ENABLING THE VERSATILITY OF FLEXIBLE FERRO-ELECTRET NANO-GENERATORS: FROM ACOUSTICS TO BRAIN VIBRATIONS

By

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ABSTRACT

This dissertation presents the characterization and use of a flexible polypropylene-based FerroElectret NanoGenerator (FENG), a quasi-piezoelectric device, in four different applications: loudspeaker, microphone, concussion detection, and brain vibration measurement. The first two applications focus on acoustical metrics that the FENG performed under various configurations and test conditions. As a loudspeaker, the relationship between sound output and electrical input is studied and found to be linear within the audible range (20Hz to 20 kHz). Ultrasonic frequencies (20 kHz - 40 kHz) are also characterized. The influence of device shape and size on directivity was also studied. A theoretical model was developed to analyze the observed behaviour. Similarly, as a microphone, the effect of area on the sensitivity (sound output for given electrical input) was studied and reported. Further, the spectral information of the output from a FENG-based microphone was compared with that of commercially available products.

For concussion detection, this work demonstrates the development of a flexible, self-powered sensor patch that can be used to estimate angular acceleration and angular velocity, which are two essential markers for predicting concussions. The device monitors the dynamic strain experienced by the neck through a thin FENG-based device that produces a voltage pulse with a profile proportional to the applied strain. The intrinsic property of this device to convert energy between the mechanical and electrical domains, along with its flexibility and thickness ∼ 100 µm, makes it a viable and practical device that can be used as a wearable patch for athletes in high-contact sports. After processing the dynamic behaviour of the produced voltage, a correspondence between the electric signal profile and the measurements from accelerometers integrated inside a human head and neck substitute was established. This demonstrates the ability to obtain an electronic signature that can be used to extract head kinematics during a collision and create a marker that could be used to detect concussions. Unlike accelerometer-based current trends on concussion-detection systems which rely on sensors integrated into the athlete’s helmet, the flexible patch attached to
the neck would provide information on the dynamics of the head movement, thus eliminating the potential of false readings from helmet sliding or peak angular acceleration. Following work related to brain injuries, the FENG was used to sense vibrations in a biofidelic brain upon blunt impact. In this work, the study of the modality of deformations is highlighted. This study is carried out using two different approaches: Particle Image Velocimetry (PIV), and using FENG as an invasive flexible sensor in the phantom. The results show that the system has a natural mechanical frequency of $\sim 25$ oscillations per second, which was corroborated by both methods. The consistency of these results with previously reported brain pathology validates the use of either technique and establishes a new, simpler mechanism to study brain vibrations by using flexible piezoelectric patches. The viscoelastic nature of the biofidelic brain is validated by observing the relationship between both methods at two different time intervals, by using the information of the strain and stress inside the brain from the PIV and flexible sensor, respectively. A non-linear stress-strain relationship was observed and justified to support the same.

In the case of a microphone, concussion detection, and brain vibrations, the FENG was configured as a sensor, i.e. a stress was exerted on the FENG and its response was recorded and studied. In the case of loudspeaker, an electrical stimuli was applied to the FENG and its strain (actuation) was analyzed. This kind of versatility demonstrated by the FENG is a testament to the world of flexible sensors and transducers.
To science.
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# TABLE OF CONTENTS

## CHAPTER 1 INTRODUCTION
- 1.1 Role of flexible devices .......................... 1
- 1.2 Problem description and motivation .......... 5
- 1.3 Thesis Statement ................................. 6
- 1.4 Outline ........................................ 6

## CHAPTER 2 BACKGROUND
- 2.1 Audio technologies ...................................... 9
- 2.2 Traumatic Brain Injury (TBI) ......................... 13

## CHAPTER 3 FABRICATION OF THE FENG, THE CHARACTERIZATION SETUP FOR VARIOUS APPLICATIONS AND SIGNAL PROCESSING ...
- 3.1 Experimental Setup for measuring Sound Pressure Levels and directivity of the FENG as a loud speaker .......................... 26
- 3.2 Experimental Setup for measuring sensitivity and directivity of the FENG as a microphone ........................................... 28
- 3.3 Experimental Setup for measuring FENG’s response to head impact .......................... 30
- 3.4 Experimental setup for measuring brain vibrations under blunt impact using the FENG ........................................... 33

## CHAPTER 4 PARAMETERS OF INTEREST AND MEASUREMENTS FOR FENG AS LOUDSPEAKER ........................................... 38
- 4.1 Area Vs. Sound Pressure Level .......................... 39
- 4.2 Linearity ............................................ 40
- 4.3 Directivity of the FENG ............................... 41
- 4.4 Frequency Response and Effect of Folding .......................... 43
- 4.5 Ultrasound performance ............................... 45

## CHAPTER 5 THEORETICAL MODELING AND VALIDATION OF FENG AS A LOUD SPEAKER ........................................... 48
- 5.1 Voltage Response Definition .......................... 48
- 5.2 Point Approximation Source .......................... 48
- 5.3 Estimating the Change in Thickness of the FENG ........................................... 49
- 5.4 High Frequency General Model .......................... 50
- 5.5 Model Accounting for Solid Back-Plate .......................... 51
- 5.6 Summary ............................................ 55

## CHAPTER 6 CHARACTERIZATION RESULTS OF THE FENG AS A MICROPHONE ........................................... 56
- 6.1 Sensitivity ............................................ 56
- 6.2 Comparison with traditional microphones .......................... 57
- 6.3 Summary ............................................ 58
CHAPTER 7  FENG AS FLEXIBLE SENSOR FOR CONCUSSION DETECTION ................................. 62
  7.1 Signal acquisition, conditioning and processing ................................................. 62
  7.2 Modeling ........................................................................................................... 63
  7.3 Estimating TBI from FENG response ................................................................. 67
  7.4 Summary ........................................................................................................... 68

CHAPTER 8  MEASURING BRAIN VIBRATIONS ............................................................ 69
  8.1 Using macro-sized particle for tracking deformation ............................................ 69
  8.2 Using finer particles for tracking deformation (PIV) ........................................... 69
  8.3 PIV results ......................................................................................................... 71
  8.4 Summary ........................................................................................................... 75

CHAPTER 9  SUMMARY ............................................................................................ 77
  9.1 Summary of Contributions .................................................................................. 77

BIBLIOGRAPHY ....................................................................................................... 79

APPENDIX ............................................................................................................... 90
CHAPTER 1

INTRODUCTION

This work is centered around flexible sensors and actuators. 4 different applications are explored and characterized using a flexible sensor/actuator, building above an already existing diversity. In order to understand the importance of flexible devices available in our everyday lives it is necessary to recognize their widespread use cases.

1.1 Role of flexible devices

Devices that are not mechanically brittle and can be conformed into different shapes and sizes and can withstand several bending cycles can be termed flexible. The concept of flexible electronics has been around for many years and is constantly growing. The origin of "flexible electronics" started with the thinning of silicon wafers in solar cells that allowed a certain degree of wrapping, giving the freedom to use them in satellites [1]. The development of polymers and organic semiconductors (among several other developments) has led to a greater leap in terms of flexibility and ease of process. This technology enables sensors/electronics to take complicated shapes and forms with limited to no compromises in terms of functionality. Flexible electronics have already found their way into our lives in several applications, some of which are elaborated below.

Flexible devices in consumer electronics

Organic Light Emitting Devices/Diodes(OLED) paved the way for lighting and displays to be flexible in the last 3 decades [2, 3, 4]. An OLED-based substrate also offers thinner, lighter, cost-effective, and shatter-proof designs. In recent years several flexible substrates have been reported with the goal of improving the compatibility with skin/clothes in the case of wearables [5]. Natural silk fibroin protein as raw materials have also shown some progress in the recent years [6]. An additional key component of a flexible light/display are the electrodes. Traditionally, Indium Tin Oxide (ITO) is used as an electrode because of its excellent optical transparency and high electrical conductivity. However, the main drawback is that ITO is not mechanically robust for flexible device applications. For this reason, using
vapor deposition techniques to deposit thin film of metals such as silver (Ag) and gold (Au) have emerged as standard electrode materials since they provide superior conductivity, in addition to flexibility. Moreover, highly conductive Poly(3,4-ethylenedioxythiophene) films have been developed to be used as electrodes for OLEDs. Recently, the use of carbon nanotubes (CNT) in combination with polymers have shown promising results for flexible devices [7].

![Figure 1.1 Flexible polymer light emitting electromechanical cell (PLEC). Reproduced with permission from [7].](image)

**Flexible devices in energy harvesting**

Since the discovery of piezoelectricity (charge accumulation in response to mechanical stress) by the Curie brothers in 1880, a lot of research has been dedicated to finding other materials exhibiting such a property. Adding flexibility as a supplementary characteristic provides an
opportunity to add this energy source to wearables that conform to different shapes and also that can be implanted. However, along with piezoelectrics there are also other types of energy harvesters such as pyroelectric (i.e., heating the material produces an electrical output) and magnetoelectric (i.e., changing magnetic field) to name a few [8, 9, 10]. Piezoelectric polymers such as polyvinylidene fluoride (PVDF) in the form of films are flexible and have a large elastic compliance, which makes them a forerunner in this domain. Lead zirconate titanate (PZT) is another popular polymer that provided a major breakthrough in energy harvesting applications. However, its mechanical brittleness made it unsuitable for wearable applications. Recently, a flexible and biocompatible polypropylene ferroelectret nanogenerator (FENG) has been shown to power wearable electronics from human motion [11]. FENG is also the choice of sensor/actuator for this work.

Figure 1.2 Pictorial representation of cross-section of the FENG and other devices that can be powered with it. Reproduced with permission from [11].

Flexible devices in health monitoring

Wearable electronics play a crucial role in the area of welfare. Its application consists of monitoring various vital signs and alert/inform alerting of the current health status. Some of the governing properties for these types of devices are physicochemical properties, high electron/hole mobility, chemical durability, and mechanical strength. Various sensors have
been developed in recent times; these include temperature sensors [12], electrocardiograms (ECG) and heartbeat sensors [13, 14, 15, 16], chemical sensors, and drug delivery systems [17, 18].

![Flexible sensor array](image)

Figure 1.3 Flexible integrated sensing array (FISA), capable of sensing glucose, lactate, sodium, potassium and temperature. Reproduced with permission from [19].

E-skin devices have attracted a lot of interest with improvements in fabrication technologies, such as printing capabilities of the active layers or the electrode layers. These also make the chemical sensors possible. An example of chemical sensors is those that measure the composition of human sweat [20]. With a high correlation between sweat composition, health condition, and overall physiological state, these types of sensor can open the doors
to real-time health monitoring. As an example, real-time monitoring of hydration levels has been done where reminders are sent to the user [19].

**Sensors for concussion detection**

The extensive research in the topic of sensors has spurred great interest in improving and developing devices that can be applied in the healthcare system, specifically monitoring concussions in collision/contact sports. For example, by using sensors in helmet designs, personal trainers can monitor the athlete’s health during certain activities. Since a concussion can be detected with certainty only by magnetic resonance imaging (MRI) or computer tomography (CT) scan, there has been progress on bio markers to estimate the likelihood of concussions. Most of these biomarkers depend on head movements, which are tailored to measure such kinematics. These devices are majorly classified into 3 types: the helmeted device [21], the skin patch [22] and the mouth guard [23]. This topic is further elaborated in Chapter 2.

### 1.2 Problem description and motivation

A part of this work is an extension of research done by Wei Li et al. [24]. After having the proof of concept and limited characterization of the FENG as a loud speaker and microphone already established, this work sets out to extensively characterize and acoustically model the working of the FENG as a loudspeaker, and derive critical specifications for the FENG as a microphone. The later sections of the work deal with using the FENG in estimating the probability of concussion in sports by studying its output in correlation with reference sensor outputs such as accelerometers and gyroscopes.

The findings addressed in this work are as follows:

- Sound pressure level and directivity of the FENG as a loudspeaker across various geometrical shapes, sizes, and stacking configurations.

- A boundary element method (BEM) model of the FENG was created and used to investigate any trends or dependency of directivity across different geometrical shapes.
- Sensitivity and directivity of FENG when functioning as a microphone across various shapes and sizes.

- A FENG based patch’s response to whiplash is studied in correlation with the angular velocity and acceleration of the human head dummy for the purpose of concussion estimation.

- Strain modality of a biofidelic human brain upon blunt impact was studied by using the FENG as an invasive vibration sensor and also by PIV (Particle image velocimetry)

In order to address the aforementioned problems, the design, fabrication, simulations, and experimental validations—all with their respective analysis—were carried out. To allow the improvement of future designs, the following chapters serve as guidelines where detailed discussion is carried out in regards to the FENG’s fabrication, mathematical models, and experimental characterization.

1.3 Thesis Statement

The application-specific characterization of the FENG as a speaker, microphone, concussion detection, and invasive brain vibration sensor is achieved through a detailed experimental characterization and theoretical modeling.

1.4 Outline

The structure of the thesis is as follows: Chapter 2 introduces the material and its fundamental properties which enables its diverse applications and expands on previous works that have used a flexible sensor/actuator. This chapter also covers a basic understanding of Traumatic Brain Injury (TBI) and several indices developed to signify the extent of the injury. It also shows the rationale towards the angular kinematics of the human head and the placement of the sensor in the concussion detection experiment. The importance of modality of brain vibrations with respect to TBI is also established. Chapter 3 summarises details on the experimental setup for each study. This involves fabrication of the FENG, data acquisi-
tion, reference sensors (if any), and other amplifier and filtering components used. **Chapter 4** consists of the metrics (that is, parameters of interest) for the FENG to be characterized as a loudspeaker. These are first defined, and their corresponding results are shown. **Chapter 5** deals with the modeling of FENG as a loudspeaker. The measured and simulated data are compared to further understand the FENG’s operation as a loudspeaker. **Chapter 6** defines the necessary parameters for a microphone and shows results of the FENG across various shapes and sizes when configured for such an application. **Chapter 7** explains the testing methods used to build a correlation between the FENG’s output and the likelihood of concussion. This chapter also deals with data acquisition, signal conditioning, and signal processing of both the FENG and the reference sensors. Finally, **Chapter 8** explains the results of PIV (Particle Image Velocimetry) analysis and FENG’s response as an invasive brain vibrations sensor to understand the modality of brain vibrations upon a blunt impact. The Fast Fourier Response (FFT) from both approaches is compared and shown to have a positive correlation.

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1The chapters 3-8 are slightly modified versions of *Ferroelectret nanogenerators for loudspeaker applications: A comprehensive study* - *Journal of Sound and Vibration* (2020)[25]; *Flexible, self-powered sensors for estimating human head kinematics relevant to concussions* - *Scientific reports* (2022)[25]; *Ferro-electret nanogenerators as flexible microphones* - *2019 IEEE SENSORS* (2019)[26] and has been reproduced here with the permission of the copyright holder.
CHAPTER 2

BACKGROUND

As mentioned in Chapter 1, this thesis revolves around the use of the FENG. FENG is classified as a piezoelectric material, which converts electrical energy into mechanical energy, and vice versa. Piezoelectrics are characterized by a set of equations known as constitutive equations [27], as shown below.

\[ S = sT + dE \]  
\[ D = dT + \epsilon E, \]  

where \( S \) and \( T \) are the strain and stress, respectively, \( E \) is the electric field, \( D \) is the electric displacement, \( \epsilon \) is the permittivity, \( s \) is the elastic compliance, and \( d \) is the piezoelectric coefficient/charge constant. For the FENG, the piezoelectric coefficient of interest, \( d_{33} \), is 250 pC/N. This coefficient refers to the charge accumulated per unit force applied (both along the third axis as shown in figure 2.1a). In the case of the FENG, this very nature is attributed to the fact that opposite charges accumulate on the upper and lower surfaces of the artificial voids that are created due to a microplasma discharge (FENG fabrication is elaborated in Chapter 3). This charge separation leads to numerous highly oriented dipoles as shown in figure 2.1a. By experiencing compression or expansion in the thickness direction, the FENG’s internal dipole moments change simultaneously in magnitude according to the applied pressure. This leads to accumulated charges at the electrodes, which can be detected as an electric potential. On the other hand, if extra charges are transferred to the surface of the electrodes (i.e., a potential difference exists between them), the change of the charge density on the surface electrodes (or the electric field across the thickness) reshapes the giant dipoles, causing the FENG to contract or expand along the direction perpendicular to the electrodes. The Scanning electron microscope (SEM) cross-section FENG is shown in figure 2.1b.
The dual nature of the FENG allows the material/device to be exploited across various applications. Among these, the loudspeaker utilizes the electrical-to-mechanical conversion, whereas the microphone, concussion detection and brain vibration sensor utilize the mechanical-to-electric conversion capabilities.

2.1 Audio technologies

Audiovisual technologies are driven by convenience and immersive experience (e.g. virtual and augmented reality). This trend dictates the path for future advancements in consumer electronics and drives the interest in the science that makes this progress possible. In particular, size and flexibility are parameters that are being heavily considered at the time of determining convenience and experience enhancement. Wearable/concealable products are becoming the most sought-after among other pocket-friendly technologies. Improving human/system connectivity and interfaces requires the optimal use of the senses. Visual components and haptic devices have been key players for many years [28, 29]. In these works, the authors fabricated a transparent haptic device and characterized it. They also leveraged transparency to use it as a display. Auditory sensing should also be part of an
inclusive system that allows for an immersive experience; and having it in a flexible form, compatible with wearable electronics is vital. To have a loudspeaker embedded within the thin lining of wearable clothes is certainly a motivating prospect [30], or even loudspeakers that can be attached to human skin [31]. Digitally embroidered actuators have also been shown to work as flexible speaker [32]. Scientific advances in thin film flexible acoustic actuators are crucial for the technological progress of human-system interactions in multiple applications such as electronic papers, virtual reality [33], and wearable electronics for the above-mentioned auditory systems [34, 35].

Traditional electrodynamic loudspeakers use a coil and a diaphragm. Electrical signals are fed to a voice coil which actuates a diaphragm to produce sound waves. This setup is known to have relatively large footprint, mainly due to the magnets required, making it unlikely to be flexible and compatible with wearable electronics [36, 37]. This led to research on the creation and study of sensitive, flexible piezoelectric materials for energy harvesting/sensors/actuators [38], with particular relevance to thin-film sensors and acoustic actuators [39]. Some of the flexible sensors and actuators are as mentioned; a flexible active sensor made of ZnO NW arrays grown on ultra-thin aluminum foil which can be triggered by the blinking of an eye [40]. The applications of thin film acoustic materials are universal. For instance, growth in population has led to construction of houses close to highways and airports, and windows are the primary path through which noise from such places enters a house. Thin film acoustic materials can work as a transparent flat-panel loudspeaker/microphone and achieve noise cancellation [41, 42, 43, 44, 45, 46]. Mirshekarloo et al. have shown that transparent piezoelectric speakers composed of SWCNT electrodes and PVDF polymer layer, PET substrate, and a clamping frame have a wide radiation pattern. They also evaluated the ANC (Active Noise Cancellation) performance using both numerical simulations and experimental results. Furthermore, microphones / loudspeakers are necessary in voice-activated electronics where size and flexibility also play an important role [47, 48]. Recently, applications for flexible acoustic actuators have been revolutionized
with the triboelectric nanogenerator (TENG) technology which provides the basis for robotic auditory systems [49]. Other nanogenerators (NGs) based on polypropylene ferroelectrets (PPFE) have been shown to be flexible, foldable, and promising devices for self-powered systems [11, 50].

Similarly, microphones are transducers that convert sound pressures (i.e., acoustic input) to electrical signals. These usually find a wide range of applications by enabling voice and audio human interface with multimedia. The traditional and most common types are electric condenser microphones (ECM) [51]. These consist of an electrostatic capacitor and eliminate the need for a polarizing power supply by using a permanently charged material. The next line of microphone design is the piezo-type which are also known as contact microphones. These are typically impervious to air vibrations but transduce only structure-borne sound [52, 53, 54, 55]. Recent times have seen a growing interest in wearable electronics [56, 57, 58, 59, 60], which has led to a greater research focus on flexible electronics. Along with flexible screens and flexible PCBs (Printed Circuit Boards) comes a larger demand for research and development of flexible acoustic sensors. One of the recent approaches in flexible acoustic sensors involves the use of TENGs, which were deployed on a robot for voice activation and also used as an energy harvester [49]. Another approach consists of the use of a FENG, with a bi-directionality capability that allows for its use as a microphone or speaker [61].

One of the demonstrated applications that shows the potential use of the FENG as a microphone included the instance in which the device was used to recognize the owner’s voice and unlock a personal computer. The objective of this work is to demonstrate the different parameters of interest in FENG-based microphone devices and to form a basis for future microphone designs. The specifications and their dependencies discussed are intended to help designers with the fabrication of microphones based on FENG. It is also demonstrated that the testing environment plays a role in the performance of the device as a microphone.
Figure 2.2 (a) A thin film transparent loudspeaker and its SPL response. Reproduced with permission from [31]. (b) FENG used in actuating a cantilever. Reproduced with permission from [62].
2.2 Traumatic Brain Injury (TBI)

Collisions in sports have been studied for causing short/long term neuropsychological changes [63] and neurodegenerative diseases [64]. One example of such disease is chronic traumatic encephalopathy (CTE), which is a progressive degenerative brain disease. It is a consequence of repeated concussions and traumatic brain injuries such as those experienced by athletes in high-contact sports. A brain with CTE gradually deteriorates and loses mass. The disease not only deteriorates skills necessary for daily life (e.g., memory, self-control, time-management, focus); but it also causes much bigger mental problems (e.g., strong suicidal thoughts, depression, cognitive and thinking problems, anxiety, violent/abusive behavior, dementia) which become worse over time. A report in 2017 showed that 99% National Football League (NFL) players in United States of America had CTE [65]. The study also showed that 91% of College Football, and 21% of high-school players also had CTE.

Defined by the centers for diseases control and prevention (CDC) [66], a concussion is a type of traumatic brain injury—or TBI—caused by a bump, blow, or jolt to the head or by a hit to the body that causes the head and brain to move rapidly back and forth. This sudden movement can cause the brain to bounce around or twist in the skull, creating chemical changes in the brain and sometimes stretching and damaging brain cells. The CDC also reported that 20% of the estimated 1.7 million concussions per year are sports-related [67, 68]. Research suggests that after a concussive event, the brain goes under metabolic crisis [69]. This metabolic disruption lasts about a week and any concussive event during this period leads to greater cognitive impairment which lasts for a longer time [70]. This is perhaps the main reason why an athlete who suffered from a concussion is removed from play and rested immediately.

Brain Anatomy

The brain is a highly complex system that has a nonlinear relationship between stress and strain, in other words, it is viscoelastic in nature. The brain is enclosed in this protective
casing known as the skull and has three main parts called the cerebrum, the cerebellum and the medulla or brain stem. The cerebral hemisphere has ridges which are known as gyri and furrows known as sulci. There are fissures that separate the two cerebral hemispheres known as corpus callosum. Each hemisphere is composed of both grey and white matter.

![Diagram of the brain with labeled structures](image)

Figure 2.3 The sagital slice of the brain [71].

The brain also has ventricles that are continuous hollow spaces. These are filled with cerebrospinal fluid (CSF), whose physical properties are similar to those of water.

**Types of brain Injuries**

Brain injuries can be divided into two types: focal and diffuse brain injuries. Focal injuries are the ones that can be seen on imaging devices. These usually occur due to very high transnational acceleration where the brain is inertial with respect to the skull, and thus putting large stress on structures that tether them together. This often leads to some form of hematoma. Diffuse injuries, on the other had, are normally due to the rotational motion of the head and are microscopic in nature. These are hard to spot using imaging techniques. Concussion or mild TBI (mTBI) falls under diffuse brain injuries. Diffuse axonal injury is
the more serious type of this injury, and it is identifiable by damage to white matter axons in the brain cell. Recent developments in diffusion tensor imaging have been shown to track damage in white matter axons [72].

Figure 2.4 Subdural hematoma. Reproduced with permission from [73].

**Head Injury predictors**

A certain amount of strain in the brain tissue beyond a recovery point is the variable of interest. The predictors are set to point at the characteristics of the force input such as
magnitude, direction, location, and map those to the probability of causing a brain injury. Linear acceleration has been associated with concussion for a long time. They are known to cause inter-cranial pressure differences due to relative movement between the skull and the brain during impact [74]. The correlation of linear acceleration to levels of brain injury was further confirmed by Nuscholtz et al. with blunt impact experiments on Rhesus monkeys [75].

Rotational acceleration is said to cause injury by influencing the deformation characteristics of the brain. Holburn was among the first ones to state that the damage to the brain could only be caused by rotational components and not linear components due to its incompressibility [76]. In addition, research has shown that rotational motion alone could explain most traumatic brain injuries, including concussion [77]. This also supported in a recent publication by studying the linear and rotational impacts on and egg, where the white matter and the yolk are analogous to the brain and the cerebrospinal fluid [78].

**Injury Criterion**

Once the evidence of a correlation between acceleration and head injury was established the tolerance curves were developed. The first of those was the wayne state tolerance curve (WSTC) [79], which was derived from animal and cadaver data.

Then the Gadd Severity Index (GSI) was developed as an extension to WSTC [81].

\[
GSI = \int_{t_0}^{t} a(t)^{2.5} dt. \tag{2.2}
\]

where \(a(t)\) is the linear acceleration.

In an attempt to improve GSI, HIC (Head Injury Criterian) was suggested and adopted by National Highway Traffic Safety Administration (NHTSA).

\[
HIC = (t - t_0) \left[ \frac{1}{(t - t_0)} \int_{t_0}^{t} a^{2.5} dt \right]. \tag{2.3}
\]
Later, the Generalized Head Acceleration Model for Brain Injury Threshold (GAMBIT) was developed to include linear and rotational accelerations.

\[
GAMBIT = \left[ \left( \frac{a(t)}{ac} \right)^n + \left( \frac{r(t)}{rc} \right)^m \right]^{\frac{1}{S}},
\]

(2.4)

where \(a(t)\) is the linear acceleration and \(r(t)\) is the rotational acceleration, while \(n, m\) and \(S\) are empirical fits.

**Head Impact telemetry**

Head Impact Telemetry (HIT) system is a technology currently being used to measure and record *in vivo* head impact exposure [82, 83]. The system consists of an array of accelerometers that are physically connected to the helmet and trigger data collection whenever any of the accelerometers measures an acceleration beyond certain threshold. This technology
was first implemented in 2003 [84], and is currently being used in commercially available helmets. This approach was first proposed by Padgaonkar et. al. [85], which uses a set of linear accelerometers to derive the angular acceleration based on kinematic principles. This was known as the 3-2-2-2 configuration as shown in figure 2.7. A total of nine linear accelerometers were needed to measure angular acceleration accurately.

The main limitation of this approach is that it relies on sensors attached to the helmet - they are not directly in contact with the athlete’s head. As it has been pointed out by experts in biomechanics, the sliding that can occur between the helmet and the head makes it difficult to predict how the brain moves inside the skull. A solution to this sliding problem was presented by the X-Patch, which had two versions: one used as a skin patch behind the ear, and the other in a mouth guard [22, 23] as shown in figure 2.8 and figure 2.9.

Both of these systems consist of accelerometers that track the rotational speed of the head upon impact. However, the resonance of the micro-mechanical structures inside the MEMS-based accelerometers are within the range of head motion frequencies. This has been
Proposed role of the FENG in estimating head kinematics

FENG device is used to monitor and describe the tensile forces developed at the neck of a human head substitute (hereinafter referred to as "dummy"). The device is placed on the neck along its length and undergoes compressive/tensile stress as the neck contracts and expands as the head swings back and forth. This stress produces a corresponding electrical
In this work, we study the relationship between these two parameters (neck strain/ FENG’s electrical output), and develop a model to correlate the electrical output profile to the kinematic signature of a human head. This is done with the goal of developing a more reliable concussion-detection system that consists of patches attached directly to the neck instead of the accelerometers typically used in high-contact sports helmets. Unlike other helmeted devices, where the sensors required to measure human head kinematics are placed inside the helmet, the sensor patches used in this work are placed directly on the neck. This extends its use to high-contact sports that do not require the use of helmets and eliminates false readings from helmet-only movements. FENG devices are self-powered sensors i.e. they do not need an external electrical power source to operate. Although this work demonstrates the system along one spatial axis, it can certainly be expanded along the other axes by placing multiple sensors around the neck; thus providing a complete and comprehensive map of the human head during a collision.
Figure 2.9 (a) The 6-Degrees Of Freedom (DOF) HITS device placed in a helmet along with an RF antenna. The mouth guard is adapted with accelerometers to estimate head acceleration. Reproduced with permission from[87].
Brain vibrations

The brain can be seen as a viscoelastic medium with complex and intricate geometry. An impact on the skull creates traveling waves that propagate at different rates and different speeds since the composition is non-homogeneous. This can create localized strain concentrations at certain regions in the brain. Thus, an understanding of the temporal dynamics of the brain upon impact is vital. To this end, modeling of the brain has helped further our understanding. Modeling of the human brain has been researched since the 1940’s. Holbourn proposed that the brain can be modeled as a mechanical system with input in the form of head motion and brain displacement as an output [76]. Since then relative brain displacement has been seen as a metric to classify brain injuries. Furthering this work, others have shown that brain injury is proportional to peak acceleration and the time sustained during that peak [88]. This led to the development of metrics such as Wayne State Tolerance Curve (WSTC) [79], Gadd Severity Index (GSI) [81] and Head Injury Criteria (HIC) [89]. Recent advancements in imaging techniques such as diffusion tensor imaging (DTI) have shown that there are changes to the white matter in the brain even in cases when the impact isn’t concussive but repetitive smaller impacts. These are shown to be the result of excessive axon stretching [90]. There is also evidence to suggest that strain in deep brain regions with a high density of axon fibers correlates the best with cognitive impairment or concussion [91]. Studies have shown that brain deformations have a strong dependence on the frequency of the input loading [92]. Most recently, a cadaver-based impact experiment was used to identify the relative motion peak of the brain around 20 Hz [93]. Kaveh Laksari et. al. in a recent work studied the spatiotemporal characteristics of the brain during head impacts using mode decomposition techniques as shown in figure 2.10. This involved using dynamic mode decomposition on brain nodal displacements. According to this work, the modal amplitudes and peak strains in the brain are reported around the 20 - 40 Hz range. This wide range is due to the non-homogeneity of the brain. This work also uses modal analysis to understand the major difference between head impact cases that lead to loss of
consciousness (LOC) and the ones that did not. This work highlights the importance of frequency domain analysis of the brain upon impact.

The strain and shear waves were studied across three planes of the brain and across three frequencies by Okamoto et. al using an MRI. The results of the study are as shown in figure 2.11. The results indicate that the wave penetration is the deepest around 30 Hz when compared to higher frequencies.
Figure 2.10 (A) schematic of the FE model of the head showing various parts of the brain, (B) strain values derived from each mode normalized by the peak rotational acceleration of the corresponding head kinematics. Here, we superimpose regional dominant frequencies for each brain part for the LOC case (red circles) and the average and standard deviations (blue solid dots) for all cases. Brain part abbreviations: corpus callosum (CC), gray matter (GM), brain stem (BS), mid brain (MB), white matter (WM), thalamus (TH), corpus callosum, cerebellum (CB), (C) structural distribution of the dominant frequency of brain regions for the LOC case, indicating out-of-phase oscillation due to significant discrepancy between regions especially in the periventricular region, (D) structural distribution of dominant frequencies for average head impact case, which indicates a lower dynamic range. Reproduced with permission from [94].
Figure 2.11 Shear wave displacement and strain at multiple frequencies for a representative subject: (A) Anatomical images (masked MRE magnitude) with crosshairs indicating location of orthogonal image views. (B) Median OSS (Octahedral Shear Strain) at each frequency. Bars show median OSS for representative subject, dashed lines show mean values of median OSS for four subjects studied. OSS magnitude at each voxel is normalized by median OSS at corresponding frequency. (C) AP (Anterior to Posterior; meaning front to back) wave displacement. Bars show median amplitude of AP wave displacement for representative subject; dashed line shows mean values of AP wave displacement for 3 subjects studied. AP wave displacement is normalized by median OSS at corresponding frequency. Scale bar equals 2 cm in all images. AP indicates anterior-posterior; MRE, magnetic resonance elastography; OSS, octahedral shear strain. Reproduced with permission from [92].
CHAPTER 3

FABRICATION OF THE FENG, THE CHARACTERIZATION SETUP FOR VARIOUS APPLICATIONS AND SIGNAL PROCESSING

The FENG starts as a Polypropylene (PP) film with thickness around 100 µm. This film is subjected to high-pressure nitrogen or carbon dioxide gas so the internal pressure within the voids becomes equal to the external pressure. The external gas pressure is then suddenly released, resulting in swelling of the voids in the PP film. Thermal treatment (usually 100 °C) is carried out to increase the crystallinity of the polymer matrix. Subsequently, by applying a large electric field to the treated film, which causes Paschen breakdown to occur inside the voids. The current within the air gap transfers a sheet charge density across the air gap. During this microplasma discharge, charges are separated by the ionization of the gas transportation under the charging field.

3.1 Experimental Setup for measuring Sound Pressure Levels and directivity of the FENG as a loud speaker

Figure 3.1 shows an artistic representation of the device cross-section, which includes artificial voids. The FENG is highly sensitive to an electrical stimulus that generates contraction and expansion across the device’s thickness. The contraction/expansion of the device’s surface will follow the time response of the input electric signal, and thus generate pressure variations in the surrounding medium.

All acoustic experiments were carried out inside an anechoic chamber as shown in Figure 3.2. This chamber was characterized by Brad Rakerd [95]. The FENG and sensing microphone was held in the middle using low-profile stands, clamps, and pedestals. Electrical connections extend from the outside of the chamber to the FENG and microphone inside the chamber via a feed-through that has minimal disruption to the absorbing cone array. A 1/2” pre-polarized free-field microphone with a sensitivity of 12.6 mV/Pa and frequency range (± 3dB) from 3.15 to 40000 Hz (378A06, PCB Inc.) was used to record/measure the pressure changes created by the FENG, as shown in Figure 3.2. The microphone was
Figure 3.1 Shows the operating principle of the FENG. a) Shows the positive half cycle of the AC voltage applied which causes the FENG to compress and b) shows the negative half cycle of the voltage which causes the FENG to expand.

Figure 3.2 Schematic diagram of the test setup. The FENG, microphone and the pre-amp are placed inside the anechoic chamber as shown in the expanded view. The MDF board on which the FENG (circle in this instance) is fixed measures 16 cm x 13 cm x 1.27 cm.
connected to a signal conditioner 484B06, PCB Inc. The FENG is placed on a 0.5 inch thick MDF board (13 cm x 16 cm) using double-sided tape having an area density of 13.17 mg/cm$^2$. This board is held in place using a pedestal and a clamp as shown in Figure 3.2.

### 3.2 Experimental Setup for measuring sensitivity and directivity of the FENG as a microphone

All the experiments are conducted in an anechoic chamber as mentioned earlier. The setup consists of a standard baffle (International Electrotechnical Commission (IEC)) on which the FENG-based microphone is mounted. Although most of the microphone characterization in industry/commercial environments does not involve using a baffle [96, 97], the baffle is used in this work to maintain constant sound pressure over the entire area of the FENG since the microphone size can be comparable to or larger than a wavelength. The FENG is attached to the copper back-plate using double-sided tape completely covering the FENG’s surface. The back-plate is fixed to the baffle using tape on all sides. The other components placed inside an anechoic chamber include the surface microphone from PCB Piezotronics (130B40), which has a sensitivity of 8.5mV/Pa, which is placed close to the device under test (DUT) so as to record sound pressures. A wireless speaker is placed at a distance of 30 cm from the DUT with the center aligned with the DUT’s geometric center. Sounds ranging from 20 Hz to 20 kHz are played through the speaker via a bluetooth transmitter. The output from the FENG is amplified using a voltage pre-amplifier (SR560) and then recorded along with the output from the surface microphone using data acquisition (NI-DAQ 6003). LabVIEW is used to perform the fast Fourier transform (FFT) on the recorded signals to obtain spectral information which allows power levels from frequency bins of interest to be read. This information translates to the sensitivity of the microphone in all the experiments described below.
Figure 3.3 Baffle with FENG mounted and dimensions; the insert shows a more detailed view of the components.
3.3 Experimental Setup for measuring FENG’s response to head impact

The testing setup consists of three main components: (i) drop towers, comprising of the rails and a center plate; (ii) head and neck assembly, and (iii) flexible FENG sensors. The drop tower rails are constructed using parallel telescopic tubes measuring approximately 0.60\text{m}. The center plate is welded only to the outer telescopic tubes such that it can move freely normally to the floor. The second piece of the set-up is a hybrid III head and neck form assembly from Humanetics (Hybrid III 50th Male, Standard ATD 78051-218-H, hereinafter referred to as a ”dummy” ), which is commonly used for crash test experiments [98, 99]. This dummy emulates a 50\text{th} percentile human body head that provides a mounting block for the triaxial accelerometer with integrated triaxial angular rate (DTS-6DX PRO; hereinafter referred to as “6DX”) sensor at its center of gravity, as shown in figure 3.5. The head and neck are mounted to the welded center plate as shown in figure 3.4. The third component is the patch which is described in the following section.

![Figure 3.4 a) Dummy neck connected to the U-bar, which is then connected to the center plate as shown in b).](image)

In this study, the voltage signal generated by the FENG was monitored and used to determine the mechanical deformation dynamics of the neck; i.e. the FENG’s output voltage profile was used to obtain angular velocity and acceleration dynamic behaviour at the centre of the head.
Figure 3.5 a) A dummy was fixed to the center plate, then dropped in free-fall. The inset shows the position of 6DX and the FENG on the dummy; b) shows concept art of how this patch will be implemented in reality and c) is the head movement (whiplash) that can be characterized using this patch.

After electrical contacts were added to the opposite FENG surfaces using sputtering, electrical leads were attached to the device (5cm x 1cm) followed by its encapsulation in Kapton tape to protect the electrodes. To this end, a thin layer of PDMS was placed on one side of the FENG, which was then glued to a therapeutic kinesiology tape (K-Tape) using epoxy. This was followed by placing PDMS and a second K-Tape on the opposite side of the FENG, resulting in a patch-like configuration as shown in the inset of figure 3.5 — a more detailed view of the patch is presented in figure 3.6. This arrangement resulted in applied pressure to the FENG device upon stretching of the tape due to the changes in the neck’s radius of curvature during a fall. In a separate experiment, it was verified that
Figure 3.6: a) FENG device after deposition of silver thin film for electrodes, and fixing wires connections at both surfaces. b) Encapsulation in kapton tape is done to protect the electrodes. c) A thin layer of PDMS is placed on one side of the FENG and glued to the first kapton tape. d) PDMS and kapton tape placement is repeated on the opposite side of the FENG, resulting in a patch-like configuration with electrical connections to the opposite surfaces of the FENG device.

Compression/buckling only at the tape regions did not produce output voltages; i.e. the produced/measured voltage was only due to stress experienced by the FENG device. For simplicity, the encapsulation of the FENG device, including electrodes and tape, will be referred to as "the patch". As shown in Figure 3.5a (insert), the patch is placed on the back of the neck and held by using hose clamps (not shown in the figure) for the experiments referred in figures 7.1a and 7.1b. Similarly, the patch is placed in the front side of the neck for the experiments referred in figures 7.1c and 7.1d.

The movement of the neck in this work is restricted to rotational displacements along the “z” plane (i.e. rotation around the y-axis), as shown in Figure 3.5a. To reproduce this
movement, the head is securely attached to the center plate, facing down the rails (shown in Figure 3.5), and dropped. This head movement is similar to the frontal collision in automobiles, where the head experiences a whiplash effect (both hyperflexion and hyperextension), as shown in figure 7.1b and d. This whiplash effect can also be observed in high-contact sports like judo, wrestling, and football when a player is suddenly moved or pushed by an opponent at chest level, causing the head to experience sudden angular acceleration. It must be noted that there is no direct impact on the head during the experiments. Although most applications/systems demonstrated with FENG devices use a mechanical input normal to the electrode surface (i.e. in- and out-of-plane motion), their generated voltage output is produced by compression/relaxation of the internal dipoles, which can be obtained through tensile mechanical input [100].

3.4 Experimental setup for measuring brain vibrations under blunt impact using the FENG

The setup comprises three major components: 1) a biofidelic test object (hereinafter referred to as the “phantom”), which represents the human brain; 2) a FENG device, which serves as an invasive vibration sensor; and 3) a data acquisition setup used to monitor the FENG device’s electrical signal output upon impact, as well as capturing images of particles embedded in the phantom. Experiments were carried out in a custom-built drop tower as shown in Figure 3.7a. The system is intended to impact the phantom with a free-falling load (2.5 kg released at 0.5 m from the subject), producing a linear acceleration impact that allows more control over the desired kinematic. A free-falling load results in a significant impact that still allows for multiple tests without damaging the phantom’s structural integrity. Since the initial position of the mass was at rest, conservation of energy calculations were performed to convert that potential energy into kinetic energy upon impact. Theoretical values are shown in Table 1, where friction and drag losses are neglected.
Figure 3.7 a) Drop tower along with the placement of phantom and neck arrangement. b) MRI from a 35-year-old healthy male and c) extruded section for computer design. Adapted from [101]. d) Mold used to create the brain phantom. e) Brain phantom with embedded finite sand particles.

Table 3.1 Impact theoretical conditions

<table>
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<th>Characteristic</th>
<th>Symbol</th>
<th>Value</th>
<th>units</th>
</tr>
</thead>
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<tr>
<td>Mass</td>
<td>$m$</td>
<td>2.5</td>
<td>kg</td>
</tr>
<tr>
<td>Speed</td>
<td>$v$</td>
<td>3.13</td>
<td>m/s</td>
</tr>
<tr>
<td>Momentum</td>
<td>$p$</td>
<td>7.83</td>
<td>kg·m/s</td>
</tr>
<tr>
<td>Kinetic energy</td>
<td>$E_k$</td>
<td>12.26</td>
<td>J</td>
</tr>
</tbody>
</table>

**Biofidelic brain and neck**

The subject utilized in this study consists of the model of a human brain shown in Figure 3.7b and c as introduced in the previous section. The cross-sectional view in the axial plane of the brain is extruded to simulate the total brain volume, creating a computer-
aided design which was utilized to create a mold as shown in Figure 3.7d. To simulate brain tissue, the hydrogel PAA was used at a weight concentration of 10%, which represents the white matter of the brain. The subject was created from 60 g of Acrylamide (purity ≥ 98%, gas chromatography, Sigma-Aldrich, USA) dissolved in 600 ml of deionized water (DI). Then 2 g of N,N’-methylenedis (MBA, purity 99%, Sigma-Aldrich, USA) was added and let to homogenize while stirring occasionally. Once dissolved, 0.52 g of Ammonium Persulfate (APS, purity ≥98%, Sigma-Aldrich, USA) was mixed in. The polymerization time was accelerated by adding 0.6 ml of N,N,N’,N’-tetramethylethylenediamine (TEMED, ReagentPlus, 99%, Sigma-Aldrich, USA). This solution was then poured into the mold filling about half to the extrusion width and left to solidify. Once cured, a layer of micron-size sand particles are randomly dispersed for visualization purposes. Finally, another 600 ml solution was prepared and added on top to obtain the brain tissue model shown in Figure 3.7e.

Finally, the PAA brain model is placed inside a 3D printed poly(lactic acid) (PLA) skull with 50% rectilinear infill that represents the skull bone composition of a spongy bone (diploë) between two layers of compact bone. The sides of this PLA skull are sealed with acrylic windows to allow imaging, and the PAA model is free to move inside the skull filled with DI water to simulate the cerebral spinal fluid (CSF) [102]. The head model was finalized by attaching the PLA skull to a Hybrid-III Neck with an custom built corner as shown in Figure 3.7a.

**FENG as an invasive vibration sensor.**

The surface area of the FENG used in this work is 2 cm x 2 cm, with a thickness of ∼ 100 µm. The FENG and the electrical connections need to be insulated in order to protect it from the cerebrospinal fluid, which is represented by water in these experiments. This is achieved by coating the FENG with commercially available liquid electrical tape and using enameled copper wire to ensure a very low profile terminals as shown in figure 3.8b. The insulated FENG is then carefully embedded in the PAA gelatin as shown in figure 3.8b, created with the procedure explained in the previous section. The terminals are drawn out of the phantom.
Figure 3.8 a) FENG after metal electrode deposition and cross-section showing the voids and silver electrode, and b) after coated with liquid electrical tape and placed inside the brain phantom. c) Charge mode amplifier circuitry to which the FENG output is fed.

while ensuring that the phantom remains sealed during impact. Two sets of data acquisition hardware were used in this experiment. Electrical signals from the FENG were recorded using a data acquisition system from National Instruments (NI-DAQ 6003) in conjunction with LabVIEW at 50000 SPS (samples per second). The voltage response from the FENG is first fed to the charge mode amplifier as shown in Figure 3.8c and the output of this charge mode amplifier is sent to the NI-DAQ for data recording. This process isolates the system’s voltage response (gain) from parasitic capacitances, such as those created by instrument connections and cables. All the measured data is in time domain, but a Fast Fourier Transform is used

Figure 3.9 a) Shows the side view of the setup emphasizing on the LED array and camera. b) Shows a sample image that the camera captures. The fine particles are clearly visible in this image.
for frequency analysis. Images of the biofidelic phantom are captured using an ultra-high-speed camera (Phantom V2512 Series) at 25000 frames per second (fps) with full resolution settings (1280 × 800 pixels) as shown in Figure 8.6. The camera frame covers an area of approximately 100 mm wide by 60 mm high, which encompasses majority of the phantom.
CHAPTER 4

PARAMETERS OF INTEREST AND MEASUREMENTS FOR FENG AS LOUDSPEAKER

To design a loudspeaker using a FENG, it is necessary to find the parameters that are most influential in the device’s acoustic response. This will not only lead to a better understanding of the device’s operation but also identify the variables that can be controlled during the device preparation that will be most impactful on different performance metrics as a loudspeaker. To this end, our first set of experiments was designed to characterize FENG devices with different parameters and study their role in different performance metrics. Factors such as device surface area, folding effects, and directivity with respect to different shapes and mounting surfaces were studied. The previous proof-of-concept work done on FENG devices as microphone/loudspeakers were focused on a functionality demonstration, and did not involve testing environments that could allow for the study of individual parameters on the device’s response. Therefore, a comprehensive characterization of the device and the derivation of theoretical models that validate the device’s functionality and describe the system were not possible [24]. In this work, a systematic approach is used to allow for a detailed study of FENG devices as loudspeakers. For example, all the experiments in this work are done in an acoustic anechoic chamber with absorbing cones (1 meter long) on all six faces of the chamber, which eliminates reflections from surrounding surfaces during testing, even for low frequencies in the human audible range. Also, FENG layers were firmly fixed to each other, thus eliminating the possibility of air pockets between layers, which affects Sound Pressure Level (SPL) output and directivity. All the testing set-up improvements made in this work allowed for a theoretical model that helps explain the use of FENG devices as loudspeakers and establishes a design platform for future designs with specific performance requirements.
4.1 Area Vs. Sound Pressure Level

SPL or acoustic pressure level is a logarithmic measure of the effective pressure of a sound relative to a reference value given by,

\[ \text{SPL} = 20 \log_{10} \left( \frac{P}{P_o} \right). \tag{4.1} \]

In this case this reference value \((P_o)\) is taken as the threshold for human hearing of 20 \(\mu\)Pa at 1 kHz. FENG devices were fabricated with different surface areas and shapes, maintaining the thickness as a constant parameter. Nonetheless, a single FENG was used and cut down into pieces of different surface areas to measure the SPL output. This was done to limit the number of varying process parameters during the manufacturing of the FENG to only differences in area and shape. The FENG devices used as loudspeakers in this work were 9 cm\(^2\), 16 cm\(^2\) and 64 cm\(^2\), fixed on an MDF board and held in place using a bracket. The microphone was placed at 30 cm from the FENG and aligned to the center of the FENG geometry. An AC signal of 127 V\(_{\text{rms}}\) was supplied to the FENG and the output was recorded using the microphone. The recorded data was sampled using a NI-DAQ 6003 at a sample rate of 100 KSPS (which sets the Nyquist frequency above our highest measured frequency). A Fast Fourier Transform (FFT) was performed on the sampled data through LabVIEW. Frequency bins of interest were identified (depending on the experiment), and the power level was determined and converted to pressure, representing the force exerted per unit area on the microphone diaphragm due to the acoustic waves created by the FENG’s contraction and expansion movements. The frequency of the input signal was swept from 100 Hz to 20 kHz. Flat-weighted sound level measurements of the background noise level in the anechoic chamber show that the noise had most of its power in the lower frequencies and settles to a minimum after 2 kHz [95]. Thus, points until 2 kHz were neglected due to poor signal-to-noise ratio (SNR). The average pressure values between 2 and 20 kHz are recorded. The same procedure was applied to a FENG of 9 cm\(^2\) and 16 cm\(^2\).

Plotting pressure (averaged between 2 to 20 kHz) as a function of area as shown in Figure 4.1 reveals that the sound pressure increases approximately linearly with the area.
4.2 Linearity

The term “distortion” is used to refer to any change in a signal upon conversion from the electrical to the acoustical domain. When the input signal is sinusoidal, “harmonic distortion” specifically refers to the strength of spurious signals which are integral multiples of the input frequency. A nonlinear input to output relation can cause harmonic distortion, in this case between voltage and sound pressure. An ideal loudspeaker is expected to have zero distortion –i.e the output (sound pressure) will scale linearly with the input voltage. In order to investigate this effect, the test was carried out on the four-layered FENG but varying the input voltage in steps of 12.5 V from 12.5 $V_{rms}$ to 127 $V_{rms}$. As seen in Figure

![Figure 4.1 Sound pressure generated by FENG with respect to area. Linear Fit ($R^2 = 0.96$) is shown.](image)
4.2, the multi-structural device exhibits linear behavior. The spectrum of the output voltage of the microphone when the FENG was excited at 2 kHz in the form of an FFT is shown in Figure 4.3.

4.3 Directivity of the FENG

The term “frequency response” refers to the variation in SPL with changes in frequency. The “directivity” describes how a loudspeaker sends sound waves in different directions. The theoretical model for an omnidirectional sound source consists of a pulsating sphere that radiates from a point in space. For a finite-sized source, the evenness of the dispersion in all directions is a function of the characteristic size of the source. The dispersion of the

![Graph showing change in sound pressure (averaged between 2 to 20 kHz) for different voltage levels. The R^2 value is 0.9998.](image)

Figure 4.2 Change in sound pressure (averaged between 2 to 20 kHz) for different voltage levels is plotted and shown to be linear. The R^2 value is shown in the graph which represents the deviation from ideal linear behaviour.
source narrows at frequencies for which the wavelength approaches or is smaller than the characteristic dimension of the source. A wide directivity loudspeaker maintains amplitude consistency between the on-axis (perpendicular to the loudspeaker diaphragm plane) and off-axis (at a direction $90^\circ$ from the on-axis) as seen in Figure 4.4. Narrow directivity loudspeakers, on the other hand, change their amplitudes substantially between the axes. Diffraction, shading and interference in the sound waves around the loudspeaker and its associated cabinetry produce lobes at different frequencies. Thus, it is important to know how directional a loudspeaker made from FENG will be. In the same manner as in previous experiments, FENG of different shapes and orientations were cut and fixed on the MDF board using double-sided tape. The MDF board was mounted on a rotatable clamp such that it can be turned and the angle in reference to the microphone can be measured as shown in Figure 4.4 (the oval shape was rotated along its long axis and the strip was rotated along its shorter side). The microphone was placed 30 cm from the geometric center of the FENG. A time-varying voltage signal of $127 \text{ V}_{\text{rms}}$, with frequencies ranging from 100 Hz

Figure 4.3 Spectrum of acoustic pressure at 2 kHz for a square FENG of side 4 cm, observed from 30 cm, and excited with $127 \text{ V}_{\text{rms}}$. 

42
Figure 4.4 a) FENG on MDF board and the microphone aligned to the center of the FENG at 30 cm (not to scale). The rest of the setup (including the electrical connections to the FENG) is not shown for clarity; b) One such instance of directivity measurement where the FENG is rotated while microphone kept stationary.

to 20 kHz is sent to the two electrodes of the FENG. The sound levels were recorded by the microphone and sampled by the Ni-DAQ6003. Figure 4.5 shows the polar plots for 5, 10, 15 and 20 kHz where only half of the polar plot is shown. The other half is symmetric about the on-axis, both in the DUT and also the testing environment. Higher intensity is observed on the on-axis, in front of the FENG as compared to behind the back-plate. This is expected since the MDF board attenuates the sound waves with wavelengths comparable to or smaller than the side length of the board.

Although all the shapes have the same surface area, which means that the sound pressure levels exerted by them should be the same at 90° (in this case since all the measurements are far field), there is a small variation. One of the reasons for this could be due to the difference in dipole distribution across the volume of the FENG. In this case, the FENG that makes up the circle shape has a slightly higher output than other shapes. As the frequency increases, it can be observed that the shapes are becoming more directional; i.e the ratio of side lobes to that of 90° decreases. Directivity patterns on these shapes will further help validate the developed model in later sections.

4.4 Frequency Response and Effect of Folding

FENG devices present flexible thin-film characteristics that allow folding and stacking to form a multilayer structure. Li et. al. showed that for a stacked multilayer FENG device,
Figure 4.5 Directivity of 4 different shapes across 2 quadrants. 90° represents on-axis direction, normal to the MDF in direction to the microphone (see Figure 4.4b).

the SPL was proportional to the number of layers [24]. The multilayer effect on the output of the device is observed as a function of added layers.

The option of stacking the FENGs and actuating them using a 127 V\text{rms} signal is explored. Since the double-sided tape was used for the parallel arrangement of the devices, the effect of mass loading was established to account for any attenuation due to the binding method. A single layer of FENG was fixed on the MDF board. As seen in Figure 4.6, adding 3 layers of double-sided tape to a FENG’s surface does not affect the device’s output. As seen in the above graph, the curves lay on top of each other until \(\sim 15\) kHz, after which they begin to diverge. This divergence, although small, could be due to the mass loading effect on the resonant frequency (which is beyond the audible range). The FENGs are now layered on
top of each other as shown in Figure 6.4a and electrically connected in parallel to study the effect of layers on sound pressure output. The results are as shown in Figure 6.4b. Here the output scaling with each added layer is normalized with the results from the single layer to show the scaling factor, so that the Y-axis in Pascals (Pa) is relative to the response of the single layer FENG. It is observed that the pressure scales linearly with the addition of layers for the FENG acting as a loudspeaker. This property will help reach higher output levels with lower input voltages for excitation.

4.5 Ultrasound performance
The operation of the present device in ultrasonic frequencies can broaden its applicability. For example, non-destructive evaluation techniques used in material characterization and structural health monitoring often operate in ultrasonic frequencies [103, 104, 105]. The characterization of the present device in ultrasound was done by using 4 cm x 4 cm (16 cm$^2$) FENGs, which were excited with AC signal of 127 V$_{rms}$ from 20 to 40 kHz. The output is shown in figure 4.8

The output of a single and two-layer FENG continues to rise at 12 dB/octave. The four-
Figure 4.7 a) The schematic for electrical connections made to the FENG. b) The output is recorded after the addition of every layer across frequency and normalised to a single layer FENG.
layer FENG has a higher slope until about 35 kHz, at which point it peaks and changes sign. This might be again due to resonance, as discussed in the previous section. This resonance peak is not observed for the single and two-layer FENG, since they have lower mass and therefore higher mechanical resonance frequencies.

Figure 4.8 SPL of FENG in the ultrasound range, along with the trend of addition of layers.
CHAPTER 5
THEORETICAL MODELING AND VALIDATION OF FENG AS A LOUD SPEAKER

When the FENG experiences an electrical input signal, dipoles expand or contract depending on the potential applied [11]. In turn, mechanical vibrations are generated and are translated as acoustic waves. A computational model for the FENG can then be assumed to behave as a rigid piston of a given shape moving forward and backward, creating the acoustic wave. However, to simulate the previous experimental configuration, a boundary condition must be considered as to represent the FENG fixed to the MDF board. The piston analogy allows to computationally/analytically solve for pressure or particle velocity at a given point in space around the FENG. To establish a relation between the FENG's input (i.e., electrical signal) and output (i.e., displacement), a voltage response definition is introduced.

5.1 Voltage Response Definition

The assumption of linear change in thickness (D) with applied voltage (V) implies an intrinsic response of the FENG material when used as a loudspeaker:

\[ R_v = \frac{1}{D} \frac{\partial D}{\partial V}. \]  

(5.1)

The intrinsic response \( R_v \) (units of \( V^{-1} \)) is the fractional change in FENG thickness per applied Volt. It is expected that \( R_v \) would depend on the dipole density and the average charge on the dipoles. The assumption that \( R_v \) is constant throughout the material implies the FENG loudspeaker sensitivity is proportional to the thickness of the FENG sheet.

5.2 Point Approximation Source

Based on the dimensions of the FENG and the acoustic wavelength that it creates, it can be classified to behave as a point source (radiates sound uniformly in all directions). The condition of this is that \( kL \ll 1 \) where \( k = \omega/c \) and \( L \) is the longest dimension of the FENG. Under these conditions, the pressure at a given distance \( r \) is given by:
\[ p(r, t) = \frac{i\omega \rho u}{4\pi r} e^{i(\omega t - kr)}, \quad (5.2) \]

where:

- \( p \) is the pressure in Pascal;
- \( u \) is the volume velocity in \( \text{m}^3/\text{s} \);
- \( \omega \) is the angular frequency in rad/s;
- \( k \) is the wavenumber = \( \omega/c \) where \( c \) is the speed of sound (343.2 m/s);
- \( r \) is the distance from the source to the observation point in meters;
- \( \rho \) is the density of air (1.18 kg/m\(^3\)).

The volume velocity \( u \) is equal to the area \( A \) of the FENG times its velocity. Since the velocity is the time derivative of the displacement, a FENG of thickness \( D \) responding to an applied sinusoidal voltage \( V \) would have a 2-sided (both front and back) volume velocity of:

\[ u = i\omega DR_v V A. \quad (5.3) \]

By substituting equation 5.3 into 5.2 we get:

\[ p(r, t) = -DR_v AV\frac{\omega^2 \rho}{4\pi r} e^{i(\omega t - kr)}. \quad (5.4) \]

Equation 5.4 reveals that the pressure is: 1) linearly proportional to the FENG area; 2) linearly proportional to the thickness; 3) proportional to the square of the frequency. This theory supports the results produced by the multilayer FENG and FENGs frequency response.

### 5.3 Estimating the Change in Thickness of the FENG

The SPL (sound pressure level) is 20 times the logarithm of the ratio of measured effective sound pressure (rms) to reference effective sound pressure. This reference sound pressure
is $2 \times 10^{-5}$ Pa. Thus, by knowing the SPL output of the FENG at a given frequency and measured from a given distance, the change in thickness of the FENG can be computed. The expression for pressure from point source approximation, converting that to SPL would be,

$$SPL = 94 + 20 \log_{10} \frac{\rho \omega^2 L^2}{4\sqrt{2\pi r}}.$$  \hspace{1cm} (5.5)

From the collected data, the SPL was 50 dB at a frequency of 2000 Hz at a distance of 30 cm. The frequency of 2000 Hz is chosen because the noise is minimum, although it is outside the domain of validity of the model (for the smallest FENG) by 180 Hz –note that for FENG of side 3 cm, $kL = 1$ at 1820 Hz. Substituting these values into equation 5.5 results in a peak displacement of 28 nm. The FENG thickness is 78 $\mu$m, so the relative change in FENG thickness is 0.04%.

### 5.4 High Frequency General Model

As $kL$ approaches unity, the simple low frequency model no longer holds, and more sophisticated methods must be used. Analytical solutions for these methods exist only for the simplest cases and it will be necessary to rely on numerical solutions to compare with measurements. One of these methods uses the Kirchhoff–Helmholtz integral equation [106] and can be used to solve for the acoustic pressure anywhere upon, or in the space surrounding the FENG at any frequency. The method accounts for the effects of scattering, diffraction, and shading. The equation is,

$$\varphi(r) = \varphi_{\text{ext}}(r) + \int_S [G(r,r')v(r') - \varphi(r') \nabla G(r,r')] \cdot dS,$$  \hspace{1cm} (5.6)

where $\varphi(r)$ is the acoustic potential measured at the point $r$. It is related to the pressure: $p(r) = i\omega \rho \varphi(r)$; $\varphi_{\text{ext}}(r)$ is the total potential at the point $r$ due to all the external sources;
\( \mathbf{v}(r') = \nabla \varphi(r') \) is the particle velocity; \( G(r,r') \) is the Green’s function for acoustics given by,

\[
G(r,r') = \frac{e^{ik|\mathbf{r} - \mathbf{r}'|}}{4\pi |\mathbf{r} - \mathbf{r}'|}.
\] (5.7)

5.5 Model Accounting for Solid Back-Plate

The FENG was measured when fixed to a solid back-plate. This removes the symmetry leading to the simpler Rayleigh equation. When there is no symmetry in the model preventing diffraction and reflection, the full weight of the Kirchhoff–Helmholtz integral equation 5.6 must be used. A numerical solution to the equation is embodied in the “Boundary Element Method” (BEM) which involves the following steps:

- Discretize the surface into \( N \) elements sufficiently small that the potential can be approximated by a simpler function. The surface integrals in Equation 5.6 can then be evaluated numerically over each element separately. The entire surface integral is the sum of the integrals over each element.

- Apply Equation 5.6 \( N \) times, each time with \( r' \) at the centroid of a different element. This step results in \( N \) equations and \( 2N \) unknowns: \( N \) unknown values of \( \varphi \) (one at each element centroid) and \( N \) unknown values of \( \mathbf{v} \).

- The \( N \) equations resulting from step 2 are assembled into a matrix equation. The boundary conditions are applied at each element to eliminate either \( \varphi \) or \( \mathbf{v} \).

- The matrix equation is solved (e.g., with Gaussian Elimination methods) resulting in values for \( \varphi \) and \( \mathbf{v} \) for every element on the surface.

- Having solved for the velocity potential and its derivative on the surface, the last step is to again apply Equation 5.6 to solve for the potential (or the velocity) anywhere in the solution domain.
The discretization of the FENG into triangular elements for this calculation is shown Figure 5.1.

The frequency response at a position perpendicular to the FENG plane and 30 cm from it is shown in Figure 5.2. The back-plate is the same size as the FENG and is 0.5 inches thick. There are a few expected features reproduced by the theory of a square FENG of side $L$:

1) At low frequencies where $L<<\lambda$, the frequency response rises at 12 dB/octave.

2) When $L \approx \lambda$, the response starts to rise above 12dB/octave as the radiator gets more directional and less energy gets sent backward.

Figure 5.1 Discretization of FENG surface for simulations. a) FENG is of the same size as the back-plate b) Discretization of the model with FENG (pink color) on a back-plate smaller (blue color) than its size.
3) When $L \gg \lambda$ the maximum boost of 6 dB is reached and the response continues to rise at 12 dB/octave.

4) There is some waviness due to diffraction. This happens when the FENG side length is multiple of wavelengths.

The experiments were performed on FENG devices mounted on back-plates (MDF) that were larger than the FENG (see Figure 3.2). The model for this (in the case of a rectangular strip) is shown in Figure 5.1b.

A simulation was carried out for different shapes. Selected results are overlaid with

![Graph](image.png)

Figure 5.2 Simulation results for a square FENG with a solid back-plate the same size as the FENG; it shows the frequency response at 30 cm in front of the FENG.
Figure 5.3 Simulation results are compared with their corresponding experimental measurement.
measurements as shown in Figure 6.3. It can be seen that for various shapes at various frequencies the directivity pattern measured is in close correlation to the simulation. It must be noted that the SNR on the back side of the FENG (180° – 270°) is poorer compared to the front side (90° – 180°).

5.6 Summary
A BEM model was developed and showed a close correlation to experimental data. The studies in this work show that the Sound Pressure Level (dB) of a FENG device, when used as a loudspeaker, increases at the rate of 12 dB/octave; and the Sound Pressure (Pa) increases linearly with the addition of layers and surface area. Thus, increasing the output Sound Pressure of FENG devices used as loudspeakers can be achieved by stacking layers connected electrically in parallel and increasing the loudspeaker’s area. For a 16 cm² FENG, the output increases from 40 dB to ~52 dB at around 3 kHz by stacking 4 layers. As expected, the output also increases linearly with the amplitude of the input signal. Directivity can be controlled by the loudspeaker’s geometrical shape. It is shown that a strip is the least directional shape in comparison with 3 other shapes tested. For further improvements, the option of increasing the dipole density during fabrication steps can be explored, along with various other electrode materials, thereby improving the $R_v$ of the FENG, which is expected to increase the output Sound Pressure.
CHAPTER 6

CHARACTERIZATION RESULTS OF THE FENG AS A MICROPHONE

Sensitivity of a microphone is usually defined as the ratio of output voltage to Sound Pressure (Pa) at the microphone position without the microphone present. This is under the assumption that the microphone is small when compared to a wavelength. The variation of sensitivity with an area of the FENG is certainly an important aspect of design since many applications include a concealed microphone.

6.1 Sensitivity

This is studied by testing 3 FENG samples: 1 cm x 1 cm; 2 cm x 2 cm; 3 cm x 3 cm as shown in Figure 6.1. The speaker was placed at a distance of 30 cm from the FENG for this experiment. The results are as shown in Figure 6.2. It is observed that the frequency response for all the FENGs remain nearly flat throughout the frequency range (20 Hz to 20 kHz). It is also observed that the sensitivity increases linearly with an increase in the area of the FENG; i.e. the measured average sensitivities are approximately -94, -82, and -75 dBV/Pa for devices with surface areas of 1, 4, and 9 cm$^2$, respectively. This result agrees with observations made while characterizing the FENG for energy harvesting applications [107]. The polar pattern or directivity of a microphone is another important performance parameter for a microphone, which describes the sensitivity to sound pressure relative to the direction or angle from which it arrives. There exist several commercially available microphones that are categorized based on their polar patterns; e.g. cardioid, super/hyper cardioid, omnidirectional [108]. The polar patterns for FENG-based microphones are studied next for 3 different shapes: flat (square), concave, and convex as shown in Figure 6.1. In order to make a fair comparison of the different shapes, the surface area of all the 3 FENG-based microphones remained the same (4 cm x 4 cm). The speaker is again placed at a distance of 30 cm from the FENG and the frequency is swept for angles from 0° to 180°. As a reference, 90° would correspond to the angle where the speaker is facing the FENG-
Figure 6.1 Samples used to study area dependency on the sensitivity and directivity; The inset shows a cross-section diagram of FENG, which consists of dipoles of different sizes. microphone’s top surface.

The results for selected frequencies are shown in Figure 6.3. The microphone tends to be nearly omnidirectional (or isotropic) at lower frequencies. Directionality increases with frequency, but this will also be dependent on the characteristic length of the FENG —when the FENG becomes comparable to a wavelength then it begins to become directional.

6.2 Comparison with traditional microphones
In order to compare FENG-based microphones with commercially available microphones, simultaneous recordings of voice through both FENG microphone and reference microphone were carried out. The spectral comparison of both recordings is shown in Figure 6.4. Voice and impulsive noise are clearly represented in front of background noise on a reference microphone, but the same was highly masked by background noise; i.e. the FENG
microphone has a lower signal to noise due to its low sensitivity. Moreover, the 60 Hz noise and harmonics are also clearly visible in the FENG-based microphone.

6.3 Summary

This work shows the performance of FENGs when used as microphones. Although they have lower sensitivity than commercially available microphones, yet comparable with SATURN [47] ( ~ -90 dBV/Pa ). Also, the frequency response and directivity characteristics stand out. Furthermore, due to their flexibility, FENG-based microphones can be configured into different shapes, enabling a re-configurable directivity. Also, different fabrication techniques can be explored to increase the dipole density in the FENG which will help increase the
Figure 6.3 Measured directivity for samples of different shapes.
Figure 6.4 Spectral comparison between FENG microphone and a traditional microphone.
sensitivity. Thus, FENG-based microphones show potential to be used in smart fabrics and wearable technologies.
7.1 Signal acquisition, conditioning and processing

The 6DX is configured in recorder mode (i.e., triggered by a pulse signal), and the data is recorded using SLICEWARE (Software by DTS for interfacing with the sensor). The data from the patch is recorded using a data acquisition system from National Instruments (NI-DAQ 6003) and, similar to the 6DX, the recording was also triggered with the same pulse signal of the 6DX. By using a double pole double throw (DPDT) switch, the 6DX and NI-DAQ are triggered simultaneously. The unfiltered data from both is stored for 2 seconds after the triggering action, and is shown in figure 7.1. Figure 7.1a shows the results for the output of the back neck area patch, while Figure 7.1b shows the measured output from the front neck area patch. In both figures, a phase delay between the FENG response and the angular velocity data from 6DX is observed, which will be addressed in later sections.

The main difference between both the experiments are the placement of the patch, i.e. for figures 7.1a) and b), the patch is placed on the back of the neck and for figures 7.1c and d, the patch is placed on the front. The raw signals were filtered through a fourth-order Butterworth low-pass filter with a cut-off frequency of 100 Hz which is one of the standard filters in the Society of Automotive Engineers (SAE) standard[109]. Given that the voltage peak response from the patch can be above the input limits of the NI-DAQ system (+ 10 V), the voltage output is attenuated through a resistive voltage divider and finally fed to the DAQ. It is important to note that the impedance seen by the FENG influences its dynamic performance[107]. In this case, the net load seen by the patch is 2.5 GΩ and this impedance has been found to result in accurate voltage output profiles [100]. The sampling rate for both sensors is set to 50 kHz, and the data is further processed using Python software [110]. Both filtered signals are shown in Figure 7.2.
Figure 7.1 Measured responses to hyper-flexion and hyper-extension of the neck. a) Hyper-flexion: Voltage response of the patch located at the back of the neck (as shown in b), where the orange shade represents the patch location) and angular velocity from the 6DX for drop tests from various heights simulating frontal collision of the center plate. c) Hyperextension: Voltage response of the patch located at the front of the neck (as shown in d) and angular velocity from the 6DX for drop tests from various heights simulating frontal collision of the center plate. Blue dots on b) and d) are rough estimations of the 6DX position.

7.2 Modeling

The FENG device as a flexible piezoelectric can be modeled as a charge source \( q_F \) with a shunt capacitor \( C_F \) and resistor \( R_F \) as shown in Figure 7.4. The charge produced depends on the piezoelectric coefficient. The capacitance is defined by the thickness, cross-sectional area, and dielectric constant of the material. The resistance represents the dissipation of the charge. The transfer function for this circuit is given by equation 7.1a. Based on piezoelectric properties, the charge is proportional to an applied force applied (with the
Figure 7.2 a) Filtered angular velocity and b) filtered voltage for different heights.

piezoelectric coefficient being constant). From the position of the FENG relative to the 6DX sensor as shown in Figure 7.3, it can be inferred that the force experienced (tensile) by the
FENG is proportional to the angular position of the 6DX (7.1b), thus making the angular velocity proportional to rate of change of force (7.1c).

Figure 7.3 Shows the head tilt causing a flexion in the neck.

From the previous analysis, we can argue that the transfer function between the rate of change of voltage and angular velocity should be similar to that of 7.1a, which is represented in 7.1d. The value of $R_F$ can be estimated based on the results from Cao et. al.[107] to be 550 MΩ, and the capacitance to be of the order of 100 pF. $q_F$ is there charge generated by the FENG upon actuation.

This result was confirmed by analytical computer-based simulations of the transfer function with the angular velocity recorded from the 6DX, and by comparing the results with the generated rate of change of voltage. A representative instance of such correlation between the simulated and measured signals is shown in Figure 7.4b –it should be noted that the scale of the voltage signal is not relevant for the correlation, since the emphasis is placed on a dynamic correspondence that allows for mapping between plots. This confirms the hypothesis that the first derivative of the FENG’s voltage can be mapped to angular velocity,
as long as the proportionality constant is known.

\[
\frac{V_F(s)}{q_F(s)} = \frac{sR_F}{1 + sC_FR_F} \tag{7.1a}
\]

\[
q_F \propto F(\text{Force}) \propto \theta(\text{Angular Position}) \tag{7.1b}
\]

\[
\frac{dF}{dt} \propto \omega(\text{Angular Velocity}) \tag{7.1c}
\]

\[
\frac{\dot{V}_F(s)}{\omega(s)} \propto \frac{sR_F}{1 + sC_FR_F} \tag{7.1d}
\]
Figure 7.5 a) and c) show the relationship between the FENG’s voltage response and the peak angular velocity during hyperflexion and hyperextension. Similarly, b) and d) show the relationship between FENG’s voltage response and the peak angular acceleration.

### 7.3 Estimating TBI from FENG response

In order to estimate the possibility of a concussion or any other TBI, it is necessary to determine the peak angular velocity and acceleration along with the duration of impact since these features show a strong correlation with brain injuries. As shown in Figure 7.5, the aforementioned features show a strong linear correlation with the FENG’s response. Figure 7.5a and 7.5b show that, during hyperflexion, the peak angular velocity and acceleration can be determined by knowing the peak \( \frac{dV}{dt} \) and peak \( \frac{d^2V}{dt^2} \) from the FENG’s response; the FENG’s output voltage by itself is a measure of strain on the neck during these events. Similar behaviour is seen when the patch is placed on the front side of the neck to determine the markers due to hyperextension.
The results indicate that it is possible to characterize the event of whiplash by acquiring data from the front/back patches simultaneously. This is in part possible due to the construction of the patches, which ensure that there is little to no effect on the FENG device during compression. This is supported by closely observing Figure 7.1c: when placed on the front of the neck, the patch produces a small voltage response during hyperflexion, but produces a deterministic response during hyperextension.

7.4 Summary

This work summarises the fabrication of the patch and its components. The results show that there is a strong positive correlation ($R^2 > 90\%$) between the patch output and rotational kinematic signatures experienced by the human head, which was recorded using a triaxial accelerometer and gyroscope placed at the center of gravity of the human head dummy. This result is also supported by the proposed model which yields a response similar to the one measured by the patch. The FENG which at the heart of this patch has $<10\%$ variation in its sensitivity across devices. Although this work demonstrates the system along one spatial axis, it can certainly be expanded along the other axes by placing multiple sensors around the neck; thus providing a full, comprehensive map of the human head during a collision. The risk of false positive signals originating from direct impact on the FENG can be mitigated through appropriate filtration schemes as mentioned earlier and also by reducing the surface area of the sensor which will make it less likely to experience an accidental direct impact. Even in the lack of a software filter the FENG’s load can be modified to change its frequency response.
CHAPTER 8
MEASURING BRAIN VIBRATIONS

The focus of this work is to establish the use of the FENG as an invasive sensor in the brain phantom to measure the frequency of brain vibrations. The FENG’s response is also compared to the strain in an equivalent region of the phantom using particle image velocimetry (PIV). This study elaborates on the setup required for both of these methods, along with the method of preparation of the brain phantom and the FENG. The results from both approaches are compared in the frequency domain using a Fast Fourier Transform (FFT).

8.1 Using macro-sized particle for tracking deformation.

Using the setup as described in chapter 3, the brain deformations are measured using PIV and also using the implanted FENG’s response. However, prior to PIV, particle tracking (macro particles) embedded in the phantom was used to interpret the major vibration mode of the brain. This phantom is shown in figure 8.1.

The macro particles in the figure 8.1 are cut pieces of PLA filaments. They are numbered in the figure are tracked using the region growing algorithm on matlab and their distance from one another is plotted with time as shown in figure 8.2. This can be interpreted as deformation. Later an exponentially decaying sinusoid is fit to this using a curve-fitting toolbox on matlab as shown in figure 8.3.

This fit yielded decaying sinusoids of around 25 Hz which is what was expected given that the phantom was designed to mimic the properties of the brain.

8.2 Using finer particles for tracking deformation (PIV)

PIV is typically used to calculate the velocity field in fluid flows. To this end, PIV uses a FFT-based algorithm to calculate the cross-correlation between corresponding regions of consecutive images [111],[112]. This algorithm is applied herein to images of tracer particles embedded in a viscoelastic material [113]. After normalizing by the grid size, this velocity
field is a direct measurement of the instantaneous strain-rate field. The frame rate used for this measurement of the strain-rate field was 2500 frames per second. The PIV analysis was performed in the same general region of interest (ROI) in which the FENG was embedded. This ROI is demarcated by a blue box in Figure 8.5. Everything outside of the ROI was eliminated from the figure with a binary mask.

The tool was applied to an initial interrogation window of $256 \times 256$ pixel, then decreasing by 50% until reaching a $16 \times 16$ pixel window. Although an initial interrogation window is typically smaller, the chosen size allowed tracking of particles even when the surrogate head displaced significantly. Spurious vectors within the region of interest were filtered out using image based validation which considers features such as contrast within a given region, and velocity-based validation where outstanding erroneous velocity vectors can be ignored. The strain-rate between consecutive frames was extracted from the PIVLab application and imported to a database for computational analysis.
Figure 8.2 Strains measured based on relative distance between the macro particles.

Since the head surrogate is fixed to a flexible mechanic neck, it is free to move out of its initial position in the camera’s field of view. To address this, an in-house code was used to track the local deformations of a specific region in the brain 13. The chosen region of interest moves every frame according to the mean of the $u$ and $v$ velocity components, and is further explained in the results section. This information was used to calculate the average strain-rate within this region of interest.

### 8.3 PIV results

In order to obtain the strain using PIV analysis, it is vital to track the bulk motion of the phantom so as to obtain the strain from a constant region of interest. This is performed with the help of average “v- velocity” and “u- velocity” obtained across the entire computational
Figure 8.3 a) Shows normalised Strain with curve fitted over it.

Figure 8.4 a) Side view of the setup emphasizing on the LED array and camera. b) Sample image that the camera captures. The fine particles are clearly visible in this image.

area as shown by the black region in Figure 8.5a (the red shaded region is neglected). These velocities are shown in Figure 8.5b. Figure 8.5c shows the captured frames from different instances in time with blue region overlaid highlighting the tracking of the bulk motion using average velocities. The strain rate from this region of interest is obtained across every frame and is shown in Figure 8.7a, along with strain, which is calculated from the strain rate. This strain is later used to analyze the modality of the deformations. The low frequency and high frequency time intervals are highlighted in the same graph.

In order to validate the results from the PIV, we observe the strains generated due to the shock-wave that propagates upon impact. This is shown in Figure 8.6.

The visco-elastic nature of the brain brings a non-linear relationship between stress and strain[114]. The FENG device provides voltage signals in response to stress, while the PIV
Figure 8.5 a) Frame of the phantom after impact with displacement vector field overlaid upon it depicted by green arrows. b) Instantaneous average bulk velocity of the phantom decomposed into $u$ and $v$ components. c) Region of interest (shaded in blue) tracks the bulk motion (from top-right to bottom-left).

analysis captures strain. Thus the study of results from both these approaches will provide useful insights into the non-linear stress-strain relationship of the brain. A Kelvin-Voigt visco-elastic material can be electrically modeled as a constant current source in series with parallel resistor-capacitor (RC) circuit [115]. In this analogy, the current source represents the applied stress and the voltage across the capacitor represents the strain.

When the stress changes slowly i.e. input of relative low frequency, the strain follows the stress. This is similar to how the voltage across a capacitor in an RC circuit is in-phase with the input. However, when the stress changes at a higher rate, the strain lags, which again
follows the behaviour of an RC circuit. This can be also approximated as an integrator circuit, where a square wave input to the RC circuit produces a triangular wave output. The high frequency components of the travelling wave occur during the initial phase of the impact, when the brain behaves predominantly as a viscous medium. This is supported by the positive correlation of the time-domain and FFT of the strain obtained from PIV and the numerical integration of FENG’s response as shown in Figure 8.7b. The FFT’s correlate by 0.795 (Pearson’s R). Similarly, the low frequency domain can be observed after $\sim 160\,\text{ms}$ from impact when the brain begins to oscillate around its natural frequency. The normalized voltage and strain after this time frame, and the corresponding FFTs are shown in Figure 8.7c. In both frequency spectra, we can see that the dominant frequencies are between 15 Hz to 60 Hz, with a peak around 25 Hz. There are other higher frequencies present in the voltage response of the FENG which could be generated from the gyri’s local oscillations. Nevertheless, the spectra have a correlation of 0.82 (Pearson’s R). This supports that the
brain is exhibiting a more elastic behaviour.

This high positive correlation supports that the FENG, although invasive, can be used in studying frequencies of brain vibrations under any form of blunt impact. The FENG involves minor signal conditioning circuitry and data acquisition hardware to capture the several metrics around the impact studies. The PIV is non-invasive, but the setup is more complex, involving more equipment (e.g. high speed camera) and being more susceptible to testing parameters (e.g. illumination). Also, it relies on the subject having minimal displacement so that it does not get outside the frame boundaries; a situation that occurs mainly with larger impact magnitudes.

8.4 Summary

These results indicate the successful use of FENG as an invasive vibration sensor to understand and validate the modality of deformations that the biofidelic brain undergoes during a blunt impact. The future prospects would be to incorporate the FENG to characterize the brain as a visco-elastic system and thereby used across all kinds of impact studies with respect to traumatic brain injuries.
Figure 8.7 a) Strain and strain rate derived from PIV analysis. b) (top) Strain obtained from PIV and the integral of voltage from the FENG. (0 - 6 ms) bottom) FFT of strain obtained from PIV and the integral of voltage from the FENG. c) (top) Normalized strain and voltage response from the FENG between 160 - 260 ms after impact. bot) FFT of normalized strain and voltage.
CHAPTER 9

SUMMARY

9.1 Summary of Contributions

This work revolves around various use cases of a flexible sensor/actuator called the FENG. All the applications presented are novel and provide useful insight into the role of such devices across these applications. The approach to application-specific characterization is one of the key takeaways from this work. In the case of speaker and microphone, the emphasis on having a 6-face an-echoic chamber helped derive faithful results and the use of baffle in the case of the microphone characterization ensured the same. Similarly, in the concussion detection patch, care was taken such that the buckling happens outside the FENG’s area there in isolating the response between hyperextension and hyperflexion. And for vibration detection, the need for waterproofing and signal conditioning of the FENG was a must to ensure good sensitivity of the device but also not to interfere with the integrity of the brain substitute.

Problems Solved in this Thesis

This work addresses the following:

- FENG was characterized as a speaker and microphone for directivity and sensitivity/SPL output. The results were validated using a model developed from the first principles of acoustics.

- FENG was used to develop a patch that is designed to be worn on the neck. This patch was shown to estimate head rotation kinematics, which is established to be an essential marker in predicting concussions.

- A circuit model of the FENG was used to reason the patch’s output when subjected to whiplash on a dummy’s neck.

- FENG was used as a vibration sensor to understand the modalities of deformations in
human brain substitute (phantom). This was compared with the results obtained from PIV based on high-speed images captured of the phantom upon blunt impact and the agreement between the 2 was established.
BIBLIOGRAPHY


Region tracking
Strain rate, u_filtered, v_filtered are imported into matlab workspace from the PIVLAB app. Below is the code used to track the region in the brain along with the moving bulk and then the strain in computed from strain-rate but numerical integration.

frames = 679;
masked_strain_rate = cell.empty(frames,0);
masked_u_filtered = cell.empty(frames,0);
masked_v_filtered = cell.empty(frames,0);

mask_x1 = 13;
mask_x2 = 97;
mask_y1 = 19;
mask_y2 = 99;

for i=1:1:frames
    inter = strain_rate{i};
    masked_strain_rate{i,1} = inter(mask_y1:mask_y2,mask_x1:mask_x2);
    inter = u_filtered{i};
    masked_u_filtered{i,1} = inter(mask_y1:mask_y2,mask_x1:mask_x2);
    inter = v_filtered{i};
    masked_v_filtered{i,1} = inter(mask_y1:mask_y2,mask_x1:mask_x2);
end
mean_u_filt = zeros(frames,1);
mean_v_filt = zeros(frames,1);

for i=1:1:frames
    mean_u_filt(i) = mean(masked_u_filtered{i},'all');
    mean_v_filt(i) = mean(masked_v_filtered{i},'all');
end
u_cumulative = zeros(frames,1);
v_cumulative = zeros(frames,1);

u_cumulative(1) = mean_u_filt(1);
v_cumulative(1) = mean_u_filt(1);
for i=2:1:frames
    u_cumulative(i) = sum(mean_u_filt(1:i));
v_cumulative(i)= sum(mean_v_filt(1:i));
\begin{verbatim}
end

u_cumulative_int = u_cumulative/8;
v_cumulative_int = v_cumulative/8;

tracked_region = cell.empty(101,0);

% matrix_x = 2;
% matrix_y = 32;
matrix_x = 34;
matrix_y = 53;
init_i = 1;
init_j = 85;

% masked strain rate is 81x85 nad max v is 45 max u is 27
tracked_region{1,1} =
masked_strain_rate{1,1}(init_i:init_i+matrix_x,init_j-matrix_y:init_j);
for i=2:1:frames
    u_add = int8(floor(u_cumulative_int(i)));
v_add = int8(floor(v_cumulative_int(i)));
    tracked_region{i,1} =
    masked_strain_rate{i,1} \((init_i+v_add:init_i+v_add+matrix_x,init_j-matrix_y+u_add:init_j+u_add))
end

mean_strain_rate = zeros(frames,1);
for i=1:1:frames
    mean_strain_rate(i) = mean(tracked_region{i},'all');
end

strain_cumulative= zeros(frames,1);
strain_cumulative(1) = mean_strain_rate(1);
for i=2:1:frames
    strain_cumulative(i) = sum(mean_strain_rate(1:i));
end
figure(6);
plot(strain_cumulative);
grid;
\end{verbatim}
% Y = fft(strain_cumulative);
% P2 = abs(Y/frames);
% P1 = P2(1:frames/2+1);
% P1(2:end-1) = 2*P1(2:end-1);
% P1 = 20*log10(P1);
% f = 2500*(0:(frames/2))/frames;
% figure(7);
% plot(f,P1);
% title('Single-Sided Amplitude Spectrum of X(t)')
% xlabel('f (Hz)')
% ylabel('|P1(f)|')

Strain rate from particle co-ordinates
Once the matrix containing all x and y co-ordinates of all trackers are loaded then the below
codes yeilds out all possible combinations of relative distances between the particles.

A = load('test_01_2tks.mat');
len = size(A.coords,2)/2;
comb = (len*(len -1))/2;
v = 1:1:len;
vav = nchoosek(v,2);
strain = zeros(size(A.coords,1),comb);
for i = 1:comb
    dist =
        sqrt(((A.coords(:,(vav(i,1)*2 -1)) - A.coords(:,(vav(i,2)*2 -1))).^2) +
             ((A.coords(:,vav(i,1)*2) - A.coords(:,(vav(i,2)*2))).^2));
    if i ==1
        distance = dist;
    else
        distance = horzcat(distance,dist);
    end
end

init_dist = distance(1,);
for j = 1:comb
    strain(:,j) = distance(:,j)/init_dist(j);
for k = 1:comb
    plot(strain(:,k));
    hold on;
end

Python for Signal processing and Data Analysis

```python
import pandas as pd
import numpy as np

def ext_data_acc(filename,dt):
    '''Extracts AVY and HEADX from the DTS sensors datafile'''
    data = pd.read_csv(filename,skiprows = 22)
    data.head()
    data['Time'] = np.arange(0,len(data['Time'])*dt,dt)
    Time = data['Time'].to_numpy()
    value = data['Chan 0:6DX0625-AV1'].to_numpy()
    value2 = data['Chan 4:6DX0625-AC2'].to_numpy()

    return Time,value,np.absolute(value2)
```

```python
from slicing import slicing
from scipy import integrate

def HIC_calc(acc,time,dt):
    '''Pass the acceleration and returns the HIC value
    slices the accelerations data to 15ms around
    the peak acceleration and then computes HIC from it'''
    tim,value = slicing(0.015,time,acc,dt)
    integ = integrate.trapz(value,tim)
    avg = integ / 0.015
    step1 = (integ / 0.015)**2.5
    HIC = step1*0.015
    return HIC,avg
```

```python
import numpy as np
def num_diff(filt_signal,dt):
    '''Takes the filtered signal and performs a numerical differentiation
    and gives out acceleration.'''
    accel = []
    for i in range(1,len(filt_signal)):
        accel.append((filt_signal[i] - filt_signal[i-1])/dt)
        time = np.arange(0,dt*len(accel),dt)
```

return accel, time

import numpy as np
def slicing(window, time, value, dt):
    ''' pass time, value and
    window size
    returns new time and
    value array for that window size around the peak value'''
    num = int(window*0.5/dt)
    maxind = np.argmax(value)
    fr = maxind - num
    to = maxind + num
    return time[fr:to], value[fr:to]

import numpy as np
def slicing_min(window, time, value, dt):
    ''' pass time, value and
    window size
    returns new time
    and value array for that window size
    around the peak value'''
    num = int(window*0.5/dt)
    maxind = np.argmin(value)
    fr = maxind - num
    to = maxind + num
    return time[fr:to], value[fr:to]

Region growing algorithm

%-------------------Created By: Bianca Davila Montero--------------%
%-----------------------Michigan State University-------------------------%
%-------------------------Drop Tower Experiment---------------------------%
%----------------------Prof. Ricardo Mejia-Alvarez------------------------%
%----------------------------Date: 02/10/2022-----------------------------%
%-------------------------------------------------------------------------%
%
% The purpose of this script is to track the position of certain markers 
% embedded in the head phantom. After positions are acquired, strains 
% can be calculated among other parameters as desired.
%
% Experiment date: 02_08_2021
% Test with weight 1.5 kg and height 0.5 m
clc, clear all, close all
addpath('C:\Users\Henry Dsouza\Documents\Head Injury\Lil_B_tracking')

PathResults = 'D:\DropTower_Feb2022\02_08_22\Test1';

PTH = 'D:\DropTests_Feb2022\test_01';
Pic1 = 1;
Pic2 = 10010;

TagResults = PTH( end - 4 : end );

Resol = 0.1346;  % resolution (mm/pix) Calculated using tracker dia.
DT = 1000 / 25000;  % time step (ms)

KeY = '*.jpg';
LnKeY = length( KeY ) - 1;

[pathFilesAll] = filesVector(PTH , KeY );
% finding paths of all images from video
pathFiles = pathFilesAll( Pic1 : Pic2 );
pathFiles = strcat(PTH,"\frame","0000.jpg")
for i = Pic1:Pic2
    istr = int2str(i);
    if size(istr) < 4
        istr = pad(istr,4,"left","0");
    else
        istr = int2str(i);
    end
    pathFiles = [pathFiles; strcat(PTH,"\frame",istr,".jpg")];
end

N = length( pathFiles );  % total number of images
FldWdth = length( num2str( N ) );  % length of numeric tag in file names

% allocating vector to save results
% 1st column: picture label, 2nd - 4th columns: polynomial fit coefficients
Rslt = zeros( N, 3 );
% time vector
Tm = ( 0 : DT : ( N - 1 ) * DT )’;
%

% retrieving the path of the 1st image
F1Pth = pathFiles{ 1 };

% retrieving 1st image
A = imread( F1Pth );

% creating single-matrix image (the original images are defined as RGB,
% with three channels, but all are identical because the images are
% originally grayscale. The resulting matrix will be of double
% precision.
B = im2gray( A );

% using the size of B to generate matrices with column and row
% indexes
[ Rows, Cols ] = size( B );
c = 1 : Cols;
r = 1 : Rows;
[C,R] = meshgrid(c,r);

% column and row indexes will be used to generate x and y coordinates.
% The row-index matrix needs to be flipped to make the y-axis grow
% vertically up
R = flipud( R );
imshow(B, []) %serves to calculate threshold and resolution

%% Making tracker pixels 0 and the rest continue as gray scale
th = 65; %threshold value according to image
for i = 1 : Rows
  for j = 1 : Cols
    if B(i,j) <= th
      B(i,j) = 0;
    end
  end
end
% B = imbinarize(B);
imshow(B, [])

%% Multiple trackers
k = 1; %number of marker to track
CntrsX = zeros(N,k); %creating matrix
of each position by tracker (each tracker
```matlab
info in a column)
CntrsY = zeros(N,k);

%%

% regionGrowing for base image
for w = 1:k
    tic
    [P, BM] = regionGrowing( B ,[], 5);
    imshow( B, [] );
    hold on
    plot(P(:,1), P(:,2),'LineWidth',2)
    hold off
    maxFsrtCol = max(P(:,1));
    minFrstCol = min(P(:,1));
    maxScndCol = max(P(:,2));
    minScndCol = min(P(:,2));
    xCoordCenter = (maxFsrtCol + minFrstCol) / 2;
    yCoordCenter = (maxScndCol + minScndCol) / 2;
end

% initial center position, this will be the first seed for the rest of the
% region growing
coordX(1) = xCoordCenter;
coordY(1) = yCoordCenter;

% ImC = ones(size(B));
% BM = double(BM);
%
% ImC = ImC .* BM;

% imshow(B, [])
% hold on
% %
% %
% hold off
% ax = gcf;

% Now this process will be repeated for all the images taking as seed the
```
for n = 2 : N
    \% retrieving the path of th n-th image
    FlPth = pathFiles{ n };

    \%---Uncomment following if you want to save all images of tracking
    \%
    \% imshow(A, []);
    \% hold on
    \% plot(coordX(n), coordY(n), '+', "MarkerEdgeColor", "red", "LineWidth", 2)
    \% hold off
    \%
    \% ax = gcf;
    \% \% filename = sprintf(PathResults, filesep, '\point\%04d.tif', n);
    \% \% imwrite(ax, strcat(filename, filesep));
    \% exportgraphics(ax, strcat(PathResults, filesep, sprintf('%04d.tif', n)))
end

CntrsX(:,w) = coordX';
CntrsY(:,w) = coordY';
coords = horzcat(coordX', coordY');
savefile(strcat("tracker_x_", int2str(k)), coords)
toc

end

figure;
FlPth = pathFiles{1};
A = imread(FlPth);
imshow(A, []);
hold on
plot(CntrsX(:,1), CntrsY(:,1), CntrsX(:,2), CntrsY(:,2), CntrsX(:,3), CntrsY(:,3), CntrsX(:,4), CntrsY(:,4), 'LineWidth', 2);
%plot(CntrsX(:,1), CntrsY(:,1), 'LineWidth', 2);
hold off
ax = gcf;
function [X,Y,A] = CntrsRegionGrowing( FlPth, X, Y, n)

% retrieving image
A = imread( FlPth );
A = im2gray( A );

[ Rows, Cols ] = size( A );
th = 65;
for i = 1 : Rows
    for j = 1 : Cols
        if A(i,j) <= th
            A(i,j) = 0;
        end
    end
end

[P, BM] = regionGrowing( A , [ round(Y(n-1)) , round(X(n-1)) ] , 5);
%locating seed at center of previous image

maxFsrtCol = max(P(:,1));
minFrstCol = min(P(:,1));
maxScndCol = max(P(:,2));
minScndCol = min(P(:,2));

xCoordCenter = (maxFsrtCol + minFrstCol) / 2;
yCoordCenter = (maxScndCol + minScndCol) / 2;

% center position
X(n) = xCoordCenter;
Y(n) = yCoordCenter;
end

function [P, J] = 
    regionGrowing(cIM, initPos,
    thresVal, maxDist, tfMean, tfFillHoles, tfSimplify)
% REGIONGROWING Region growing algorithm for 2D/3D grayscale images

% Syntax:
% P = regionGrowing();
% P = regionGrowing(cIM);
% P = regionGrowing(cIM, initPos)
% P = regionGrowing(..., thresVal, maxDist, tfMean, tfFillHoles, tfSimpl)
% [P, J] = regionGrowing(...);

% Inputs:
% cIM: 2D/3D grayscale matrix {current image}
% initPos: Coordinates for initial seed position {ginput position}
% thresVal: Absolute threshold level to be included {5% of max-min}
% maxDist: Maximum distance to the initial position in [px] {Inf}
% tfMean: Updates the initial value to the region mean (slow) {false}
% tfFillHoles: Fills enclosed holes in the binary mask {true}
% tfSimplify: Reduces the number of vertices {true, if dpsimplify exists}

% Outputs:
% P: VxN array (with V number of vertices, N number of dimensions)
% P is the enclosing polygon for all associated pixel/voxel
% J: Binary mask (with the same size as the input image) indicating
% 1 (true) for associated pixel/voxel and 0 (false) for outside

% Examples:
% % 2D Example
% load example
% figure, imshow(cIM, [0 1500]), hold all
% poly = regionGrowing(cIM, [], 300); % click somewhere inside the lungs
% plot(poly(:,1), poly(:,2), 'LineWidth', 2)
% %
% % 3D Example
% load mri
% poly = regionGrowing(squeeze(D), [66,55,13], 60, Inf, [], true, false);
% plot3(poly(:,1), poly(:,2), poly(:,3), 'x', 'LineWidth', 2)
% %
% % Requirements:
% % TheMathWorks Image Processing Toolbox for bwboundaries() and axes2pix()
% % Optional: Line Simplification by Wolfgang Schwanghart to reduce the
% % number of polygon vertices (see the MATLAB FileExchange)
% %
% % Remarks:
% % The queue is not preallocated and the region mean computation is slow.
% % I haven’t implemented a preallocation nor a queue counter yet for the
% % sake of clarity, however this would be of course more efficient.
% error checking on input arguments
if nargin > 7
    error('Wrong number of input arguments!')
end

if ~exist('cIM', 'var')
    himage = findobj('Type', 'image');
    if isempty(himage) || length(himage) > 1
        error('Please define one of the current images!')
    end
    cIM = get(himage, 'CData');
end

if ~exist('initPos', 'var') || isempty(initPos)
    himage = findobj('Type', 'image');
    if isempty(himage)
        himage = imshow(cIM, []);
    end
    % graphical user input for the initial position
    p = ginput(1);
    % get the pixel position concerning to the current axes coordinates
    initPos(1) = round(axes2pix(size(cIM, 2), get(himage, 'XData'), p(2)));
    initPos(2) = round(axes2pix(size(cIM, 1), get(himage, 'YData'), p(1)));
end

if ~exist('thresVal', 'var') || isempty(thresVal)
    thresVal = double((max(cIM(:)) - min(cIM(:))) * 0.05);
end

if ~exist('maxDist', 'var') || isempty(maxDist)
    maxDist = Inf;
end

if ~exist('tfMean', 'var') || isempty(tfMean)
    tfMean = false;
end
if ~exist('tfFillHoles', 'var')
    tfFillHoles = true;
end

if isequal(ndims(cIM), 2)
    initPos(3) = 1;
elseif isequal(ndims(cIM), 1) || ndims(cIM) > 3
    error('There are only 2D images and 3D image sets allowed!')
end

[nRow, nCol, nSli] = size(cIM);

if initPos(1) < 1 || initPos(2) < 1 ||...
    initPos(1) > nRow || initPos(2) > nCol
    error('Initial position out of bounds, please try again!')
end

if thresVal < 0 || maxDist < 0
    error('Threshold and maximum distance values must be positive!')
end

if ~isempty(which('dpsimplify.m'))
    if ~exist('tfSimplify', 'var')
        tfSimplify = true;
    end
    simplifyTolerance = 1;
else
    tfSimplify = false;
end

% initial pixel value
regVal = double(cIM(initPos(1), initPos(2), initPos(3)));

% text output with initial parameters
% disp(['RegionGrowing Opening: Initial position (' num2str(initPos(1))...
%       '|' num2str(initPos(2)) '|' num2str(initPos(3)) ') with '...
%       num2str(regVal) ' as initial pixel value!'])

% preallocate array
J = false(nRow, nCol, nSli);

% add the initial pixel to the queue
queue = [initPos(1), initPos(2), initPos(3)];
%*** START OF REGION GROWING ALGORITHM
while size(queue, 1)
    % the first queue position determines the new values
    xv = queue(1,1);
    yv = queue(1,2);
    zv = queue(1,3);
    % .. and delete the first queue position
    queue(1,:) = [];
    % check the neighbors for the current position
    for i = -1:1
        for j = -1:1
            for k = -1:1
                if xv+i > 0 && xv+i <= nRow &&... % within the x-bounds?
                    yv+j > 0 && yv+j <= nCol &&... % within the y-bounds?
                    zv+k > 0 && zv+k <= nSli &&... % within the z-bounds?
                    any([i, j, k]) &&... % i/j/k of (0/0/0) is redundant!
                    J(xv+i, yv+j, zv+k) &&... % pixelposition already set?
                    sqrt( (xv+i-initPos(1))^2 +... 
                           (yv+j-initPos(2))^2 +... 
                           (zv+k-initPos(3))^2 ) < maxDist &&... % within distance?
                    cIM(xv+i, yv+j, zv+k) <= (regVal + thresVal) &&... % within range
                    cIM(xv+i, yv+j, zv+k) >= (regVal - thresVal) % of the threshold?
                end
                J(xv+i, yv+j, zv+k) = true;
                % add the current pixel to the computation queue (recursive)
                queue(end+1,:) = [xv+i, yv+j, zv+k];
            end
        end
    end
    if tfMean
        regVal = mean(mean(cIM(J > 0))); % --> slow!
    end
end
%*** END OF REGION GROWING ALGORITHM
% loop through each slice, fill holes and extract the polygon vertices
P = [];
for cSli = 1:nSli
    if ~any(J(:,:,cSli))
        continue
    end

    % use bwboundaries() to extract the enclosing polygon
    if tfFillHoles
        % fill the holes inside the mask
        J(:,:,cSli) = imfill(J(:,:,cSli), 'holes');
        B = bwboundaries(J(:,:,cSli), 8, 'noholes');
    else
        B = bwboundaries(J(:,:,cSli));
    end

    newVertices = [B{1}(:,2), B{1}(:,1)];

    % simplify the polygon via Line Simplification
    if tfSimplify
        newVertices = dpsimplify(newVertices, simplifyTolerance);
    end

    % number of new vertices to be added
    nNew = size(newVertices, 1);

    % append the new vertices to the existing polygon matrix
    if isequal(nSli, 1) % 2D
        P(end+1:end+nNew, :) = newVertices;
    else % 3D
        P(end+1:end+nNew, :) = [newVertices, repmat(cSli, nNew, 1)];
    end
end
if size(P,1)==0
    imshow(cIM,[]);
    disp(initPos);
    chk = 0;
end

% text output with final number of vertices
% disp(['RegionGrowing Ending: Found ' num2str(length(find(J)))...
%       ' pixels within the threshold range (' num2str(size(P, 1))...
%       ' polygon vertices)!'])
LabView for Data Capture and Analysis
The figure A 1 shows the VI block diagram used to collect data from NI-DAQ and also perform data analysis.
Figure A.1 Labview VI for data capture using NI-DAQ and obtaining FFT.
Figure A. 2 Labview VI for data capture using NI-DAQ and writing into a file with file name updates for continuous recording.