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TESTING AND ANALYSIS OF PRESSURE FABRIC SENSORS IN IMPEDANCE DOMAIN

Master's Thesis

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RÕHUTUNDLIKE MATERJALIDE IMPEDANTSI TESTIMINE JA ANALÜÜS

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Author's declaration of originality

I hereby certify that I am the sole author of this thesis. All the used materials, references to the literature and the work of others have been referred to. This thesis has not been presented for examination anywhere else.

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Abstract

E-textiles is a rapidly growing field in the current market. Their applications are not only restricted to fashion or sports, but can be used in military, health and in other important sectors. With such increase of potential applications, and new sensor solutions, certain concerns of their accuracy, ageing in longer terms, and lack of other useful information will arise. A good sensor is flexible in functionality, and provides data that is accurate and repeatable. Yet this information for E-textile sensors is not widely available, and mostly sensors are being created for specific application. This work covered the analysis of the textile sensors, specifically two material samples, so that it can be used for different applications, in different fields.

This thesis is written in English and is 58 pages long, including 5 chapters, 33 figures and 3 tables.

Keywords: E-Textiles, Smart Textiles, Eeonyx, Eeontex, Fabric Sensors, piezoresistive, pressure fabric sensors

Annotatsioon

Rõhutundlike materjalide impedantsi testimine ja analüüs

E-tekstiilid on kasvav segment turul. Nende rakendusvaldkonnad ei ole üksnes piiratud moe või spordiga, vaid võivad kasutust leida ka sõjanduses, tervishoius ja muudes olulistes valdkondades. Seoses potentsiaalsete rakenduste kasvuga tõstatuvad küsimused täpsusest, vananemisest ja muu kasutusinfo ebapiisavusest. Hea sensor on paindlik oma funktsionaalsuses, tulemused on täpsed ja korratavad. Hetkel selline info e-tekstiilist andurite kohta ei ole levinud, enamus sensoritest on loodud spetsiifiliste rakenduste jaoks. Käesolev töö käsitleb tekstiilandureid, spetsiifiliselt kahte materjali, et neid saaks kasutada erinevates rakendustes ja kasutusaladel

Lõputöö on kirjutatud inglise keeles ning sisaldab teksti 58 leheküljel, 5 peatükki, 33 joonist, 3 tabelit.

Võtmesõnad: e-tekstiilid, targad tekstiilid, Eonyx, Eeontex, kangast sensorid, piezoresistiivne, rõhukanga sensorid

List of abbreviations and terms

TCP/IP	Transmission Control Protocol/Internet Protocol
TUT	Tallinn University of Technology
EAA	Estonian Academy of Arts
E-Textiles	Electronic Textiles
ECG	Electrocardiogram
ICP	Intrinsically Conductive Polymers
PPY	Polypyrrole
USB	Universal Serial Bus
EIS	Electrical Impedance Spectroscopy
DC	Direct Current

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1 Introduction

The idea of clothing started when human race decided to cover their body parts, and as people has evolved, clothing has also evolved from leaves to fabrics and so do the concept. The idea also progressed from just covering the body, and to make it more feasible and functional, like attachment of pockets so we can carry our stuff more easily. With time the clothes became more efficient providing warmth for cold weather and vice versa for warm weather. It kept progressing till the extent of combining electronics into textile, hence, concept of E-Textile or Smart Textiles initiated.

Smart Textiles can be described as combination of textile product with electronic components, which adds value to it for the wearer. The use of integrating electronics into textile have always been around but was significantly increased during 19^{th} century. Currently a lot of research is being done in this area, and several forecasts shows that it will increases with time.

Cientifica provides analytical insights on different topics. According to one of theirs research report on Smart Textile markets, identifies three generation of E-textile technologies:

1. First Generation: A sensor is basically attached to some fabric.
2. Second Generation: Sensor is embedded in some fabric.
3. Third Generation: The garment is a sensor on its own. These are mainly possible because of the use of conductive textiles materials [1].

In this work 3^{rd} Generation smart textile piezo-resistive pressure sensors will be considered and their behaviour under different conditions will be the focus of this work.

1.1 Problem Statement

As E-Textiles is a young field and forecasted to be researched thoroughly makes it very useful and interesting area to be worked on. By looking at the work of different textile and design researchers are developing different sensors for different applications, details of which is shared in 2^{nd} Chapter, it has been noticed that most of the materials are custom made for the specific application or the ones which are available in the market only show results as a colour coding with respect to the pressure applied, yet it doesn't show how much repeatable or linear the change is.

Whereas, Tallinn University of Technology is also working on wearables for monitoring human body movement, and they plan to move towards stretchable materials rather than conventional MEMS, as fabric sensors are least harmful to human body unlike mechanical sensors.

In summary therefore, by this work I achieve the following:

1. Investigate the behaviour of sample sensors with respect to the pressure/force applied on it.

2. Analyse the behaviour of sample piezo-resistive pressure sensors in impedance domain to see how much linear, repeatable and accurate the change is.

1.2 Hypothesis

To assess the parameters mentioned above a hypothesis is constructed that investigating the piezo-resistive pressure sensor in multi frequency impedance domain may or may not give me additional information to assess the materials accuracy, repeatability and sensitivity. Generally, fabric sensors are being assessed in DC domain, therefore, AC impedance domain can provide useful information.

1.3 Thesis Structure

This thesis work is presented in five different sections.

In section 1, introductory information related to the objectives of the thesis work is presented.

Section 2 covers relevant background details related to the Smart textiles, smart sensors and the materials used to develop them. Specific products and work done related to the topic is considered. Information regarding how to find equivalent electronic circuit is also mentioned. Finally, the existing products will be reviewed followed by a justification of the need and relevance of this work.

In section 3, the overview of the methodology used is discussed, with insights to how it is implemented in this work. It also provides the information about the sample materials used in this work.

Section 4 provides a detailed analysis of the experiments done on the sample sensors to analyse its performance.

Section 5 concludes the work and gives insight into possible future work related to the implementation and improvement of the sensor.

2 Background of the Work and Literature Overview

Relevant background information related to the work will be presented here. Firstly, a brief description of E- textiles is provided, which is followed by conductive materials and textile sensors. And then the similar works is reviewed along with the equivalent circuits for these materials.

2.1 History and Overview of E-Textiles

Word textile is expressed as a flexible material which is made up mostly of natural or artificial fibres, such as yarn or threads. When electronics elements are integrated with these fibres, offering flexibility, stretch ability and characteristic length scale which generally cannot be accomplished by other manufacturing methods, e-textiles or smart textiles are produced. On terms of how they are manufactured, textiles can be divided into three major categories.

- Woven Textiles

  Woven fabrics are produced by interlocking weft and warp yarns perpendicular to each other. The basic structure of woven fabric is shown in Figure 1 [2].

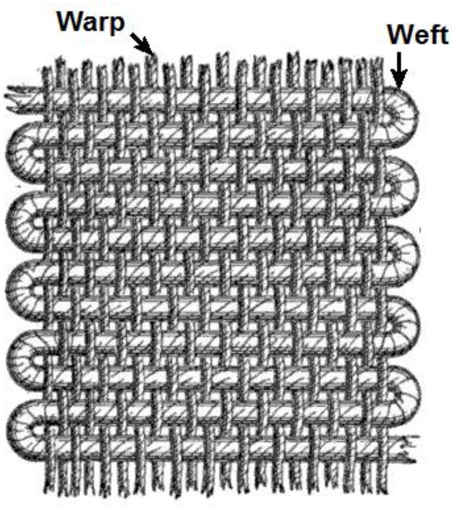


Figure 1. Structure of Woven Fabric.

- Knitted Textiles

  Knitted fabric is made by forming yarns into loops, which is released just after a succeeded loop has been shaped and interlinked with it to achieve a secure loop like structure.

  There are two different types of knitting, warp and weft knitting. In warp knitting the yarn moves in a vertical direction through the fabric, where as in weft type knitting, it moves in horizontal direction across the fabric, which is also shown in Figure 2 [3].

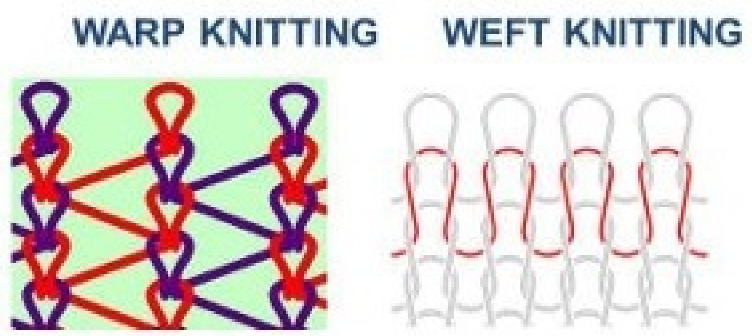


Figure 2. Different types of Knitting.

- Coated Textiles

  Coating is done to provide some extra properties to the fabric, which is mostly uncommon by normal fabrics. It's achieved by applying polymeric layer to the fabric in the form of liquid, which increases the functionality of the fabrics like; waterproofness, ultraviolet resistant etc. [4].

The idea of combining electronics into textile has always been around. It was a common practice to wrap queen's gown with gold threads. First of the smart textile application was made in 1850 to provide electrotherapy as various corsets [5]. Later its use was also noticed during late 18th century [6] when music industry people were using bulbs and in nineteenth century when electrically heated glove was introduced [7],[8].

The inventions in this area kept continuing till 1990's when researchers from Massachusetts Institute of Technology (MIT) started working in this area and developed touch sensitive smart kerchief [9]. In 1993 a whole computer was attached to the garment [10], which devolved the concept of E-textiles, to the integration of ready-made electronics into garments. During this time the two major areas of smart textiles research were medical [11], [12], and military areas.

The new millennium noticed quite a surge in related works, and shift towards electronics textile products rather than electrical textile products. Key industries like Philips, Infineon, Deutsche Telekom started to file patents in this area [9]. In 2003 Georgia tech presented their motherboard shirt, to monitor human vitals during combat [13]. During 2005 Adidas [14] and NuMetrex [15] presented wearable's for monitoring body behaviours. During 2008, fashioning technology was published [16]. Along with numerous developments by industries, European commission funded a project worth (14.6 million) to explore smart wearable's [9]. Stretchable conductive Dupont ink was presented in 2014 [17], whereas, Bebop sensors launched textiles using the same ink [18].

During last decade wearable market has been matured, as well as, smart textile market. European commission has launched WEARsustain project (3 million euros) under the horizon 2020, to increase interaction between technologists and people from textile industry [19]. E-textiles, is a constantly growing sector predicted with 40% growth annually [9], and is expected to surpass 10.2 million units annually by 2020 [20].

2.2 Fabrication Techniques and Materials

These days the materials in our surroundings are being used smartly and efficiently. These materials are capable to interact, communicate and to sense. Shrinking of electronic component have able us to achieve more functionality by covering small area on the application.

When it comes to E-textile, we are mostly using metals or materials with electric properties like silver, steel and conductive polymers. The integration of these conductive materials can be achieved by following methods:

1. Filling fibres with conductive material i.e. conductive yarn
2. Coating fibres with conductive polymers or metal
3. Combining fibres with metallic or plastic conductive threads [21].

A graph in Figure 3 shows the comparison of how much e-textiles are being manufactured in which way [22].

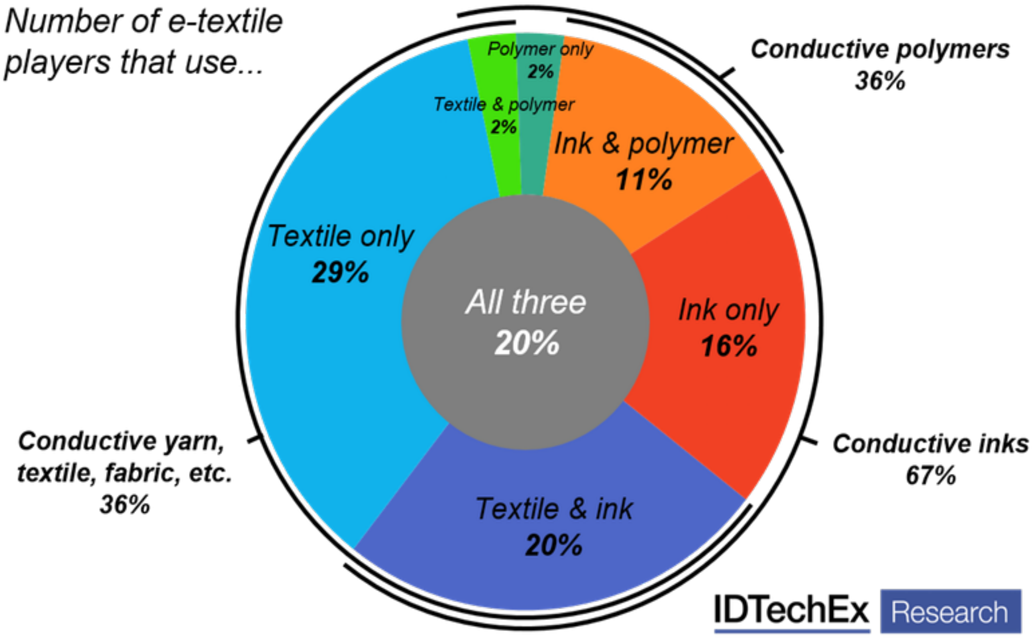


Figure 3. Percentage of E-Textile materials used in market [22].

We notice from this pie graph that out of three general fabrication techniques, conductive inks are used mostly.

2.2.1 Metallic Fibres

Metal threads are composed of very thin metal fibres called filaments. A patent from 1997 shows that this concept has been around since years [23]. But generally, they are produced made by cutting metal shit into very thin thread like strips. They are achieved by wrapping yarn with metal, by filling textile fibres with metal and by either combining metallic strips with base textile material, as shown in Figure 4. Red colour indicates the metal in the picture.

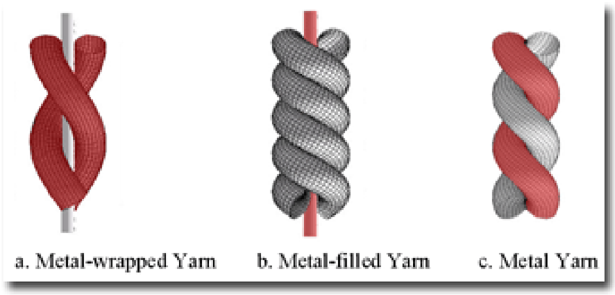


Figure 4. Different ways of producing metallic yarns [24].

The conventional method to produce metallic strips undergoes through four steps; coarse, medium, fine and carding train, shown in Figure 5.

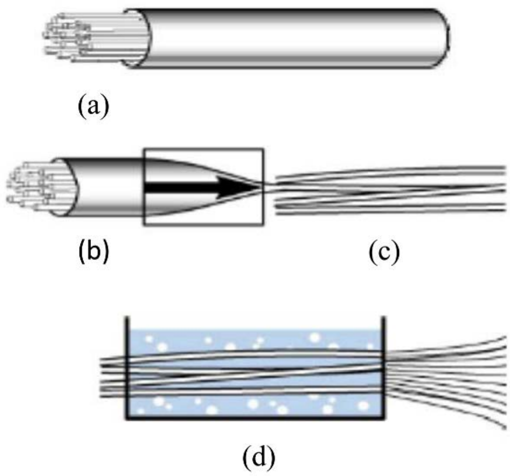


Figure 5. Conventional way to produce metallic fibres [25].

As shown in Figure 5, first the metallic wire is combined to make a tube, followed be reduction in its diameter. After it tubes are bundled and in the end different single fibres are realized [25]. Some real-life examples of metal yarns are shown in Figure 6.

Figure 6. Metal yarns [26].

These fibres can be used in different application like electrodes for ECG, for motion sensing, but as metal tends to be heavier than other textile materials and have brittle characteristics which might become uncomfortable for the wearer.

2.2.2 Conductive Inks

The other way to produce smart textiles are conductive inks. Carbon, copper, silver and other metals are mostly mixed with conventional ink to make it conductive. These conductive inks can be printed on many materials to make electrical components and circuits for using them in different applications. Mainly printing has been done by using inkjet printers and has seen a lot of increase in its use during early 20th century minimizing the use of conventional Nano-particle printing process [27].

With printing circuits on the textile, had the drawback that conventional ink can't be stretched. But since last few years printable elastic ink has been made to overcome that problem. One of the example to use it measure arm EMG signals [28] as shown in Figure 7.

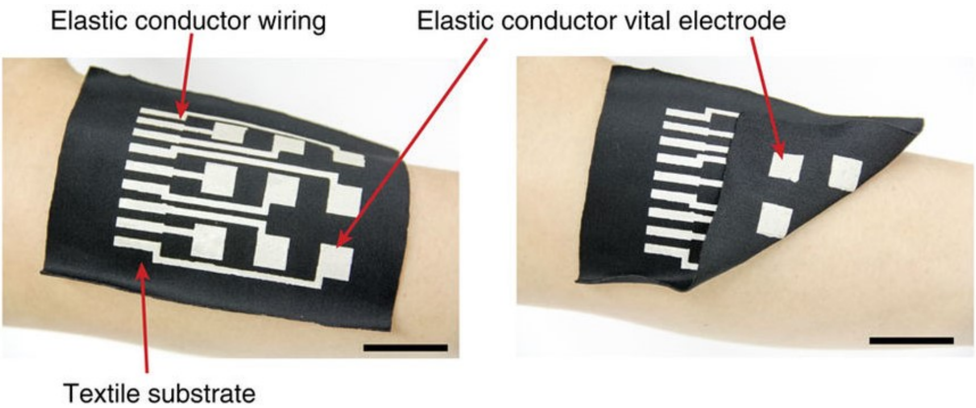


Figure 7. EMG measurement using elastic conductive ink.

2.2.3 Intrinsically Conductive Polymers

The intrinsic nature of these polymers is because of their conjugated bonding chain structure. This structure also gave the ICP's the ability to sense and actuate [29]. These days a huge variety of conductive polymers are available. Structure of different common types are shown in Figure 8.

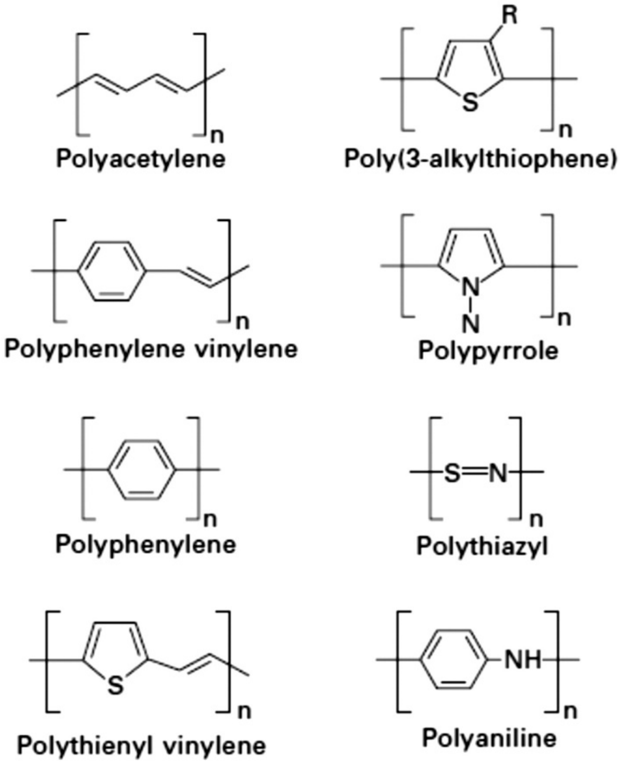


Figure 8. Different types of conductive polymers [30].

Polypyrrole has the highest mechanical strength yet making it more valuable to be used, as it doesn’t change its shape. The only disadvantage of using this technique is difference in its response time and resistance [29].

2.3 Fabric Sensors

Fabric sensing methods have been discovered for use with different applications in mind. Typical examples of these sensors are pressure\force sensors and stretch sensors. As my topic is related to force sensors, therefore I will only discuss about them.

2.3.1 Force/Pressure Sensors

Fabric which undergoes some electrical changes when some pressure or force is applied are knows as force/pressure sensors.

Generally, there are basically five methods of sensing the force. These includes:

1. Gravity based: In this method unknown force is balanced against the gravitational force which is acting on a known mass. In this case the applied force will be known as gravitational force. i.e.

$$F = mg \quad (1)$$

Where

m = known mass

g = gravitational force.

The force acting on a body due to gravity is also known as weight [31].

2. Acceleration based: Force can also be measured by measuring known acceleration with a given mass i.e. [32].

$$F = ma \quad (2)$$

Where

a = acceleration of the body

3. Strain based: Change in shape of a body from its original shape, when force is applied is called strain [33].

4. Flux based: When a current carrying coil interacts with a magnet it generates the magnetic field, is than balanced against the force, this force is also known as strength of the magnetic field.

Based on their manufacturing and sensing techniques, fabric sensors are majorly of three types.

2.3.2 Capacitive Pressure Sensors

Capacitive pressure sensors are mainly used for sensing the force applied on the sensor. With time a lot of research has been done in developing different types of them, but all of them have some dielectric element which separates the two electrodes. According to the principle of capacitance, capacitance can be changed by changing the area or distance between the electrode plates, or by changing dielectric. The capacitance of flat capacitor can be found by the given equation [34];

$$C = \frac{\varepsilon_r \varepsilon_0 A}{d} \quad (3)$$

Where;

A= Area of the two plates

d= Distance between two plates

ε_r= Permittivity of the dielectric

ε_0= Permittivity of the free space

ETH Zurich has developed a capacitive sensor, with an array of textile capacitors covered by shielding layers on the both sides of the sensor, to be used for pressure sensing in textiles [35]. Figure 9 shows the structure of the sensor built by ETH.

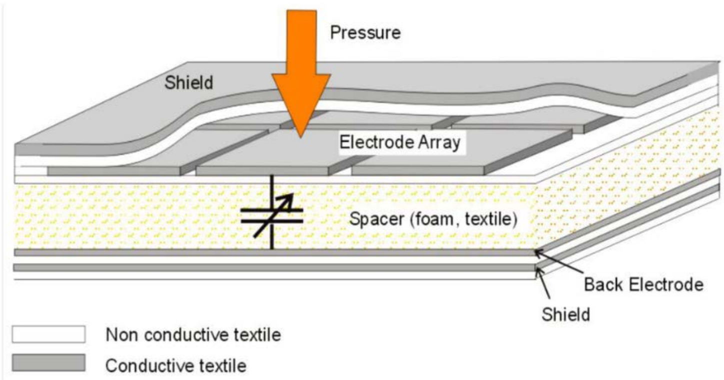


Figure 9. Structure of capacitive pressure sensor from ETH Zurich [35].

Table 1 taken from IOPscience shows the details of different type of capacitive fabric pressure sensors and their properties [36] where c stands for conductive element and d for dielectric.

Table 1. Different types of Fabric capacitive sensors.

Type	**Elements**	**Measured Variable**	**Sensitivity**	**Pressure Range**	**Size**
e-broidery	c-Conductive thread, d-cloth	Electrical contact	Switching voltage threshold of CMOS logic buffer	Sensing by contacts	mm-cm
Coated fabric	c-silver-coated woven, conductive thread, d-textile spacer	Thickness compression, t = 6 mm	0.192 pF (N^{-1} cm^{-2}) with 20%–30% hysteresis error	0−12 N cm^{-2}	2*2 cm

Type	Elements	Measured Variable	Sensitivity	Pressure Range	Size
Surface touch	c—PEDOT, d—Nylon	Capacitance coupling between fingers and c-film	0.02 pF mm^{-1}, w.r.t. object width	0–2 pF	Core: 470 μm diameter Pitch = 5 cm
Laminated electrodes	c—thin film deposited metals, d—parylene substrate–silicone rubber	Capacitance change at intersecting points	0.01ΔC mN^{-1}	0–50 mN	Diameter = 250 μm thickness = 40 μm
3D textile capacitor	c—conductive fabric, d—3D textile	Thickness compression = 5.5 mm	2 pF N^{-1} cm^{-2} mean, 1.25 pF N^{-1} cm^{-2} for (0.1−0.4 N cm−2)	0−0.75 N cm^{-2}	Sensor area = 3 × 3 cm2
Croslite capacitor	c—silver-coated textile, d—PCCR (proprietary closed cell resin)	Thickness compression t = 5 mm	0.05 pF N^{-1} cm^{-2}	0−30 N cm^{-2}	10 mm × 10 mm

2.3.3 Resistive Pressure Sensors

The other conventional way of making textile fabric sensors was to use resistance network to sense change in resistance whenever the pressure is applied. According to one paper, resistance network for knitted textiles depicts that change in electrical length related resistance for the conductive yarn can be detected by change in cross sectional area of the conductive yarn [37].

In 2010, Lili and Wai Man provided a complex resistor network shown in Figure 10.

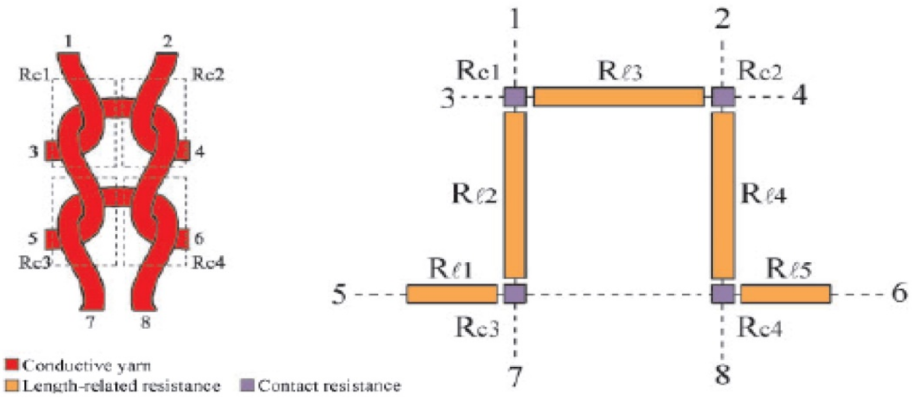


Figure 10. A complex resistive network for sensing pressure.

Table 2 taken from the IOPscience, provides the specifications of different resistive textile pressure sensors [36].

Table 2. Different types of fabric sensors with resistive behaviour.

Type	**Elements**	**Sensitivity**	**Pressure Range**	**Size**	**Characteristic**
Switch tactile sensor	Plated fabric Cu, Ni	Threshold at 500 g mm^{-2}	70−500 g mm^{-2}	Sensing cell: 2.3 mm × 4.35 mm	Activated number of sensing cells gives the output
Tooth-structured	Conduct. fabric	>2.98 × 10^{-3} kPa^{-1}	0–2000 kPa	10 × 16 × 4.8 mm^3	When force is applied, strain is produced by teeth
Polyurethane foam	PPy	0.0007 mS N^{-1}	1000−7000 N m^{-2}	1.7 cm × 1.7 cm ×1.3 c m	Conductance increases as compression force increases
Conductive rubber based	Carbon polymer with beryllium Au-coated copper wire	0.25 kΩ MPa^{-1}	0–0.2 MPa	3 mm × 3 mm	Applied load produces change in the resistance
QTC—Ni based	Pressure sensitive composite	~106 Ω/1% compression	25% compression	Diameter = 5.5 mm, thickness = 2 mm	By switching mechanism output is obtained

2.3.4 Piezo-resistive Pressure Sensors

A lot of the pressure sensors made in start were capacitive, but had some drawbacks like high hysteresis. Because of capacitive sensing element they consumed high electricity, were thick, and inflexible [38].

The piezo-resistive effect can be defined by change in resistance of the material, when an external force is applied to it [39]. Piezo-resistive fabric sensors are made by coating them with polymers. Polypyrrole (PPY) polymers are commonly used for coating the fabrics. Coating is done by polymerization of PPY onto textile fabrics. First sample is dipped in pyrrole solution and then subjected to polymerization bath with oxidant solution, and after cooling down the polymer is added onto the textile via polymerization bath.

The coated material sensors are under influence of several factors while it provides output resistance. For ppy- coated lycra fibres two strain models have been presented. First model is presented by Wang J, who presented model of resistance as a function of strain for ppy coated lycra fibres with micro crack behaviour [40], which is:

$$\frac{R}{R_0} = \left[\frac{L_0(1+\varepsilon)-N(\varepsilon)W(\varepsilon)}{\pi d_0(1-v\varepsilon)} + \frac{N(\varepsilon)W(\varepsilon)}{\pi d_0(1-v\varepsilon)-2L`}\right]\frac{\pi d_0}{L_0(1-v\varepsilon)} \qquad (4)$$

Where;

L_0 = Unstrained fibre length,

v = Poisson's ratio

L` = Average length of micro cracks

d_0 = Initial diameter of the fibre

The other model was presented by Xue P, for the ppy coated lycra fibres, which includes the effect of rate of strain, humidity and temperature, [41] as shown under:

$$\frac{R}{R_0} = \frac{\rho}{\rho_0}(1+\varepsilon)(1+2v\varepsilon+3v^2\varepsilon^2)f_1(\alpha,\epsilon^{\cdot}) \times f_2(\beta,T)f_3(\gamma,RH) \qquad (5)$$

Where;

f1 = Function of strain rate

f2 = Function of temperature

f3 = Function of relative humidity

α, β, γ = experimental parameters

The test sample Eeontex-NW-SLPA-2K, is also made by coating PPY onto the non-woven fabric.

2.4 Similar Works

The research in the field of smart textiles and its sensors is in high demand, but as mentioned earlier most of the sensors made are custom made, and are for specific application, except very few of them which are generic. The work of exact same scope hasn't been done in same manner, but Eeonyx products like test sample Eeontex-NW-SLPA-2K has been used for different applications, which are discussed in this section.

2.4.1 Piezo-Resistive Stretch Sensor for Home Monitoring of Arthritis

Researchers from National Centre for Sensor Research Dublin, Centre Microelectronique de Provence France and University of Ulster Derry, used the PPY coated piezo-resistive sensor from Eeonyx to monitor the movement of hand joints for arthritis patients and capturing the motion of human hand [42].

They used stretchy fabric, where stretch was performed by hydraulic fatigue rig from ESH Company and output resistance was measured by using Arduino microcontroller. After performing several tests it was noticed that the resistance of sample is directly proportional to the change in length of the sensor [42].While experimenting one abnormality about drift in maximum resistance of 13kΩ was also noted and the final product was embedded into textile glove which can be easily worn by patients, also shown in the Figure 11.

Figure 11. Prototype of Glove made by Research Centre Dublin.

2.4.2 Flexible Fabric Tactile Sensor

Researchers from Centre of Excellence Cognitive Interaction Technology from Bielfield University provided a stretchable tactile sensor based on Eeonyx Piezo-resistive pressure sensor. The sensor developed was capable of sensing pressures from the range of 1kPa to 500kPa [43].

The sensor developed comprised of 4 layers of plain and conductive fabrics to ensure good elasticity and to improve repeatability of the sensor. The main sensing material used a piezo-resistive stretchable knitted fabric made by Eeonyx. The construction of the sensor and schematic is shown in Figure 12, with the help of this method they were able to achieve high good repeatability.

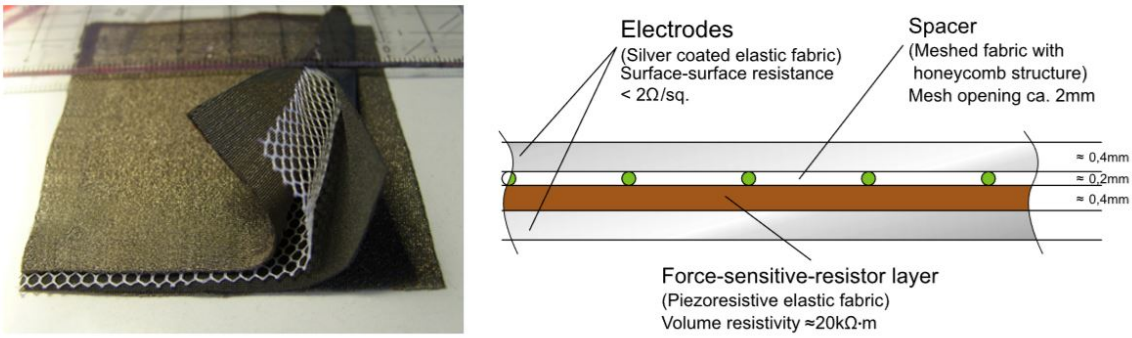


Figure 12. Tactile Fabric Sensor with four layers (on left side is physical appearance, on right side demonstration of a structure).

2.5 Impedance Spectroscopy

Impedance spectroscopy is while assessing the system under AC domain. They are basically of two types Electrochemical Impedance spectroscopy and dielectric impedance spectroscopy [44].

During Impedance spectroscopy measurements, a small AC voltage and Angular frequency is applied to the system, and respective response current is measured at the same frequencies and impedance is calculated by Ohms law as:

$$Z(\omega,t) = \frac{V(\omega,t)}{I(\omega,t)} \quad (6)$$

Where;

$Z(\omega,t)$ = Total Impedance

$I(\omega,t)$ = Response Current

$V(\omega, t)$ = Applied voltage

The common way to analyse EIS data is by fitting into an equivalent circuit model. The common circuit elements used are resistor, inductor or capacitors. When it comes to EIS capacitors doesn't have an ideal behaviour, but they tend to act like constant phase element (CPE). CPE is a phenomenological term which was first used by Brug in 1984. According to Brug, CPE is an empirical impedance, whose phase angle is independent of frequency [45]. The impedance of capacitor as CPE can be expressed as [46]:

$$Z_{CPE} = \frac{1}{(j\omega)^{\alpha} Y_0} \tag{7}$$

Where

Y_0 = C = Capacitance

α = an exponent equalling 1 for a capacitor

2.6 Summary

In chapter 2, key aspects regarding e-textiles were considered. Brief history and manufacturing techniques of e-textiles and different types of e-textiles were presented few related works which were done on the sample works were also discussed, which current works also aims to improve.

In summary, the increasing use of e-textiles was covered along with common different materials used in making them. As a growing field, e-textiles and its sensors has wide applications in different fields. A brief overview regarding EIS was also mentioned, the technique aimed to be used in this work, but as the fabric sensors are quite complex, it's not quite easy to find equivalent circuit, but by using z-flat tool analysis of bi-0-logic, it's assumed that sample material is combination of multiple R parallel with C circuit.

In the chapter that follows, provides information about sample materials and the equipment used for the experiments.

3 Methodology

The nature of this thesis is scientific research, more specifically the method used is experimental research method. The experimental research method works usually by manipulating one variable while assuming other factors constant [47].

Generally, the experimental research methods are used in three ways [48]:

- Pre-experimental Research: In this researcher performs basic steps of experiments like testing and analysing results, but they don't use control groups. This research becomes the base for the true experimental research.

- True Experimental Research: This is the actual way to do proper experiments on the subjects, where different sample groups or sample data is achieved and one variable is tested at a time, depending upon which variable is under examination.

- Quasi Experimental Research: This method is very commonly used when it comes to social experiments. It's quite like true method with only difference of lacking proper control data group.

The basic steps which are used for performing experimental research method are described in Figure 13 which also explains how the process works [49].

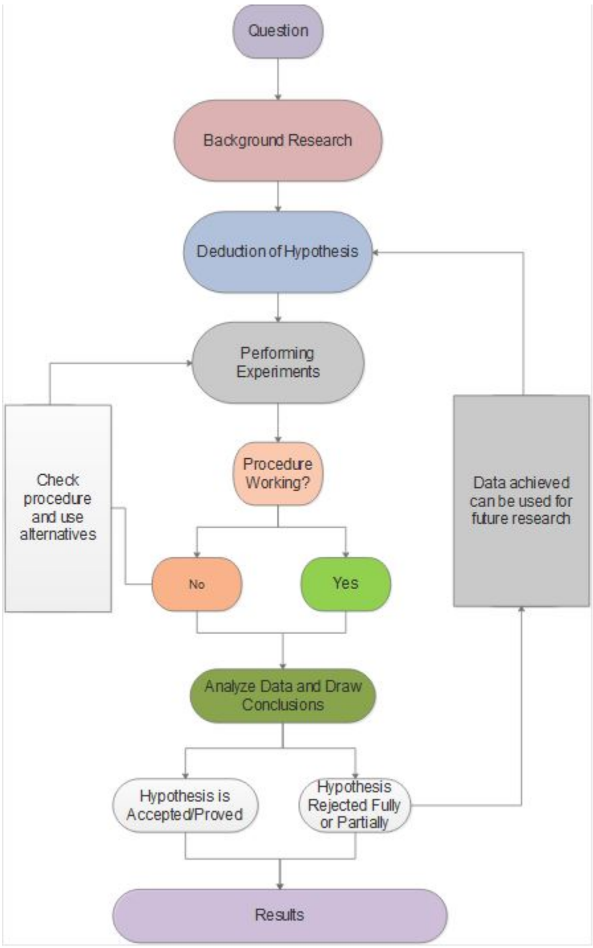


Figure 13. Overview of steps used for experimental research method.

This thesis work follows the steps shown in the Figure 13. The brief overview about some stages is given in the Table 3.

Table 3. Overview of basic steps took for this work.

Steps	**Description**
Question	The available fabric pressure sensors/ products available in market have only visual output, which doesn't show how much accurate or repeatable is the sensor is?
Background Research	After reviewing different products, it was realized that majority of products available lacks the important specifications about itself. Apart from them electrical impedance spectroscopy is popular technique to analyse the behaviour of the sensors, as the piezo-resistive sensors tend to have imaginary or capacitive element in it, can provide us with extra useful information.
Hypothesis	By performing AC impedance analysis on these sensors can provide us with extra information to determine repeatability and accuracy of the sensor, and it might also help us to minimize errors, hysteresis and drift problem.

Steps	Description
Experiments	To analyse the behaviour of sample sensors, different tests were done to see following performances; • How sensors respond to different frequencies, and where it is more sensitive with low error as possible. • Checking how much time does a weight or force takes to be applied, which is also knows as transient time for the weight to be properly applied. • Inspecting the relation between applied weight and impedance. • To see the aging behaviour, how the sensor responds if the force is applied on it for time longer than usual, and how fast can it settle back to original value.
Conclusions	The constructed hypothesis has been partially rejected, as complex part of impedance didn't provide with useful information, whereas, it was observed that on higher frequency real impedance works better than DC domain, and helps in minimizing the drift problem common in fabric sensors.

3.1 Hardware Used

The hardware devices I used to obtain the results for my thesis work are:

- Agilent 4294A Precision Impedance Analyzer

  4294A precision impedance analyzer, used for effective impedance measurement and components analysis. It has a frequency range of 40Hz to 110Mhz with an accuracy of +/- 0.08% [50].

- Agilent 16047D Test Fixture

  This test fixture is compatible with 4294A, and is designed to use for impedance measurement and with a frequency range up to 40MHz [51].

- HF2IS Impedance Spectroscope by Zurich Instruments for Impedance Analysis

  To keep the results as much as accurate and precise as possible, I used HF2IS. It consists of two differential measurement units and four dual phase modulators, and with 128-bit DSP engine to match the precision. It can provide multifrequency measurements from, 1 Hz to 50 MHz, with high accuracy and is being used in leading research laboratories [52].

- HF2TA Current Amplifier by Zurich Instruments

  HF2TA is attached to the input channels of HF2IS, which converts 2 input currents into output voltage over the wide range of 50MHz. It is used for applications where voltage is used for excitation, and ensures steadiness and smooth operation [53].

- Personal Laptop by Dell

  HF2IS Impedance spectroscope sends the data to the laptop via USB cable. Dell Inspiron Core i7 was used to run the dedicated software to see the behaviour of sample sensors.

3.2 Software Used

The software used to analyse the results are:

- ziControl

  ziControl is a dedicated graphical user interface for HF2IS Impedance Spectroscope. It provides interactive visualization tools, data storage, and collaborating HMI. It can communicate with local instruments via USB or remote instruments via TCP/IP [54].

- MS Excel

  MS Excel is used for taking, analysing and plotting the data from ziControl.

3.3 Sample Materials

Two types of sample materials were used which underwent a series of experiments. The sample materials were chosen based on availability and there’s existence in the market.

3.3.1 Eeontex NW170-SLPA-2K

Eeontex NW170 is a non-woven conductive pressure sensing fabric and works on piezo-resistive principle [55]. These conductive materials made by Eeonyx [56] are called Eeontex. The sample is shown in Figure 14, and has a length of 12cm, and width of 8cm.

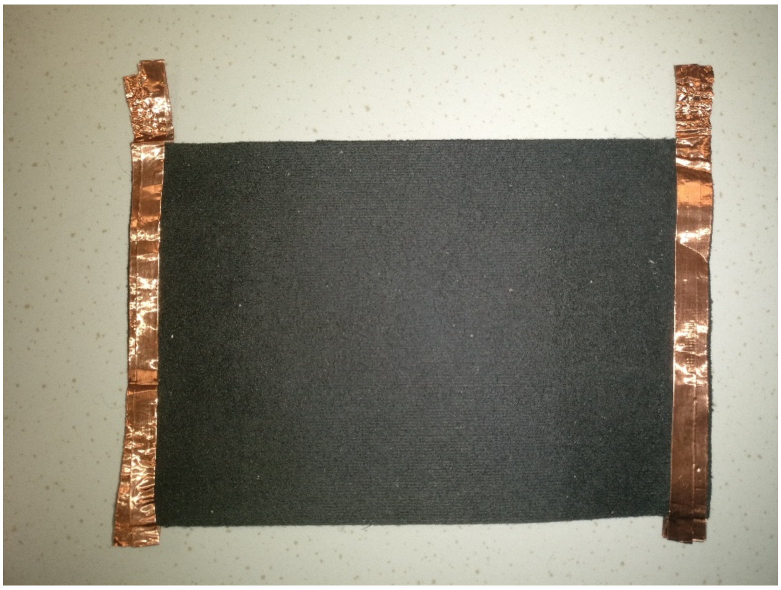


Figure 14. Eeontex NW170-SLPA-2K.

Eeontex NW170 is made by coating textile fibres, like yarn with uniformly doped polypyrrole (PPY), which is an inherently conductive polymer. The coating is done via aqueous process which makes the fabric conductive causing the least effect on strength and flexibility of the fabric [57].

It’s used for measuring bend, pressure, angle stretch and torsion. The specifications of this sample is shown in Figure 15 [55].

Part number:	**EeonTex™** NW170-SLPA-2k
Surface resistivity:	2K ohms/ square
Dynamic range:	5g-100kg
Data acquisition rate:	500 cycles per second
Density:	170 g/m²
Thickness:	0.80 mm

Figure 15. Specifications of Eeontex NW170-SLPA-2K.

These specifications are the only information available on the datasheet which also shows that there is need to do different experiments on this sample so its datasheet can be developed and they can be used for different applications.

In current work, this sample is referred as, Eeontex fabric sample/Eeontex-2K.

3.3.2 Custom Made Sample by Estonian Academy of Arts

The second sample was custom made and provided to me by Estonian Academy of Arts [58]. According to the information provided by EAA, this is a machine knitted material which is made by one conductive steel thread of state and one thread of cotton. These two threads are knitted together by flatbed plain knitting technique. Sample is shown in Figure 16 and has a length of 12 cm, and width of 4.5 cm.

Figure 16. Sample Provided by Estonian Academy of Arts (EAA).

The plain knit is a basic knitting method, which can be done by hand or machine, in which each loop is made through other loops to the right side of the fabric, which gives the material circular look on the front and transverse rows on the back side of the fabric.

In this work this sample has been referred as, sample provided by EAA/EAA sample/EAA fabric sample.

3.4 Summary

In chapter 3, the important aspects regarding methodology were covered and details about the hardware and software to be used for experiments were presented. The details about hardware and software used were presented, whereas, available specs of sample materials were also presented which are intended to be checked in upcoming experiments.

4 Experiments and Results

Several number of experiments were done to assess and analyse the behaviour of the sample sensors, and verify the hypothesis. The whole process can be summarised in following steps:

1. Define the parameters or variables to be assessed. In the case of the work done, the variable under analysis was surface impedance of the sample sensors in the multi-frequency domain.

2. Minimizing the effect of contact point and to find the best possible way to create read out contacts, so the sample can be repeatedly tested under the similar conditions, as well as, for the different conditions.

3. Performing the tests and mapping the results in the form of the graph.

4.1 Experiments done on Eeontex NW-170-SLPA-2K

Several numbers of experiments were performed on test sample to analyse its surface resistivity in multifrequency impedance domain and to assess accuracy, repeatability and linearity of the sensor.

To ensure accuracy and to minimize human error, following practices were followed:

- The repetitive readings were taken within 15-30 minutes.

- The plastic spacer was kept in between applied weights and sample sensor, to avoid capacitance effect and to ensure that the force is equally applied to the whole fabric.

- After each applied weight, it was removed along with the spacer before next measurement to be done and waited till the sensor achieved approximately its initial value, so the effect of hysteresis doesn't hinders the measured data.

- Physical contacts between human body and sample material was avoided while placing the weight on it.

- Every time weight was applied with the plastic spacer, which weighs 125 grams. The values of weights mentioned in this work, are exclusive of spacer weight.

- To minimize error caused by sweep, each value has been taken multiple times and the graphs are plotted by averaging them.

4.2 Calibration/Setting Environment for Experiments

Before starting experiments for accuracy and repeatability, it was necessary to ensure that device is properly calibrated. Agilent 4294A Precision Impedance Analyzer along with its test fixture 16047D was used for initial tests. It was calibrated each time by doing open and short test for the device, whereas, for HF2IS Zurich Impedance Spectroscope a fixed resistor of 100kΩ was used to verify the correct functioning of the device.

To ensure that behaviour of the sample sensor doesn't depend upon the connection different connectors were used to provide output. As shown in Figure 17 aluminium metal plate, aluminium foil and copper tape were used. All the connectors showed similar waveform but by using copper conductive tape on both sides of the sample material gave a stable waveform with minimum noise.

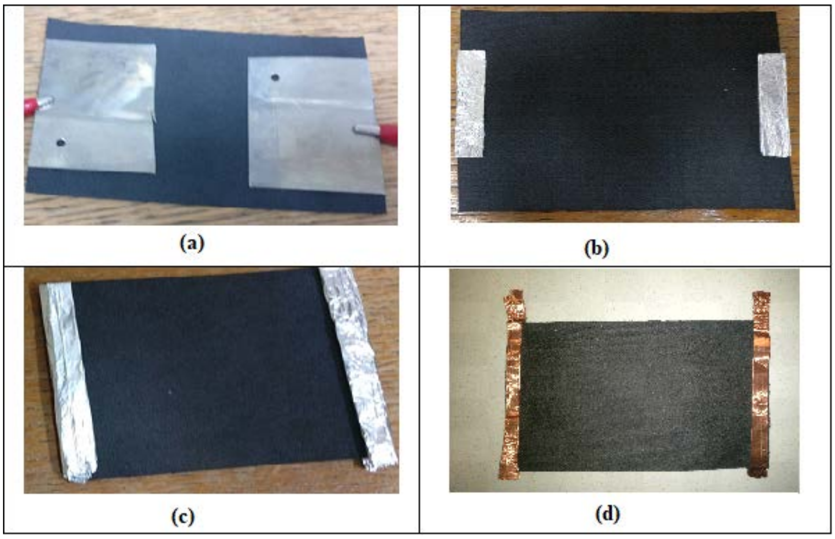


Figure 17. Different materials used to have output from the sensor (a) aluminium plate, (b) thin aluminium foil, (c) thick aluminium foil and (d) double sided copper tape.

The impedance values were chosen to be assessed in Cartesian form as a Real and Imaginary values, because they are easier to be analysed. The sensor was exposed to a frequency range from 10Hz to 1MHz, to see its behaviour in both domains, which are also shown in Figure 18. Sample sensor showed big impedance value on lower frequencies but had lots of noises, whereas, even from 50kHz the graph becomes very linear and the frequency becomes very big, so the range of 100Hz to 100K was selected to be observed.

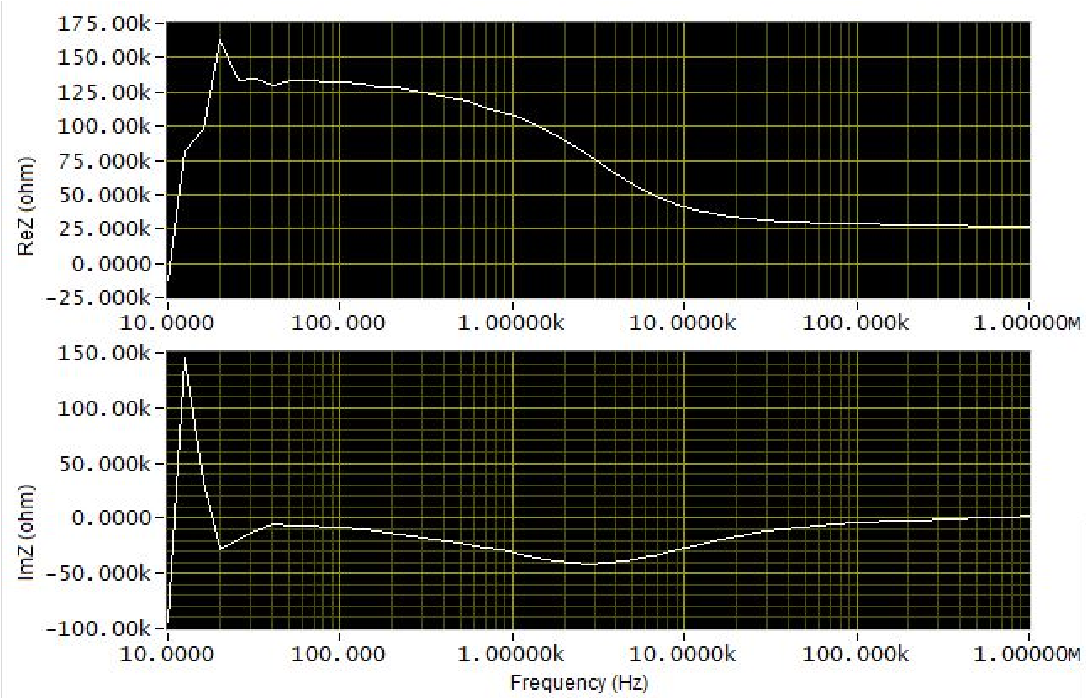


Figure 18. Introduction of multifrequencies on Eeontex-2K (10Hz to 1MHz).

From 100Hz to 100kHz sample produced a clean waveform as shown in Figure 19.

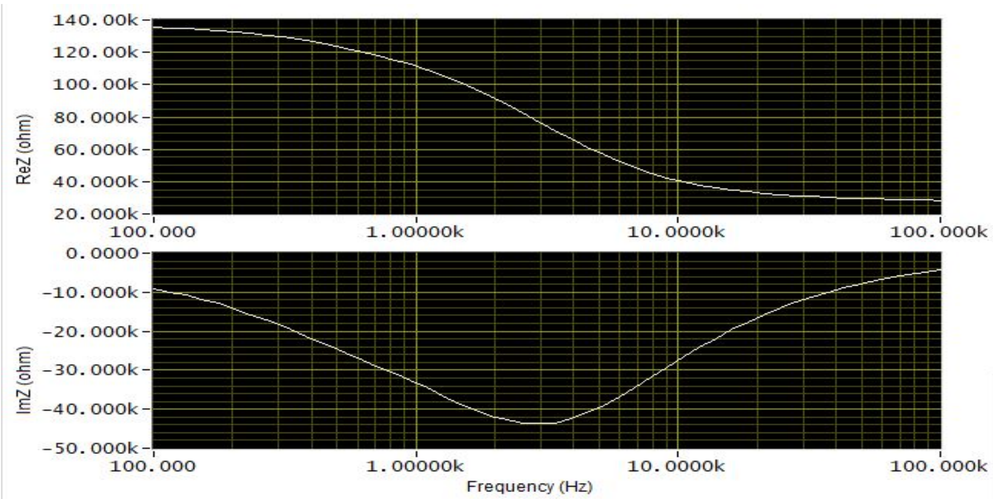


Figure 19. Real and Imaginary Plot of Eeontex-2K (100Hz to 100kHz).

To check which frequency gives more accurate results and is more sensitive to the weight, five different weights were applied over a range of 100Hz to 100kHz. It can be seen clearly from the Figure 20, with the range of 100Hz to 1kHz, that at point when, no weight is applied, impedance is in the middle, whereas, on increasing the weight it behaves irregularly. At frequency 1kHz, weight 3000g has lowest real impedance and 1000g has the highest one, whereas at no load condition, the real impedance is in the middle of them. On 10kHz frequency it's seen the no load condition has highest real impedance and as weight increases the impedance decreases showing the linear behaviour with respect to force applied. Therefore, 10kHz is chosen as the excitation frequency for the experiments.

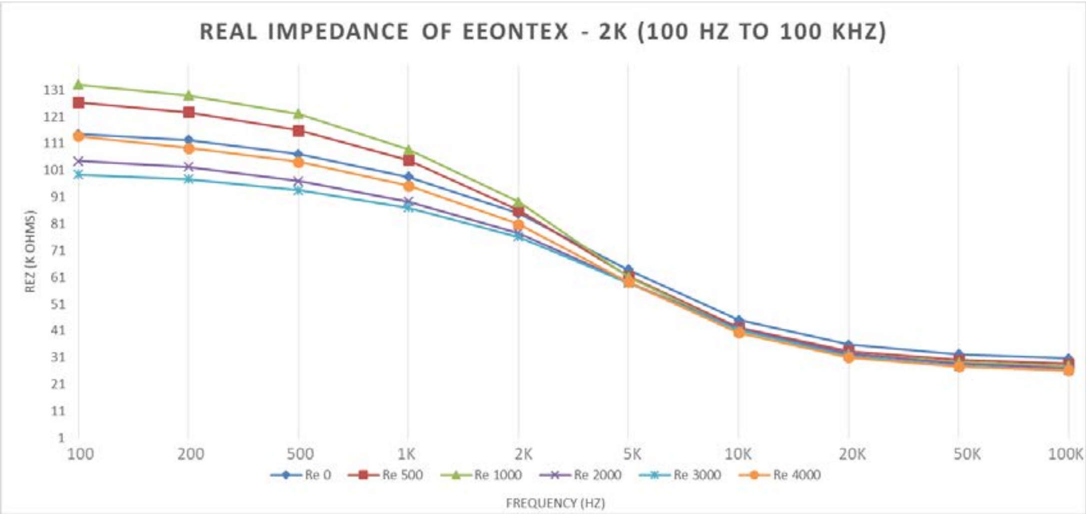


Figure 20. Real Impedance Values with respect to force applied

On the contrary the Imaginary impedance doesn't show the linear behaviour at 10kHz as shown in Figure 21.

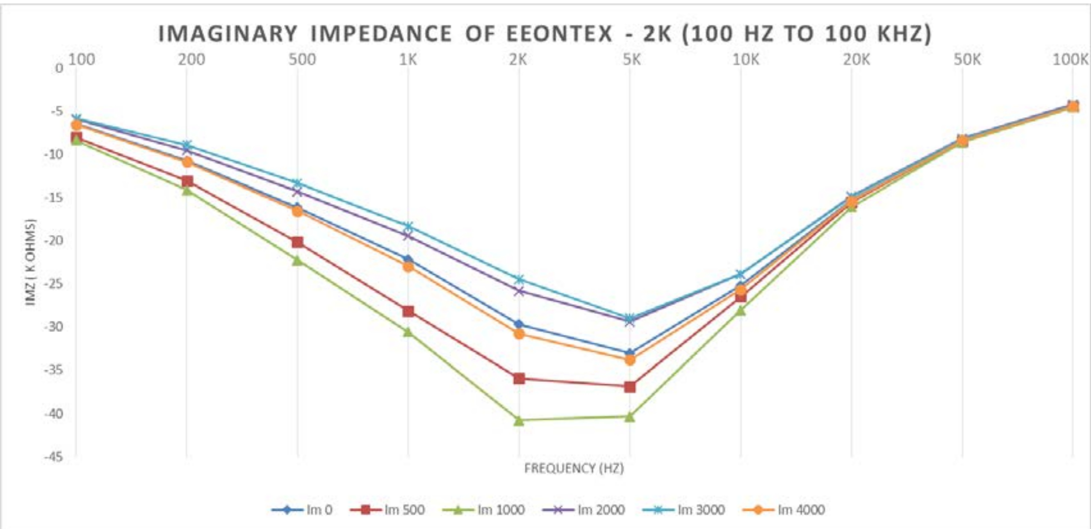


Figure 21. Imaginary Impedance Values with respect to force applied.

4.2.1 Transient Time Analysis

Response time is a very important element of the sensor. For testing these seven different weights were tested for the duration of 60seconds. The results achieve after the tests are shown in the form of graph in Figure 22. Initially no weight was applied for 10seconds, and at time = 10sec, weight was introduced to the sensor. Different weights had different settling time, while small weight seemed to have irregular behaviour and short settling time.

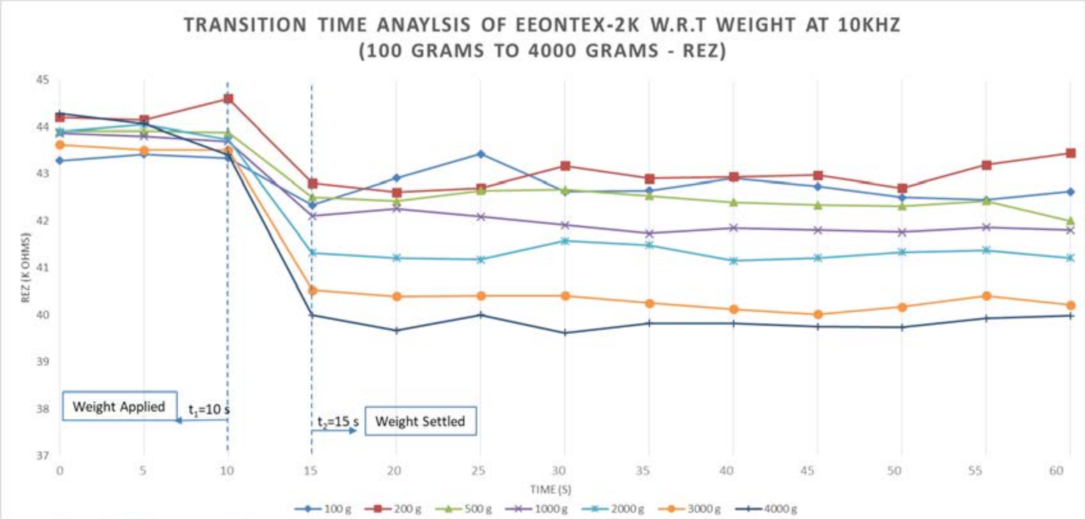


Figure 22. Transition time analysis of Eeontex-2K.

Therefore, the graph presented in Figure 23 only shows only the four weights from 1000g to 4000g. The approximate time taken by a weight to settle down is $t_2 - t_1$ = 5 sec. After the weight is settled graph doesn't becomes linear but keeps jumping approximately within 1% of the settled value.

While seeing the behaviour on spectroscope, it was observed that the sensing time for the sensor to sense some force is applied is approximately one second, but after the weight is applied the real part of the impedance increases and approximately equals to the settled value with an error of +/-2%. And the error decreases as the weight increases, making Eeontex-2K good for heavy weights.

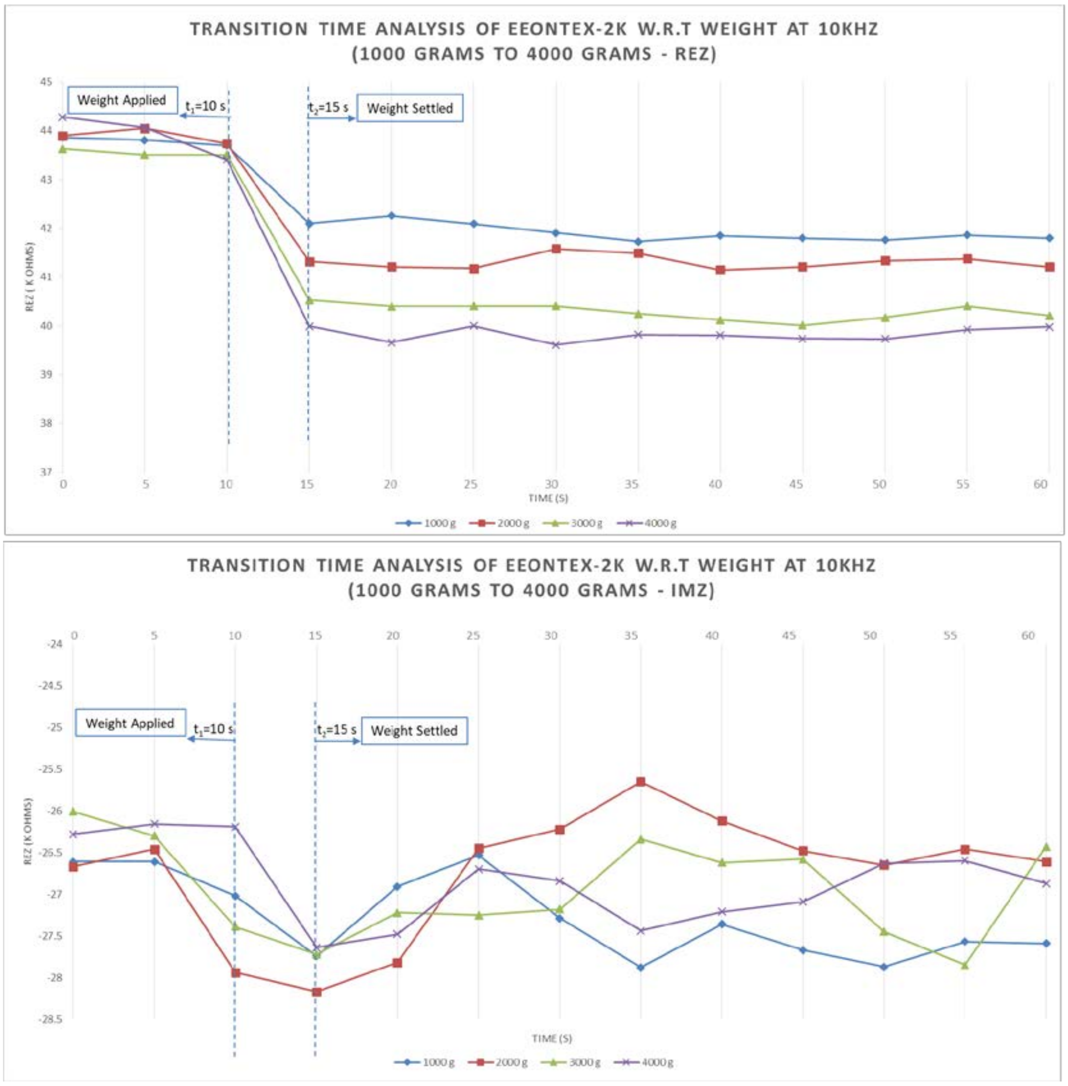


Figure 23.Transition time in Real and Imaginary Domain of Eeontex-2K for heavy weights.

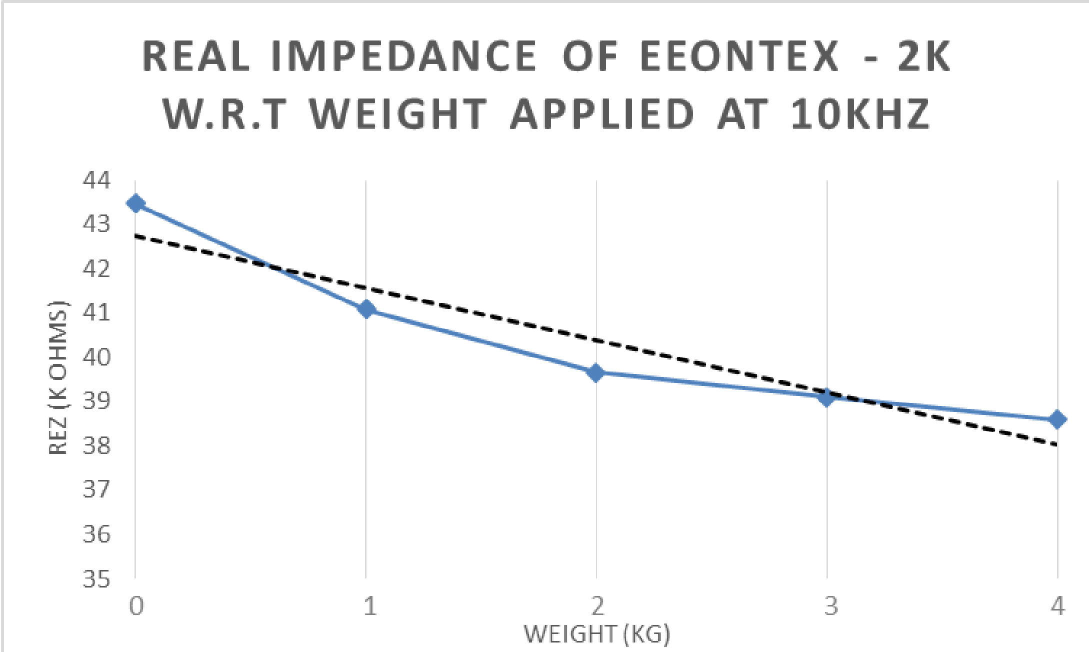
Whereas, the Imaginary graph has a very irregular response, yet doesn't provide valuable information.

Figure 24. Transition time analysis in Real and Imaginary domain of Eeontex-2k for low weights.

The graphs in Figure 24, shows the behaviour of low weights in real and complex domain. Even though the manufacturer claims the sensor can sense from 5g to 100kg, but after performing repetitive tests, it has been concluded that the sensor manufactured is not good for weights less than 1000g and has more than 50% error margin.

4.2.2 Linearity

To assess linear response of Impedance of Eeontex-2K against force, each value was taken around 30 times, and the graphs were plotted against the average of these values (ReZ, ImZ, R, and Parallel C). Graph in Figure 25, shows a linear decreasing trend as the weight applied increases and so do the imaginary impedance.



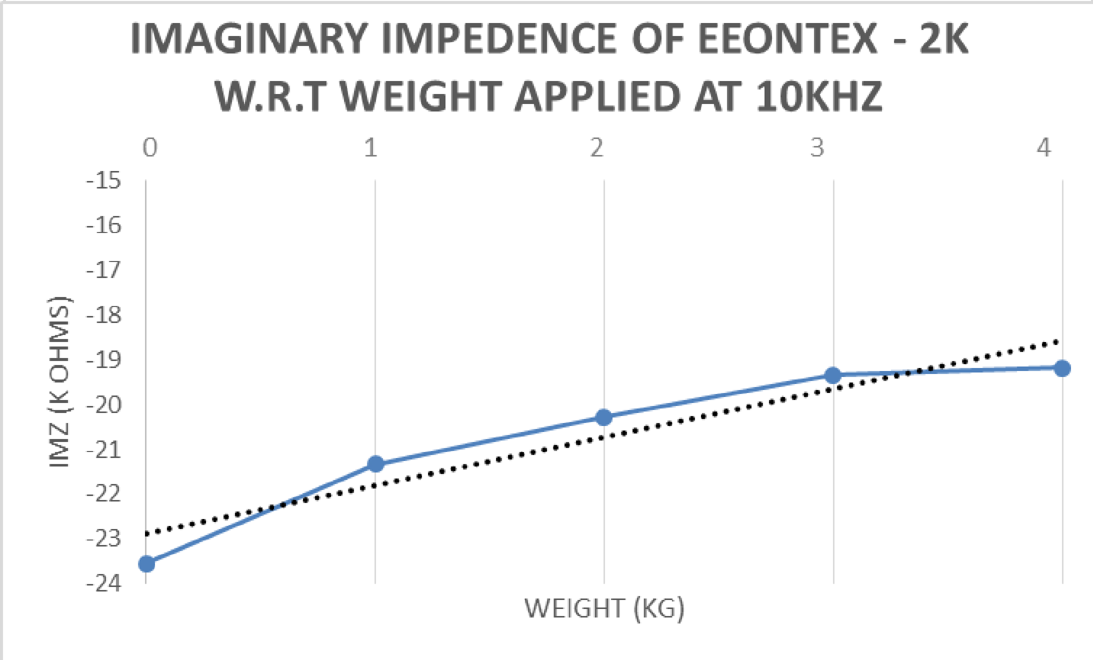
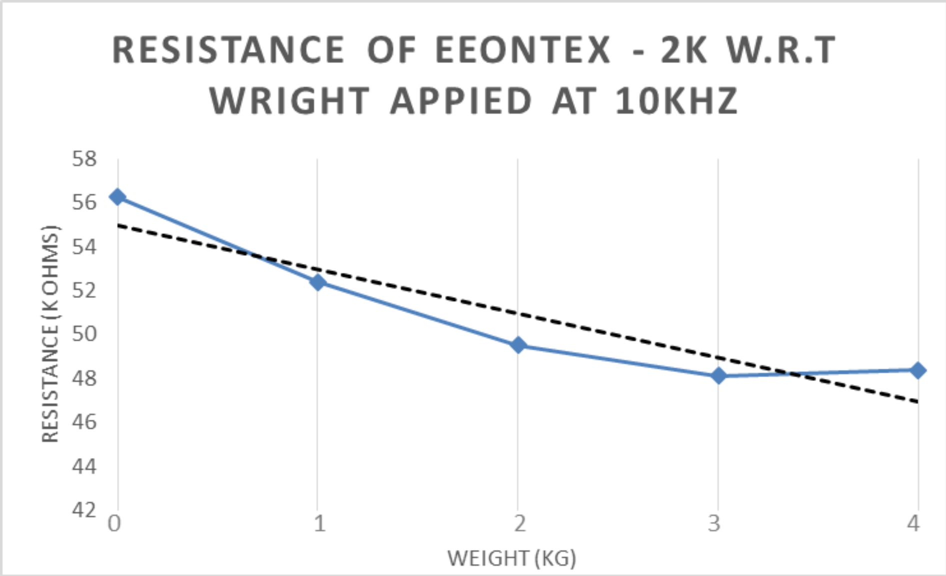


Figure 25. Real and Imaginary Analysis w.r.t force.

By observing closely in Figure 25, it's observed, that the graph is not decreasing with the same ratio as the weight is increasing, it's because as the weight keeps on increasing, the sample keeps moving towards its saturation value, therefore, change in resistance decreases. Whereas, the graph can be divided into two linear regions, from 0-2000g, is one linear region and from 2000g to 4000g is second linear region. Standard deviation was also calculated for each value, which was maximum at no load situation with a value of 0.7kΩ for ReZ and at 4000g it reached up to 0.35kΩ.



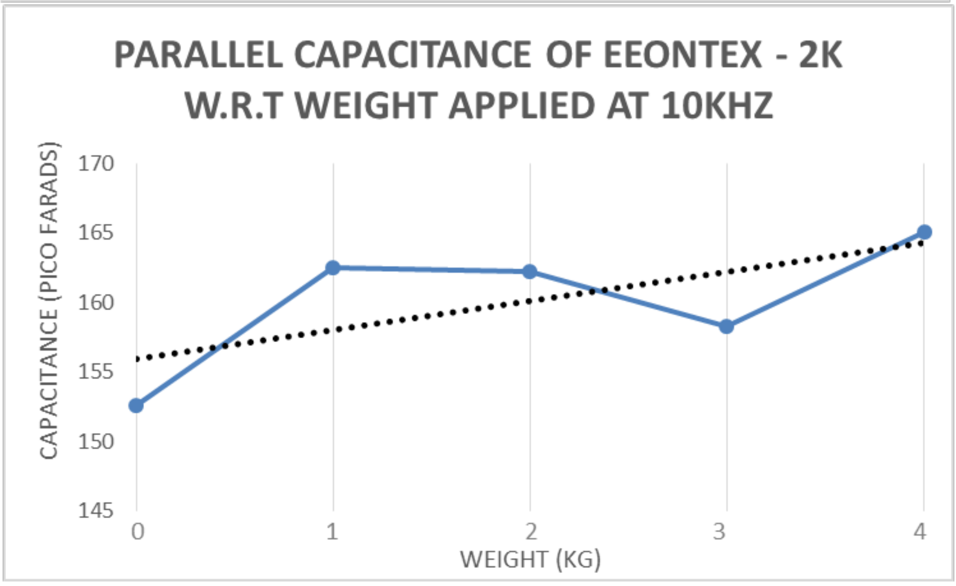


Figure 26. Resistance and Parallel Capacitance w.r.t force applied.

To understand the linearity in more simple way, results were also presented in R Parallel C format, as shown in Fig 26, which R shows similar behaviour like ReZ, whereas, capacitance shows irregularity.

4.2.3 Aging

Here aging is referred to the mechanism, in which force is applied on the sensor for a longer time. Two cases of aging have been assessed. Graphs in Figure 27 shows, that sample is kept under observation for 30minutes. Weight is applied on the sensor after 10seconds of under examination. Settling time for weight is approximately around 5seconds.

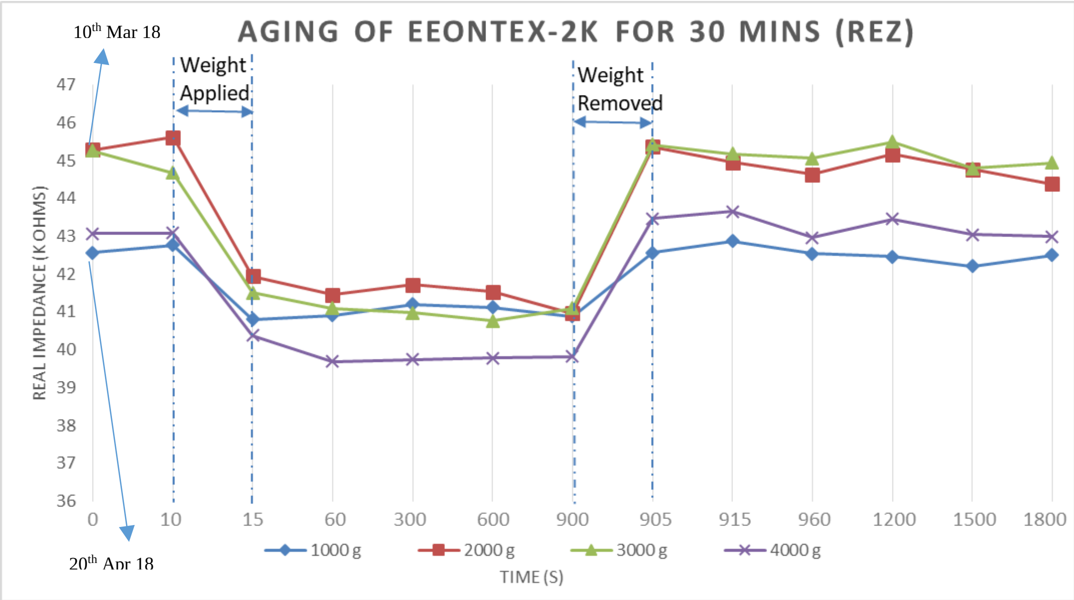


Figure 27. Eeontex-2K Aging for 30mins.

Test weights were removed approximately after 15minutes. Approximately for all weights it took almost 5seconds to reach initial value, except 4000g. After the weight 4000g is removed the ReZ value increased by 1% mainly because of hysteresis, which shows that heavy weight can take longer time to reach back its initial position after it's applied for a longer time. The different initial values for different weights is caused because of mechanical aging, as in start lower weights were focused more to assess the sensitivity of the sample, whereas, after discovering abnormal behaviour of lower weights the shift was focused towards higher weights.

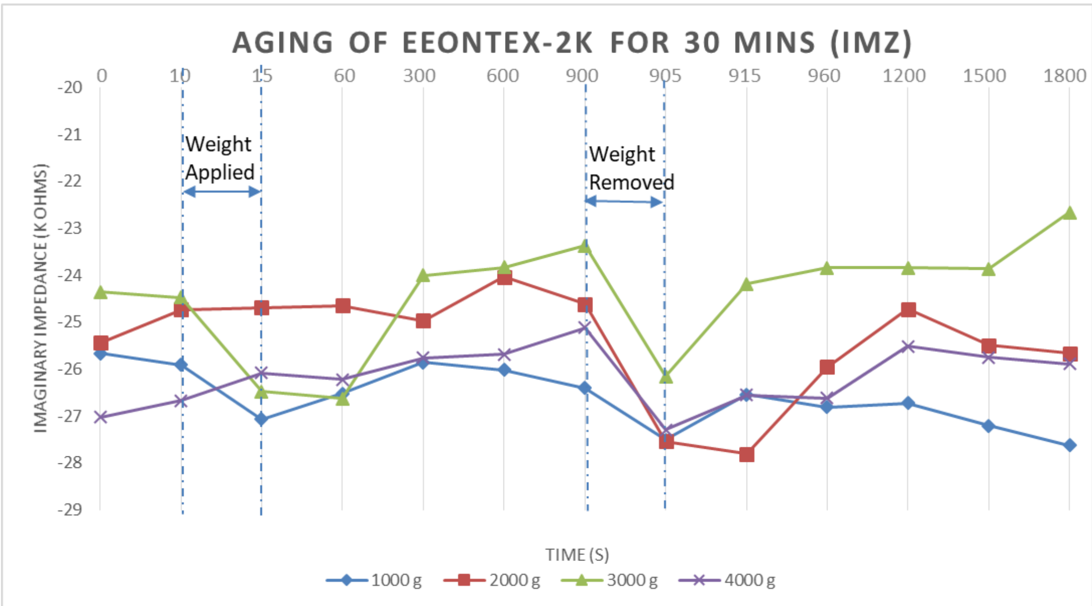


Figure 28. Eeontex-2K Aging in Imaginary Domain for 30mins.

The part of the hypothesis that Complex impedance of the material will provide us with additional information, hasn't been effective, as even for aging the behaviour in complex domain is quite irregular.

To ensure the aging effect of heavy weights on Eeontex-2K, 4000g weight was applied to sample fabric for 8hours, while monitoring first and last 30 minutes of the whole process. Graph in Figure 29 shows the behaviour.

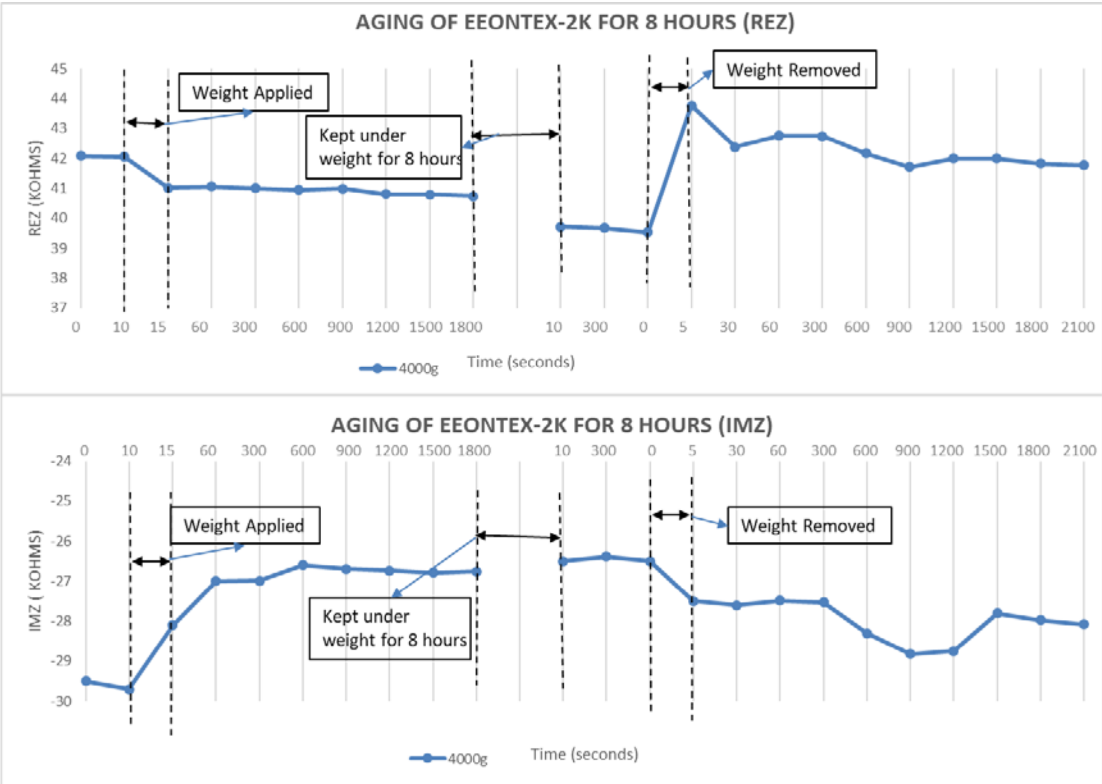


Figure 29. Eeontex Aging for the period of 8 hours in Real & Imaginary Impedance Domain.

From the graph, while observing real domain, we can see that the value is decreasing slowly with respect to time. For first 30mins, after weight is applied the graph is almost linear, but after checking it for 8hours, difference of around 1kΩ is observed. Whereas, after weight is removed the material has some hysteresis in it, and its Real Impedance value is more than its initial one, but after around 300s, it comes closer to its original value.

By observing imaginary impedance domain, it's noticed that its behaviour is quite like real part, except the hysteresis is more, and after weight is being removed, it shows irregular behaviour. Therefore, to use eeontex under longer period of applied weights, a system is required to recalibrate the system, or to weight for some time so that it can reach its initial value.

4.3 Tests done on Sample provided by EAA

Sample provided by EAA also known as Estonian Academy of Arts has a big resistance of 1.9MΩ at 10Khz frequency and very small capacitance of 250pF at 10Khz, hence parasitic capacitances cause a large effect to AC measurements. On the other hand, the Impedance, as well as, Resistance too (checked by multimeter) from initial value of MΩ to kΩ, constantly keeps on decreasing without any force applied.

The possible reasons for it can be dry connection between the device and connector, or some Nano particles behaviour, which are uncertain. Therefore, first test was done on EAA sample material was its no load behaviour against time.

4.3.1 Testing Impedance Curve at no-load

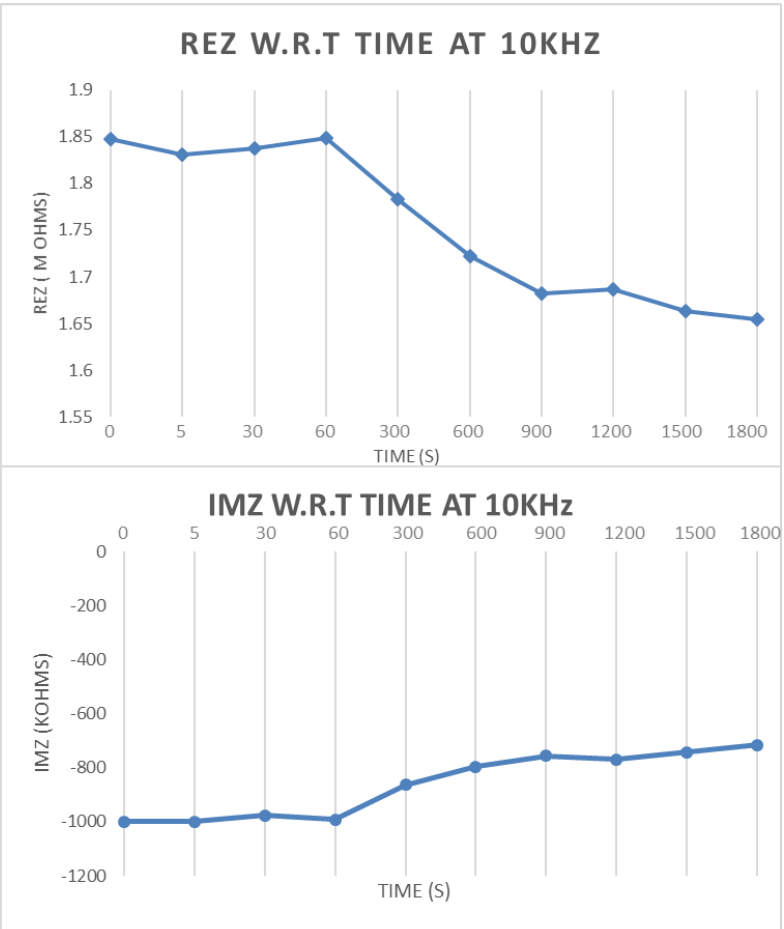


Figure 30. Impedance Curve of EAA sample for 30 minutes.

After analysing the EAA sample for 30 minutes repeatedly, as shown in Figure 30, it has been observed that the decrease in impedance at no load condition, is not linear with respect to time. From 0-30s the impedance has been non-linear with very little change, but from 60-900s it keeps on dropping linearly, and becomes non-linear again from the duration of 900-1800s. Whereas, for EAA sample, the Imaginary part behave more linearly than the Real part of the Impedance.

4.3.2 Sensitivity Analysis

For such materials it's very difficult to observe its repeatability and the impact of force, as change can be caused because of the applied weight or because of materials changing property. EAA sample material is quite sensitive, so a solution designed to measure its sensitivity, is by analysing the change in resistance with initial resistance.

Applied weight time, was fixed to be 10 seconds, and the impedance, in both real and imaginary domain, was noticed just before the impact of force and after 10 seconds of being applied on it. And relative impedance as sensitivity was calculated using this formula:

$$Relative\ Impedance = Sensitivity = \frac{Change\ in\ impedance}{Initial\ Impedance\ (Before\ Force\ is\ Applied)} \quad (8)$$

Results achieved using this way are plotted shown in Figure 31.

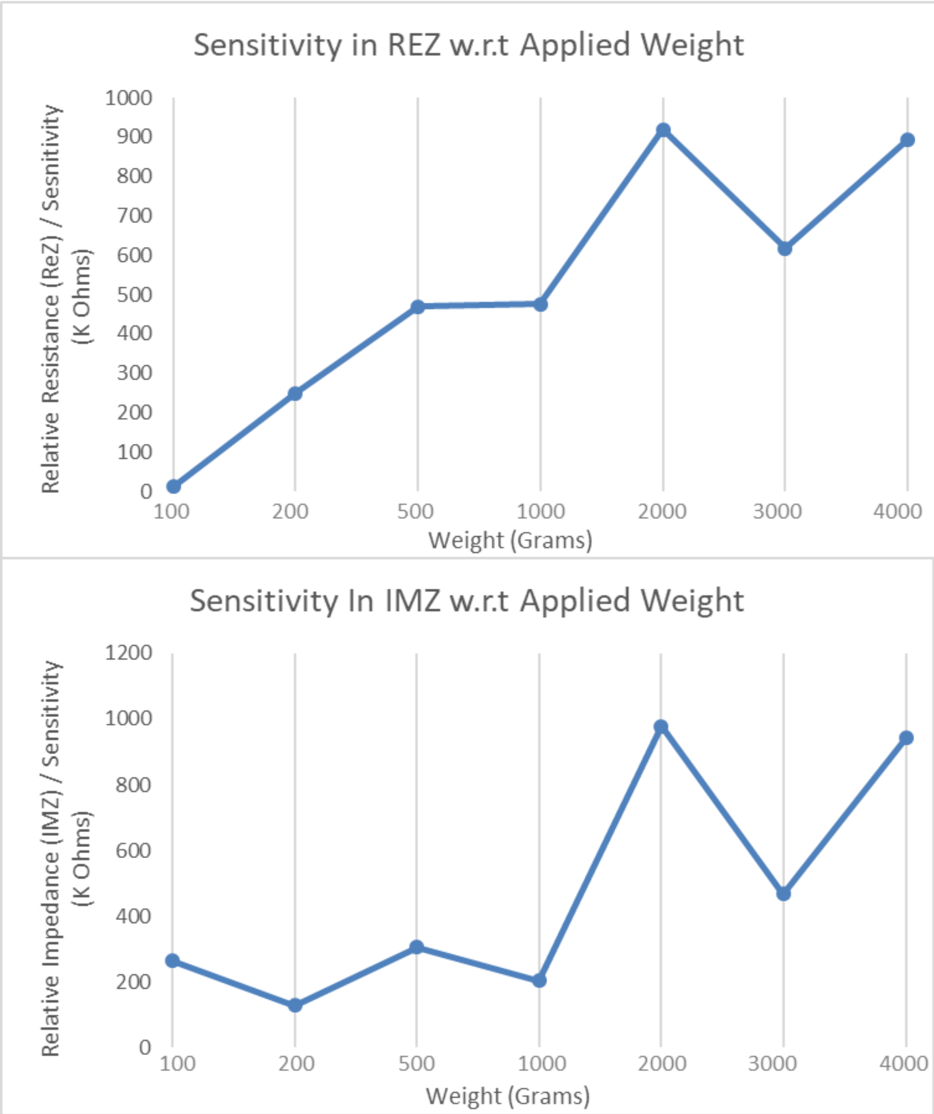


Figure 31. EAA Sample Sensitivity w.r.t Applied Weight.

The other way to measure sensitivity is by finding change in impedance w.r.t weight. The time during which sample is under applied force is fixed to be 10 seconds. Different weights were applied on the EAA sample material and sensitivity for each applied force is plotted against applied weight, as shown in equation (9).

$$Sensitivity = \frac{Change\ in\ Impedance}{Applied\ Weight} \tag{9}$$

Each point in graph was taken after thirty minutes, and each reading was noted 3 times, and based on their average sensitivity in terms of impedance w.r.t weight was calculated. This way of measuring sensitivity gave us two linear zones, in real impedance domain with non-irregular behaviour as shown in Figure 32.

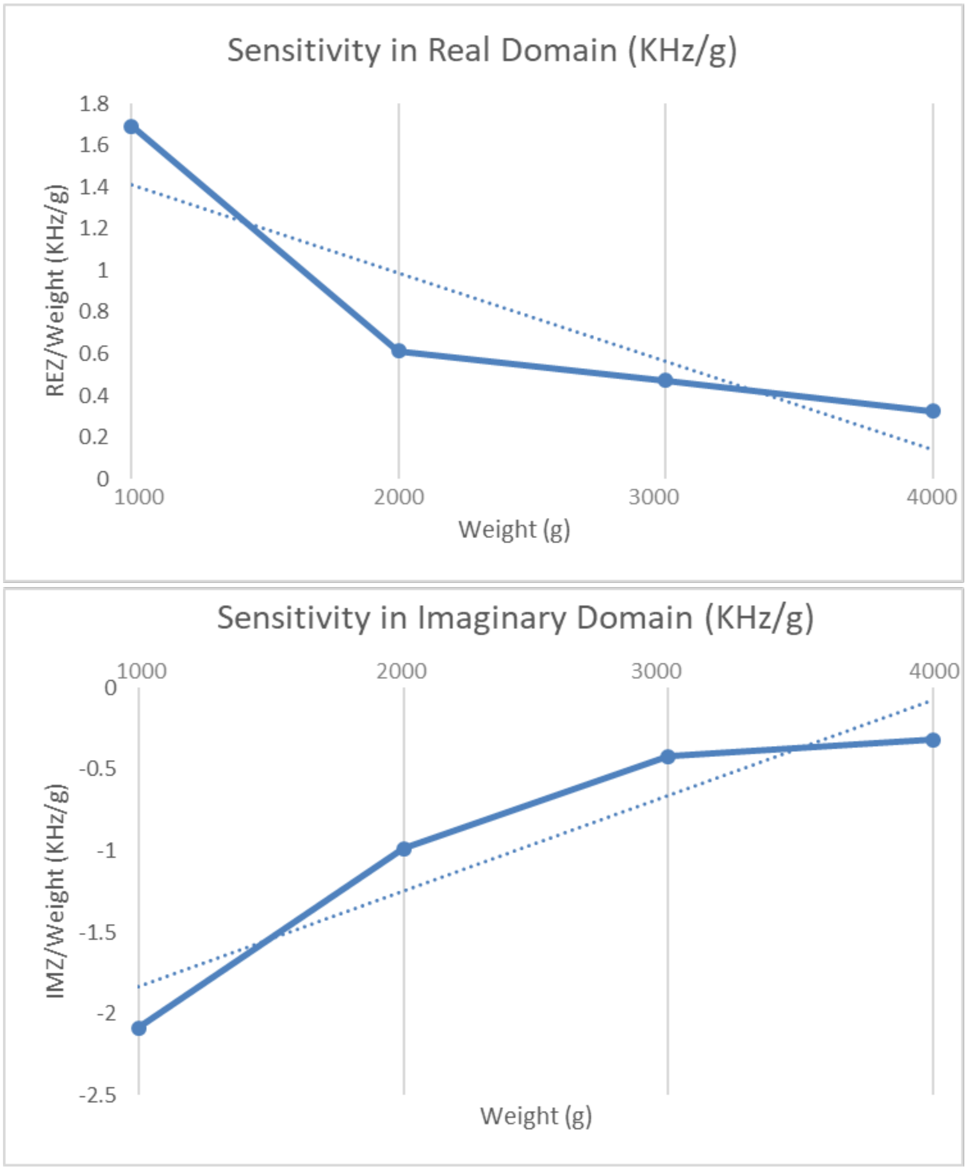


Figure 32. Sensitivity of EAA sample w.r.t Weight applied.

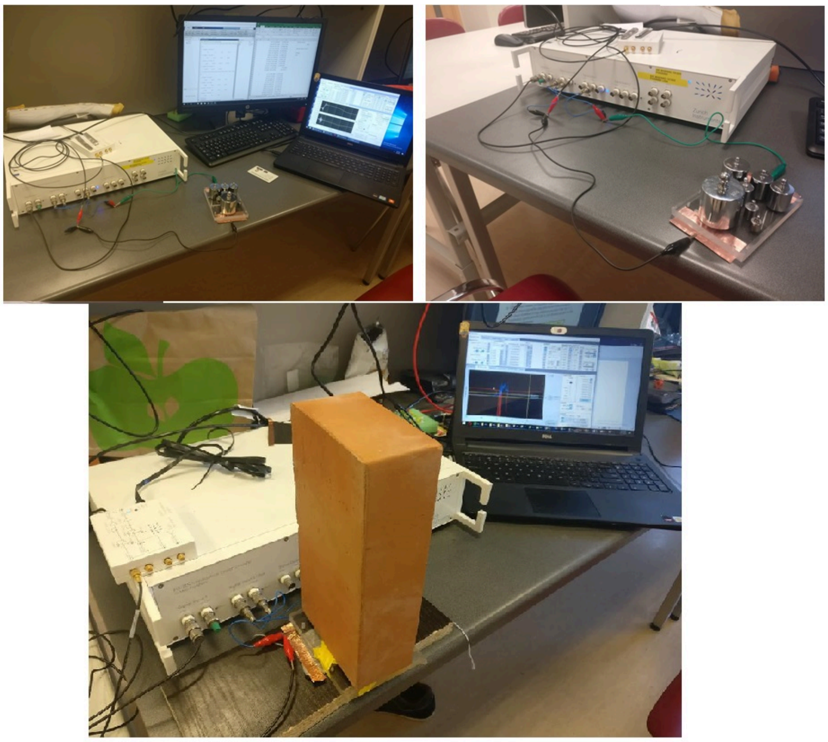


Figure 33. Setup used for performing experiments

The Figure 33 shows experimental setup used in this work.

4.4 Summary

This chapter gave a detailed information about the experiments performed on each sample in this work. The sample Eeontex-2K, has somewhat linear behaviour and is not much disturbed by parasitic capacitance, and by using impedance domain the drift problem in eeontex sensor has been minimized. DC drift for the sample appeared to be around 5kΩ to 30kΩ with the increasing trend as weight increased. Eeontex-2K, is not reliable for low weights, even though according to specifications it should be able to measure low weight up to 10g, whereas, manufacturers have recently discontinued this product. The irregular behaviour and unverified specifications can be one cause.

EAA sample has is hugely affected by parasitic capacitances, whereas, its value depletes with time, as soon as, the voltage is applied. Possible causes can be noise, ion movement, yet the main cause is unsure. EAA sample, can be used for the real-time applications, where its values are continuously measured. When it comes to sensitivity, its better at sensing than Eeontex-2K, and follows the increasing trend as the weight increases, whereas, Eeontex is more stable than EAA fabric sample.

5 Conclusion and Recommendations

Based on the experiments done, the initial hypothesis that testing samples in multi-frequency impedance domain has been partially rejected, as complex behaviour of material samples if very irregular. Whereas, by using multifrequency impedance domain, and testing sample at 10kHz, the drift problem shown many textile sensors, has been minimized. As mentioned above in chapter 2.4, for similar Eeontex stretchy sample they faced the drift of 13kΩ, but according to the tests performed on sample Eeontex-2K, the drift was reduced to maximum of 3kΩ, which increases accuracy of the sensor. The sample Eeontex-2K ReZ at 10kHz is repeatable up to +/- 700 Ω at no load (+/- 1.6%), whereas, as the load increases deviation decreases, and at the weight of 4000g, the Eeontex has the repeatability with +/- 400 Ω (+/- 0.7%).

Sample Material Eeontex is good to be used in heavy load applications, whereas, sample provided by EAA, can only be used in real-time applications, where change is detected with respect to its initial resistance.

5.1 Future Works

There are still lots of parameters need to be checked for the samples, the current work done can be used as a base for future research and material can be tested against different variables.

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