cut and cauterize tissue. Ultrasonic technology is used in cautery by converting the ultrasonic energy to mechanical energy at the active blade. The main mechanism in the ultrasonic cautery is the active blade which will deliver high-grade frictional force while there is inactive arm to hold the tissues in position.

The ultrasonic cautery work by applying pressure on the targeted vessel and applying ultrasonic vibration to denature the hydrogen bonds to perform vessel coagulation. The transducer to produce the ultrasonic energy is normally the piezoelectric. (Dutta and Dutta 2016)

The ultrasonic cautery coagulates vessel or tissues at around 55kHz of ultrasonic energy transmitted between the instrument blades. The range of excursion of the active blade of the instrument when it vibrate in longitudinal direction against the inactive blade is 50-100μm. (Dutta and Dutta 2016) (Blackstone, Pickron et al.) (Lee, Kim et al. 2017)

2.4 Comparison harmonic scalpel and electrocautery.

There are several surgical that are emerging with the objective of reducing operation time, rates of surgical injuries, and post operative complication. Amongst them all, the ultrasonic cautery is the most popular that has used in many surgeries like cholecystectomy, colectomy, and glossectomy.

With the high frequency of 55kHz of wave vibration, the ultrasonic cautery able to facilitate target tissues concretion and degeneration to accomplish hemostasis. Normally, the ultrasonic cautery can cut off and seal the vessels with the diameter less than 5 mm. Compared with conventional monopolar electrocautery or silk thread ligation, the ultrasonic cautery is capable of simplifying surgical procedures and reducing operation time by one-step cutting and coagulation.

A more systematic review and meta-analysis to compare the surgical efficacy and postoperative recovery of the ultrasonic cautery with conventional electrocautery in the surgical operation has done show that the ultrasonic cautery has indeed safer and more effective technique with more short term advantages in open surgery. These advantages include shorter operation time, better hemostatic control and superior postoperative recovery. (Chen, Chen et al. 2014, Lee, Kim et al. 2017)

2.5 Application of the ultrasonic cautery

Electrocautery is the most common coagulating technique used for the preparation of patients for open-heart surgery. However it has a potential risk of serious pacemaker dysfunction in patients with implanted pacemaker. An alternative to the currently used technique for dissection of paced patient may be offered by ultrasonic scalpel (US).

The danger of using unipolar electrocautery in patients with pacemakers have been well described. In the experiment, even after the current precautionary guildlines are followed, catastrophic pacemaker failure still occurred. Bipolar electrocautery has been used to explant a patient's pulse generator with subsequent pacing via the patient's permanent leads with an external pacing device before the use of unipolar electrocautery. Unfortunately, bipolar electrocautery may not be as effective as unipolar electrocautery in establishing hemostasis, which can lead to wound hematoma and the potential for wound infection.

An ultrasonically activated scalpel was successfully used to explant two generators without causing electromagnetic interference on the surface electrocardiogram, pacemaker inhibition, or pacemaker reprogramming. Analysis by the explanted pacemakers' manufacturer demonstrated no adverse electrical effects. As shown in the experiment, an ultrasonically activated scalpel can be safely and effectively used in patients with preexisting pacemakers without the need for prior pacemaker explantation. (Epstein, Mayer et al. 1998)

In conclusion, the ultrasonic cautery is indeed suitable to be use in the open-heart reoperation of a patient with pacemaker and thus prove the significant of the ultrasonic cautery in medical field.

2.6 Design of sonotrode

A sonotrode is used to amplify the amplitude of ultrasonic vibration (usually from piezoelectric actuator). The issues involved in sonotrode design are material, shape, frequency, resonant length and gain. Proper design of the sonotrode is crucial so that the entire ultrasonic assembly tuned to the same frequency for transfer of maximum energy while amplifying the amplitude. In a complete sonotrode assembly, the transducer is mounted on the larger end of the sonotrode and the tool is mounted on the smaller end. It works on the principle which states that velocity of sound wave is directly proportional to decrease in cross-sectional area. Thus in order to amplify the amplitude, the wave entry area is made larger and the exit area is made smaller. (Tadvi, Pandey et al. 2015)

Generally, the sonotrodes are made of metals that have high fatigue strengths and low acoustic losses. The most important aspect of sonotrode design is a sonotrode resonant frequency and the determination of the correct sonotrode resonant wavelength. The wavelength should be usually integer multiple of the half wavelength of the sonotrode. The resonant frequency of sonotrode, which has simple geometrical shape can by determined analytically (cylindrical shape). For complicated geometrical shape, the resonant frequency is usually determined numerically using finite element method.

4.2 Comparison between cautery

Different type of cauterisation method will use in different surgical operation and all type of cauterisation has its own specific advantage. In designing a safe thermal cautery device, the focus the research on electrocautery and harmonic cautery. The main differences between unipolar cautery, bipolar cautery and harmonic cautery are compared in the table below.

Type of cautery / Devices Differences	Unipolar	Bipolar	Harmonic (Ultrasonic)
Working Principle	The current passes from the probe electrode, to the tissue and through the patient to a return pad to complete the electric current circuit.	The current only passes through the tissue between the two arms of the forceps shaped electrode (visualize the tip of a pair of tweezers.)	The scalpel surface cuts through tissue by vibrating in the range of 55,500 Hz. high frequency vibration of tissue molecules generates stress and friction in tissue, which generates heat and causes protein denaturation.
Advantages	- Can coagulate large surface.	- Use lower voltage - Better control over the target.	- can cut through thicker tissue - creates less toxic surgical smoke - offer greater precision
Limitation	- More likely to cause cautery burn	- Limited ability to cut and coagulate large bleeding areas.	- Can only coagulates as it cuts.

Table 4.1: Comparison between unipolar, bipolar and harmonic cautery. (Ammar Ismail 2017) (Epstein, Mayer et al. 1998, Cuesta 2001, Yehiel Ziv 2001, Kerim Bora Yilmaz 2011, Guclu Kaan Beriat 2012, Chen, Kallakuri et al. 2015, Lalgudi Dorairajan Prakash 2015, Lee, Kim et al. 2017)

Chapter 3: Theory and Methodology

3.1 Overview

In this chapter, the theory and working principles of the piezoelectric and its amplification mechanism will be discussed. The experiment set up to test the piezoelectric, the step in adopting finite element analysis (FEA) to the amplification mechanism and the formula including also will be explained and discussed.

3.2 Working Principles of the piezoelectric actuator

Most ultrasonic cautery used piezoelectric actuator to produce ultrasonic frequency. Piezoelectricity is a phenomenon in which electricity is created from pressure on piezoelectric actuator. Piezoelectrics either produce a voltage in response to mechanical stress (known as direct mode) or a physical displacement as a result of an applied electrical field (known as indirect mode). Due to these modes, piezoelectric materials have considerable use in both sensors and actuators and are often called “smart” or “intelligent” materials. One material in particular, lead-zirconate-titanate (PZT), has found prolific use for piezoelectric devices. Consequently, PZT is the ceramic material that makes up the bulk of piezoelectric actuator devices available on the market.

In an ultrasonic cautery, the function of a piezoelectric is to transmit the ultrasonic vibration to the scalpel so that the scalpel has enough ultrasonic energy to function as a cautery device. This can be achieved by controlling the piezoelectric so that it displaces longitudinally through its own axis. A stacked actuator is more suitable for this application since it can achieve higher displacement longitudinally. The displacement of a piezoelectric actuator can be calculated by using the equation (1999-2018):

$$\Delta h = n.\, d_{33}.\mathrm{V} \tag{1}$$

Where Δh is the displacement of the piezo, n is the number of stacks, V is the voltage supplied to the piezo and d_{33} is the piezoelectric constant.

In analysing and designing an ultrasonic cautery, frequency is an important aspect to control so that the ultrasonic cautery can have apprioprate ultrasonic frequency to be function as a cautery. The frequency can be controled by controlling the peak-to-peak voltage supplied to the piezoelectric. The equation that relate the frequency of the piezo and the peak-to-peak voltage supplied is(1999-2018):

$$I_{ave} = f.C.V_{pp} \tag{2}$$

Where I_{ave}= current, f=frequency of the sinulsoidal signal, C= capacitance of the piezo, V_{pp}=peak-to-peak voltage supply.

3.3 The characteristic of an ultrasonic cautery

Ultrasonic technology was firstly used in cautery approximately a decade ago with the objective of reducing the risk of injuries of traditional electrocauetry. (Blackstone, Pickron et al.) Ultrasonic cautery implement different method to mitigate bleeding. Unlike thermal cautery which implement high temperature to remove or close off blood vessel by means of cellular vaporisation (which is usually range from 600-700°C) to mitigate bleeding, the ultrasonic cautery mitigate bleeding by denaturing the protein by using ultrasonic vibration at a frequency of 55 500Hz with a vibratory excursion of 50 to 100μm. (Matthews, Nalysnyk et al. 2008, Dutta and Dutta 2016)

3.4 Experimental set up to contol the piezoelectric actuator

The working principle of the ultrasonic cautery is studied by seting up an experiment on the piezoelectric actuator.

The set up of the experiment is shown in figure 3.1 below. In the figure the system include a computer, a National Instrument module (including the NI compact data acquisition chasis, cDAQ-9174, NI sound and vibration input module, NI-9234 and NI voltage output module, NI-9263), a Physik Instrumente, PI voltage amplifier and a PI-010 piezo (with diameter 10mm and length 9mm).

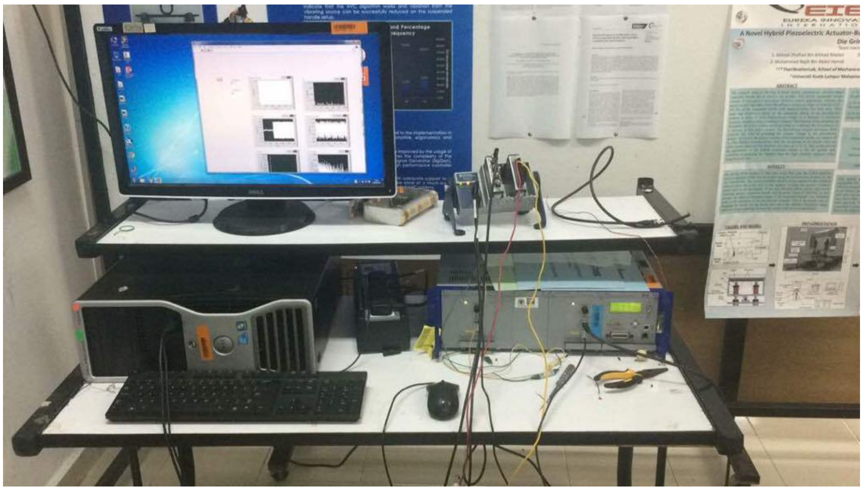


Figure 3.1: Set up of the piezoelectric actuator control system.

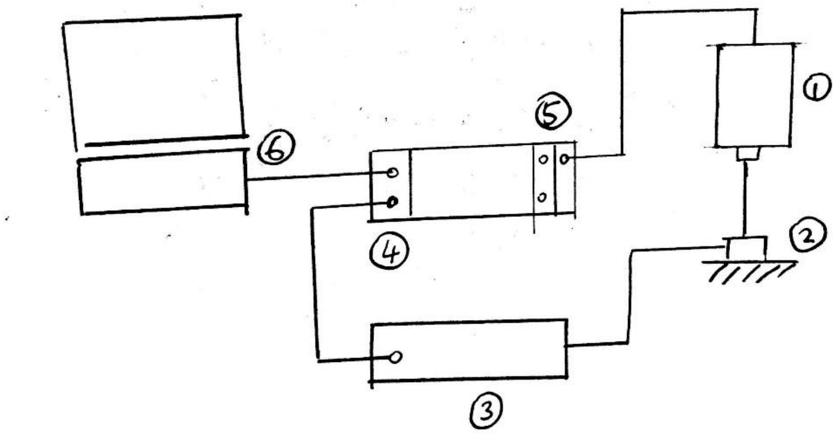


Figure 3.2: Schematic diagram of the piezoelectric actuator control system.

Respective labelling of the item in figure 3.2:

1. Keyence Laser Sensor
2. PI 010.00P piezoelectric actuator
3. Voltage amplifier
4. cDAQ-9174, NI sound and vibration input module
5. NI-9234 and NI voltage output module
6. A computer.

After all the apparatus have checked and set up properly, the block diagram programme as shown in figure 3.3 to control the outout voltage and the system is set using NI labview.

The function of this block diagram is to give sinulsoidal voltage output, to control the output voltage and to receive feedback data output from NI output module.

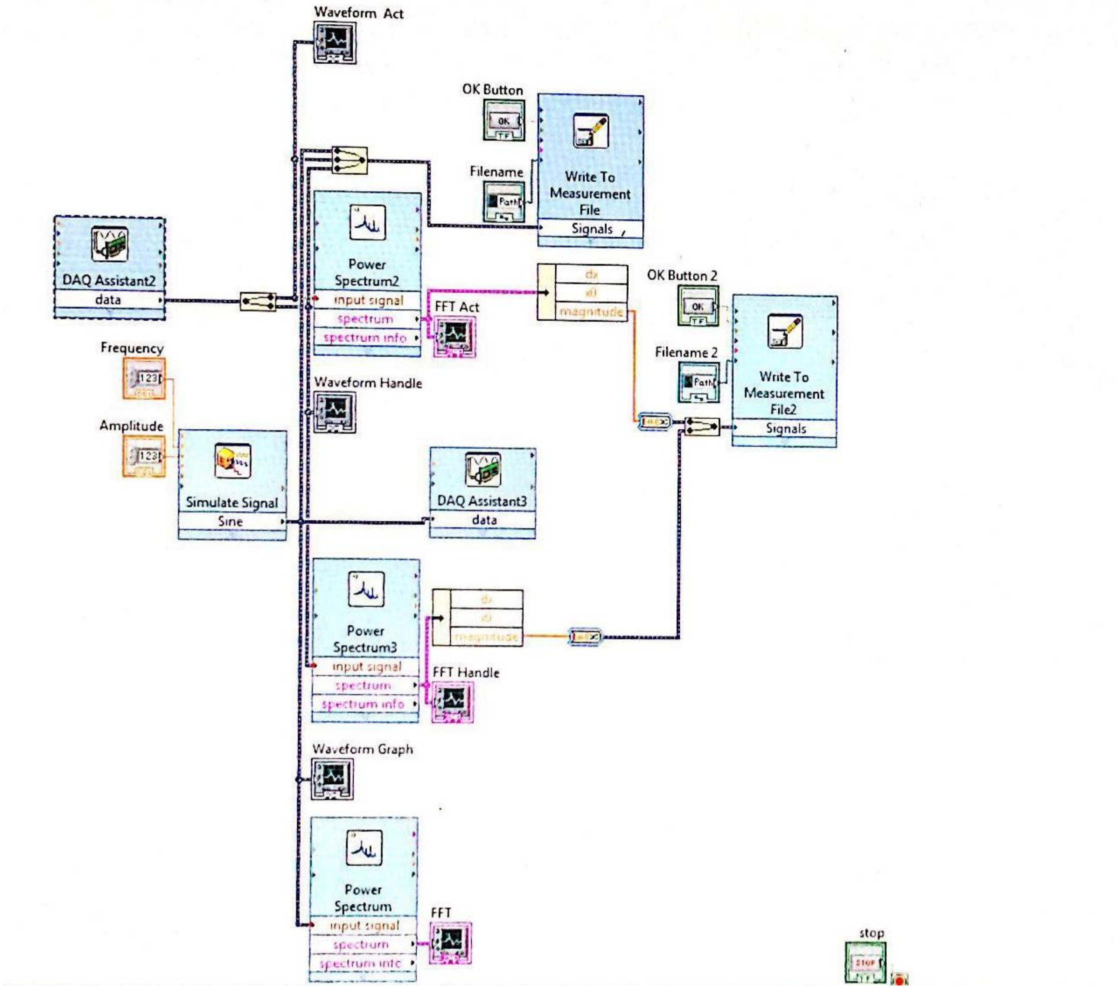


Figure 3.3: Block diagram set up using labview.

The range of the frequency input is set from 10 Hz to 55 000Hz. Then, the displacement of the piezoelectric is measured using Keyence laser sensor as shown in figure 3.4, the reading is then used to verify the theoritical value.

Figure 3.4: A keyence laser sensor

3.5 The amplification mechanism for the piezo stroke.

The requirement for ultrasonic cautery is that the actuator can generate stroke of 50 to 100μm at 55kHz. The piezoelectric actuator available in the laboratory is PI 010.00P piezo which can provide the 55kHz frequency but cannot achieve the required stroke of 50 μm. The PI 010.00P piezo can displace at maximun 5 μm, which is not enough for the piezoelectric actuator to function. Therfore, an amplification mechanism is required so that the ultrasonic cautery can travel at more than 50 μm of stroke.

There are several ways to amplify a displacement, as followed:

1. using a lever mechanism
2. using gears
2. using a resonator
3. using a sonotrode

Since the magnitude is in micron, it will be too small for a lever or gears mechanism. It is because the tolerance to built an appropriate lever mechanism or a gears mechanism on the piezoelectric actuator will be too small. The use of lever or gears mechanism in the small scale will also damage the mechanism easily when the mechanism is in high frequency vibration.

On the contrary, the resonator and the sonotrode does not need tolorance to work properly with the piezoelectric actuator to amplify the stroke of the piezoelctric actuator. Both the resonator and the sonotrode also suitable to be used to amplify small displacement such as in micron. Therfore, both the resonator and the sonotrode are more suitable to be used to the develop a amplification mechanism for the piezoelectric actuator. The sonotrode is widely used in ultrasonic machining. (Blackstone, Pickron et al.)

3.6 Determination of the geometry of the resonator based on analytical equation.

Resonator are extended objects that can experience resonance due to vibration inside them. It apply the concept of resonance where the vibrating system or external force drive another system so that the system will oscillate at the greater amplitude. It occurs when the vibrating system vibrate at the natural frequency of the system its act on.

In order to show the practically the concept of a resonator, a mild steel rod is used. The mild steel rod is attached on the piezoelectric actuator, when the piezoelectric actuator vibrate at the natural frequency of the mild steel rod, the mild steel rod will amplify the stroke of the piezoelectric actuator. Then the amplified displacement is measured. Finite element analysis (FEA) is carried out on the mild steel rod with piezoelectric actuator to know the amplified displacement of the piezoelectric actuator by the mild steel rod.

The realationship between the length and frequency required for a resonance to occur in a metal rod is given below(Talukdar 2016):

$$Natural\ frequency, \overline{\omega}_r = (2r-1) \cdot \frac{\pi}{2} \cdot \sqrt{\frac{E \cdot A}{m \cdot L^2}}\ ;\ \ r = 1,2, \ldots \tag{3}$$

Where r is mode of the natural frequency, E is the elastic modulus, A is the cross sectional area, m is the mass and L is the length of the rod.

The mild steel rod used in this experiment has elastic modulus, E = 210 GPa with radius, r = 4mm. The formula of the cross sectional area, A and mass, m is as followed.

$$Cross\ sectional\ area, A = \ \pi r^2 \tag{4}$$

$$mass, m = \rho \cdot (\pi r^2 L) \tag{5}$$

Substitue equation (4) and (5) into equation (3),

$$Natural\ frequency, \overline{\omega}_r = (2r-1) \frac{\pi}{2} \sqrt{\frac{E \cdot (\pi r^2)}{\rho \cdot (\pi r^2 L) \cdot L^2}}\ ;\ \ r = 1,2, \ldots \tag{6}$$

From equation (6), the formula become

$$Natural\ frequency, \overline{\omega}_r = (2r-1) \frac{\pi}{2} \sqrt{\frac{E}{\rho \cdot L^3}}\ ;\ \ r = 1,2, \ldots \tag{7}$$

From equation (7), it is known that the natural frequency of the rod is independent of the radius.

The density of the mild steel rod, $\rho = 7860 kg/m^3$. Thus the length of the mild steel rod to achieve natural frequency of 55kHz can calculated.

3.7 Determination of the amplification of the resonator on the piezoelectric actuator using Finite element analysis (FEA).

After the required dimension of the resonator is determined. Finite element analysis (FEA) can be performed to analyse the amplification response of the resonator. The amplification response is in term of displacement. The FEA of the resonator is carried out using ANSYS Mechanical APDL. The step in applying finite element analysis (FEA) on the resonator is reported in Appendix 1.

3.8 Determination of the geometry of the sonotrode based on analytical solution.

The required performance of sonotrode is assessed by an amplification factor (Naď 2010) :

$$\vartheta = \left|\frac{A_1}{A_0}\right| \quad (8)$$

Where A_0 is the amplitude of input end of sonotrode and A_1 is the amplitude of output end of the sonotrode.

The governing equation of longitudinal vibrating sonotrode with variable circular cross-section

S(x), which is valid for 1D continuum (thin elastic bar), is expressed in the form

$$\frac{\partial^2 u(x,t)}{\partial t^2} = c_p^2 \left[\frac{1}{S(x)} \cdot \frac{\partial S(x)}{\partial x} \cdot \frac{\partial u(x,t)}{\partial x} + \frac{\partial^2 u(x,t)}{\partial x^2}\right] \quad (9)$$

Where x is the coordinate in the longitudinal direction,

$u(x,t)$ is the longitudinal displacement of cross-section,

$S(x) = \pi(r(x))^2$ is the cross-sectional area,

$r(x)$ is the radius of circular cross-section,

$c_p = \sqrt{E/\rho}$ is the velocity of the longitudinal waves in 1D continuum,

E is the Young’s modulus of sonotrode material,

ρ is the density of sonotrode material.

For a free sonotrode vibration of cylindrical shape (r(x)=r) is described by wave equation

$$\frac{\partial^2 u(x,t)}{\partial t^2} = c_p^2 \cdot \frac{\partial^2 u(x,t)}{\partial x^2} \quad (10)$$

From the solution of equation (10), the natural frequency of the sonotrode with cylindrical shape (r(x)=r) can be known,

$$natural\ frequency\ of\ the\ k^{th}\ mode\ shape, f_{0k} = \frac{k}{2l_0} \cdot \sqrt{\frac{E}{p}} \quad (11)$$

In order to achieve the desired effect on ultrasonicmachining, only the first twomode shapes of sonotrode are used, i.e. for k = 1 so-called “half wave” shape and k = 2 “wave” shape. From equation (11), the length, l_0 of the cylindrical rod can be known. The radius of the cylindrical rod however does not have any relationship with the frequency, thus it doesn’t affect the analysis on the amplification of the amplitude. This can be shown from the relation between the amplification factor, ϑ_k and the slenderness ratio, δ as shown in figure 12, this is the result obtain from finite element analysis (Naď 2010). Where slenderness ratio is defined as

$$\delta = \frac{d_0}{l_0} \tag{12}$$

Where d_0 is the diameter of the rod and l_0 is the length of the rod.

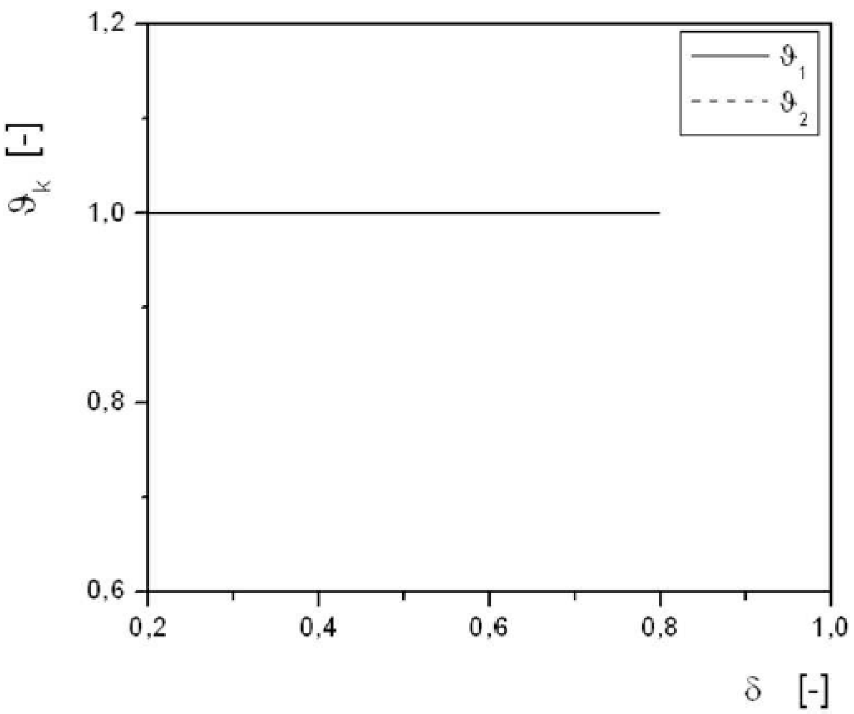


Figure 3.14: Graph of amplification factor, ϑ_k against the slenderness ratio, δ. (Naď 2010)

Fihure 3.14 shows the relationship between amplification factor and slenderness ration that relates to diameter of the rod. The analytical determination of mode shapes and the natural frequencies of cylindrical shape of sonotrode is relatively simple. Analytical determination of these parameters for non-cylindrical shapes is more complicated. The non-dimensional resonant frequencies for different geometrical shapes of the horn are defined as

$$\theta_k = \frac{f_k}{f_{0k}} \tag{13}$$

Where f_k is the k^{th} natural frequency of analysed horn,

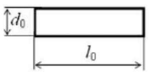
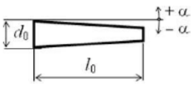
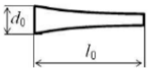
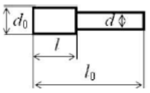
f_{0k} is the k^{th} natural frequency of cylindrical sonotrode shape for corresponding slender-ness ratio.

The value of resonant frequency of corresponding geometrical horn shape is determined using following equation

$$f_k = \theta_k \cdot f_{0k}$$

$$= k \cdot \frac{\theta_k}{2l_0} \cdot \sqrt{\frac{E}{\rho}} \tag{14}$$

Various sonotrode shape and geometrical parameter can be defined as shown in table 1.

Sonotrode Shape		Slenderness Ratio	Shape Parameters	Shape Function
cylindrical			–	$r(x) = r = \frac{d_0}{2}$
tapered			$\alpha \in \langle -5°; 5° \rangle$	$r(x) = \frac{d_0}{2}(1 + l_0 \tan(\alpha))$
exponential		$\delta = \frac{d_0}{l_0}$	$a \in \langle 0.3; e \rangle$	$r(x) = \frac{d_0}{2} a^x$
stepped			$\eta = \frac{l}{l_0}$ $\eta = \{0.25; 0.5; 0.75\}$	$r\{x \in \langle 0; l)\} = \frac{d_0}{2}$ $r\{x \in (l; l_0\rangle\} = \frac{d}{2}$

Note: d_0 – diameter on input side of sonotrode, d – step changed diameter, l_0 – length of sonotrode.

Table 3.1: Geometrical parameters of sonotrode shapes. (Naď 2010)

The steps to find the dimensions of sonotrode is as followed, the steps will take tapered sonotrode as an example:

1. Since the amplification of amplitude is the main concerned, the graph of amplification, ϑ against tapered angle of the sonotrode, α is analysed and the incline angle, α where maximum amplification is achieved is chosen.

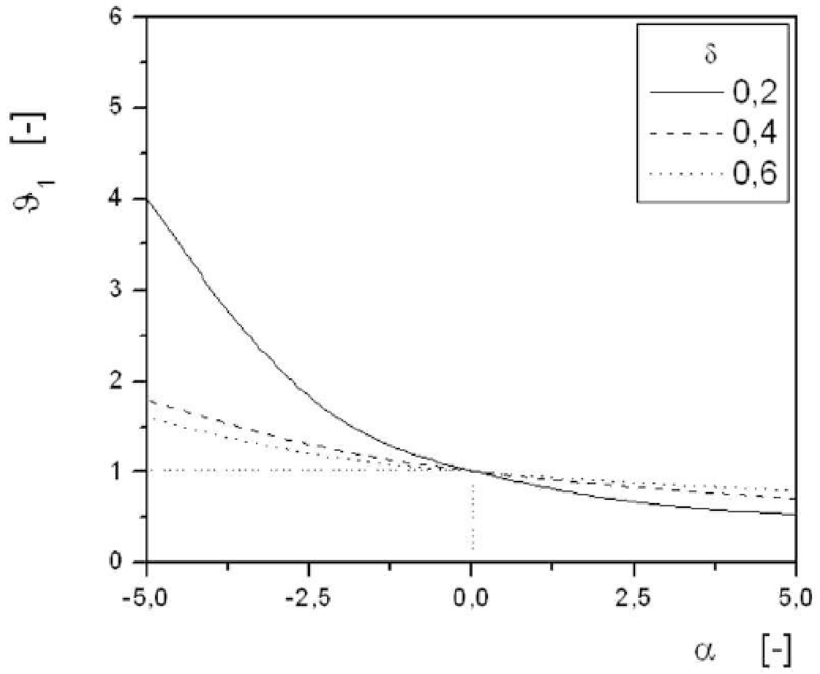


Figure 3.15: Graph of amplification, ϑ against incline angle of the sonotrode, (Naď 2010)

2. Then, the length of the tapered sonotrode is find using the graph of non-dimensional frequencies, θ against incline angle, α.

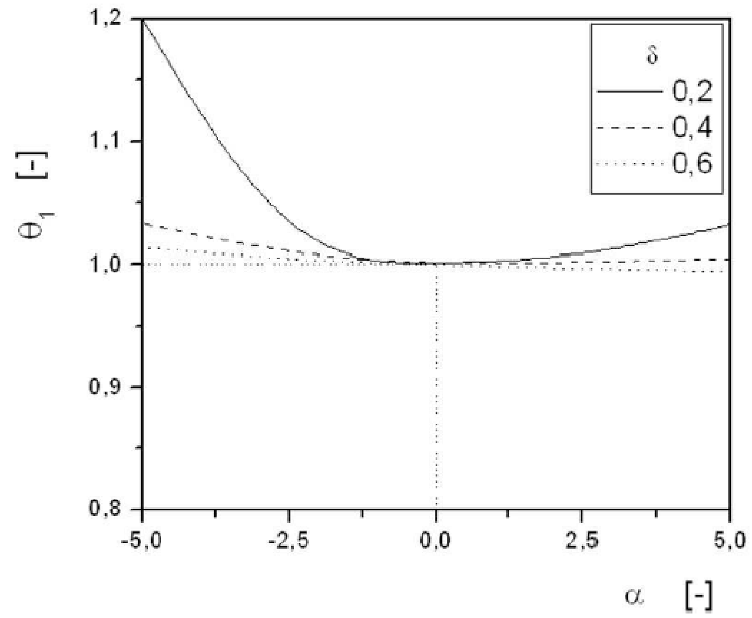


Figure 3.16 : Graph of non-dimensional frequencies, θ against incline angle, α. *(Naď 2010)*

3. From the non-dimensional frequency, θ the length of the tapered sonotrode required can be calculated from the equation (14).

4. The diameter of the input side of the sonotrode can be calculated from the slenderness ratio.

5. Then, the required shape of the sonotrode is known and is validated using finite element analysis.

3.9 Determination of the amplification of the sonotrode on the piezoelectric actuator using Finite element analysis (FEA).

After the required dimension of the sonotrode has been determined. Finite element analysis (FEA) can be performed to analyse the amplification response of the sonotrode. The amplification response is in term of displacement. The FEA is run on the resonator using ANSYS Mechanical APDL. The step in applying finite element analysis (FEA) on the resonator is as shown in Appendix 2.

Chapter 4: Result and discussion

4.1 Overview

In this chapter, the results obtained from the experiment for the piezoelectric are presented. The result of vibration analysis obtained from the ANSYS Mechanical APDL will also be presented. The results are then compared.

4.2 Stroke of the piezoelectric actuator at different voltage

From equation (1) and (2) the stroke of the piezo can be determined at different frequencies. The voltage supplied to the piezoelectric actuator can be known by measuring the voltage at piezo from the experimental set up. The current supplied to the piezoelectric, I_{avg} is 12mA from the voltage amplifier, the capacitance, C of the P010.00 piezo is 17nF. For piezoelectric operating at 55500Hz, the peak to peak voltage supplied to the piezoelectric actuator can be calculated. From equation (2),

$$I_{ave} = f.C.V_{pp} \tag{2}$$

$$V_{pp} = 12.7V$$

At $V = 1000V$, the stroke of the piezoelectric actuator is $5\mu m$. From the equation (1), the stroke of the piezoelectric actuator at 55500Hz can be known.

$$\Delta h = n.d_{33}.\mathrm{V} \tag{1}$$

$$\Delta h = 0.0635\mu m$$

Thus the stroke of the piezoelectric actuator at 55500Hz is $0.0635\mu m$. This result is validated using the experiment set up to measure the stroke of the piezoelectric actuator. The stroke of the piezo is measured using laser sensor and the signal is then taken at different frequency, the result is as shown below:

Frequency (Hz)	Stoke (μm)	Stroke from theoretical calculation (μm)
10	4.4	5.00
50	4.2	5.00
100	4.5	5.00
500	4.6	5.00
1000	3.0	3.53
2000	1.5	1.76
3000	1.0	1.18
4000	N/A (the sensor can't detect)	0.88
5000	N/A	0.71
10000	N/A	0.35
50000	N/A	0.071
55000	N/A	0.064

Table 4.2: Result of the measurement form the control system set-up of the piezo.

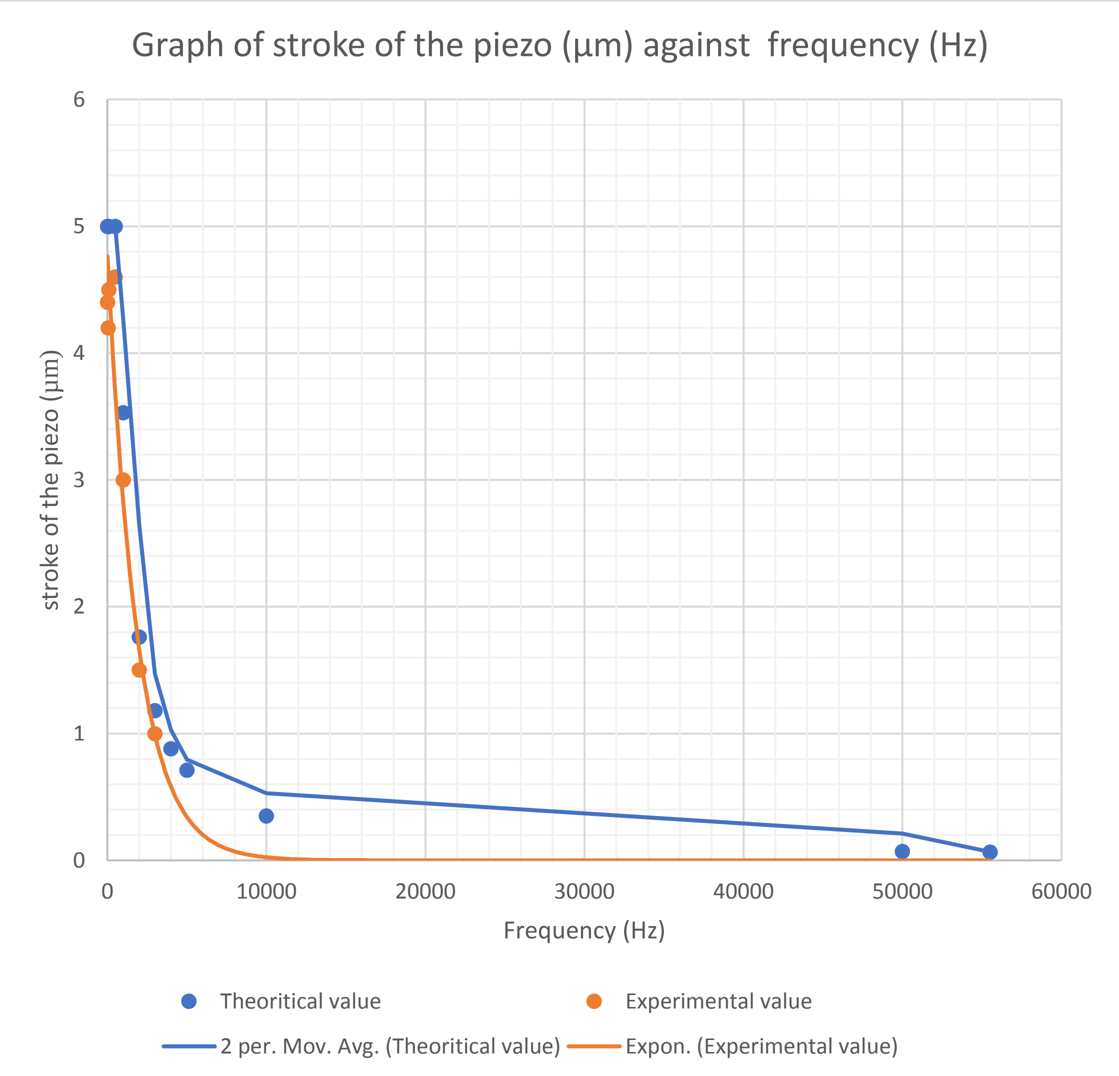


Figure 4.1: Graph of stroke of the piezo (μm) against frequency (Hz).

From the experimental results, it can be shown that the trend matched well. The differences is caused may be by the noise in the signal send to the piezoelectric. Furthermore, the stroke of the piezoelectric actuator cannot be detected when its frequency is more than 3000Hz, this is due to the limitation of the laser sensor used. It cannot detect the dynamics displacement less than 1 μm.

From equation (1) and (2), the frequency of the piezoelectric actuator is 3530Hz when the stroke is 1 μm. For the frequency of the piezoelectric actuator more than 3530Hz (thus less than 1μm for the stroke, the laser sensor cannot detect. Therefore the laser sensor cannot detect any change in the piezo when the frequency of the piezoelectric sensor is 55000Hz. (which will theoretically has 0.064μm of stroke.)

Furthermore, it is noticed that the stroke of the piezoelectric actuator remain at 4 to 5μm when the frequency of the input voltage range from 10 to 500Hz. This is due to the maximum stroke that can be travelled by the piezoelectric actuator is only 5μm. Besides, the maximum peak-to-peak voltage that can be supplied by the piezoelectric actuator is 1000V. From the equation (1) and (2), when the frequency of the input voltage to the piezoelectric actuator is less than 700Hz, the peak-to-peak voltage needed will be greater than 1000V which cannot be supplied by the voltage amplifier.

For a ultrasonic cautery to be functioning, its end blade need to vibrate at around 55000Hz with displacement range between $50\mu m - 100\mu m$. (Dutta and Dutta 2016) However, the P010.00 piezoelectric actuator can travel at stroke maximum 5 μm. While at the frequency 55000Hz, the stroke of the P010.00 piezoelectric actuator is only 0.064 μm, which is far less than the required displacement range of the ultrasonic cautery. Therefore, suitable amplification mechanism is required so that the stroke of the piezoelectric actuator can be amplified to the required displacement range. The amplification mechanism used will be resonator and sonotrode.