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**PLANAR ELECTROMAGNETIC
SENSORS:
CHARACTERIZATION AND
EXPERIMENTAL RESULTS**

A Project Report

submitted in partial fulfilment of the
requirements for the Degree of

Master of Engineering

in

INFORMATION AND TELECOMMUNICATIONS ENGINEERING

By

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AUGUST 2005

To my parents:

Mahendra Gooneratne

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ABSTRACT

Planar type electromagnetic sensors have simple structures and are very useful for the inspection of material properties, in a non-destructive and non-invasive way. The operating principle of the sensing technique is based on the interaction of electromagnetic fields with the materials under test. Three types of planar sensors: meander, mesh and interdigital configuration have been analyzed to determine their characteristics. Finite element software has been used for the analysis of flux distribution for all three types of sensors. The nature of the impedance characteristics has also been obtained through experiments. It has been reported that meander and mesh type sensors respond well at moderately high frequencies. To avoid relatively costly instrumentation systems at high frequencies, interdigital sensors having good response at low frequencies have been considered. The response of all the sensors, especially the interdigital types to milk of varying fat content, quality estimation of saxophone reeds and non-invasive estimation of fat content of pork belly cuts have been determined. The different types of sensors can be made as a sensor array, to estimate the properties of mixtures of electric, magnetic and dielectric materials. A microcontroller based low cost sensing system is under development.

ACKNOWLEDGEMENTS

I'm infinitely grateful to my supervisor, Dr. Subhas Mukhopadhyay for giving me the opportunity to do my masters study, continuously supervising my research work, providing valuable advice and expert guidance, and above all for his technical, financial and emotional support.

I would like to thank the Institute of Information Sciences and Technology (IIST) and Massey University Technical Assistance Award (UTA), for providing me financial support to pursue my studies. My special thanks go to Mr. G. Sen Gupta for his help and guidance related to microcontroller programming.

Part of the work presented in this thesis was done in close consultation with Associate Professor Roger Purchas. I would like to thank him for his valuable advice and insightful input into the research. I would also like to acknowledge the Institute of Food Nutrition and Human Health (IFNHH) for providing samples for experimentation.

I would like to acknowledge the efforts of Mr. Ken Mercer and Mr. Colin Plaw for their help on technical matters. I would like to thank Mr. Humphrey O'Hagan for his help on mechanical fabrication.

On a personal level I would like to thank Associate Professor Ravi Gooneratne and Dr. Anoma Gooneratne, my Uncle and Aunty, for all the help and support they have given me. I would like to thank Ms. Margaret J. Humphreys and Mrs. Alexandra G. Cook (Nana), for providing me a place to stay, constant encouragement and for all the interesting and informal talks, which were always a welcome and refreshing break from study. I would like to acknowledge Mr. Joe Manning for being kind enough to proof read my thesis. Many thanks go to all my friends and my twin brothers, Dinuk and Dinal, for helping me in various ways.

Finally and most importantly I would like to thank my parents for their unconditional love and support. Thank you for all the sacrifices you have made to give me a better chance in life.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Sensors are widely used in scientific research and as an integral part of commercial products and automated systems. A sensor is a device which is used to record the presence of something or changes in something. Sensors gather information from the environment and act as transducers, converting the energy form associated with the information that is sought into a form in which it can be easily processed [1]. The energy forms typically involved in sensing processes include chemical, electrical, magnetic, acoustic, mechanical, optical and thermal.

Table 1.1: Signal domains with examples [1]

Energy Form	Examples
(Bio)Chemical	Composition, Concentration, pH, Reaction rate
Electrical	Current, Voltage, Electric field, Conductivity, Permittivity
Magnetic	Magnetic field, Magnetic Flux, Permeability
Acoustic	Wave velocity, Spectrum, Wave(amplitude, phase)
Mechanical	Acceleration, Force, Stress, Pressure, Torque, Mass, Density
Optical	Wave velocity, Refractive Index, Refractivity, Absorption
Thermal	Temperature, Flux, Specific Heat, Thermal conductivity

Sensors are classified into passive or active sensors [2]. Passive sensors can only be used when naturally occurring energy is available. Hence for all reflected energy, this can take place only when the sun is illuminating the earth. Given that the amount of energy is large enough to be recorded, naturally emitted energy such as thermal infrared can be detected anytime of the day.

Active sensors emit their own energy that travels from the instrument to the target to be investigated. The reflected radiation from the target is detected and measured by the sensor. Active sensors can obtain measurements anytime, as well as examining wavelengths which are not sufficiently provided by the sun (e.g. microwaves). They also have better control of the way a target is illuminated. The disadvantage of active sensors is the large amount of energy that has to be generated by the system, to adequately illuminate targets.

Sensors are calibrated for certain conditions and are capable of reporting changes at certain speeds. Many sensors need to be amplified to be useful [1]. Sensors are either direct indicating (e.g. mercury thermometer) or are paired with an indicator (usually indirectly through an analog to digital converter, a computer and a display) to make it easier to read values. In general, most sensors fall into one of two categories: digital and analog sensors. Digital sensors involve representation of quantities in discrete units. The output signal is a digital representation of the input signal, and has discrete values of magnitude measured at discrete times. The logic level output of the digital sensor must be compatible with the digital receiver. Some standard logic levels include transistor-transistor logic (TTL) and emitter-coupled logic (ECL). Examples of digital sensors include switches and position encoders. Some digital sensors are more complicated. These sensors produce pulse trains of transitions between the 0 volt state and the 5 volt state. With these types of sensors, the sensor's measurement is conveyed through the frequency characteristics or shape of this pulse train.

Analog sensors produce an output signal that is directly proportional to the input signal, and is continuous in both magnitude and in time. The sensors employed by the author for experimentation measures impedance (magnitude) and phase (time). Physical variables that are continuous in nature such as air flow, temperature and speed can be measured by analog sensors. Examples of analog sensors include resistance temperature devices (RTD), microphones and strain gauges. Disadvantages of analog type sensors are crosstalk or electrical system noise as well as performance reductions over transmitting the analog signal over long distances.

The general properties of a good sensor are:

- optimum measurement accuracy (not as good as possible, but as good and as accurate as necessary)
- durability
- ease of calibration and reconditioning
- sensitivity and good resolution
- selectivity
- provision of reproducible measurements
- long term stability

- fast response (important for control)
- continuous operation
- insensitivity to electrical and other environmental interference
- low operation and maintenance cost
- acceptance by users
- meet safety requirements

Sensors play an important part in real-world systems, straddling a variety of applications such as industrial, medical, robotic, military, consumer and automotive applications. Sensors are critical to today's society since they provide the connection between the "real" world and the world of process control and computers. The overall accuracy and the reliability of the control system is determined by the sensors accuracy. Environmental concerns along with health and safety issues have necessitated in an increased use of sensors in the areas discussed above. Sensor technology has been successful in improving energy efficiency and service and product quality and reducing emissions [2]. Selecting a sensor depends on many factors such as availability, cost, power consumption, environmental conditions etc. Sensors are integral when it comes to controllability, reliability and profitability of a process [1, 2].

Sensor technology follows a pattern of continuous development and many prototypes will be introduced destined for success on the long run. The feasibility of a sensor technology is determined by various factors. The main factors that sensor manufactures will keep in mind when designing sensors are: cost reduction, reliability, system compatibility, safety in hazardous/hostile environments and non-invasive/non-intrusive design.

Sensing devices have been traditionally developed by employing trial-and-error techniques rather than following a solid scientific approach. Many of the sensor technologies that are in use today apply complex mixtures of several different materials, where the principles of functionality of each component is not known or well understood [3]. Furthermore, the degeneration methods that lead to aging behavior are not fully understood in most cases. For the successful implementation of novel sensor technologies it is therefore essential to have a good grasp of sensing mechanisms and their degradation behavior. This will aid in the development of advanced, affordable, reliable and novel technologies that will have a major impact on today's society. Fundamental understanding of the material characteristics is also

important in selecting the appropriate combination of sensing elements to achieve selectivity in complex array structures [3]. Hence, important sensor performance parameters such as stability, sensitivity and selectivity must be improved, even in the case of commercially available products [1]. These parameters depend mainly on the physical and chemical characteristics of the materials that were used to build the sensing device.

There is a high demand for novel sensors that are able to cope in extreme hostile/hazardous environments [4]. Novel technologies which are reliable in extreme environments are continuously being researched and developed. However, the specifications and the boundaries for sensing systems are becoming more demanding (e.g. example operation of sensors to detect landmines in harsh environments). It is therefore important to understand the sensing mechanisms and how they operate in each case. The miniaturization of such devices seems to be the next step in sensor technology, and the importance of designing materials with controlled microstructures was clearly shown in the semiconductor industry's paradigm.

1.2 Sensors and Non-Destructive Sensing

Non-destructive testing (NDT) or Non-destructive evaluation (NDE) has evolved over the years to become one of the critical measurement techniques in industry today. It is a very broad and an interdisciplinary field that can be used to detect defects and measure physical or mechanic characteristics of a material or component, independent of orientation. It is a reliable and a cost effective way to detect and evaluate structural components and systems and seeing if they are performing to their potential. The popularity and acceptance of NDT as a measurement technique is due to the fact that the system or material under test is not harmed or damaged during testing, and thus the integrity of the object under test is retained [25]. In an age where health and safety standards in industry have reached high limits, the importance of NDT is even more. NDT has the potential to stop many disasters that are waiting to happen. Typical engineering failures such as airplane crashes, pipeline explosions, reactor failures, machine failure, bridge failure and trains derailing can be successfully avoided with NDT. NDT is used many areas including automotive, nuclear, aviation, aerospace, construction, petro-chemical, electronics, food industry, medical science, power, transportation and the metal industry [24, 25]. There are NDT applications at almost any stage in the production or the lifecycle of a component.

The demand for highly reliable and high performance inspection techniques during manufacturing, production and use of a system or structure is increasing daily. Hence the number of suitable inspection techniques is also on the rise. Shown below are a few of the most commonly used methods in NDT.

- Visual and Optical Testing [5,6]

This is the most basic NDT inspection method. The methods range from visual examiners checking the object of interest for visible imperfections, to computer controlled camera systems which automatically recognize and measure features of the system under test.

- Radiography Testing [7]

In radiography testing, penetrating gamma or x-rays are employed to analyze the defects and internal features of the object under consideration. A source of radiation is required when an object is being tested with radiography techniques. Normally an X-ray machine or a radioactive isotope is used for this purpose.

- Magnetic Particle Testing [8]

In magnetic particle testing a magnetic field is induced in a ferromagnetic material. The surface is then dusted with iron particles, which are either dry or suspended in liquid. Testing is done so that defects in the material under test can be observed. When a surface or a near surface flaw is detected, magnetic poles are produced or the magnetic field is distorted so that the iron particles are attracted and concentrated. This paves the way for visible detection of defects on the surface of the material.

- Ultrasonic Testing [9]

Ultrasound detection involves the transmissions of sound waves with a frequency higher than 20 kHz into a medium. These sound waves are then reflected on boundaries between materials with different acoustical properties.

The detection of imperfections or the location of changes in material properties are achieved this way.

- Penetrant Testing [11]

A solution that contains a visible or fluorescent dye is used to coat the object that is being tested. After excess solution is removed from the surface of the object it is left in surface breaking defects. The penetrant is then removed from the defects using a developer. The next step involves detecting the imperfections. In the case of fluorescent dyes, imperfections are visible when ultraviolet light is used to make the bleed out fluoresce brightly. Visible dyes on the other hand have vivid color contrasts between the penetrant and the developer, which makes it easier to see “bleedout”.

- Leak Testing [10]

A leak can be flow of a gas or liquid through the wall of a vessel, due to holes or cracks in the system. There are various techniques that are used to detect and locate leaks in pressure vessels, pressure containments and structures. Methods such as gauge measurements, liquid and gas penetrant techniques, soap-bubble tests and electronic listening devices can be used for detection.

- Acoustic Emission Testing [12]

The structural or the material integrity of the object under test is based on the short energy of acoustic energy called “emissions” that are emitted, when the object is stressed. Special receivers are used to detect these acoustic emissions. The intensity of the emissions as well as the arrival time to collect information about the source of the energy, such as their location can be used to evaluate the status of the object under test.

- Electromagnetic Testing [13]

There are several methods such as eddy current inspection, remote field testing, flux leakage and Barkhausen noise that use the electromagnetism as the principle of operation. Eddy current testing (ECT) is the most commonly used method of inspection. The principles of ECT is used for the mesh and meander type sensors that have been used by the author.

Electromagnetic induction is the root of ECT. The English scientist Michael Faraday discovered electromagnetic induction in 1831. The brilliance of Faraday was instrumental in discoveries such as electromagnetic induction, electromagnetic rotations, the magneto-optical effect, diamagnetism and many others. In 1879, metals of different conductivity and permeability were tested with a coil, and the changes in the coil were recorded by Welsh Professor David Edward Hughes. However it was not until World War 2 that these effects were put into practical use for the inspection of materials. The now widely used and well understood ECT was pioneered by Friedrich Forster in the 1940s. He was an important figure in the introduction of ECT as a non-destructive method of inspection.

ECT has developed rapidly since its practical introduction in the 1940s. ECT can be performed on any material that is electrically conducting. A brief overview of the industries and the areas that use ECT is shown below [24].

- Metal Industry – for the inspection of cracks, defects and any other flaws and their characterization, wall thickness, quality assurance, fatigue estimation, determination of hardness and coating thickness testing etc in steel production and steam and pressure vessel construction.
- Power stations – Conventional and nuclear power plants
- Civil engineering – inspection of bridges, concrete structures, infrastructure due to aging
- Aviation – fatigue estimation in aircraft surface and other parts
- Pipe inspection – inspection of pipes and piping systems in industrial plants

Unlike volumetric techniques such as radiography and ultrasonic, ECT, like liquid penetrant and magnetic particle techniques is a surface technique, and can only be used to detect surface and near surface defects.

In the case of testing materials with poor electrical conductivity Dielectric Analysis (DEA) techniques have been used [27-32]. DEA is based on the principles of electrostatics. Electrostatics is one of the oldest branches of physics, and it continues to this day to be an ever emerging field, and an important part of our daily lives. DEA techniques are non-destructive and can be used to relate molecular motions observed in an electrical field, to a variety of polymeric properties. Capacitive sensing dielectrometry is used to provide information for materials with poor conductivity in electroquasistatic applications [29]. Through measurements of the material electrical properties such as dielectric constant, conductivity, loss tangent or complex permittivity, information on things such as layer thickness, thermal conductivity, presence of defects, porosity and cure state can be obtained.

Dielectric analysis as a measurement tool in industry started more than 20 years ago, and is developing rapidly in industry today. Some of the industries and areas that dielectric analysis is used are shown below.

- Metal Industry – material characterization, presence of defects
- Pharmaceutical Industry – coating thickness of tablets, size of tablets
- Paper Industry – estimation of moisture and fiber concentrations in paper pulp
- Landmine detection – detection and imaging of plastic landmines
- Food Industry – estimating dielectric properties of various types of meat

1.3 Sensing based on Planar Electromagnetic Sensors

The sensors designed and fabricated for the non-contact measurement of material properties are of planar type and can be used in curved, bent surfaces. The operation principle is based on the electromagnetic field. A high frequency electric or magnetic field is created by the exciting coil of the sensor in the system under test. The system usually interacts with the high frequency electric [27-32] or magnetic field [15-21, 24-26] and modifies either or both. The modified field is usually detected by a separate coil known as the sensing coil or by the exciting

coil itself [24]. The modified field is usually manifested by a change of impedance or transfer impedance of the sensor [26]. The impedance or the change of impedances is related to the system properties in a very complex way. The impedance is used for the indirect determination of system properties. The detailed description and operating principle of the sensors are discussed in chapter 2.

1.4 Organization of the Thesis

This thesis is organized into nine chapters. After the general introduction in chapter 1, chapter 2 describes the configuration and operating principle of planar electromagnetic sensors. The finite element model formulation for the characterization of all three types of sensors, meander, mesh and interdigital configuration is described in chapter 3. Chapter 4 describes the experimental characterization of the sensors. The application of the sensors for the non-invasive determination of fat content in milk has been investigated and the details are given in chapter 5. The application of the sensors for the quality inspection of saxophone reeds is described in chapter 6. The main contribution of the work done for this thesis is the experiments conducted to observe the interaction of planar sensors to pork belly cuts, and the non-invasive estimation of fat content of pork meat, which is described in chapter 7. Chapter 8 describes the development of a low cost sensing instrumentation system based on the Cygnal 8051CF020 mixed signal microcontroller. Finally the work is concluded in chapter 9.

