Design of a Ultrasonic Harmonic Scalpel Circuit for Precise Tissue Cutting

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Abstract: This paper presents the design and optimization of a low-cost ultrasonic harmonic scalpel circuit aimed at achieving precise tissue cutting with minimal thermal damage. The study involved experiments to optimize blade geometry, ultrasonic frequency, and power settings to enhance cutting efficiency and reduce collateral tissue damage. The research underscores the importance of fine-tuning these parameters to maximize surgical precision while minimizing postoperative complications. The developed circuit lays the groundwork for next-generation ultrasonic surgical tools tailored to specific tissue types and surgical applications, offering potential advancements in surgical precision and patient outcomes.

1 INTRODUCTION

Surgical procedures have witnessed significant advancements with the introduction of ultrasonic harmonic scalpels, which utilize ultrasonic vibrations to achieve precise tissue cutting and coagulation. These devices offer enhanced surgical precision, reduced blood loss, and faster recovery times compared to traditional surgical tools. However, the high costs associated with ultrasonic harmonic scalpels have limited their widespread adoption in medical practice. To address this barrier and make this technology more accessible, this study focuses on designing a low-cost ultrasonic harmonic scalpel circuit without compromising efficiency. The work aims to determine the resonant frequency range of the ultrasonic transducer, design and test a PCB-based ultrasonic generator circuit, integrate the transducer with the circuit, and ensure the transfer of vibrations for precise tissue cutting and cauterization. By optimizing blade geometry, ultrasonic frequency, and power settings, the research seeks to enhance cutting efficiency while minimizing collateral tissue damage. The ultimate goal is to develop a cost-effective solution that maintains surgical precision and improves patient outcomes in various surgical applications. (Massarweh, et al., 2020), (Li, et al., 2023)

This paper presents the design and optimization process of the low-cost ultrasonic harmonic scalpel circuit, highlighting the importance of fine-tuning parameters to achieve optimal performance. The outcomes of this study have the potential to pave the way for the development of next-generation ultrasonic surgical tools tailored to specific tissue types and surgical requirements. By addressing the cost barrier associated with ultrasonic harmonic scalpels, this research contributes to advancing surgical technology and improving healthcare delivery. Ngo, et al., 2020), (Smith, et al., 2019)

2 METHODOLOGY

2.1 Introduction

The ultrasonic harmonic scalpel has indeed ushered in a new era in surgical technology, offering a plethora of benefits that have transformed the landscape of modern surgical practice. Its innovative design allows for the simultaneous cutting and coagulation of tissues, a feat previously unattainable with traditional surgical instruments. This dual functionality not only streamlines procedures but also significantly reduces the risk of intra-operative bleeding, a common concern in many surgeries. One of the key mechanisms behind the effectiveness of the

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ultrasonic harmonic scalpel lies in its ability to convert electrical energy into mechanical vibrations. This unique process enables surgeons to achieve precise tissue dissection while minimizing trauma to surrounding structures. As a result, patients experience faster healing times and reduced postoperative complications, leading to shorter hospital stays and quicker return to normal activities. Furthermore, the precise haemostasis achieved by the scalpel enhances surgical visibility, providing surgeons with a clear field of view to perform intricate procedures with unparalleled accuracy. This improved visibility is especially crucial in delicate surgeries where precision is paramount, such as neurosurgery and laparoscopic procedures. The widespread adoption of the ultrasonic harmonic scalpel across various surgical specialties underscores its versatility and effectiveness in optimizing patient care and outcomes. From general surgery to plastic surgery, this advanced tool has become indispensable in the hands of skilled surgeons, revolutionizing the way surgeries are performed and ultimately improving the quality of life for countless patients worldwide. As technology continues to evolve, the ultrasonic harmonic scalpel stands as a shining example of innovation in healthcare, paving the way for even greater advancements in surgical practice. (, (Jones, et al., 2017), Garcia, et al., 2018), (Lee, et al., 2019)

2.2 Functionality of the Ultrasonic Harmonic Scalpel

The ultrasonic harmonic scalpel is a remarkable advancement in surgical technology, designed to enhance precision and minimize tissue damage during surgical procedures. It operates by converting electrical energy into mechanical vibrations, utilizing ultrasonic frequencies to cut and coagulate tissues with remarkable precision. The scalpel consists of several key components, including the power supply section, scalpel unit, and vibrational heat production mechanism. The power supply section converts standard mains power supply into the required voltage for the device, ensuring consistent performance. The scalpel unit, comprising a handpiece and blade tip, is responsible for transmitting mechanical vibrations to the tissue, enabling precise dissection and coagulation. Vibrational heat production plays a crucial role in tissue cutting by generating frictional heat at the blade tip, facilitating haemostasis and minimizing bleeding. Through meticulous design and engineering efforts, the ultrasonic harmonic scalpel offers surgeons a powerful tool to improve surgical outcomes and patient safety. Its integration of advanced technology and ergonomic design exemplifies the intersection of science and medicine in advancing surgical techniques.

The block diagram of the ultrasonic harmonic scalpel shown in Figure 1. encompasses several crucial components that work seamlessly together to achieve precise tissue dissection and coagulation. Below is a detailed description of each section:

2.2.1 Power Supply Section

The power supply section is responsible for providing the necessary electrical energy to the ultrasonic harmonic scalpel. It begins with a transformer that converts the standard mains power supply from 220 volts at 50 Hz to the required voltage of 110 volts at 60 Hz. This step is essential to ensure compatibility with the electrical specifications of the device. After the voltage conversion, the power supply section may include additional circuitry to regulate and stabilize the output voltage, ensuring consistent performance of the ultrasonic generator circuitry.

This regulation is critical for maintaining the optimal operation of the scalpel unit and ensuring safety during surgical procedures.

2.2.2 Generator Circuit

Printed Circuit Board (PCB) was designed for the ultrasonic generator circuit. For making up the PCB, Proteus software was utilized. The PCB consists of dedicated input and output slots for connecting input supply and output respectively. First, the schematic of an ultrasonic generator circuit was designed to make a PCB. Using a schematic capture tap in the Proteus a PCB design was developed. The components were placed randomly upon the PCB, later all the scattered components were placed according to the input and output configurations. The diodes, choke inductors, and resistors were placed near the input slot.

2.2.3 Scalpel Unit

The scalpel unit is the physical component of the ultrasonic harmonic scalpel that comes into direct contact with the tissue during surgery. It consists of a handpiece that houses the blade tip and connects to the generator circuitry through a specialized cable. The blade tip of the scalpel unit is designed to focus the mechanical vibrations generated by the generator circuit, enabling precise tissue dissection and coagulation. This component was contributed by author 3.

Additionally, some scalpel units may include a cleaning transducer mechanism, typically in the form of a rod, which helps to prevent tissue build-up on the blade tip during prolonged use.

2.2.4 Transformers

The transformers were kept near the output slot of the PCB. As the transistors were sensitive to supply power, these were kept away from both the input and output slots of the PCB.

The working principle of the ultrasonic generator circuit is exactly like the working principle of switching mode power supply. In the PCB rectifier has been used to rectify the AC supply voltage into a DC voltage so that the rectified voltage would be supplied to the capacitors, and then these capacitors store the rectified voltage.

The main reason for storing the rectified voltage is to repair the voltage waveforms generated by the rectifier circuit used in the input section. The PCB design is shown in the below figures.

In the Figure 2 the secondary voltage of the transformer T1 amplifies the voltage generated by the FJP transistors. Other transformer just acts as a filter to the generated output waveform. To produce mechanical oscillations inductor coil is directly attached to the output slot of the PCB, which in turn connected to ultrasonic transducer. In this manner the effective generation of ultrasonic frequency with harmonics would be accomplished.

The main components for the accomplishment of the ultrasonic generator are transistors, transformers, and inductor coil.

2.2.5 Piezoelectric Transducer

The transducer within our project serves as a vital component connecting the generator circuit with the scalpel rod, orchestrating the generation of ultrasonic vibrations at a frequency of 40 kHz. This frequency plays a pivotal role in heating the scalpel blade, thereby facilitating the precise cutting of tissues during surgical interventions. As electrical energy is supplied from the generator circuit to the transducer, it undergoes a transformative process wherein the electrical signals are converted into mechanical vibrations.

The transducer's design and composition enable it to resonate at the specified frequency of 40 kHz, producing high-frequency oscillations with remarkable precision. These mechanical vibrations are then transmitted along the length of the scalpel rod, where they culminate in oscillations at the blade's cutting edge. The focused energy at the blade's tip induces frictional heat, effectively elevating its temperature to levels conducive for tissue cutting. The application of heat in conjunction with mechanical force enhances the scalpel's efficacy in dissecting tissues with unparalleled precision. This heat-assisted cutting mechanism minimizes tissue trauma, reduces the risk of bleeding, and promotes faster healing post-surgery. By harnessing the power of ultrasonic vibrations, surgeons can achieve smoother incisions, finer tissue dissection, and improved surgical outcomes. The integration of the transducer into the ultrasonic harmonic scalpel system underscores its significance as a technological innovation in modern surgical practice. Its ability to convert electrical energy into mechanical vibrations, coupled with its precise frequency control, enables surgeons to execute intricate procedures with enhanced precision and efficiency. In conclusion, the transducer serves as the backbone of the ultrasonic harmonic scalpel, providing the essential link between electrical energy and mechanical vibrations. Its role in generating ultrasonic frequencies and facilitating heat-assisted tissue cutting exemplifies its value as a transformative technology in advancing surgical techniques and improving patient outcomes.

The major components of the ultrasonic harmonic scalpel are ultrasonic generator, input power supply and piezo transducer was contributed by the 2nd author.

The documentation and component selection were made by author 4 and 5.

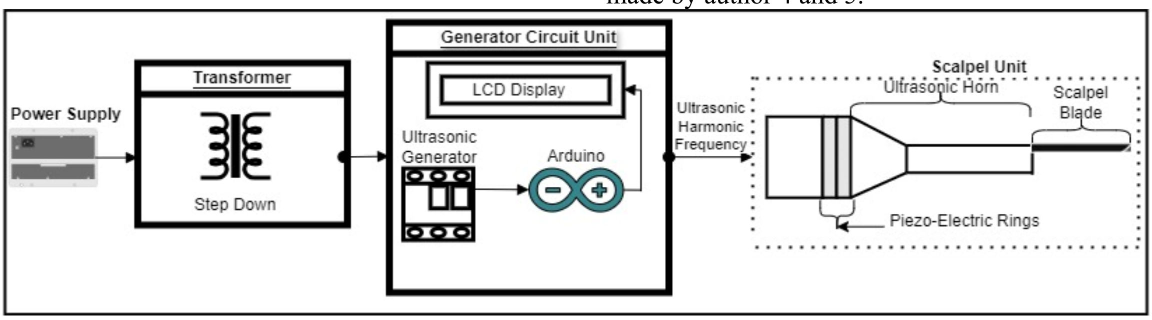


Figure 1: Block diagram of the ultrasonic harmonic scalpel.

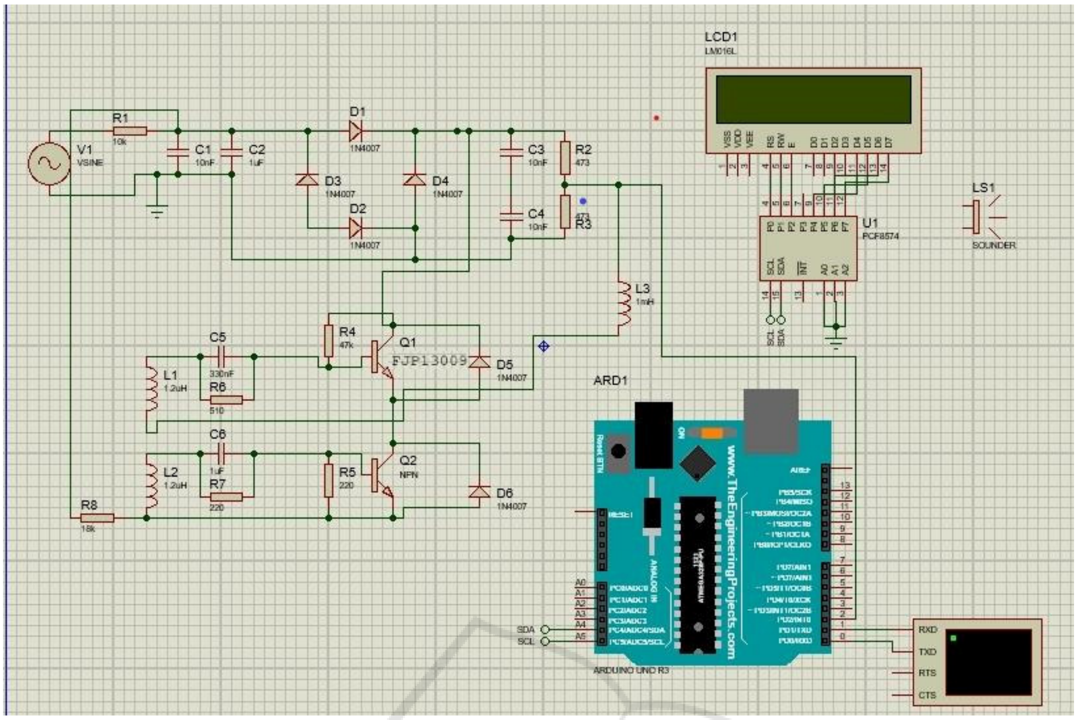


Figure 2: Schematic diagram of ultrasonic generator.

Figure 3: Ultrasonic Scalpel for cutting tissue.

3 DESIGN OF SCALPEL BLADE

The scalpel blade and rod form the core components of the ultrasonic harmonic scalpel, each playing a crucial role in its functionality and effectiveness in surgical procedures. The rod, constructed from aluminium, serves as the conduit for transmitting heat generated by the transducer's ultrasonic vibrations to the blade, while the blade itself, typically a generic surgical blade, undergoes thermal activation to aid in tissue cutting. The rod, crafted from lightweight yet durable aluminium, serves as the structural backbone of the scalpel assembly. Its design allows for optimal transmission of mechanical vibrations generated by the transducer to the blade's cutting edge. Aluminium's excellent thermal conductivity ensures efficient transfer of heat from the transducer to the blade, facilitating rapid heating and precise thermal control during surgical procedures.

The blade, a standard surgical component, undergoes a transformative process when subjected to the thermal energy transmitted through the rod from the transducer. As the ultrasonic vibrations induce frictional heat at the rod's interface with the blade, the blade's temperature rises, resulting in thermal activation. This heat-assisted mechanism enhances the blade's efficacy in tissue cutting, allowing for smoother incisions, finer dissection, and reduced tissue trauma compared to conventional surgical blades. In conclusion, the synergy between the scalpel blade and rod, facilitated by the transducer's ultrasonic vibrations, represents a significant advancement in surgical technology. The integration of thermal activation into the cutting mechanism enhances the scalpel's precision, efficiency, and safety, revolutionizing modern surgical practice and improving patient outcomes. Through innovative design and engineering, the ultrasonic harmonic scalpel exemplifies the intersection of science and medicine in advancing surgical techniques. For any type vibrating material, it's resonant frequency matters a lot to vibrate in the desired frequency.

As the scope of the project was based on generating ultrasonic frequency, so this scalpel unit was a simple proof of concept to demonstrate the working of entire unit.

3.1 Transformer Design for Ultrasonic Harmonic Scalpel Circuit

3.1.1 Transformer Specification

The ultrasonic generator circuit designed in this project requires a voltage of USA standard, as some parts of the generator circuit are imported. In India, the standard supply is 220V voltage. For the development of this described transformer, MATLAB simulation environment was utilized. Using this step-down transformer, the Indian standards would be converted into USA standards i.e., 220V to 110V and 2A current. This described transformer can also work as an isolation transformer for the ultrasonic generator circuit and scalpel unit.

3.1.2 Design Transformer

The transformer design involves the creation of electromagnetic devices capable of transferring electrical energy from the main supply to the submodule circuit. This section describes the input and output requirements for the ultrasonic generator circuit. The input requirements are 220V voltage and 3A current for the transformer. As the ultrasonic generator circuit requires 110V voltage with 2A current, this requires stepping down the input main supply to required specifications.

The core area (CA) of a transformer is calculated using the formula:

$$CA = 1.152 \times \sqrt{(output\ voltage \times output\ current)}\ cm^2 \quad (1)$$

The turns per volt (TPV) of a transformer can be calculated using

$$TPV = {(4.44 \times 10^4 \times CA \times B \times f)}/{V_p} \quad (2)$$

*w*here ,

B is flux density, f is the operating frequency, Vp is the primary volatge

The number of turns for primary and secondary windings are calculated as

For the primary winding:

- Primary winding current: Ipri = 0.41A
- Number of turns in primary winding:

Npri = TPV × Primary Volts = 698 turns

For the secondary winding:

- Secondary winding current: Isec = 0.91A
- Number of turns in secondary winding:

Nsec = 1.03×(TPV ×Secondary Volts) = 360 turns

Thus, for the primary winding the I_{pri} and N_{pri} are 0.41 A and 698 turns respectively. For the secondary windings the I_{seci} and N_{sec} are 0.91 A and 360 turns respectively. In this CA value will be 11.55cm^2.

4 DESIGN OF SCALPEL BLADE

After integrating the scalpel blade with the ultrasonic horn, the project reached its final stage, marking the culmination of careful design and engineering. The scalpel blade enabled cutting and cauterization of infected tissues, enhancing the ultrasonic harmonic scalpel's functionality.

The ultrasonic generator circuit was integrated with the scalpel unit and housed in a Medium Density Fibreboard (MDF) instrument box, which also featured an LCD display for monitoring the ultrasonic frequency.

Wires and ceramic plates were insulated to prevent overheating, and an emergency stop switch was added for safety. With the generator circuit PCB and Arduino enclosed in the instrument box and a protective cover for the piezo ceramic, the ultrasonic harmonic scalpel was prepared for use.

4.1 Determination of Resonant Frequency

In the ultrasonic frequency domain understanding of the resonant frequency of the used ultrasonic transducer is very much important. To do the experiment some major components are needed. The major components are CRO, probes, ultrasonic transducer, and power supply. To know the resonant frequency, the first channel of the CRO should be connected to the input frequency in the range of ultrasonic frequency and the output must be connected to ultrasonic transducer.

The experiment goes like this, keep on increasing the input frequency in the range of ultrasonic frequency until it aligns with output waves from the ultrasonic transducer. When the input and output waves from the ultrasonic transducer align with each other, at this moment the input frequency will be noted for future reference. This resonant frequency of the ultrasonic transducer helps in the understanding of the generation of resonant frequency for the tested transducer.

In the experiment conducted for the resonant frequency determination, the frequency observation was in the range of 39KHz to 40KHz ultrasonic frequency. When one provides this resonant frequency to ultrasonic transducers, it starts vibrating in the ultrasonic frequency. The resonant meaning in layman language is the intersection of ultrasonic cleaner transducer waves with that of function generator used. The Figure 5(a) describes the resonant frequency of the ultrasonic transducer. This is a kind of prior work to be done before designing and development of the generator circuit. The above experiment gives the perfect requirements of the ultrasonic piezo ceramic plates which later be used for development.

More precaution has to be taken While doing experiment, the polarity of an ultrasonic transducer has to be ensured because the current generated by the transducer may destroy the CRO utilized for testing. The proper input wave generator must be very precise to avoid wrong results from the experiment.

The Figure 5(b) represents practical determination of Scalpel's ultrasonic transducer which was used in the designed project and the resonant frequency is observed in the CRO used for the measurement of the resonant frequency.

4.2 Testing with Temporary Ultrasonic Cleaner Transducer

Initial testing involved using a temporary ultrasonic cleaner transducer with a direct 100-watt sine wave from the high switching power MOSFET. The gate of the MOSFET was driven by a function generator with 5Vpp.

The purpose of this test was to observe the response of the transducer to the applied sine wave.

The output from the MOSFET was taken from the drain to the source and connected directly to the ultrasonic cleaner transducer. The ultrasonic transducer did not produce vibrations because of a lack of harmonics in it. The power supply to the MOSFET was given by the DC regulated power supply. The voltage given from the DC-regulated power supply was 30V DC. To produce the 2A current in it, utilized a resistor to produce the required current. The Figure 6 represents the complete setup for MOSFET based determining the ultrasonic vibrations.

4.3 Design and Testing of Custom Ultrasonic Transducer

Based on the initial testing, a custom ultrasonic transducer was designed and fabricated. This transducer was tailored to handle higher power levels and to operate efficiently at the desired frequencies. The custom transducer was tested under similar conditions as the initial testing.

The results showed a significant improvement in performance. The custom transducer was able to handle the 100-watt sine wave without excessive heating, and the efficiency of the ultrasonic wave generation was much higher.

This custom transducer was built from the existing ultrasonic cleaner transducer. From the existing transducer piezoelectric rings were taken and optimized with the aluminium bar in the front and rear part of the transducer.

4.4 Frequency Response Analysis

The ultrasonic generator circuit was simulated using the Proteus software. The generator circuit consists of several passive components such as resistors, capacitors, and inductors. These passive components play crucial roles in the generator circuit such as resistors for limiting the current, and capacitors and inductors for generating harmonics in the circuit. The diodes are included in the circuit to provide voltage conversions. The high-power switching transistors are used to produce an ultrasonic frequency to drive the piezo ceramic plates. The simulated circuit can generate an ultrasonic frequency of 20KHz to 60KHz which is a requirement for a various model of ultrasonic transducer. In practical scenarios, the different models of the high-power switching transistors would be used based on the requirement.

The MJE models of transistors has the capacity to produce up to 60KHz ultrasonic frequency and FJP models of transistors would produce up to 40KHz ultrasonic frequency. The output of the transistor will be a pure sinewave without any harmonics, it requires a suitable transformer to produce the harmonic in addition to the generated ultrasonic frequency. In the ultrasonic generator circuit, it includes two transformers, one will be directly included in the production of harmonics and the other one is required for just bypassing of the signals from the inductor. Mainly in this generator circuit it includes a choke inductor to safeguard the circuit from uncertain changes in the input supply. In this section, only the most used resonant frequencies output is shown. The commonly used resonant frequencies for ultrasonic transducers are 40KHz and 60KHz.

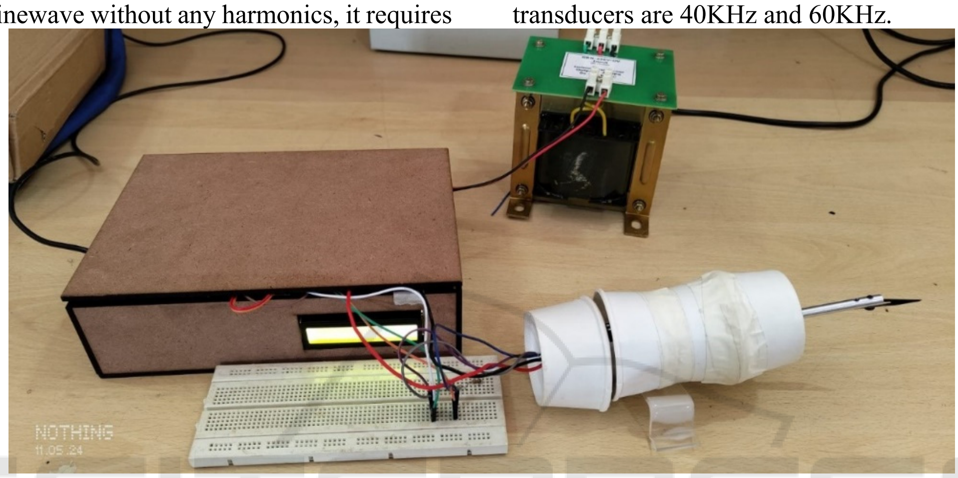


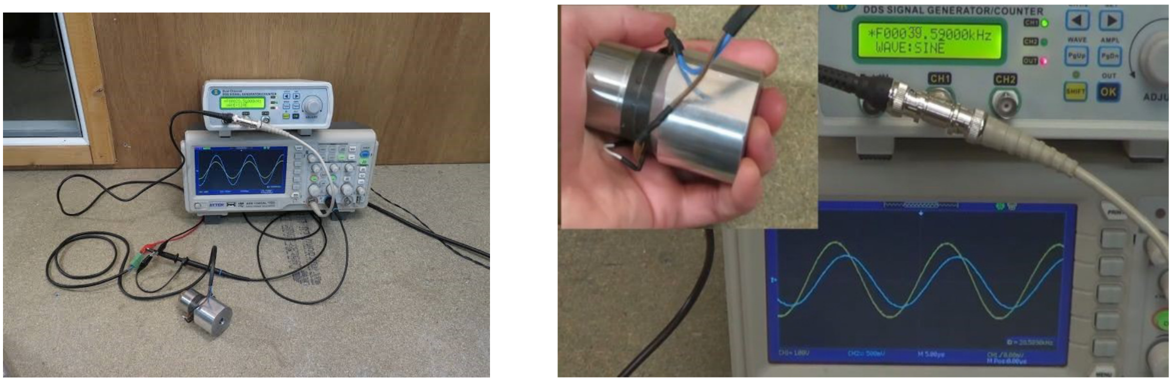
Figure 4: Ultrasonic harmonic scalpel final setup.

These resonant frequencies would be given to the ultrasonic piezo ceramic plates, this in turn converts the input ultrasonic harmonics frequencies into an ultrasonic vibration. The generated ultrasonic vibrations are then given to the scalpel unit directly involved in cutting the tissue. The output frequencies shown in this section are taken using the Proteus environment using CRO in it. The output image has been plotted as Amplitude vs Generated frequency. The below images describe the generated frequency in the range of ultrasonic.

The Figure 7 represents the generated frequency of 40KHz which was generated when the circuit included with only FJP high power transistor. Then it produces a 40KHz ultrasonic frequency, this would use for driving 40KHz ultrasonic transducer.

The Figure 8 represents the generated frequency of 60 KHz which was generated when the circuit included with only the Maculae Junction Emitter (MJE) high-power transistor. Then it produces a 60 KHz ultrasonic frequency, this would use for driving 60 KHz ultrasonic transducer.

The Figure 9 represents the relationship between generated ultrasonic frequencies and the temperature. The generated temperature could be used for cutting and coagulating the infectious tissues inside the human being. This kind of approach helps the doctors to easily handle the difficulty scenarios in the real world. The measurement of the temperature was done using IR temperature measurement device and frequency measurement using Arduino. The x-axis represents the generated ultrasonic frequencies using generator circuit in KHz and y-axis represents the heat generating using ultrasonic harmonic scalpel with piezoelectric rings in degree Celsius.



(a) (b)

Figure 5: (a)Setup for Resonant frequency determination, (b) Resonant frequency of Scalpel's ultrasonic transducer.

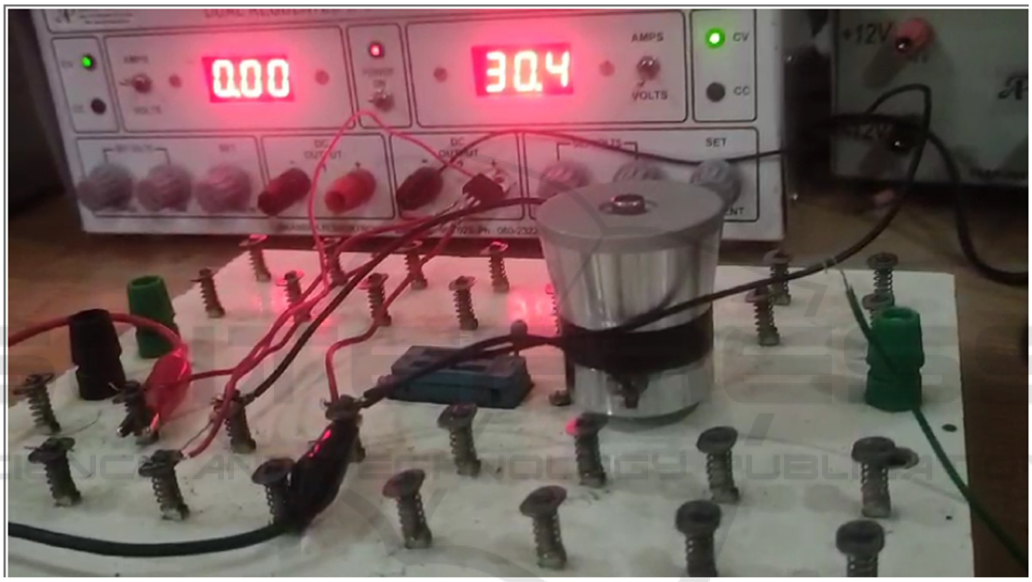


Figure 6: Initial setup with the temporary ultrasonic cleaner transducer.

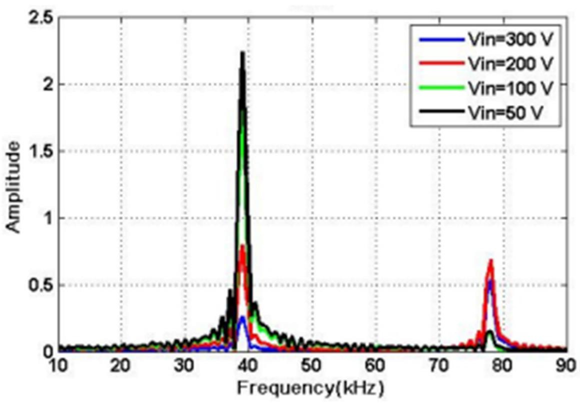


Figure 7: Output frequency of 40 KHz.

The above diagram represents the output of 40 KHz generated ultrasonic frequency with different input voltages.

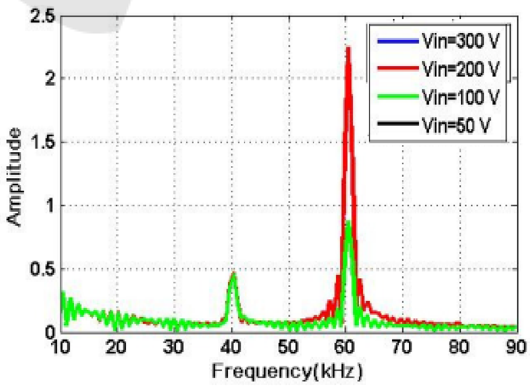


Figure 8: Output frequency of 60 KHz.

The above diagram represents the output of 60 KHz generated ultrasonic frequency with different input voltages and this frequency has not been used in this project.

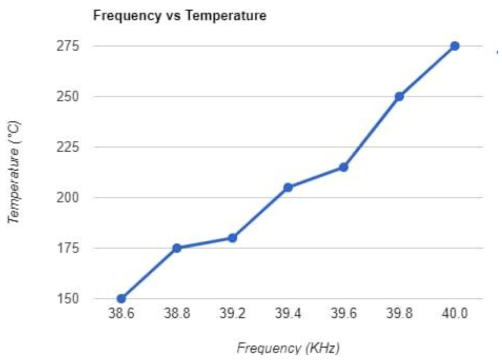


Figure 9: Output Graph indicating the increase in vibration temperature with frequency.

5 CONCLUSIONS

The experimental results and implementation of the ultrasonic harmonic scalpel circuit design were successful. The custom ultrasonic transducer demonstrated improved performance and efficiency. The final circuit implementation met the design specifications and operated reliably under various conditions. The thermal analysis confirmed that the components were operating within safe limits, ensuring the longevity and stability of the circuit.

The integration of ultrasonic transducers, transformer configurations, and piezoelectric elements has further validated the device's ability to convert electrical energy into mechanical vibrations and transmit them effectively to the surgical site. The design and fabrication of specialized components such as the ultrasonic horn and scalpel blade have demonstrated the feasibility of producing precise tissue cutting and coagulation. By encapsulating the generator circuit within an instrument box and incorporating features such as thermal insulation and emergency stop switches, the device's reliability and usability in clinical settings have been enhanced. These advancements represent significant strides towards realizing the vision of a next-generation surgical instrument that combines cutting-edge technology with user-centric design principles.

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