Piezo-Tribo Nanogenerator (PTNG) for Powering Wearable Electronic Gadgets

A PROJECT REPORT

submitted by

Anagha Mohan AM.EN.U4ECE17009
J R Kannan AM.EN.U4ECE17028
Abhijith R AM.EN.U4ECE17101
Akshay Viswanath A P AM.EN.U4ECE17105
Sreenath K AM.EN.U4ECE17155

under the guidance of

Dr. Sreenidhi P R
Mrs. Baby Sreeja S D

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AMRITA VISHWA VIDYAPEETHAM

AMRITAPURI (INDIA)

BONAFIDE CERTIFICATE

This is to certify that the project report entitled **“Piezo-Tribo Nanogenerator (PTNG) for Powering Wearable Electronic Gadgets”** submitted by **Anagha Mohan (AM.EN.U4ECE17009), J R Kannan (AM.EN.U4ECE17028), Abhijith R (AM.EN.U4ECE17101), Akshay Viswanath A P (AM.EN.U4ECE17105), Sreenath K (AM.EN.U4ECE17155)** in partial fulfillment of the requirements for the award of the Degree Bachelor of Technology in Electronics and Communication Engineering is a bonafide record of the work carried out by them under my guidance and supervision at Amrita School of Engineering, Amritapuri.

Signature of Supervisor:
Dr. Sreenidhi P R
Assistant Professor
Department of ECE

Signature of Examiner with Name

Signature of Co-Supervisor:
Mrs. Baby Sreeja S D
Assistant Professor
Department of ECE
Date:

AMRITA SCHOOL OF ENGINEERING

AMRITA VISHWA VIDYAPEETHAM

AMRITAPURI - 690 542

DEPARTMENT OF ECE

DECLARATION

We, **Anagha Mohan (AM.EN.U4ECE17009), J R Kannan (AM.EN.U4ECE17028), Abhijith R (AM.EN.U4ECE17101), Akshay Viswanath A P (AM.EN.U4ECE17105), Sreenath K (AM.EN.U4ECE17155)** hereby declare that this project report entitled **"Piezo-Tribo Nanogenerator (PTNG) for Powering Wearable Electronic Gadgets",** is the record of the original work done by me under the guidance of **Dr. Sreenidhi P R,** Assistant Professor, Department of ECE, Amrita School of Engineering, Amritapuri and **Mrs. Baby Sreeja S D,** Assistant Professor, Department of ECE, Amrita School of Engineering, Amritapuri. To the best of my knowledge this work has not formed the basis for the award of any degree/diploma/ associateship/fellowship/or a similar award to any candidate in any University.

Place: Amritapuri
Date: 07/05/2021

Signature of the Students

Contents

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Pranams to our chancellor Sri Mata Amritanandamayi Devi, Amma We would like to express our special thanks of gratitude to our mentors Dr. Sreenidhi P R and Mrs. Baby Sreeja S D of Electronics and Communication Engineering department, Amrita Vishwa Vidyapeetham for providing us with the opportunity to assimilate ideas and gain knowledge. Our special words of thanks should also go to Dr. Balakrishnan Shankar (Dean, Amrita Vishwa Vidyapeetham, Kollam), Dr. Jyothi S. N (Principal, Amrita Vishwa Vidyapeetham, Kollam), Dr. Ravisankar (Head of department, Electronics and Communication Engineering, Amrita Vishwa Vidyapeetham, Kollam) and Br. Remya (Vice Chairperson, Electronics and Communication Engineering, Amrita Vishwa Vidyapeetham, Kollam) for their continuous support, and guidance. We hope to expand our grasp in this domain and move forward.

Anagha Mohan

J R Kannan

Abhijith R

Akshay Viswanath A P

Sreenath K

Abstract

In this work, authors designed an optimized structure of power generating shoe sole for energy harvesting technology based on piezoelectric and triboelectric effect using COMSOL multiphysics simulation software. This work gives a basic review on the structural layout and performance evaluation of various piezoelectric and triboelectric materials used as energy generating layers for shoe sole. In this study the device structure is optimized by the method of contact electrification. Various piezoelectric and triboelectric materials are used as energy generating layers for the shoe sole and comparative study on the effect of these materials on different structures were also carried out. Electric fields and potential voltages generated by these materials were studied by varying the gap between the structures. In this work we also build a prototype for the nanogenerator model. It involves fabrication using the materials and completing the circuit necessary for harvesting, converting the energy and storing it in a capacitor. The dimensions of the actual nanogenerator model are slightly reduced for the prototype model.

Chapter 1

Introduction

1.1 Introduction

In this modern scientific era there is a developing advancement of wearable and implantable gadgets, nanogenerators (NGs) have been paid significant consideration as of late because of their high transformation productivity and minimal effort with natural nano-materials. The forces of miniature/nano scale gadgets or frameworks provided by conventional batteries have a few issues, for example, scaling down, similarity and long lifetime. Along these lines collecting the energy from conditions by NGs can be a potential and compelling choice to meet such prerequisites. The customary instruments of NGs have been reviewed, including electrostatic, piezoelectric and electromagnetic techniques[1]. The part examines about energy needs, energy gathering and two kinds of energy gathering strategies.

1.1.1 Energy needs and energy harvesting

Energy gathering is the capturing and transformation of restricted amounts of instantly open energy in the encompassing into usable electrical energy. The electrical energy is adjusted for either direct use or accumulated and set aside for soon. This gives an elective method of power for applications in territories where there is no system force and it is inefficient to present breeze turbines or sunlight based boards.

Other than outside sun based, no little fuel sources give a great deal of energy. Regardless, the energy got is adequate for most far off applications, distant identifying, body supplements, RFID, and various applications at the lower segments of the force range. Additionally, whether or not the gathered energy is low and unequipped for filling a contraption, it can regardless be used to grow the presence of a battery.

Energy harvesting is the way toward catching and putting away moment electrical energy got from outer fuel sources found in the encompassing foundation. The outer fuel sources incorporate the sun, wind, vibrations, temperature and so on. The energy subsequently determined can be utilized to run low power as well as high power electronic gadgets. A typical energy harvester is shown in Figure 1.1.

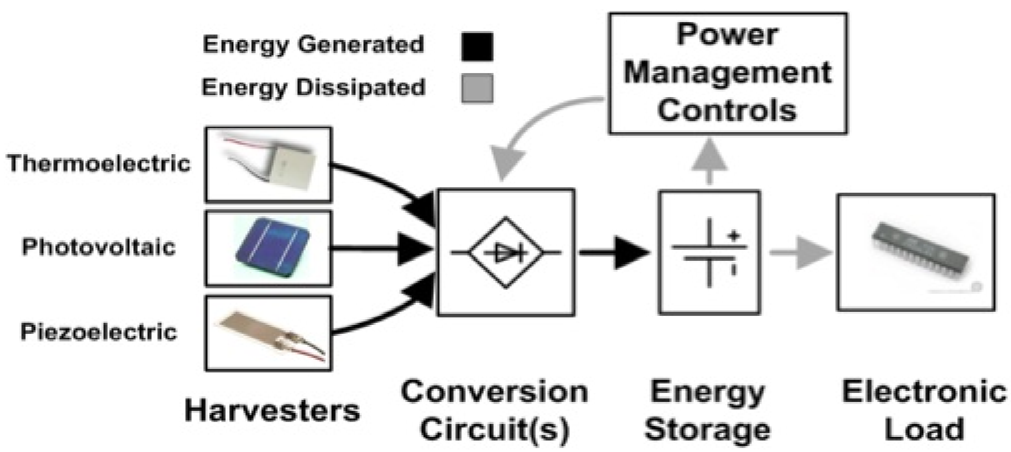


Figure 1.1: Example for energy harvesting.

1.1.2 Piezoelectric energy harvesting

Piezoelectric material followers mechanical vibrations into electrical energy using clear plan. This can likewise be named as pressing factor power or as immediate piezoelectricity which is the characteristic property of a certain glass like material like quartz, rochelle salt, tourmaline and barium titanate to create power when pressing factor is applied. These precious stones likewise show misshapen when an electric field is applied to it which is named as a roundabout piezoelectric impact. In gems with non-reversal evenness, a straight connection among mechanical and electrical states happens during the use of strain or twisting because of the division of charge across the gadget which prompts the creation of the electric field, along these lines a voltage drop corresponding to applied power and at last piezoelectric impact. The principal showing on piezoelectric impact was given by Pierre Curie and Jacques Curie in the year 1880. Applications of piezoelectric impact remember use for bend age in cigarette and gas lighters, sensors, electronic recurrence age to use in examining test microscopy strategies. Energy harvesting using piezoelectric nanogenerator is shown in Figure 1.2.

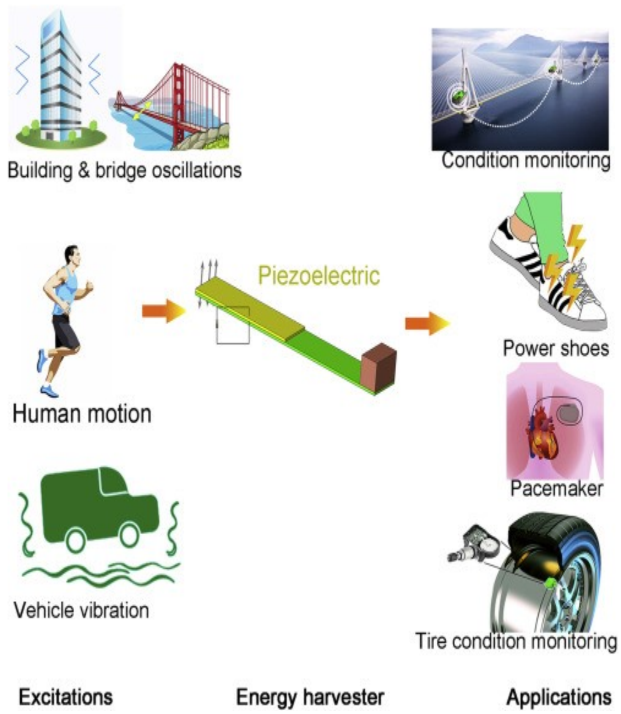


Figure 1.2: Energy harvesting using piezoelectric nanogenerator.

1.1.3 Triboelectric energy harvesting

Triboelectric generator uses triboelectric impact for changing mechanical energy over to create electrical energy. The triboelectric impact utilizes the electrostatic charge made on a superficial level when two disparate materials come into contact with one another. The instigated charges create a potential inclination when isolated by a mechanical power. The material determination relies upon the triboelectric arrangement which depends on the electron liking of materials in contact.

A triboelectric energy gatherer changes mechanical energy over to electrical energy from erosion or on the other hand ephemeral contact between two unmistakable triboelectric materials. Its fundamental energy gathering instrument relies upon merged contact charge and electrostatic acceptance. TEH is a promising advancement that has pulled in much thought and developed rapidly. Four crucial energy harvesting techniques for TEHs are upward contact-partition (CS) mode, lateral sliding (LS) mode, single-electrode (SE) mode, and freestanding triboelectric-layer (FT) mode show in Figure 1.3. Occurrences of studies on depiction and improvement of the electrical show of triboelectric and terminal materials, device production, and environment condition control are the going with examinations .

Moreover, researchers examined the temperature impact on the triboelectric electrical yield of a single-terminal mode and revealed that, at a low temperature, the TEH had the option to produce high electrical yield, and the other way around. The general dampness is additionally a basic factor that influences triboelectric charge thickness. Hence, a gadget appropriately introduced in a controlled climate could be profoundly effective. In addition, expanding the size of a TEH and parallel interfacing a considerable lot of them in the same gadget can possibly expand the electrical yield. What's more, hybridizing TEH with another energy collecting gadget that works by an alternate reaping component has been researched and found to build energy creation proficiency.

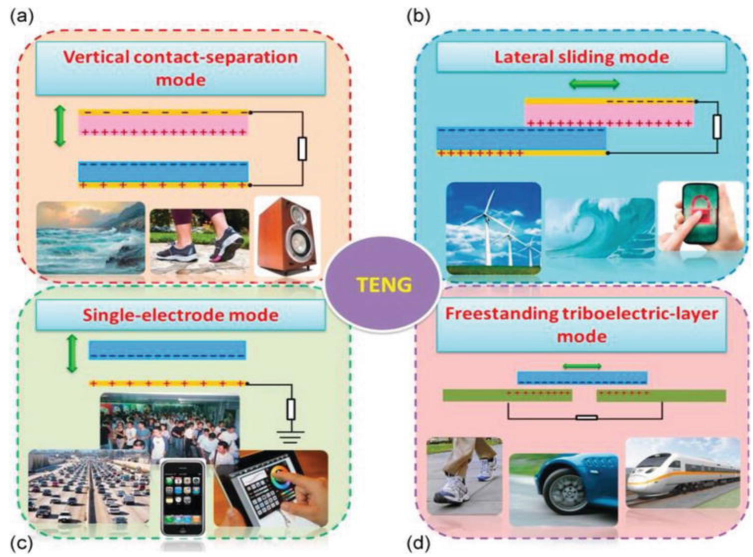


Figure 1.3: Triboelectric energy harvesting methods.

1.1.4 Applications of energy harvesting devices

- Internet of Things (IoT)
- Elective force sources give a methods for expanding the battery life of distant sensors
- Door security
- Industrial monitoring
- Highway bridge monitoring

Chapter 2

Background and Literature survey

Mechanical energy in its miniature just as large scale structure is found in the environment. Tackling of the potential mechanical energy is trying in full scale energy harvesting than in miniature energy harvesting systems. The squandered mechanical energy is the best contender for energy collecting because of its ubiquitous nature. Specialists have utilized an assortment of models for building energy harvesting gadgets and not many of them are material utilized as dynamic layer, varieties in underlying model, varieties in excitations gave to the gadget, impact of natural changes on the gadget. This chapter details on the foundation background and literature survey of two energy harvesting procedures, piezoelectric energy harvesting and triboelectric energy harvesting.

2.1 Piezoelectric effect and piezoelectric energy harvesting

In this paper Zhong Lin Wang et.al. recommended that biomechanical energy reaping is a huge course for offering ability to monetarily drive wearable contraptions, which as of now regardless of everything use batteries and thusly ought to be charged or superseded/orchestrated routinely. Here a technique that can perseveringly control wearable contraptions just by human development, recognized through a triboelectric nanogenerator (TENG). The TENG has appealing features including adaptability, stretchability, isotropy, wearability, water-obstruction and a high surface charge thickness of 250mCm^{-2}. With simply the energy acquired from running or running by the TENG that is underlying outsoles, wearable devices, for instance, an electronic watch and health tracker can be rapidly and relentlessly controlled. The TENG cylinder has an inward cathode, dielectric layer and external terminal surface. External and internal anodes are set up from combinations of silicone elastic, carbon dark and carbon nanotubes (CNT). Silicone elastic gives the versatile property to TENG, carbon dark and CNT gives electric conductivity other than that CNT expands the contact region by framing a nanostructured surface. Inward cathodes have high charge thickness.

Working of the TENG-tube depends upon a coupling of triboelectric influence and electrostatic acknowledgment. Exactly when the chamber is compacted, the internal terminal comes to contact with the dielectric layer. Since the dielectric layer has a higher ability to pull in electrons, electrons on the internal cathode surface will move to the outside of the dielectric layer, achieving an oppositely charged dielectric layer surface and an emphatically charged internal terminal surface. At long last the outcome shows that the helix contact construction of the TENG gives the most extreme charge thickness of 250mCm^{-2}.[2]

In this paper distributed in the year 2017 Young-Man Choi et.al. Recommended that power is required for driving little electronic gadgets like shrewd watches, brilliant glasses and so forth It is likewise required in conditions where stable electric stockpile is beyond the realm of imagination. So the answer for this issue is by utilizing wearable gadgets that can be worn by people in everyday life for energy collecting. In this paper, they are thinking about both piezoelectric energy collector (PEH) and triboelectric nanogenerator (TENG).

PEH: It utilizes piezoelectric impact in which power is produced when power is applied. Despite the fact that they have low force yield they can create power even in low removal. To expand the piezoelectric impact, we introduce the PEH in a piece of the human body that is mounted into the shoe soles.

TENG: In these gadgets, charges happen because of the contact between two polymers or between a polymer and a metal. Along these lines, electric potential is produced between the two materials. The effectiveness of TENG relies upon the triboelectric material, surface condition, contact speed and so forth They are normally light weight, adaptable, and effectively versatile. It has a high open-circuit voltage accordingly hard to get a lot of force since human body development or human strolling has a low recurrence.

Foot-strike wearable energy gatherer: It utilizes the effect or pressing factor produced by the foot while strolling, running and so forth The gadget is mounted on a shoe sole, and it enhances strolling movement utilizing a trapezoidal sliding system and passes the intensified movement to a nanogenerator. Four vertical springs and two level springs are utilized to give a reestablishing power to the trapezoidal slider system.[3]

By 2018, specialists Tong Li et.al. Came to bring up that the quick improvement of hardware wearables and contraptions are forcing a test to us as batteries. Electrochemical batteries raise various concerns including lifetime, charging accessibility and dangers to the climate. The current headway design in wearable equipment is toward mix, flexibility, downsizing, and legitimacy. Subsequently, a wearable piezoelectric-driven self-controlled planned electrochromic supercapacitor (ESC) is presented in this paper, which is consolidated with the energy procuring, change, amassing and sign progressions. The planned polyaniline (PANI) terminals electrodeposited by coupling cyclic voltammetric and galvanostatic (CV-GS) techniques were assembled as planned ESC, which served to store the energy and exhibit the charging/delivering status meanwhile. With the advantages of flexibility and biocompatibility, the polyvinylidene difluoride (PVDF) nanofibers were made by electrospinning to set up the piezoelectric nanogenerators (PENGs) as the energy-gathering device, which can be annexed to human body to change over a huge segment of the energy wasted from development into electrical energy.

Oneself filled planned ESC basically joins two sections: the energy-gathering contraption and the energy accumulating and sign device. The planned PANI anodes electrodeposited by a coupling techniques for CV and GS strategies were amassed as ESC, which was used as the energy accumulating and sign device for showing the charging/delivering status. PVDF nanofibers made by electrospinning were embraced to develop the PENG as an energy gathering device for looking through human development energy. The organized wearable self-controlled system can be associated with the human body to gather human development energy, by then move the mechanical energy to electric energy for charging planned ESC, which can store energy and show the constant charging/delivering status.[4]

In this paper C. Rodrigues et.al. Proposed in 2019 that, for estimating pulse, consumed calories, strides, circulatory strain, and time spent for practicing or athletic execution we utilize wearable and movable electronic gadgets. Accordingly the need for shiny new and independent force sources that grant endless activity of those little gadgets required, to suit such requests we can utilize TENGs,Triboelectric Nanogenerators (TENGs) is the principal feasible answer for procure energy from low-recurrence mechanical movements. Here, they have hybridized a triboelectric nanogenerator, an electromagnetic generator (EMG) and a piezoelectric nanogenerator (PENG) and inserted in a shoe sole to harvest energy from human strolling. Various designs like equal, arcked and crisscross triboelectric plates (in light of the contact-division mode and fitting to be collected in footwear) were created and considered their highlights. What's more, discovered that, the equal plate structure created electrical yields more than different constructions. The distance between two layers and the quantity of the triboelectric layer in the setup was advanced and in this way the yield execution of the TENG is expanded, To more improve energy age properties, they manufactured a nanogenerator through a mix of triboelectrification, electrostatic and attractive enlistment and piezoelectric impact, it upgraded 20 level of the charging ability which is more than TENG"s alone limit. This upgraded gadget opens new skylines for strategies to supply and store squandered energy and, in a near future, to control remote sensors or electronic contraptions.[5]

In this paper creators suggested that wearable and implantable equipment (WIEs) have experienced a period of fast new development and are progressively critical and interesting to general society. These days, wearable and implantable contraptions have attacked into each piece of our lives, making individuals' ways of life more able and beneficial. As the middle pieces of WIEs, sensible versatile sensors require mix limit with embellishments and surfaces, for instance, arm groups, watches, eyeglasses, accessories, or the implantation into the human body. Further, for implantable devices especially, flexibility is particularly important. Fluoride (PVDF).

One of the constraint is the force supply. For full limits, most current flexible equipment really requires outer power supplies, conventionally batteries to give power. The battery has most of the weight and volume, and discontinuous replacement of it will provoke electronic waste, genuine weight, and money related strain. So oneself fueled frameworks are basic to reasonable wearable and implantable hardware. Our bodies contain an assortment of energy, including warm, synthetic, and mechanical energy, among which mechanical energy is the most bountiful. For using this energy, a nanogenerator (NG) which changes mechanical energy into electric energy was presented by Professor Zhong Lin Wang in 2006 and has gained stunning ground of late.

Typically, NGs are regularly partitioned into three kinds:-Based on electricity generation mode, namely, triboelectric nanogenerator (TENG), piezoelectric nanogenerator (PENG), and pyroelectric nanogenerator (PYENG). Taking into account that more number of implantable and wearable electronic sensors have been utilized by people, creating NG-based innovation is incredibly likely.

For conformal blend in with the organs or skin, inconceivably lightweight and versatile energy-gathering contraptions were of the essence. The construction of PENG has created from single nanowires to films, so that to acquire great soundness and high yield. The TENG has a wide choice of materials, and new plans of the plan are when in doubt consistently devised for higher and steadier electric execution.

By and large in this survey, a presentation of the NG standards is given first. Furthermore, the specific materials and contraptions of NGs were summarized. In addition, the employments of NGs as implantable and wearable self-filled sensors in prosperity noticing, biosensor, human-PC correspondence, and various fields are summarized.[6]

2.2 Triboelectric effects and triboelectric energy harvesting

In this paper Yanbo Zhu et.al. suggested that triboelectric nanogenerators (TENGs) have been given the most consideration by numerous scientists to change over mechanical energy into electrical energy. TENGs for the most part have a straightforward construction also, a high yield voltage. Notwithstanding, their high inside obstruction brings about low yield power. In this work, the creators proposed an adaptable triboelectric nanogenerator with the twofold side tribological layers of polydimethylsiloxane (PDMS) and PDMS/multiwall carbon nanotube (MWCNT). MWCNTs with different obsessions have been doped into PDMS to tune the internal check of triboelectric nanogenerators and advance its yield power.

In this paper the authors designed a nanogenerator. The generator has two layers of PDMS with metal electrodes and the composite layer of PDMS (polydimethylsiloxane) /MWCNT (Multiwall carbon nanotube). PDMS/MWCNT is designed with miniature constructions to build the reaching territory and improve electrical yield of TENG. The nanogenerator layers are protected with a consistent little partition hole at the consistent balance state. The working guideline of the twofold finished pillar triboelectric nanogenerator is as per the following, triboelectric yield is brought about by the coupling between the triboelectric impact and electrostatic enlistment under occasional contact and partition of the two materials surfaces. The PDMS/MWCNT surface will be positively charged while the PDMS surface will be negatively charged when they are kept in contact with each other. The twofold supported PDMS column will twist until it contacts the base PDMS/MWCNT when an upward power is applied.

The surface charges are moved from PDMS/MWCNT to PDMS because of triboelectrification impact since they have distinctive accuse fondness of units of nC/J. The greater loving differentiation between two triboelectric materials adds to the greater proportion of moved charges. While the force is conveying, electric conceivable differentiation between the PDMS and PDMS/MWCNT will drive electrons, which achieves the saw yield, from the base PDMS/MWCNT layer to the top terminal. When the nanogenerator is squashed, the two triboelectric material surfaces will be censured for a practically identical surface thickness. The electric potential differentiation will in like way appear at as far as possible worth when the opening between the two material surfaces shows up at the greater worth. Subsequently the improvement stretch between the two triboelectric material surfaces will impact the yield voltage of the nanogenerator. The applied power is delivered and electrons have been collected on the terminal. Electrons are driven from the top cathode to the base PDMS/MWCNT layer inciting an opposite triboelectric stream when the stretch decreases.[7]

Power control has always been the problem of the triboelectric nanogenerators' feasibility. With the power management modules (PMM) introduction, around 85 percentage of the energy can be delivered from the TENG. As indicated by analysts, TENG's widespread force the executive's technique guarantees a full miniature energy answer for controlling wearable hardware and mechanical remote organizations. The thesis was published in the 'The Next Generation Nanogenerator' open-source journal.A tribotronic energy extractor for TENG has been constructed and roughly 85 level of the energy can be moved self-sufficiently. Put away energy has been improved fundamentally at a low recurrence of 1 Hz with the PMM. Boosting energy move from the TENG to the back-end circuit is the initial step of the force the board methodology. The maximised energy transfer and DC buck conversion have established the mechanism of power management. A tribotronic energy extractor (TEE) is suggested, based on the implemented switch and rectifier. Without any external power source,it can independently and maximally separate energy from the TENG and move it to the back to the circuit. The Power Management Module (PMM) has been introduced and is defined by TENG. From the original state, the output voltage continuously increases and arrives at the consistent state inside 20 s. At 80.4 percent productivity, the force is held. The critical boundaries in the PMM are the LC units and have additionally been widely explored. To apply the force the board structure, the procedure of expanded energy move, DC buck transformation and self-administration measure is utilized. Tribotronics centers around the investigation of triboelectricity-semiconductor cooperation. Utilizing the self-sufficient electronic switch, the energy of the TENG was maximally moved. TENG's Universal Power Management Strategy guarantees a hearty miniature energy answer for wearable gadgets, appropriated remote sensor organizations and the future Internet of Energy. The PMM has shown the comprehensiveness of the Power Management system for various TENGs by catching human motor and natural mechanical energy.

Tribotronic is an expansion of data hardware. It plans to upgrade the change of assets, DC buck transformation, and interaction of self-administration. To outfit human dynamic and ecological mechanical energy, the comprehensiveness of this technique has been incredibly illustrated. An absolute miniature energy answer for dispersed remote sensor networks for wearable gadgets is promising.[8]

This survey targets giving and summing up the significant and deterministic fundamental hypotheses, standards, and systems for the triboelectric impact. Because of the inborn attributes of the triboelectric impact for being framework related and climate subordinate. a few factors that have an effect on the triboelectric are arrangement of construction, molecule size, burden, and mugginess reliance, from the start, the survey examines the charging media in the triboelectric framework and sums up the expected instruments for these charging media like an electron, particle, and nano material to move, i.e, about the charging cycle, in a more numerical and actual clarification with their principles exhaustively. With this determination, a total rundown, and subtleties of the triboelectric arrangement are summed up and the strange triboelectric grouping marvels are talked about with more clear numerical and actual clarifications. After all the review into the triboelectric structure and its associated depictions for the triboelectric sway, the critical components influencing the triboelectric execution are systematically gathered in a comparative logical manner. By exploring the distinction between each charging media, the electron, particle, and material exchange are examined and the hypothetical derivation in the previous many years is applied. Likewise, they portray the potential applications for these theories and principles for additional expansive fuse with the triboelectric research and related fields, and how it might be used for an ordinary arrangement of the triboelectric structure is furthermore associated with each part. This audit illuminates how the crucial hypotheses are created and affirm their deterministic capacities in planning more viable triboelectric frameworks with these generally exact numerical and actual portrayals.[9]

Triboelectric nanogenerators capture the wasted forms of mechanical energy and convert them into usable electrical energy. They reap encompassing mechanical energy through contact charge and can be utilized as a force source in self-ruling gadgets. Various systems are liable for contact charge and rely upon the material utilized. The journal discusses the idea of contact electrification and how contact electrification applies in triboelectric nanogenerators for energy harvesting. The transfer of electrons between surfaces that were in contact once and removed after is considered the main electrification mechanism for triboelectric nanogenerators. This paper showed that contact electrification can be controlled by intramolecular forces in the polymer bulk and adhesive forces at the contact interface and surface charge of polymers can be controlled by their physicochemical properties such as the strength of macromolecular interactions in bulk and the surface adhesion. The outcomes from this paper additionally showed that Covalent Bond Cleavage or CBC, the breaking of covalent connection between particles, is an instrument of contact charge in polymer encasings. Higher surface charge can be anticipated from the polymers that show solid surface attachment and low union energy in mass.[10]

2.3 Piezo-tribo hybrid energy harvesting

In this article, an adaptable self-angled biosensor dependent on a crossover nanogenerator is made. It for the most part revolved around the TENG in vertical contact-parcel mode, which has been extensively used due to its extraordinary adequacy, versatility, and adaptability for some sensible circumstances. One of the major developments of TENGs is a spacer to ensure contact-separation measure working consistently. Here, they use the wonder of pressure confuse that happens on the interface between two distinctive polymer materials to manufacture an adaptable self-curved construction which can supplant spacers in ordinary TENG gadgets.

Displayed a self-calculated nanogenerator (SANG) for beat recognizing, which misuses the basic shape achieved by the pressing factor bewilder existing at the interface of two silicone elastomer film materials. And furthermore to additionally improve the detecting exhibitions, a PVDF film is acquainted with be installed into oneself angled design of the SANG to shape a crossover nanogenerator dependent on the half breed impact of piezoelectricity and triboelectricity, which can upgrade the security, the sign to-commotion proportion and yields of the gadget when recognizing beat signals.

From this paper it very well may be derived that self-curved nanogenerator (SANG) is a without spacer cross breed nanogenerator with a self-angled design dependent on the impact of pressure befuddle existing at the interface between two polymers.The morphology of oneself angled construction can be tuned by the mass proportion of PDMS and Ecoflex. Utilizing distinctive mass proportions, the twisting levels of oneself curved construction of the SANG are unique. Here overabundance use of PDMS in oneself curved construction may cause a bigger bowing level of it. For improving yields of the gadgets, a cross breed mode that joins triboelectric and piezoelectric impacts was presented in the SANG. As a piezoelectric nanogenerator part a slight PVDF film was added into the curved layer.

The pinnacle upsides of the short out voltage and the open circuit current of the SANG are 500nA and 5.2V. We can unmistakably see from the outcomes that the mixture sign of the SANG is more steady and clear than that of the triboelectric and piezoelectric parts. The SANG has significant dependability and affectability to go about as an appropriate gadget for detecting beat waveform of the spiral course. Also, moreover, SANG with an interesting development gives a favorable method to manage making physiological sensors, especially to perceive micromechanical signals.[11]

2.4 Problem under investigation

- Low cost production of device has to be identified.
- Alternative choice of materials for replacing the health and environmental hazardous material.
- Simulations for identifying mechanism behind the process of energy generation has to be computed.
- Identification of material and structure suitable for making a hybrid nanogenerator that can be placed in a shoe sole must be found out.

Chapter 3

Theory of proposed work

3.1 Theory of energy harvesting

Energy harvesting has various structures dependent on the source, sum, and sort of energy being changed over to electrical energy. Energy harvesting systems require a source of energy like heat, light, or vibration.[12] The method of recovering energy from body movement is called Body motion energy harvesting (BMEH). Researchers explored the possibility of recovering the energy produced by body movements, during everyday activities. They found out that human beings while walking produce the highest amount of energy[13]. Recently, to convert mechanical energy into electrical energy, triboelectric nanogenerators (TENGs)[14] and piezoelectric transducers have got the most attention by many researchers[15].

3.2 Theory of piezoelectric nanogenerator

A piezoelectric nanogenerator is a transducer that uses the external change kinetic or mechanical energy into an electrical charge by the principle of piezoelectric effect. The piezoelectric material is one sort of nanogenerator[16]. At the point when we crush this piezoelectric material or apply any power, pressure or weight, the nanogenerator changes over this energy into voltage. This voltage is a component of the power, pressure or weight applied to it. Piezoelectric Effect is the capacity of specific materials to create an electric charge because of applied mechanical pressure[17].

Piezoelectric energy harvesting has pulled in wide consideration from specialists particularly somewhat recently because of its benefits like high power density, compositional effortlessness, and versatility. Therefore, the quantity of studies on piezoelectric energy gathering distributed over the most recent 5 years is more than twice the amount of distributions on its electromagnetic and electrostatic partners.

Crystalline structures which possess dipole moment is said to possess piezoelectric property and such materials are called piezoelectric materials. Depending on their structure, these materials are categorized into four namely, piezoelectric ceramics, single crystals, piezoelectric polymers and composites.

Piezoelectric inorganic material usually called as piezoelectric ceramics are polycrystalline ferroelectric material with the perovskite crystal structure.These materials have high stiffness, hardness, thus application of low tensile strain may lead to fracture. These are polycrystalline materials with many grains that are single crystal having same chemical compositions. They possess good piezoelectric nature but are brittle and rigid in nature. Some of the example of piezoelectric ceramics are lead zirconate titanate (PZT) and barium titanate (BaTiO3), which is widely used as sensors and actuators.Piezoelectric single crystals are single crystal counterparts of ceramics with ions of positive and negative charges organized in periodic fashion. PMN-PT (leadmagnesiumniobate lead-titanate) and PZN-PT (lead zinc niobate-lead titanate) are most widely used piezoelectric single crystal.Unlike ceramics, the piezoelectric polymers possess polar groups in the crystalline structure of thepolymer. Piezoelectric polymers such as Poly vinylidenefluoride (PVDF) and its copolymers are widelyknown for its piezoelectric nature.

3.3 Theory of triboelectric nanogenerator

Triboelectric nanogenerators (TENGs) are promising electric energy harvesting devices as they can deliver inexhaustible clean energy utilizing mechanical excitations from the surroundings[18]. A TENG is an energy gathering device that uses contact electrification also known as triboelectric effect and electrostatic induction for converting the mechanical energy acquired from human motion such as jogging, running, swimming etc. to electrical energy[19]. The triboelectric impact can be seen in our regular day to day life and it results from two unique materials coming into contact. It is viewed as a negative impact in industry, given that the electrostatic charges initiated from it can cause dust blasts, dielectric breakdown, electronic harm etc[20]. From an energy viewpoint, those electrostatic charges include a capacitive energy device when the two triboelectric surfaces are secluded, which prompted the making of early electrostatic generators, for instance, the "rubbing machine" and Van de Graaff generator[21].

Triboelectric energy gathering is the way toward changing over mechanical energy over to electrical energy from erosion or brief contact between two assorted triboelectric materials. Its fundamental energy gathering framework relies upon consolidated contact jolt and electrostatic acceptance.

Triboelectric materials will be materials which are electrically charged when they interacts with another material by righteousness of contact. When a pressure/force is applied to such materials a surface charge is observed to develop in them. Triboelectric series illustrates the list of materials which exhibits the tribolectric effect in terms of electronegativity or electropositivity. Poly(methylmethacrylate) (PMMA) is a non-cross linked transparent thermoplastic which is light weighted and has lower modulus of elasticity. PMMA is an ester of methacrylic corrosive with methyl bunch forestalling polymer chains from pressing intently. Due to more electropositive nature, they attain positive charge when in contact with electronegative materials. Thus promises to be perfect contact layer for triboelectric generators. Poly dimethylsiloxane (PDMS) is a sensitive hydrophobic polymer with multi utilitarian properties like high versatility, the capacity to have the surface plans, trustworthiness to temperature applications and its triboelectric nature. PDMS is an optically clear, non poisonous and inactive mineralorganic polymer. PDMS gets hydrophobic after cross-connecting. Electronegativity of PDMS assists them with accomplishing a negative accuse when in contact of metal or materials with electropositivity.

Chapter 4

Optimizing Structures and Materials for Footwear based Piezoelectric Nanogenerator

In this study, we designed an optimized structure for shoe sole energy harvesters for harnessing energy from footwear based on the principle of piezoelectric effect using COMSOL Multiphysics simulation software. In this study the device structure was optimized by considering the pressure variation applied onto the nanogenerators which can be kept on a shoe sole for generating the electrical energy during normal gaits of a human. Various piezoelectric materials were used as energy generating layers for shoe sole and comparative study on the effect of these materials on different structures were carried out. Voltage generated by these materials was studied based on application of force on top and bottom sides of the structure. The displacement occurring on structures were also plotted using colour contours.

4.1 Materials

Four piezoelectric materials namely,Lead zirconate titanate (PZT 5A), Lead zirconate titanate (PZT 4), Polyvinylidene fluoride (PVDF) and Barium Titanate are selected for study[22-23]. The properties of these materials are enlisted in Table 4.1 [24].

Table 4.1: Properties of the piezoelectric materials.

Properties/Materials	PVDF	PZT 5A	PZT 4	Barium Titanate
Relative permittivity	13	1700	1300-1475	1700
Piezoelectric constant (pm/V)	17	390	350	350
Young's modulus (Gpa)	3	48-135	48-135	67
Resistivity (Ω.m)	10^{11}	10^{12}	$> 10^{12}$	$0.2 - 10$

4.2 Methodology

COMSOL multiphysics software has been used to simulate the structures of shoe soles based on different piezomaterials. The multiphysics study involves solid mechanics study, electrostatics and piezoelectric study to perform displacement and voltage analysis on structures[25]. Two cases for each structure were considered based on the application of force and fixed constraints applied to the system. Case 1: Force applied only on top surface. For this case the applied force was taken in the range 200-600 N/m^2 in steps of 50 N/m^2.

Case 2: Force applied on both top and bottom surface. For this case the applied force on the top surface was taken in the range of 100-600 N/m^2 in steps of 100 N/m^2. For each value of force applied on the top surface, the values of 10 N/m^2, 30 N/m^2 and 50

N/m^2 force were applied on the bottom surface.

These values were considered on the basis of the pressure exerted back from ground while a person with average weight and height is walking or jogging[26].

4.3 Footwear sole designing

The structure of the nanogenerator which is to be kept in a shoe sole is selected based on the pressure points of the human foot. Four different shapes such as, 'mirror c', '0', 'T', 'a' and'd' as shown in Figure 4.1 (a-e). The dimensions of the structures are as follows: length 5 inch, breadth 3 inch and height 0.5 inch considering the shoe size of an individual with average weight and height. The area of contact of various structures are as mentioned in Table 4.2[27].

The surface area for each structure is calculated.

Table 4.2: Surface area of each structure.

Structure	Surface Area ($inch^2$)	Dimension (inch)
Mirror C	28	5×3×0.5
0	38	5×3×0.5
T	22	5×3×0.5
a	36	5×3×0.5
d	30	5×3×0.5

4.4 Nanogenerator modelling

The nanogenerator has to be modelled in such a way that it is to be kept in a shoe sole. Based on this condition, all the structures shown in Figure 4.1 (a-e) is designed in such

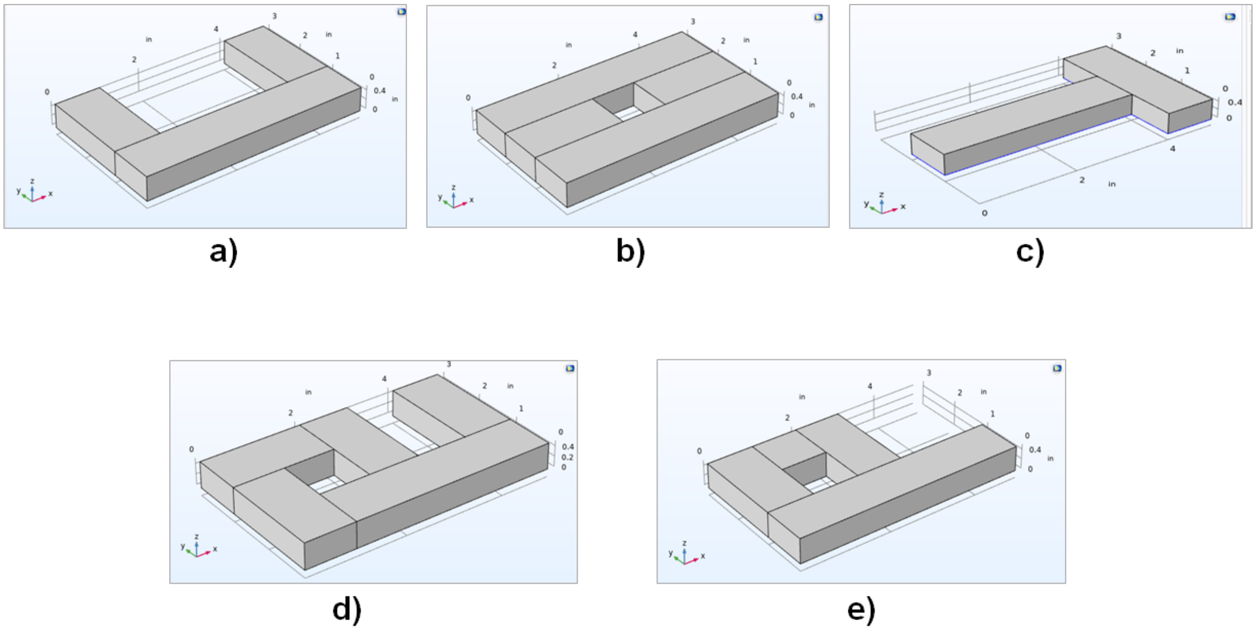


Figure 4.1: **Structures:** a) “Mirror C”, b) “0”, c) “T”, d) “a”, e) “d”.

a way that it will cover the pressure points of the sole. Each structure has dimensions of 5.0 inch × 3.0 inch × 0.5 inch. Piezoelectric materials are added on to the proposed structures and corresponding electric potentials are obtained for each structure with four different materials[28-29].

4.5 Simulation study and parameters

The structural mechanics module involves an interface known as solid mechanics. This interface defines various parameters, quantities and features required for stress analysis, general linear and nonlinear solid mechanics and displacement solving. Material models are hyper-elasticity (Nonlinear Structural Materials Module), linear viscoelastic material and linear elastic material models. Linear elastic material is commonly used and considered as the default material model in the interface. Elastic material models can be expanded with increase in temperature, damping, and changing stress and strain features[30]. Upon entering inelastic strains as additional initial strain contributions, inelastic strain features are defined. Constants, look-up tables, variables and composite and nonlinear expressions that are time and space varying are used to describe the coefficients of materials[31]. At the point when the piezoelectric material node is added to the solid mechanics interface without a functioning piezoelectric effect multiphysics coupling node, the material acts also to a linear elastic material node[32].

$$V = g(F(N)t(m))/(A(m^2)) \tag{4.1}$$

$$g = d/(\epsilon_0)(\epsilon_r) \tag{4.2}$$

$$P = 1/2CV^2.f \tag{4.3}$$

$$P \propto g.d \tag{4.4}$$

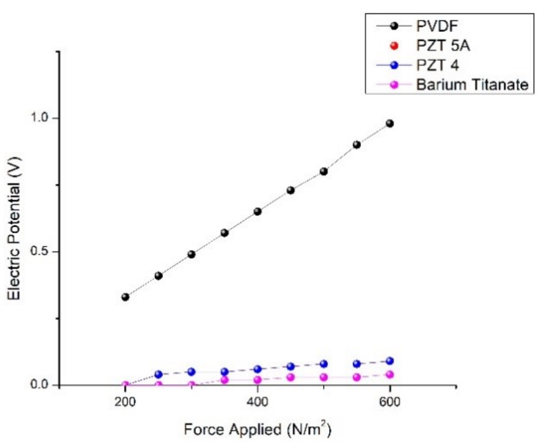
4.6 Results and discussion

The following section deals with piezoelectric characterization and voltage evaluation of proposed structures under study (Figure 4.1).

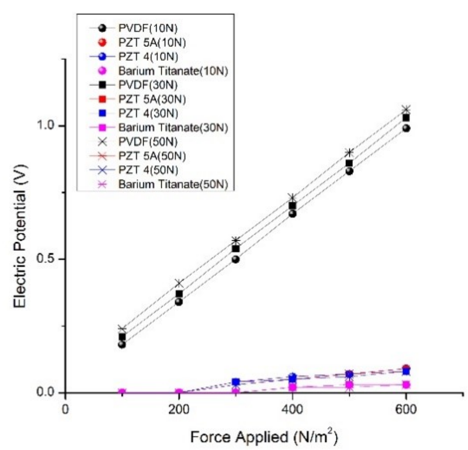
4.6.1 "Mirror C" structure.

The shape has been computed with Lead zirconate titanate (PZT 5A), Lead zirconate titanate (PZT4), Polyvinylidene Fluoride (PVDF) and Barium Titanate. The output voltage values are plotted for both the cases as shown in Figure 4.2 (a, b). As observed from the graph, the maximum voltages for PZT 5A, PZT 4, PVDF and Barium Titanate are 0.09 V, 0.09 V, 0.98 V and 0.04 V respectively for case 1.

For case 2, the maximum voltages are observed under 50 N external force and the voltages are 0.08 V, 0.08 V, 1.06 V and 0.03 V for PZT 5A, PZT 4, PVDF and Barium Titanate respectively.



[a]



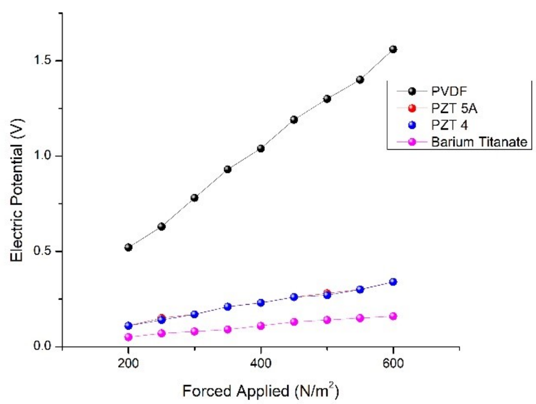
[b]

Figure 4.2: **Force vs. Electric potential graph of 'Mirror C' structure for** a) Force applied on the top surface and b) Force applied on top and bottom surface.

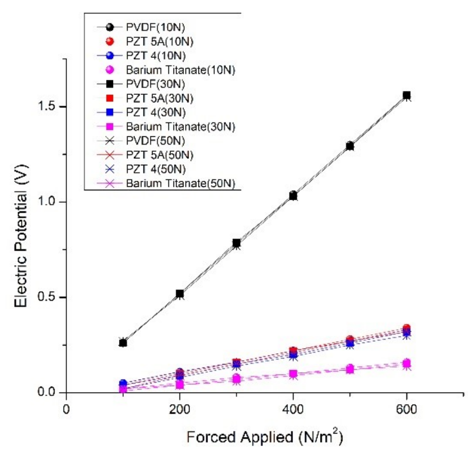
4.6.2 "0" structure.

The shape has been computed with Lead zirconate titanate (PZT 5A), Lead zirconate titanate (PZT4), Polyvinylidene Fluoride (PVDF) and Barium Titanate. The output voltage values are plotted for both the cases as shown in Figure 4.3 (a, b). As observed from the graph, the maximum voltages for PZT 5A, PZT 4, PVDF and Barium Titanate are 0.34 V, 0.34 V, 1.56 V and 0.16 V respectively for case 1.

For case 2, the maximum voltages are observed under 50 N external force and the voltages are 0.32 V, 0.3 V, 1.55 V and 0.14 V for PZT 5A, PZT 4, PVDF and Barium Titanate respectively.



[a]



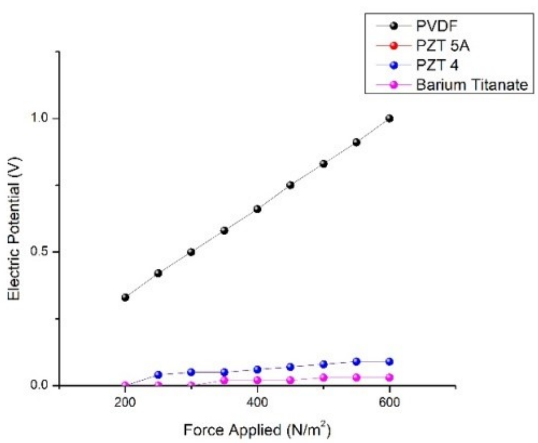
[b]

Figure 4.3: **Force vs. Electric potential graph of '0' structure for** a) Force applied on the top surface and b) Force applied on top and bottom surface.

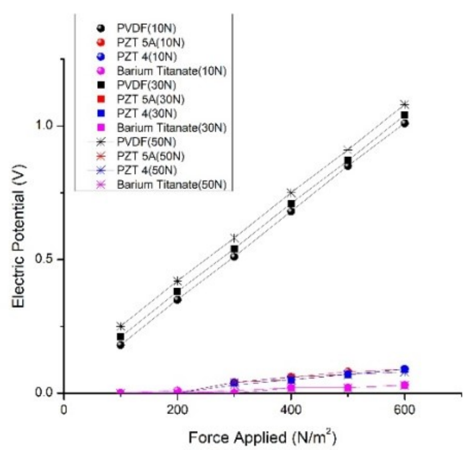
4.6.3 ”T” structure.

The shape has been computed with Lead zirconate titanate (PZT 5A), Lead zirconate titanate (PZT4), Polyvinylidene Fluoride (PVDF) and Barium Titanate. The output voltage values are plotted for both the cases as shown in Figure 4.4 (a, b). As observed from the graph, the maximum voltages for PZT 5A, PZT 4, PVDF and Barium Titanate are 0.09 V, 0.09 V, 1.0 V and 0.03 V respectively for case 1.

For case 2, the maximum voltages are observed under 50 N external force and the voltages are 0.08 V, 0.08 V, 1.08 V and 0.03 V for PZT 5A, PZT 4, PVDF and Barium Titanate respectively.



[a]



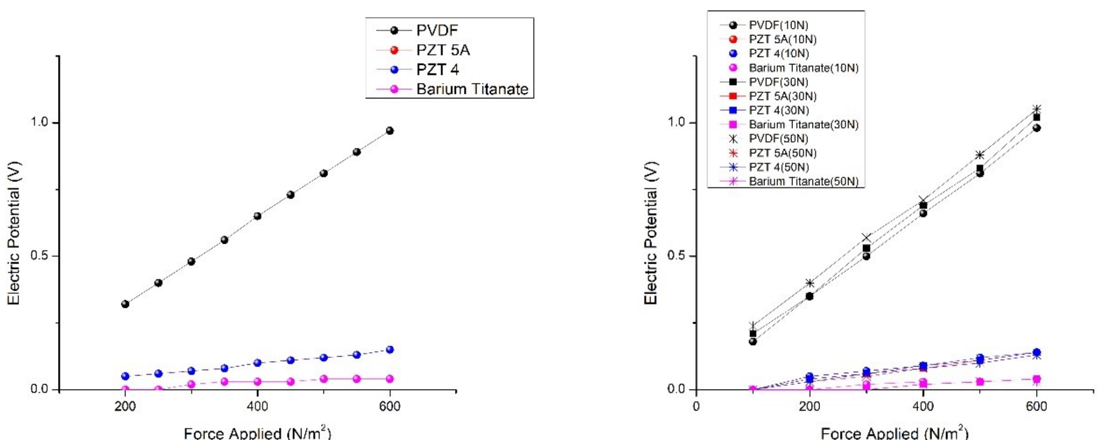
[b]

Figure 4.4: **Force vs. Electric potential graph of ‘T’ structure for** a) Force applied on the top surface and b) Force applied on top and bottom surface.

4.6.4 “a” structure.

The shape has been computed with Lead zirconate titanate (PZT 5A), Lead zirconate titanate (PZT4), Polyvinylidene Fluoride (PVDF) and Barium Titanate. The output voltage values are plotted for both the cases as shown in Figure 4.5 (a, b). As observed from the graph, the maximum voltages for PZT 5A, PZT 4, PVDF and Barium Titanate are 0.15 V, 0.15 V, 0.97 V and 0.04 V respectively for case 1.

For case 2, the maximum voltages are observed under 50 N external force and the voltages are 0.13 V, 0.13 V, 1.05 V and 0.03 V for PZT 5A, PZT 4, PVDF and Barium Titanate respectively.



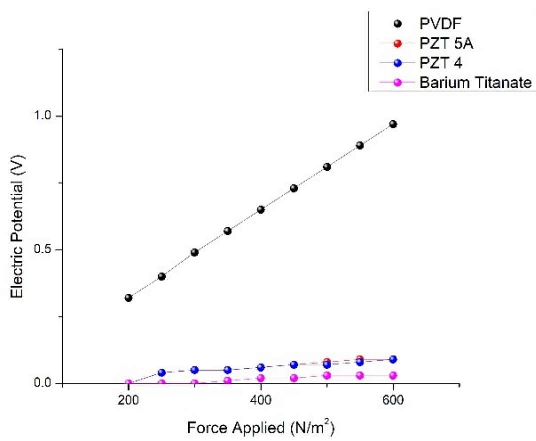
[a] [b]

Figure 4.5: **Force vs. Electric potential graph of ‘a’ structure for** a) Force applied on the top surface and b) Force applied on top and bottom surface.

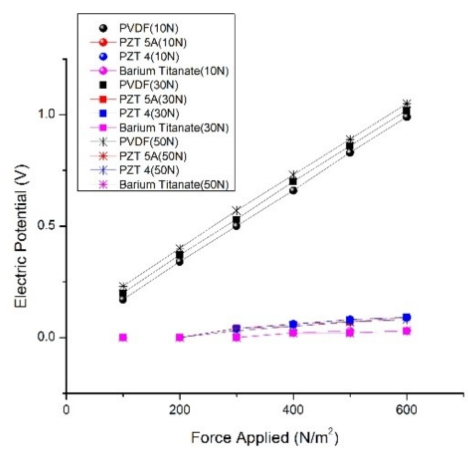
4.6.5 “d” structure.

The shape has been computed with Lead zirconate titanate (PZT 5A), Lead zirconate titanate (PZT4), Polyvinylidene Fluoride (PVDF) and Barium Titanate. The output voltage values are plotted for both the cases as shown in Figure 4.6 (a, b). As observed from the graph, the maximum voltages for PZT 5A, PZT 4, PVDF and Barium Titanate are 0.08 V, 0.07 V, 0.81 V and 0.03V respectively for case 1.

For case 2, the maximum voltages are observed under 50 N external force and the voltages are 0.08 V, 0.08 V, 1.05 V and 0.03 V for PZT 5A, PZT 4, PVDF and Barium Titanate respectively.



[a]



[b]

Figure 4.6: **Force vs. Electric potential graph of ‘d’ structure for** a) Force applied on the top surface and b) Force applied on top and bottom surface.

All the output values obtained for each structure with different materials for both the cases were considered and a graph for comparison has been obtained as shown in Figure 4.7 for case 1 and Figure 4.8 (a-c) for case 2.

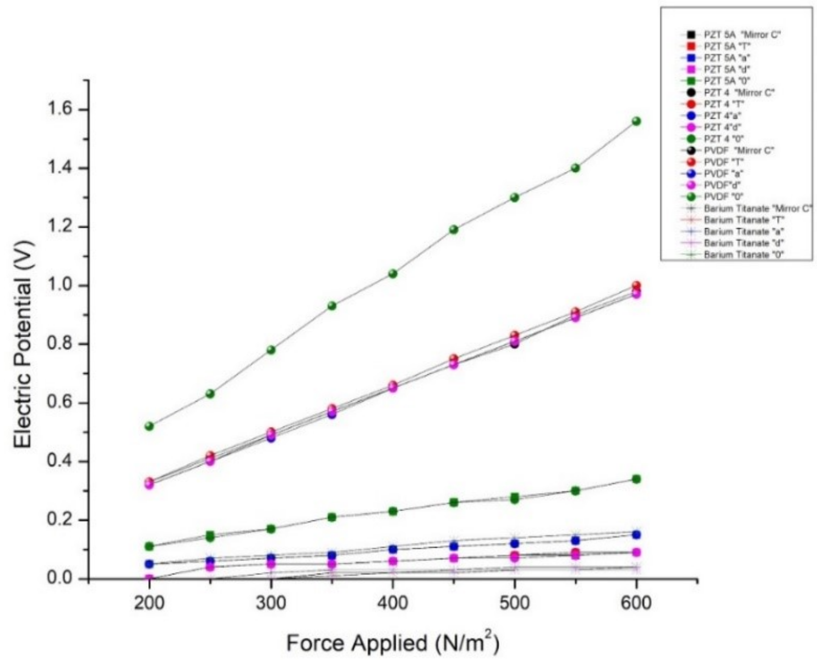


Figure 4.7: Case 1 graph for applied force versus electric potential.

From the graphs for case 1 (Figure 4.7) and case 2 (Figure 4.8) it is clear that PVDF gives better output compared to all other piezoelectric materials. Now considering PVDF as the material the structure which gives maximum output has to be obtained. For that the comparison between the graphs of all the structures with PVDF as the piezoelectric material is plotted for both the cases as shown in Figure 4.9 (a) and (b). PVDF is a mainstream piezoelectric polymer in view of its high adaptability, biocompatibility, and low cost[33]. These highlights make PVDF alluring for energy trans-

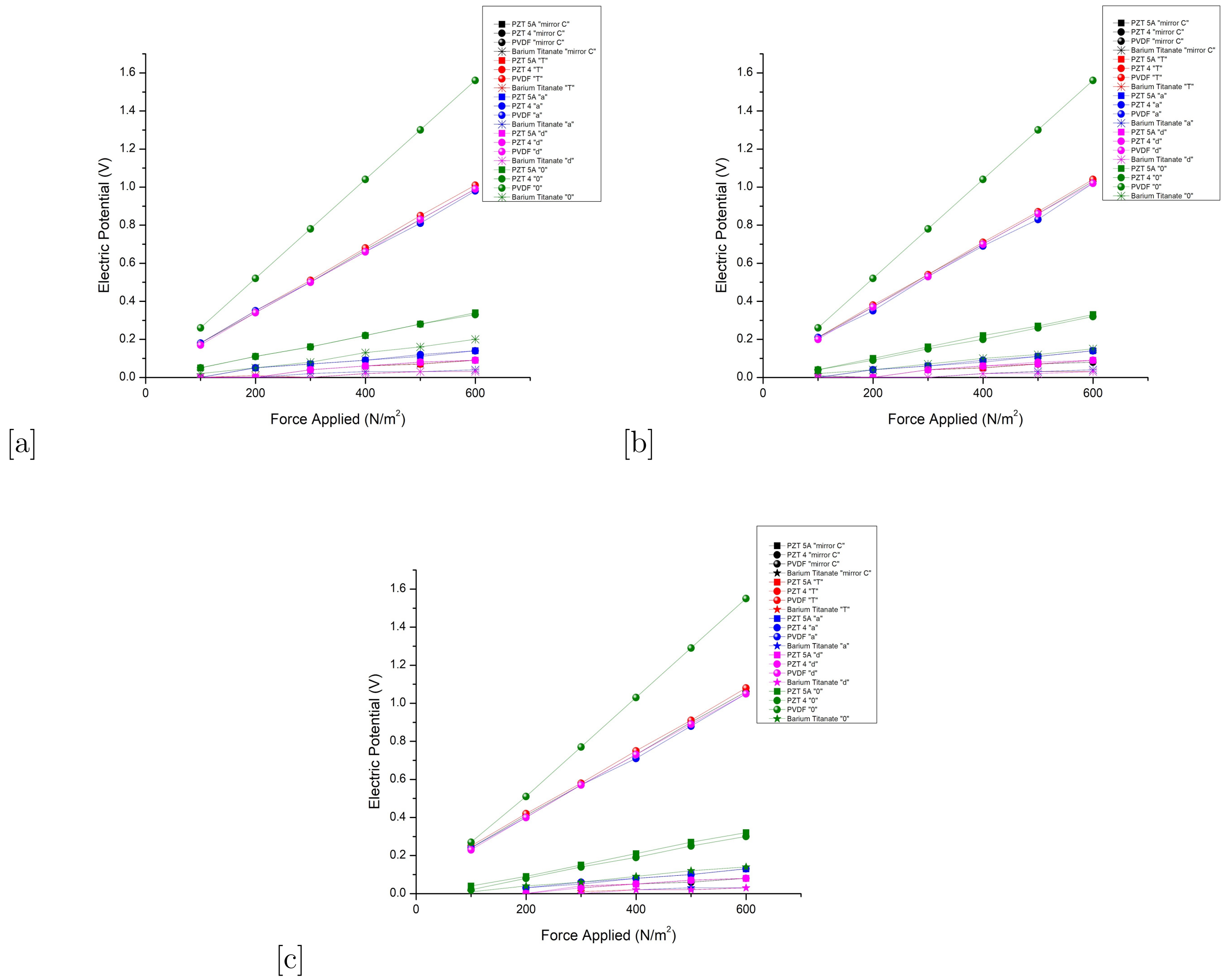
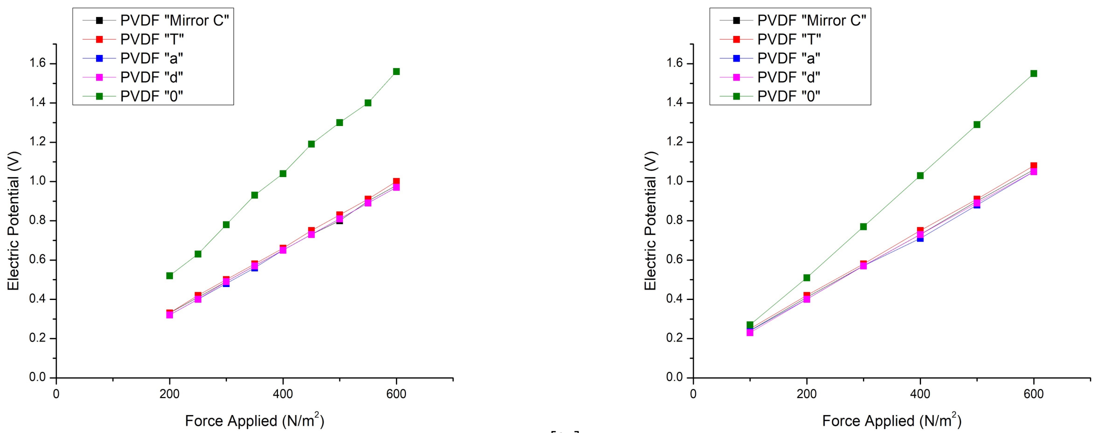


Figure 4.8: **Case 2 graph for applied force versus electric potential-**a) When applied force on the bottom surface is 10 N/m^2, b) When applied force on the bottom surface is 30 N/m^2, c) When applied force on the bottom surface is 50 N/m^2.

formation applications including micro electric-mechanical gadgets, electromechanical actuators, and energy harvesters. The high crystalline and surface tension properties of PVDF give exceptionally low saturation esteems contrasted with other fluoropolymers. Structure '0' is found to be generating the maximum voltage output. As compared to all other structures, ‘0’ structure has a total surface area of 38 inch^2. Structure ‘0’ combined with the PVDF material provides the maximum voltage output value of 1.56 V.



[a] [b]

Figure 4.9: **Comparison graph for applied force versus electric potential of all the structures for PVDF material-** a) For case 1: force applied only on the top surface, b) For case 2: force applied on both top and bottom surface (force applied on the bottom surface is 50 N/m^2).

4.7 Summary

Considering all the results obtained from the tables and graphs as shown above it can be concluded that PVDF is a better piezoelectric material compared to all other piezoelectric materials namely PZT 5A, PZT 4 and Barium Titanate. Because PVDF gives better output than other materials. Its semi-crystalline structure makes it a better piezoelectric material. Also, it is flexible, cost efficient, has high mechanical resistance and unlike other piezoelectric material PVDF have a negative value for piezoelectric coefficient it will compress instead of expand and vice versa when exposed to the same electric field.

The structure '0' has given a better output compared to all other structures as shown in Figure 4.9 (a) and (b) because it has more surface area than other structures. As applied power expands there is an expansion in electric potential for both the cases, applying power just on top surface and for power applied on both top and base surface.

Chapter 5

Optimizing Materials for Footwear based Triboelectric Nanogenerator

In this study, we have designed an optimal structure for generating power from shoe sole through energy harvesting technology based on triboelectric effect using COMSOL Multiphysics simulation software. The study provided basic insights on structural designs and helped in performance evaluation of various triboelectric materials used as energy generating layers inside a shoe sole. In this study, the device structure is optimized by the method of contact electrification and various triboelectric materials were used as energy generating layers for the shoe sole. A comparative study on the effects of these materials for different structures were carried out and the electric fields generated by these materials were studied by varying the gap between the structures.

5.1 Materials

The materials selected for the study were three polymers, namely PVDF (Polyvinylidene Fluoride), PTFE (Polytetrafluoroethylene), PMMA (Polymethyl Methacrylate), and Aluminium[34-35]. Surface charge densities of these materials are displayed in

Table 5.1.

Table 5.1: Surface charge density of each material.

Triboelectric materials	Surface charge density(C/m2)
PVDF	55×10^{-2}
PTFE	0.7×10^{-9}
PMMA	-40.5×10^{-3}
ALUMINIUM	2×10^{-6}

5.2 Methodology

COMSOL Multiphysics software was used to simulate different structures of the device along with different triboelectric materials and combinations to be implemented inside shoe sole.

Combination of materials were used for the material study.

- Polymer-Polymer combinations

  1) PVDF and PTFE

  2) PTFE and PMMA

  3) PMMA and PVDF

- Metal-Polymer combination

  Al and PVDF

5.3 Footwear sole designing

Based on various pressure points under a human foot, different structures for the nanogenerator model were selected, namely ‘mirror C’, ‘T’, ‘0’, ‘a’ and ‘d’. Structure ‘0’ was found to be the optimal structure from the piezoelectric study conducted earlier, shown in Figure 4.1(b).

The dimensions of the structure are 5.0*3.0*0.25 (inches) for length, breadth and height respectively considering the shoe size of an average individual. Two structures are arranged parallel to each other in the form of a capacitor whose gap will be varying between 0cm and 3cm by 0.75 cm[36-37].

For polymer-polymer combination, two of the same structure are kept parallel to each other as shown in Figure 5.1(a) and for metal-polymer combination, metal is kept as a sheet parallel to the structure as shown in Figure 5.1(b).

5.4 Nanogenerator modelling

The nanogenerator had to be modelled in such a way that it can be implemented inside a shoe sole. Taking this under consideration, the dimensions of each structure were taken as 5.0*3.0*0.25 (inches) and the dimension of rectangular sheet was taken as 5.0*3.0*0.05 (inches). Triboelectric materials are added to structures for both the types and the corresponding electric field are obtained for all combinations.[38-39].

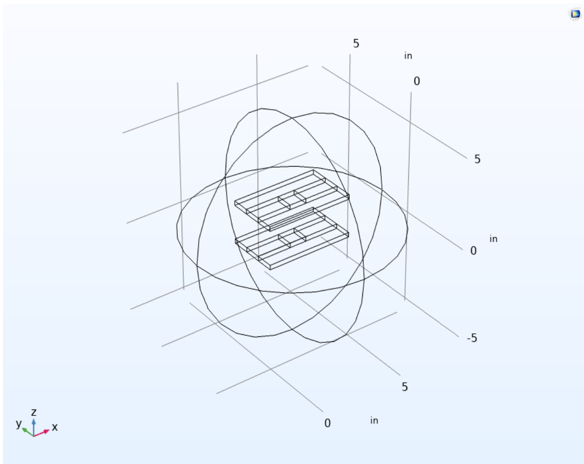
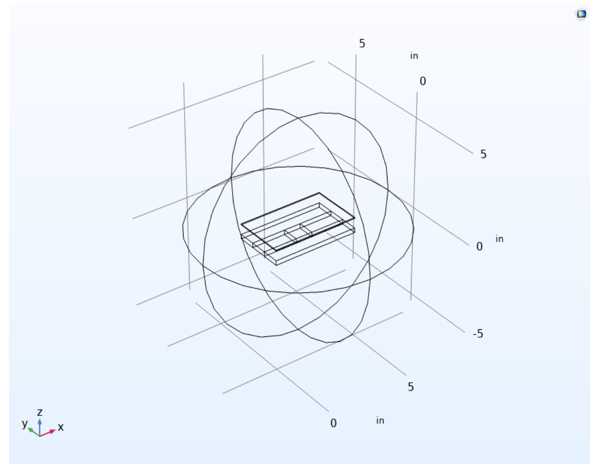
[a]  [b] 

Figure 5.1: **Structures:** a) Both structures are '0' shaped, b) one structure is a rectangular plate and the other is an '0' structure.

5.5 Simulation study and parameters

The project mainly consists of two phases. The first phase is piezoelectric and the current phase is triboelectric. Triboelectric phase is performed by taking the capacitor fringing field as a reference[40]. COMSOL provides various number of triboelectric materials but has limitations. The main drawback is that the surface charge density values which play an important role in the triboelectric study are still not found for many listed materials.

Therefore, this phase was carried out using only two combinations

- 1) Polymer -polymer combination such as PTFE-PMMA, PMMA-PVDF and PVDF –PTFE[41]
- 2) Metal - polymer combination of Al - PVDF[42].

These combinations are carried out in the selected '0' structure and triboelectric simulations were done for two cases, two of the same structure (thickness 0.25 inch) in parallel for polymer-polymer combination and structure (thickness 0.25 inch) - sheet (thickness 0.05 inch) in parallel for metal-polymer combination[43].

Triboelectric effect is generated due to the frictional force between two surfaces. The simulation procedures conducted are as follows,

- opened the model wizard in COMSOL multiphysics,
- selected the space dimension as 3D
- selected physics as AC acoustic and capacitor fringing field
- Defined parameter (gap between two parallel plates) and unit of measurements.
- added selected geometry (two same parallel structures and one structure and a thin sheet) and added materials (PTFE, PMMA, PVDF, and Al)
- Defined initial values, floating potentials, charge conservations and surface charge density of materials in electrostatics.
- defined one plate's terminal value as 0 to begrounded and the other plate's terminal value with a terminal voltage value which was calculated manually according to the surface charge density values of each material

Terminal Voltage equation.

$$V = -\sigma/\epsilon_0 D \tag{5.1}$$

- Later the finest mesh was added and the simulation was carried out.

- Finally, the output in terms of terminal voltages in the entire structure according to the different range of gaps between the two structures was obtained and a better combination of triboelectric pair was determined[44].

5.6 Results and discussion

Simulation study was carried out and the results were obtained. Change in electric field and potential voltages were studied with change in gap between the plates. It is found that as the gap between the plate increases, it can be seen that electric field norm increases and potential voltage decreases as shown in Figure 5.2 and Figure 5.3. Here only one plate is kept static while the other plate is in motion, this is called contact electrification.

Decisions are made based on the following results and characteristics. Two material combinations were chosen, namely polymer-polymer combination and metal-polymer combination. The polymer-polymer has the combination of PVDF - PTFE, PTFE-PMMA and PMMA-PVDF whereas metal-polymer has Cu combination and Al combinations.

From the polymer-polymer combination, PMMA-PTFE generates a better output compared to others. A high output value is noticed when there is minimum distance between the two surfaces and decreases as they move further apart. Metals draw more electrons compared to polymers and it's easy to obtain output through metals.

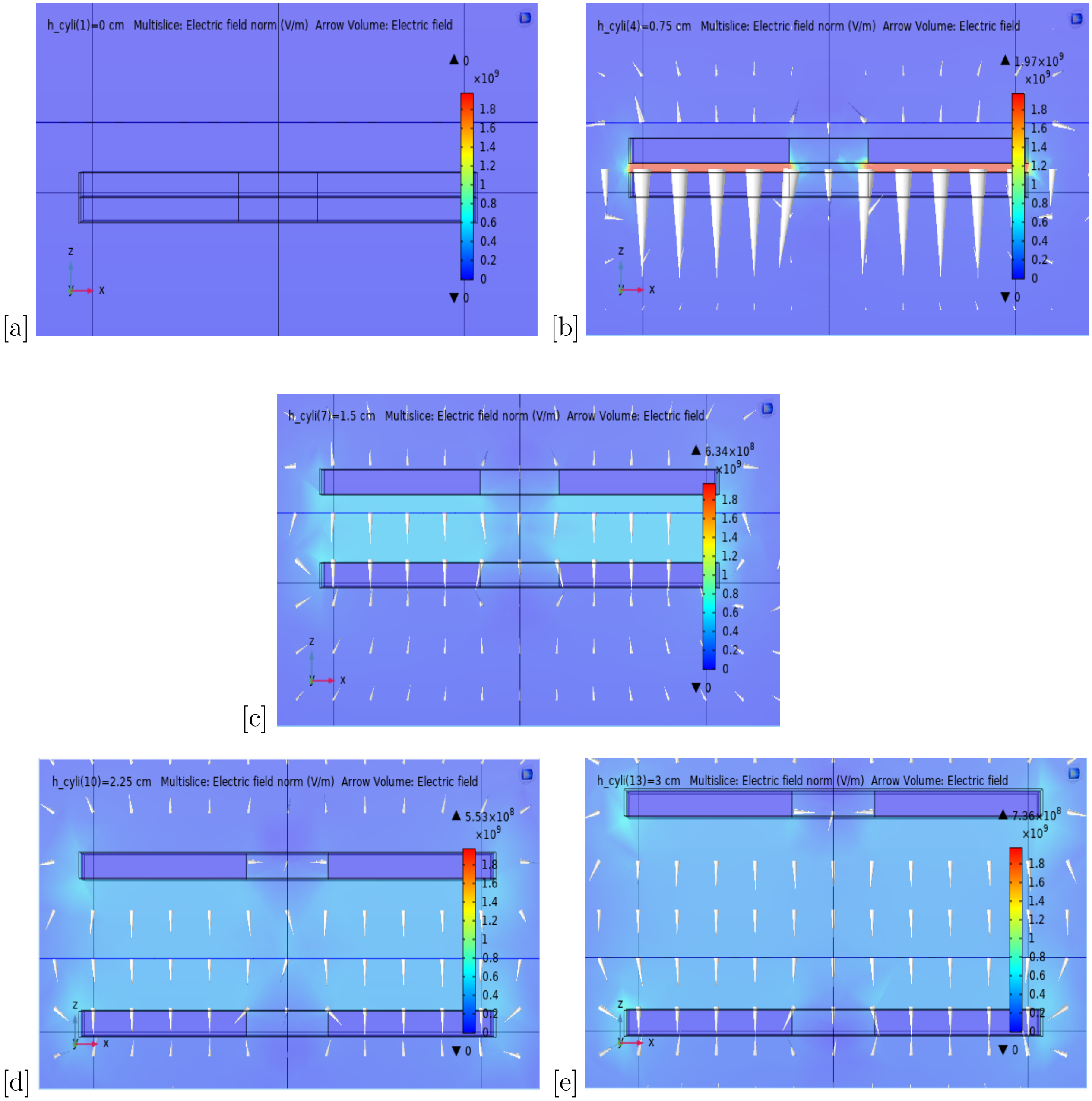


Figure 5.2: **Simulation result of polymer-polymer combination (PMMA-PTFE):-**Change in electric field for change in gap between the plates are a) 0cm b) 0.75cm c) 1.5cm d) 2.25cm e) 3cm.

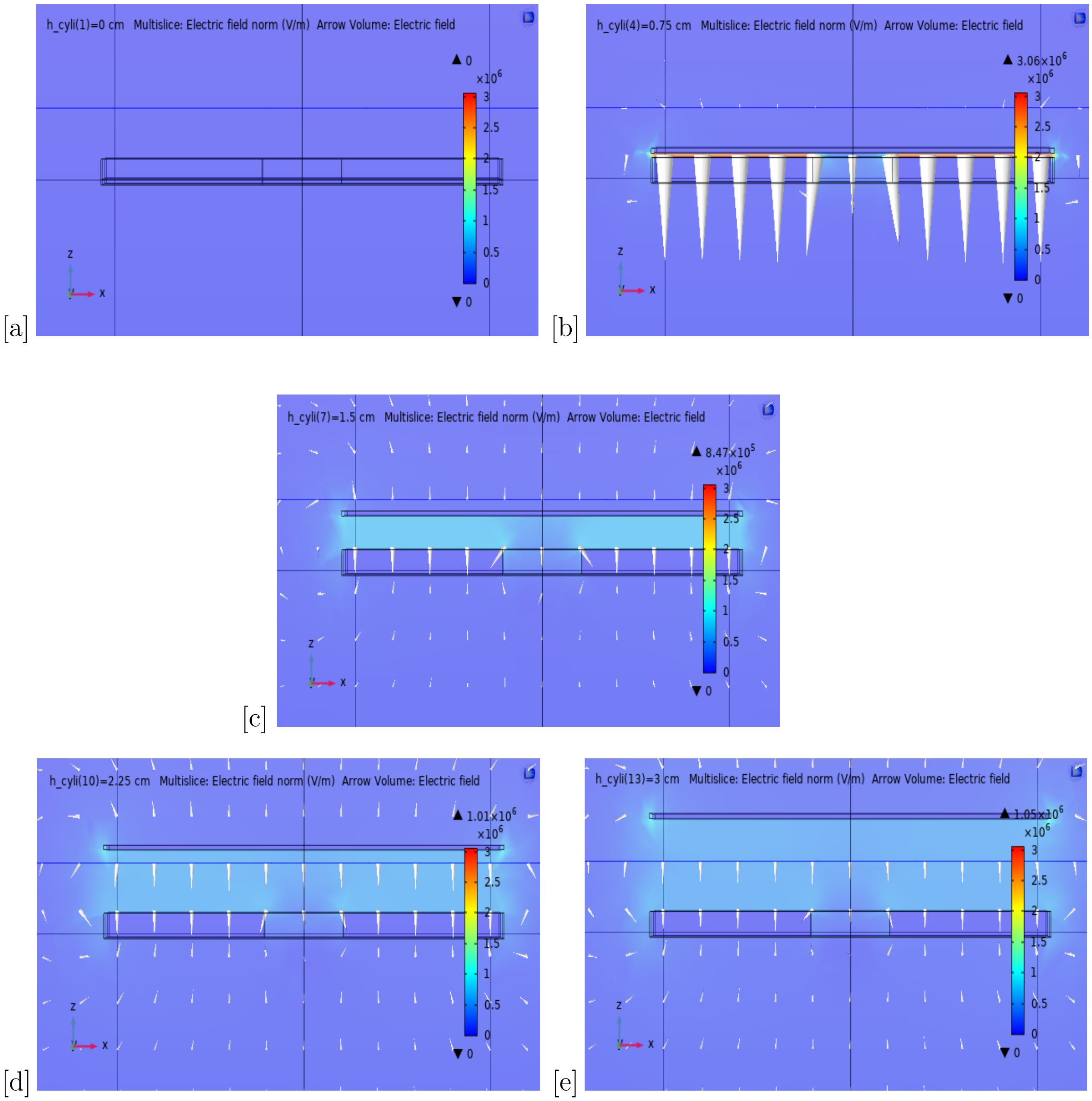


Figure 5.3: **Simulation result of metal-polymer combination (Al-PVDF):-** Change in electric field for change in gap between the plates are a) 0cm b) 0.75cm c) 1.5cm d) 2.25cm e) 3cm.

The Figure. 5.4 shows the output voltage for the combinations and it can be seen that the combination of PTFE-PMMA and Al-PVDF has more output values.

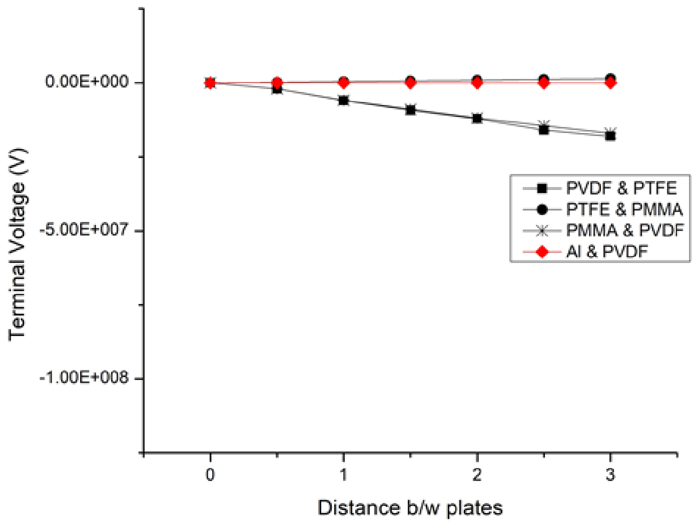


Figure 5.4: Terminal voltage v/s distance between the plates.

5.7 Summary

From the triboelectric simulation and analysis of the three polymer-polymer and the one metal-polymer combination, it has been evident from Figure 5.4 that metal-polymer combination gives a better output while compared to the three choices of polymer-polymer combinations.

Since PVDF has proven itself with better performance as a piezoelectric material in our initial stage of the piezoelectric study, it also provides good results in our triboelectric study also, so we are considering PVDF as a triboelectric material as well.

Now coming on to the metal-polymer combination we have selected Aluminum to combine with PVDF as a hybrid combination. We have selected aluminum as a triboelectric material because of its property, availability and the surface charge density value is very low compared to other materials, so when it combines with any other material it won't dominate over them. For example, in the case we have taken copper which has a reasonable surface charge density dominant over any other material to give a combined surface charge density value which is equal to that of copper.

Chapter 6

Prototyping the Piezo-Tribo Nanogenerator for Footwear Application

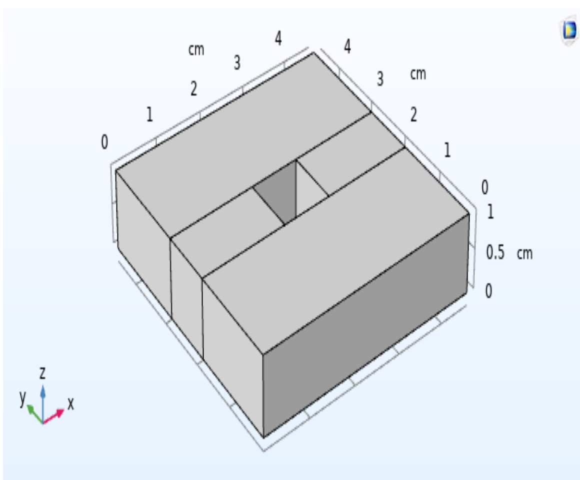
Earlier phases of the work, including material and structural studies, were all simulated and completed with the help of a virtual platform, COMSOL Multiphysics. The next phase of the work is to implement all these results and observations and build a prototype for the nanogenerator model. It involves fabrication using the materials and completing the circuit necessary for harvesting and converting the energy. The dimensions of the actual nanogenerator model are slightly reduced for the prototype model.

6.1 Materials and methods

The materials used for fabrications are Aluminium sheet of dimension 25cm × 10cm × 1cm, PVDF sheet of diameter 4.7cm × 0.45µm thickness (EMD Millipore HVLP04700 Durapore Membrane, PVDF, 0.45 Âµm, 47 mm dia), jumper wires, breadboard, capacitor(1000µF, 25V), diodes and voltmeter.

The actual nanogenerator extends between the dimensions $5.0 \times 3.0 \times 0.25$(inches). Dimensions were reduced for the prototype model. Simulation was carried out for reduced size of '0' structure with dimensions 4.6 cm $\times$ 1.8 cm $\times$ 1 cm as shown in Figure 6.1 for both piezoelectric and triboelectric study with PVDF as piezoelectric material and Al-PVDF as triboelectric material pair. The results obtained are shown in tables 6.1, 6.2 and 6.3. These results could not be compared due to the limitations of the virtual platform COMSOL Multiphysics.

[a]



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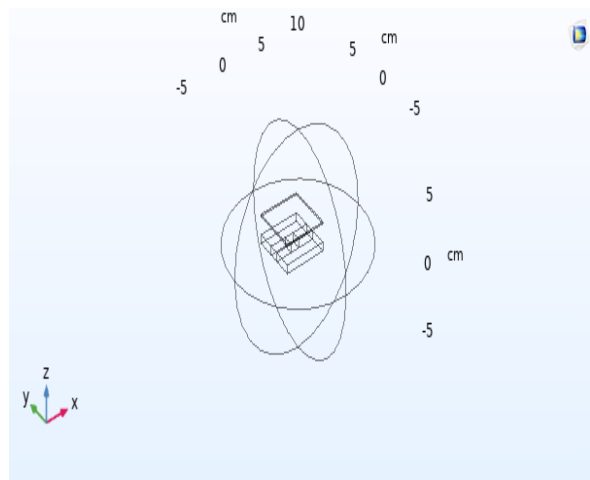


Figure 6.1: **Structures:-**a)'0' structure used for piezoelectric study, b)'0' structure and plate pair structure used for triboelectric study.

Table 6.1: ‘0’ structure output potential values for force applied on the top surface.

Force (N/m^2)	Potential Voltage (V)
200	0.23
250	0.29
300	0.35
350	0.41
400	0.47
450	0.53
500	0.59
550	0.65
600	0.7

Table 6.2: ‘0’ structure output values for force applied on top and bottom surface.

Force (N/m^2)	Potential Voltage (V)		
	10N	30N	50N
100	0.13	0.15	0.18
200	0.25	0.27	0.29
300	0.36	0.39	0.41
400	0.48	0.5	0.53
500	0.6	0.62	0.65
600	0.72	0.74	0.76

Table 6.3: Terminal voltage obtained after triboelectric study.

Gap between the plates (cm)	Terminal Voltage (V)
0	0
0.5	-0.2×10^2
1	-0.4×10^2
1.5	-0.6×10^2
2	-0.8×10^2
2.5	-1×10^2
3	-1.5×10^2

6.2 Fabrication of device

- Two circles of diameter 4.6cm are made from an aluminium sheet as show in Figure 6.2(a)(first structure), Type 1.

- Two circles of diameter 3.5cm are made from the aluminium sheet with a hole of diameter 1cm in the center as shown in Figure 6.2(a)(second structure), Type 2.
- Wires are soldered to the aluminium sheets as shown in Figure 6.2(a).
- PVDF sheet(Figure 6.2(b)) is placed between a Type 1 and Type 2 aluminium sheet in two ways.
- Case 1: PVDF sheet placed between Type 1 and Type 2 aluminium sheet.
- Case 2: Hollow PVDF placed between Type 1 and Type 2 aluminium sheet.
- Model is made compact and held together using tape (Figure 6.2(c)).
- Bridge rectifier circuit is made using diodes and breadboard as sown in Figure 6.2(d).
- Wires from the model is connected to the input of the rectifier circuit.
- Multimeter is connected to the circuit to measure the voltage reading.

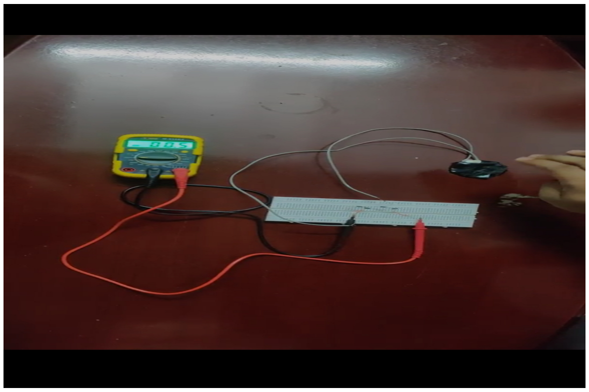
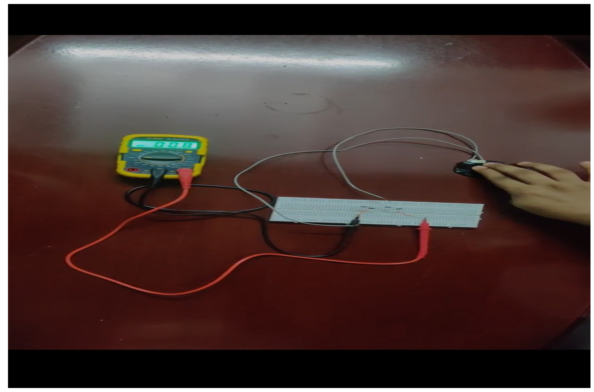
Figure 6.2: **Fabrication process:** a)Wires are soldered to the aluminium sheets, b)PVDF sheets, c)Fabricated structure, d)Bridge rectifier circuit is made using diodes and breadboard, e)circuit

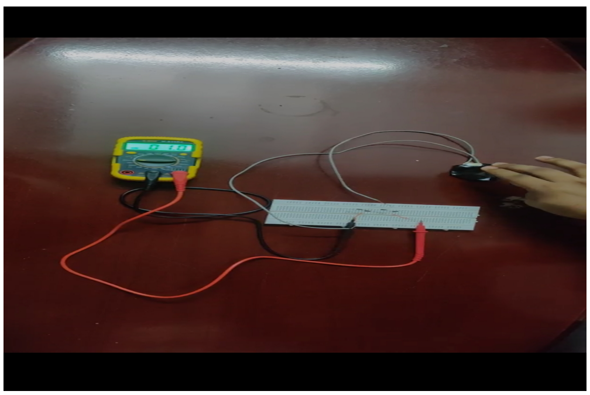
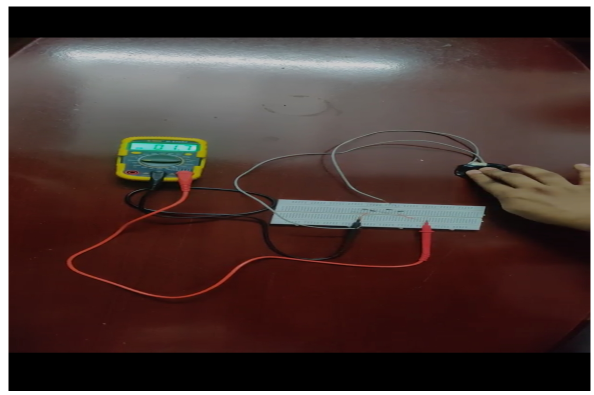
6.3 Results and discussion

The output results for both the cases have been noted using multi-meter. In case 1 it was seen that when the pressure is applied it gives voltages like 0.5mV, 0.8mV, 1mV, the readings are shown in Figure 6.3(a-c) and in case 2 when pressure is applied it gives voltages like 1.7mV, 1.9mV, 2mV as shown in Figure 6.3(d-e). From the readings it is clear that case 2 that is the hollow PVDF placed between Type 1 and Type 2 aluminium sheet gives maximum output voltage when pressure is applied.

When more force is exerted by punching on the device (case 2) it was seen that a voltage up to 7mV was obtained. This shows that as the force/pressure is more the output voltage also increases that is force/pressure is directly proportional to voltage.

The oscilloscope reading were taking for different forces as shown in Figure 6.4 and it was seen that when force is more the output voltage obtained is 3.35V which is high.

[a]  [b] 

[c]  [d] 

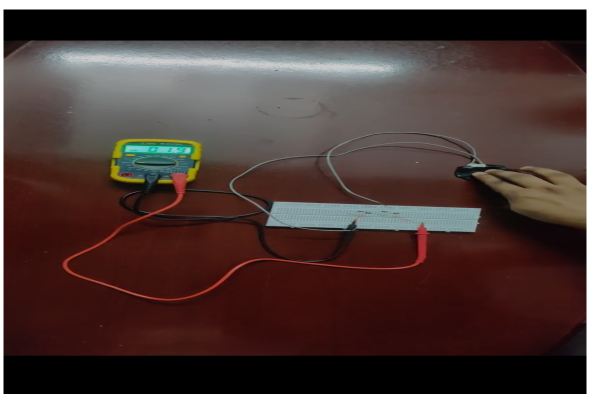
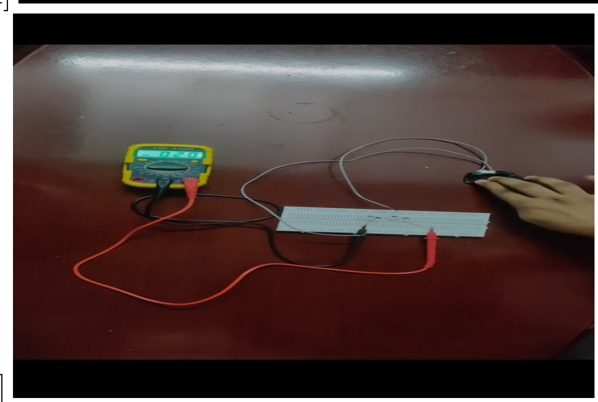
[e]  [f] 

Figure 6.3: **Readings:**Case 1 results a)0.5mV, b)0.8mV, c)1mV, Case 2 results d)1.7mV, e)1.9mV, f)2mV.

[a] [b] [c] [d]

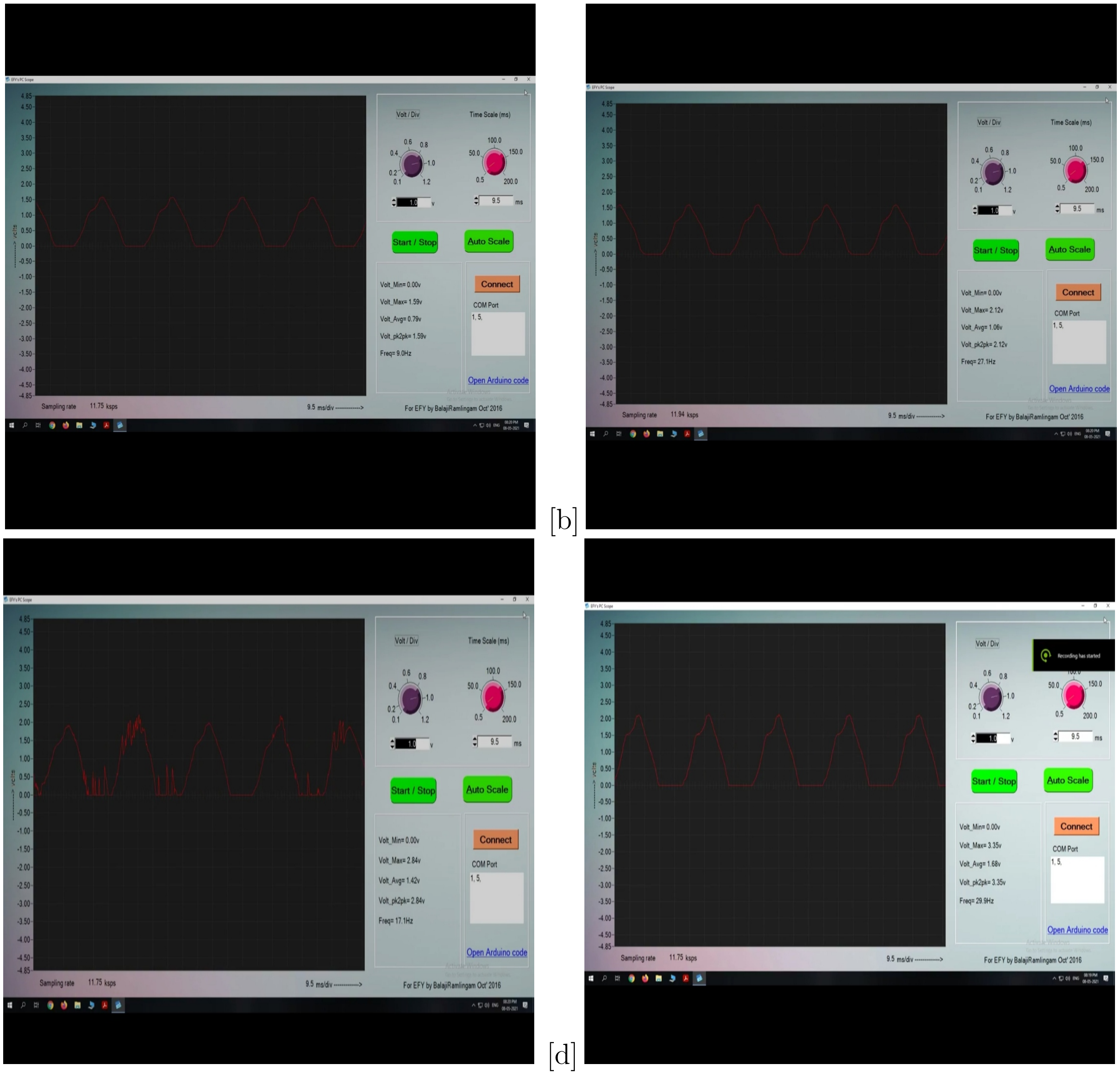


Figure 6.4: **Oscilloscope readings:**a)1.59V, b)2.12V, c)2.84V, d)3.35V.

Chapter 7

Conclusion and Future works

7.1 Conclusion

The piezoelectric study includes structural and material optimization of four materials namely PVDF,PZT 5A, PZT 4 and Barium Titanate and five structures namely ‘mirror C’, ‘T’, ‘0’, ‘a’ and ‘d’. Simulations were carried out on each structure with all the four materials individually and output was obtained and compared. The results showed that PVDF is a better material compared all other materials and ’0’ structure is the better structure than other structures.

The triboeletric study includes material optimization of four materials namely PVDF, PTFE, PMMA and Aluminium. From piezoelectric study ’0’ structure was obtained as better structure so simulation was carried out with ’0’ structure and four materials combinations namely PTFE-PMMA, PVDF-PTFE, PVDF-PMMA and Al-PVDF. The results were obtained and it shows that Al-PVDF and PTFE-PMMA combination give better output. Al-PVDF combination was selected as tribo pair because PVDF has proven itself with better performance as a piezoelectric material in our initial stage of the piezoelectric study it also provides good results in our triboelectric study also, so we are considering PVDF as a triboelectric material as well. We have selected aluminium as a triboelectric material because of its properties such as it's easily available, and the surface charge density value is very low compared to other materials, so when it combines with any other material it won't dominate over them. For example in the case we have taken copper which has a reasonable surface charge density dominant over any other material to give a combined surface charge density value which is equal to that of copper, which is the reason we decide to go for aluminium as said earlier which is easily available.

The prototype has been made and results was obtained. It is seen that case 2 that is the hollow PVDF placed between Type 1 and Type 2 aluminium sheet gives maximum output voltage when pressure is applied compared to case 1 that is PVDF sheet placed between Type 1 and Type 2 aluminium sheet. The maximum voltage obtained is 2mV. Also, it was seen that when we exert more force by punching hard on the device a voltage up to 7mV was obtained. This shows that when the force/pressure is more voltage also increases.

7.2 Future works

- Build prototype with increased dimensions.
- Implementation of the work.
- Nanoparticles addition.

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- Anagha Mohan, Abhijith R, Akshay Viswanath A P, J R Kannan, Sreenath K, Baby Sreeja S D, Sreenidhi P R, Sundararaman Gopalan, "Optimizing Structures and Materials for Footwear based Piezoelectric Nanogenerator," 2021 Third International Conference on Materials Science and Manufacturing Technology (ICMSMT 2021), Coimbatore, Tamil Nadu, India.

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