SIMULATION OF FLEXIBLE CAPACITIVE STRAIN SENSOR FOR FOOD PACKAGING APPLICATIONS

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DECLARATION

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This thesis is the result of my investigations, except where otherwise stated. Other sources are acknowledged by giving explicit references. Bibliography/references are appended.

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In the present world of competition, there is a race of existence in which those are having the will to come forward and succeed. A project is like a bridge between those are having the will to come forward.

First and foremost, I would like to express my gratitude to the supreme power of the Almighty God who is the one who has always guided me to work on the right path in life. Without his grace, this project could not become a reality.

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LIST OF ABBREVIATIONS

The following table describes the significance of various abbreviations and acronyms used throughout the thesis.

Abbreviations	Meaning
APDL	Ansys Parametric Design Language
IDC	Interdigitated Capacitive
PPC	Parallel-Plate
FEA	Finite Element Analysis
PDMS	Polydimethylsiloxane
PET	Polyethylene terephthalate
PI	Polyimide
LM	Liquid-Metal
MPC	Multi-Point Contact
MEMS	Micro Electro-Mechanical System
AgNPs	Silver-nanoparticles

ABSTRAK

Disebabkan oleh kepelbagaian kegunaan untuk penderia terikan, terdapat permintaan yang semakin meningkat untuk peranti yang fleksibel, mampu milik dan berkuasa rendah untuk terikan. Kertas kerja ini membentangkan simulasi penderia terikan Interdigitated Capacitive (IDC) fleksibel untuk aplikasi pembungkusan makanan. Dalam aplikasi pembungkusan makanan, pembangunan bahan kimia dan biosensor membayangi keupayaan penderia terikan dalam mengesan kerosakan dalam aplikasi pembungkusan makanan. Oleh itu, sensor terikan kapasitif mudah dan biasa direka untuk memenuhi keperluan khusus ini. Untuk memastikan kecekapannya dalam aplikasi tersebut, prestasi penderia terikan IDC yang fleksibel diakses dengan menggunakan Ansys Workbench, khususnya Ansys Static Structural dan Ansys Electric. Dalam Ansys Static Structural, prestasi penderia terikan IDC yang fleksibel disimulasikan untuk variasi terikan besar dan kecil. Iaitu dari 0GPa hingga 200GPa untuk menentukan sensitivitinya. Perubahan bentuk penderia terikan IDC yang fleksibel seterusnya dipindahkan ke analisis Ansys Electric untuk mendapatkan kapasitans nominal dan perubahan kapasitans model penderia akibat regangan yang dialami model penderia. Dalam analisis Elektrik, hanya voltan sederhana 0.02V disediakan kepada elektrod interdigitated dalam simulasi supaya kapasitor boleh berfungsi dengan sewajarnya. Penemuan simulasi dibezakan lagi dengan pemerhatian sebenar menggunakan penderia terikan kapasitif IDC fleksibel yang menggunakan Polydimethylsiloxane (PDMS) sebagai dielektrik dan substrat manakala Silver Nano-Particles (AgNPs) sebagai elektrod interdigitated. yang telah dibangunkan untuk tujuan yang sama seperti kajian ini. Model penderia mempamerkan kelinearan (R2 = 0.9957) yang merupakan trend biasa bagi penderia terikan IDC fleksibel biasa. Kapasiti nominal simulasi dan eksperimen yang dicapai oleh model sensor menggunakan Ansys ialah 0.997pF dan 4.37pF masing-masing. Ini menghasilkan perbezaan peratusan antara kapasitans nominal eksperimen dan kapasitans nominal simulasi sebanyak 368.78%. Apabila menggunakan nilai kemuatan daripada pengiraan, kemuatan nominal yang diperolehi ialah 1.010 pF yang menghasilkan perbezaan peratusan sebanyak -3.73%.

ABSTRACT

Due to the variety of uses for strain sensors, there is a growing demand for flexible, affordable, and low-power devices for strain. This paper presents the simulation of the flexible Interdigitated Capacitive (IDC) strain sensor for food packaging applications. In the food packaging application, the development of chemical and biosensors overshadow the capability of the strain sensor in detecting damages in the food packaging application. Thus, a simple and common flexible capacitive strain sensor is designed to fulfill this specific requirement. To ascertain its competency in the said application, the performance of the flexible IDC strain sensor is accessed by using Ansys Workbench, specifically Ansys Static Structural and Ansys Electric.In the Ansys Static Structural, the flexible IDC strain sensor performance is simulated for large and small strain variations from 0GPa to 200GPa to determine its sensitivity. The changing deformation of the flexible IDC strain sensor is tranferred to Ansys Electric analysis in order to obtain the nominal capacitance and the changing capacitance of the sensor model due to the strain experienced of the sensor model. In the Electric analysis, only a modest voltage of 0.02V is provided to the interdigitated electrodes in the simulation so that the capacitor can function accordingly. The simulation findings are further contrasted with actual observations using a developed flexible IDC capacitive strain sensor that uses Polydimethylsiloxane (PDMS) as the dielectric and substrate and Silver Nano-Particles (AgNPs) as interdigitated electrodes which has been developed for the same purpose of this study. The sensor model exhibits a linearity (R^2 = 0.9957) which is a common trend of a common flexible IDC strain sensor. The simulated and experimental nominal capacitance achieved by the sensor model using Ansys was 0.997pF and 4.37pF respectively. This results in percentage difference between experimental nominal capacitance and simulated nominal capacitance of 368.78%. When using the capacitance value from calculation, the nominal capacitance obtained is 1.010 pF in which results in percentage difference of -3.73%.

CHAPTER 1 INTRODUCTION

1.1 Introduction

Flexible strain sensors have been been a significant topic that has been under research for decades due to their expanding capabilities in sensing dynamic strain. Strain sensors are widely used in various applications such as health monitoring, automobile, motion detection, robotics, prosthetics, and more [1, 2]. The working mechanisms of the flexible strain sensors are to change mechanical deformation into the change in resistance in form of current at a constant voltage. In addition, they should be mechanically compliant to intimately conform to the curved and soft surfaces. To attain this feature, the flexible strain sensor should be able to conform to curved and soft surfaces, be chemically resistant, and able to overcome any atmospheric conditions such as variability in humidity, shock, and temperature [3].

The construction of a capacitive sensor typically consists of two parallel metal conducting plates and a layer of dielectric material that is sandwiched in between the plates. Elastomeric materials such as polydimethylsiloxane (PDMS), and polyurethane (PU) are used in capacitive sensors for the substrate and the dielectric layer, in contrast to the stiff dielectric material that is often used in capacitive sensors. The output of these sensors is very sensitive to the characteristics of the dielectric substance that they are embedded in. However, the structure of the flexible IDC strain sensor has a much thinner structures, resulting in a more compliant and flexible configuration for various types of applications [4].

Various advanced nanomaterials have been incorporated into flexible strain sensors to develop flexible strain sensors with better design parameters such as stretchability, sensitivity, linearity, hysteresis, and dynamic durability. Nanomaterials in the form of electrically conductive networks serve as active sensing films and stretchable electrodes for resistive- and capacitive-type strain sensors. Some of the nanomaterials include silver nanoparticles (AgNPs), carbon-based nanofibers, carbon nanotubes, graphene, and carbon black nanoparticles [4]. These nanomaterials are a huge factor in producing flexible strain sensors with excellent properties.

Historically, packaging materials had been chosen for their convenience and to avoid unintended interaction with food [7]. In this day and age, food packaging is essential it is able to protect the packed product from externval elements, such as pollutants, physical damage, and mechanical loads [1]. According to Fuertes [8], protection, containment, communication with the user, ergonomics, and marketing are also the purposes of the packages. Exposure to external elements can cause oxidation of the content or microbial growth, producing undesired gas indicating the loss of quality and shelf-life of the food [9]. Packaging optimal control tactics such as variable pack sizes that help customers purchase the proper quantity and diverse package designs that protect the quality of food and improve its shelf life have been proposed and implemented. However, globally prevailing trends such as increased industrial food processing, import and export of food products, and decreased time for prepared foods have compelled the food and beverage industries to undergo better quality control methods [5 - 8].

Food quality management is critical in the food sector henceforth effective quality assurance is becoming a focus in the modern day. According to A. Q. Roya and M. Elham [3], due to the growing challenges of modern society, legislation, worldwide markets, extended shelf-life, ease of consumption, safer and healthier food, environmental concerns, and food waste are all factors that affect the food industry. For instance, The Food and Agriculture Organization of the United Nations (FAO) estimates that around one-third of all food produced for human use is lost or wasted globally [4]. This gives rise to the increased food producers' demand for efficient quality control methods [5, 6].

Thus, this project will be aiming to investigate and design a flexible capacitive strain sensor and aim to compute the capacitance and its sensitivity due to mechanical deformation sensed by a flexible strain sensor attached to food packages which can lead to potential damage to packages during transportation using finite element analysis (FEA).

1.2 Main Objectives

- To simulate the performance of the flexible IDC strain sensor under stretching condition.
- To obtain the sensitivity of the flexible IDC strain sensor in a stretching condition.
- To validate the experimental capacitance values with the simulated values.

1.3 Problem Statement

Chemical sensors had been eclipsing the food industry in food packaging applications. The advancements of the chemical sensors in the food packaging industry are inevitable and continue to keep growing. Due to this, the flexible of the IDC strain sensors had not yet been realized of its capabilities in detecting contaminations in the food packages. The flexible IDC strain sensor detection is based on the change of the output values of the capacitance. The change in the capacitance caused by any strain on the food packages can tell the provider the contaminations of germs or bacteria from the environment into the food in the packages. The sensitivity of the flexible IDC strain sensor will be playing a huge role in detecting any deformations in the food packaging applications. The issue is to create a compact and sensitive flexible IDC strain sensor which is capable to detect the slight deformation on the food packages.

1.4 Scope of the Project

This study attempts to determine the flexible IDC strain sensor's nominal and changing capacitance corresponding the variations of strains. A sensor model must endure common food packaging strain to compare with experimental capacitance. Ansys Static Structural and Ansys Electric are used to determine strain and capacitance. The findings establish the sensor model's properties and its implications on food packaging applications. Experimental data will be utilised to check simulation findings against experimental data and theoretical data.

CHAPTER 2 LITERATURE REVIEW

2.1 Overview

This chapter highlights the past studies and research conducted by various researchers to investigate the final year project topic at hand. An overview of food quality management and smart packaging is presented. This chapter will be discussing comparison between resistive, electric, and capacitive strain sensors. Additionally, the theoretical method for capacitive strain sensors is also discussed to find the relevance of applying this method. Next, the capacitive strain sensors in food packaging applications are also reviewed and their designs by previous researchers. Materials for the interdigitated capacitive strain sensor are also discussed based on past studies and research. Lastly, the type of FEA simulations is reviewed to discuss their applications and contributions to the final year project.

2.2 Smart packaging

Smart packaging can be defined as a system that monitors the condition of packaged food to offer information regarding quality during transport and distribution [5]. Another definitions of smart packaging suggest that the package function turns on and off in response to changing external/internal conditions, and might include a notification to consumers or end users regarding the product's status [6]. The global market for active and intelligent packaging will double between 2011 and 2021, growing at an annual rate of 8% until 2016, when it will reach the US $17,230 million, and then at an annual rate of 7% until 2021 when it will reach the US $24,650 million. Demand for electronic smart packaging will rise around the world to more than $1.45 billion in the next decade [7]. Intelligent packaging can be achieved by incorporating detectors, sensors, or other devices capable of exchanging data within the packaging system [3]. In order to collect information on temperature [6–8], pressure , strain [8], [9], humidity [10,11], pH [12], and volatile organic compounds (VOCs) [13], etc., several physical and chemical sensors have been developed for this cause. For instance, time-temperature indicators (TTIs) is a smart label or device which exposes the accumulated time-temperature history of a certain product [14]. TTIs now available on the market have operating mechanisms based on chemical, physical, and biological principles [15]. Timestrips are intelligent labels that track how long a product has been opened or in use as shown in Figure 2.1 below. They may monitor elapsed time ranging from minutes to more than a year, in the freezer, refrigerator, or at extreme temperatures.

Figure 2.1. Timestrip® TTIs product from Timestrip Plc.

Using TTIs is able to give consumer quality assurance especially perishable food products as it is able to provide the consumers 'best by' date stamping for safe consumption [6]. This, however, excludes the possibilities of other factors which is exposed during transportation or or other sections in food managements such as physical intrusion during transportation that could lead to damage towards food products.

Biosensors are also used in Smart Packaging. They are devices that can precisely detect, record, and communicate data about biological reactions occurring within the packaging. In common practice, biosensor possessing knowledge of the product's quality, packaging, and environment creates a sense of accountability and provides history across the food supply chain from storage, transportation, distribution, and consumption [6, 15, 5]. For instance, Micro- and nanoscale sensors with a variety of transduction mechanisms are for detecting quality and safety attributes in packaged foods. The changes in microbial in the food products will determine the food quality during the transit of the food products [3]. Integration of biosensors with radiofrequency identification (RFID) or near field communications (NFC) systems inform and offer real-time information about the status of the product has a significant potential for food safety, quality, and process control [15].

The substrate or the sensing element can be derived from a bio-based source in bio-based sensors. However, bio-based sensors must have at least one bio-based component. The majority of sensors relating to bio-based materials used in food packaging rely on colorimetric detection of analytes as their primary method of operation. Although colorimetric pH-sensitive sensors are typically not convenient for selective analysis, it is often sufficient to evaluate the food quality based on the change of the pH, as deteriorating proteins produce alkaline volatile nitrogen compounds (cadaverine, putrescine, histamine, and ammonia).

Integration of biosensors with radiofrequency identification (RFID) or near field communications (NFC) systems inform and offer real-time information about the status of the product has a significant potential for food safety, quality, and process control [15]. electrochemical devices developed further their solvent melting point based colorimetric temperature sensor by using an electrically conductive film of carbon nanotubes being a part of an RFID tag. When the temperature approached the melting point of the solvent, it flowed through a capillary toward the nanotube layer, soaked it, and raised the resistance sensed by the RFID reader. The sensors might be included in RFID tags and read by a smartphone equipped with NFC.

2.3 Comparison between electric, resistive and capacitive strain sensor

Strain sensors are divided into three types: electric, resistive, and capacitive [16,4]. There are many distinct types of strain sensors available, all of which perform the same functions but use various underlying technologies to convert pressure to an output signal. The followings are the types of pressure sensors with their own respective advantages and disadvantages:

Table 2.1 The pros and cons of different strain sensor [20].

	Resistive Strain Sensors	Capacitive Strain Sensor	Electric Strain Sensor
Pros	• Most widely used type of pressure sensor. • Good resistance to shock, vibration, and dynamic pressure changes. • Used for a wide range of pressure measurements from 3 psi up to about 20,000 psi (21 kPa to 150 MPa). • Can operate at higher temperatures and are more suitable	• The capacitive element is mechanically simple and robust. • Able to operate over a wide temperature range and are very tolerant of short-term overpressure conditions. • Can be used to measure a wide range of pressure from the vacuum (2.5 mbar or 250 Pa) to high pressures	• Robustness and low power. • Requires only a very small deformation to generate an output. • Extremely robust and suitable for use in a range of very harsh environments. • The sensor elements are self-powered so they're intrinsically low-power devices. It also

	for use in harsh environments.	up to around 10,000 psi (70 MPa). • Low power consumption. • Passive devices may not require a power source at all. • Exhibits low hysteresis and good repeatability of measurements. • They also have low-temperature sensitivity. • The response time is in the order of milliseconds, and even faster in the case of MEMS devices.	means they're insensitive to electromagnetic interference. • The elements can be very small with an extremely fast response to changes in pressure. • Simple to construct.
Cons	• The sensor has to be powered. This makes them unsuitable for low-power or battery-operated systems. consumption.	• Non-linearity exhibited because the output is inversely proportional to the gap between	• Can only be used for dynamic pressure measurement. • The sensors are overly sensitive

	• Limitations on scaling because strain averaging reduces the sensitivity of the sensor. • The sensor output is temperature-dependent.	the parallel electrodes.	to vibration or acceleration

In overall, capacitive-based strain sensors offer several advantages over other strain sensors, such as higher linearity, less hysteresis, and quick reaction time, as well as simple fabrication, low cost, high sensitivity, good stability, and straightforward readout functions, which are significant limitations when the sensors are intended for use in real-world applications especially in food packaging applications.[20,21].

2.4 Capacitive strain sensor and sensing mechanisms

The inclusion of physical sensors such as strain sensors remains a novel option for monitoring the status of the package as previous studies were focused on chemical sensors or biosensors for smart packaging initiatives. Strain sensors create an electrical signal in response to the mechanical deformation or strain of the surface to which they are linked [20].

2.4.1 Theoretical methods on calculating the IDC strain sensor

An analytical model for the performance and the sensitivity of the capacitive strain sensor gauges presented by Igreja et, al. [17]. Igreja et, al. [17] provided an estimation for the determination of interdigital electrode capacitance by integrating the elliptic integral of the first type with the modulus k and the complementary modulus k'. The estimation was acquired by using the strain value and total capacitance for each electrode for electrodes more than 3.

The capacitance of two interdigital electrodes can be obtained via the following equations:

$$C = (n-1).\frac{\varepsilon.\varepsilon_r.W.t}{d} \quad 2.1$$

where C stands for the capacitance value; ε and ε_r are the permittivities that are associated with open space and the dielectric layer, respectively; t represents the thickness of the conductive electrode; W and d represent the overlapping length of the electrodes and the distance that separates the two electrodes, respectively and n is the number of interdigital electrodes that are included inside the structure. These values correlate with the values of the capacitance of the flexible IDC strain sensor. The strain on the distance between the electrodes, g is given as follows:

$$\varepsilon_{strain} = \frac{\Delta g}{g_i} \quad 2.2$$

Where Δg stands for the difference between the changed distance between electrodes and its initial distance. g_i stands for the initial electrode between electrodes. For capacitive sensors the gauge factor which is the ratio of relative change in distance, to the mechanical strain ε can be determined using the equation below:

$$G_F = \frac{\Delta C}{C_0 . \varepsilon_{mech}} \quad 2.3$$

Where ΔC stands for the difference between of capacitance. C_0 stands for initial capacitance of the flexible IDC strain sensor. ε_{mech} is the strain on the distance between the electrodes.

A paper written by Atalay et, al. [19], it is stated that the capacitance of the interdigital capacitive sensors can be modelled as a simple, interdigitated capacitive sensor based on the Electro-Mechanical Theory. In the theory, capacitance value of interdigitated capacitive strain sensor can be obtained by providing the values for number of electrodes, permittivities associated with free space and dielectric layer, the overlapped length of the electrodes and the gap separating the interdigitated electrodes.

For analyzing the complicated interaction of mechanical strains in a three-dimensional material compound, complex designs and their effect on capacitance, an analytical method is inadequate to cover the whole structure [33]. Thus, simulation method is required for this purpose.

2.4.2 Traditional capacitive strain sensor

In terms of strain sensors, metal strain gauges are by far the most frequent and traditional capacitive strain sensor. A metal strain gauge is comprised of a thin layer of metal on a polymer substrate. The pressure from the environment will change the gauge's width and length, which will change the resistance value [21]. Traditional strain sensors are rigid [24], making them ineffective in detecting even the slight deformations in food packages [25]. Additionally, the development of traditional strain sensors requires the completion of a number of difficult preparatory procedures. This leads to higher cost of fabrication as well as substantial material waste, both of which can hinder their usage development. However, this problem may be solved by using flexible strain sensors.

2.4.3 Flexible Parallel-Plate Capacitive (PPC) Strain Sensor

In past researches, silicon-based parallel plate capacitive strain sensor was used to fabricate the detecting structures. Figure 2.3 illustrates an example of a parallel plate capacitive strain sensor comprising of titanium as the electrodes and polydimethylsiloxane (PDMS) as its dielectric layer. In this framework, a thin, dielectric layer is placed between two thin, conductive plates, and conductive components are used to act as the comparable terminals for the detecting system. When a strain is applied perpendicular to dimension of the sensor, the Poisson effect causes the distance between the conductors to shrink and the area of the sandwiched dielectric to increase, resulting in an increase in capacitance [26]. The overlapping region of the parallel surfaces usually acts determinant for the sensors' sensitivity. In order to enhance the PPC sensor, increasing the surface coupling area is a common approach [22].

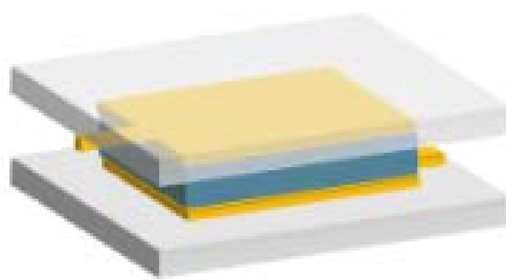

Figure 2.2 Schematic diagram of parallel-plate capacitive strain sensor using titanium as electrode and PMDS as the dielectric layer [27].

2.4.4 Flexible Interdigitated Capacitive (IDC) Strain Sensor

In contrast to the PPC arrangement, the IDC arrangement for the capacitive strain sensor is a one-layer construction in which the conductive dielectric layer is put in a comb-shaped arrangement for thinner structures, resulting in a more compliant and flexible configuration [23,26]. The IDC strain sensor is created using the same PPC dimension as the IDC structure's unit cell [23]. Also, typical PPC strain sensors are incapable of distinguishing between strain and normal stress. When strain is applied to the sensor, the distance between the electrodes reduces according to the Poisson's ratio effect, which means that the width of the electrodes decreases when the sensor's structure is stretched. The capacitance value of the sensor increases as the effective overlapped length between the electrodes increases while the thickness of the electrodes decreases. For instance, a liquid metal (LM)- IDC strain sensor as shown in Figure 2.4 that is insensitive to normal stress is proposed by Zhang, et. al [26], in which the capacitance between the LM electrodes only decreases with increased strain due to geometric changes.

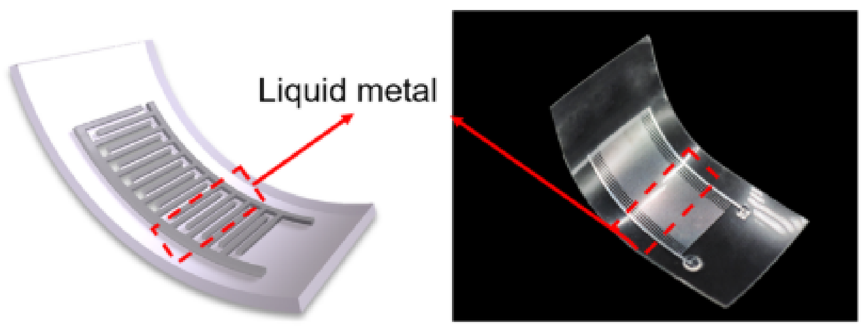

Figure 2.3 Interdigitated capacitive strain sensor (LMICSS) consisting of PMDS.

Lastly, according to Zeiser, et. al [28], there are several restrictions that must be abide in designing an IDC strain sensor layout for FEA simulations. One of them is in order to maximise sensitivity, the sensor substrate should not be more than the electrode pitch thicker than the substrate. The gauge factor rises with decreasing electrode interdigital distances. Thus, sensor structures should be in the 10 to 50 μm range for a 1 cm^2 sensor area. With increasing electrode metallization thickness, the capacitance-to-strain curve changes from linear to hyperbolic.