DESIGN OF CAPACITIVE MEASURING SYSTEM FOR HIGH FREQUENCY BAND TRANSDUCER

BY

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ABSTRACT

Capacitance measurement system is no longer a fringe technology that only can be used in the factory to select a defect product on the assembly line. It is a mature technology employed in thousand of products and a newer application, coming into widespread use is in the consumer product of human-to-machine interfaces such as on the mobile phone, PC peripherals, portable digital entertainment devices, appliances, remote controls, access control and digital cameras application. It is also reported that this technique has been used in industrial applications for many years to measure liquid levels, humidity, and material composition. The proposed capacitance-to-voltage converter is designed based on CMOS 0.13 μm technology using switched-capacitor technique which reduces size of the circuit and lowers the power supply requirement. The circuit is able to detect a capacitance, C_x change within a wide range of capacitance variation under two detectable range; first is lower detectable range in *femto* Farad from 100 *f*F to 1640 *f*F and secondly in *pico* Farad detactable range from 120 *p*F to 380 *p*F. The output voltage of the circuit varies linearly with the variation of capacitive transducer within these detectable ranges. The output voltage for both the detectable range of capacitance C_x shows less than 1 V with power dissipation of 0.939 *m*W. The evaluation of the proposed circuit is done by analytical approach and using the simulation tool of PC based Simulation Program for Integrated Circuit Emphasis (PSpice) OrCAD version 16.0. The circuit requires less supply voltage, able to detect wide capacitive sensors capacitance variation, suitable to be used at high frequency and produces less power consumption. The proposed capacitance-to-voltage converter can be used in various capacitive sensors such in communication, automotive and medical field that are making use of high frequency system.

خلاصة البحث

لم يعد نظام قياس السعة تقنية ثانوية تستخدم فقط في المصنع لتحديد الخلل في خط التجميع. بل هي تقنية متطورة/ناضجة وظفت في آلاف المنتجات و في التطبيقات الحديثة، وفي الاستخدام الواسع في قطاع المنتجات الاستهلاكية من قبل الإنسان في التخاطب مع الأجهزة الآلية مثل الهاتف المحمول، أجهزة الكمبيوتر، أجهزة الترفيه الرقمية المحمولة، الأجهزة المنزلية، أجهزة التحكم عن بعد، أجهزة التحكم بالدخول و تطبيقات الكاميرات الرقمية. وكذلك فقد تم استخدام هذه التقنية لعدة سنوات في التطبيقات الصناعية لقياس مستوى السوائل و الرطوبة و تركيب المواد حسب ما ورد في التقارير. إن الجهاز المقترح لتحويل السعة إلى جهد كهربائي قد صمم اعتماداً على تقنية 0.13 CMOS ميكرو متر (μm) باستخدام تقنية المكثف المحول والتي من شأنها أن تقلل من حجم الدائرة الكهربائية و كذلك أن تخفض من مقدار الطاقة الكهربائية المطلوبة. إن الدائرة قادرة على اكتشاف/ضبط التغير في السعة (C_x) ضمن مدى واسع من اختلاف السعة ضمن النطاقين التاليين القابلين للضبط: الأول باستخدام وحدة الفيمتو فاراد *femto* Farad وذلك ما بين 100 *f*F إلى 1640 *f*F و ثانياً باستخدام وحدة البيكو فاراد *pico* Farad من 120 *p*F إلى 380 *p*F. إن ناتج الجهد الكهربائي من الدائرة يتغير خطياً مع تغير سعة جهاز قياس السعة ضمن المجالات/النطاقات المذكورة. إن ناتج الجهد الكهربائي في كلا نطاقي السعة القابلين للضبط أقل من 1 فولت (1 V) مع استهلاك لا يتجاوز 0.939 ميللي واط (*m*W) من القدرة الكهربائية. إن التقييم للدائرة المقترحة يتم عن طريق النهج التحليلي و استخدام برنامج OrCAD نسخة 16.0 والذي يعد أحد برامج الكمبيوتر الشخصية لمحاكاة الدوائر المتكاملة (PSpice). الدائرة تتطلب إمداد أقل من الجهد الكهربائي، وهي قادرة على اكتشاف نطاق واسع من التغير في السعة، وهي مناسبة للاستخدام في الترددات العالية و تستهلك طاقة أقل. يمكن استخدام الجهاز المقترح لتحويل السعة إلى جهد كهربائي في عدة حساسات للسعة كما في الاتصالات، السيارات والمجال الطبي والذين يستفيدون من أنظمة الترددات العالية.

APPROVAL PAGE

I certify that I have supervised and read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a thesis for the degree of Master of Science Electronics Engineering.

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DECLARATION

I hereby declare that this dissertation is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

Nurul Arfah Haji Che Mustapha

Signature……..…… Date……..

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…… ……

Signature Date

I dedicate this research work to my father, Che Mustapha Abdullah and mother, Zabidah Mohd Isa, siblings, lecturers and friends. Thank you for your love, patience, advices and supports. May this research work benefit all.

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LIST OF SYMBOLS

$2\|\phi_F\|$	Surface inversion potential
Å	Amstrong
A	Area of plates
A_d	Differential gain
A_V	Voltage gain at dc of a circuit
C	Capacitance
C_L	Load Capacitance
C_C	Compensation Capacitance
d	Separation of the two plates
dc	direct-coupled or direct current
*f*F	*femto* Farad (10^{-15})
f_{3dB}	3dB frequency of a circuit
k	Boltzmann's constant
k	Dielectric constant of the insulator
L	Device length
n_i	Intrinsic carrier concentration
*p*F	*pico* Farad (10^{-12})
P_{diss}	Power dissipation
R_{out}	Output resistance
Vdd	Positive supply voltage
V_{G0}	Silicon bandgap (27 ºC)
V_{in}	Voltage input or power supply

$V_{in(max)}$	Maximum input comman-mode range
$V_{in(min)}$	Minimum input comman-mode range
V_{OS}	Offset voltage
V_{OUT}	Output DC
$V_{out(max)}$	Maximum output voltage swing
$V_{out(min)}$	Minimum output voltage swing
Vss	Negative supply voltage
W	Device or channel width
γ	Body-effect parameter
ε	Dielectric constant
ε_0	Permitivity of free space
ε_{ox}	Permitivity of SiO_2
ε_{Si}	Permitivity of silicon
λ	Channel length modulation parameter
μ	micro (10^{-6})

LIST OF ABBREVIATIONS

A/D	Analog-to-Digital
CBCM	Charge Based Capacitance Measurement
CMOS	Complementary Metal Oxide Semiconductor
COX	Gate-oxide capacitance, per unit area
CVC	Capacitance-to-Voltage Converter
GB	Unity gain bandwidth
IC	Integrated Circuit
ICMR	Input Common Mode Range
KP	Process transconductance parameter
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
Op-amp	Operational Amplifier
PHI	Surface inversion potential
RHP	Right half plane
PM	Phase margin
PRS	Pseudo-random Sequence
PSpice	PC version of Simulation Program for Integrated Circuit Emphasis
PSRR	Power supply rejection ratio
SR	Slew Rate
TOX	Gate-oxide thickness
UO	Carrier mobility
VTO	Zero-bias threshold voltage

CHAPTER ONE

INTRODUCTION

1.1 OVERVIEW

Capacitive measuring system is essentially an important technology in the transducer system. The motivation behind using capacitive measuring system is that it easily provides an efficient conversion of changes in the parameter of interest into a wide range of capacitance changes, which are in turn changed into proportional voltage or frequency changes. The advantage here is that these conversions take place without functionality loss compared to other systems such as the inductive (Osoinach, 2008) or resistive measuring systems (Wilson, 2005). This chapter presents a brief background about transducer, followed by general view about capacitance measuring system and the converter. It also presents the problem statement, highlights the research objectives and details the research methodology. Lastly, this chapter presents the organization of this dissertation with the chapter summary given at the end.

1.2 BACKGROUND

Transducer are widely used in instrument measurement and control systems, most commonly in the biomedical (Morris, Rivens, Shaw & Haar, 2008), telecommunications (Harris, Maruvada & Gamme, 2004), water treatment plants (Ross, 1983), automotives, food, and chemical industries (Chiang, Wang & Huang, 2008). The sensor itself can be defined as a device that is able to measure (or detect) changes in physical stimuli such as acoustic pressure, electrical or magnetic field changes, optical, thermal and mechanical. The sensed stimuli are in turn changed into

recordable signals or pulses. On the other hand transducer are basically devices which convert one form of input energy into the same or another form of output energy, however from an application view point they may be sensors, actuators or a combination of both.

Emerging work on transducer convert capacitance changes into corresponding frequency has been reported. Some applications are for converting pressure variations (Chatzandroulis, Tsoukalas, & Neukomm, 2000), humidity measurements (DeHennis & Wise, 2005) into frequency variations of the corresponding signal. Further, such transducer have been used in water level measurement system (Ross, 1983), wireless pressure sensor (Pearce, 2006), sensor for human interface (Pratt, 2006) and telemetry systems (Chatzandroulis & Tsoukalas, 2001).

Capacitance measurement system or sensing method using capacitance plays a vital role in automation and measurement that can also be used in the factory to detect a defect product on an assembly line. It is a mature technology employed in thousand of products such as consumer products of human-to-machine interfaces as on the mobile phone, PC peripherals, portable digital entertainment devices and domestic appliances such as refrigerators, washing machines, remote controls, access control and digital cameras just to name a few. It is also reported that this technique has been used in industrial applications for many years to measure liquid levels, humidity, and material composition (Pratt, 2006).

Capacitance-to-voltage conversion (CVC) is a simple and attractive method for accurately measuring very low value capacitance variations over a wide range of capacitance changes, leading to almost linear relationship between the capacitance variations and the resulting voltage fluctuations obtained. Another added advantage of this technique lies in its simple implementation in MOS technology

(Krummenacher, 1985). Also, this technique bypasses the usage of the conventional analog-to-digital converter, as the signal obtained is already digital, thus reducing the hardware cost by saving an important stage in the whole process (Chiang, Wang, & Huang, 2008). The resulting output signal is digital which can be easily transmitted, received and processed even by systems including wireless sensor networks. To meet such expectations, the 0.13 μm CMOS technology transducer is used.

1.3 PROBLEM STATEMENT AND ITS SIGNIFICANCE

As devices are becoming more compact with reduced power requirements especially for portable gadgets, it is desirable that the design undergoes continuous changes in design to meet up such expectation. Designing a sensitive sensor device is more challenging when it takes into consideration low power consumption, fast response time and functionality.

Many present detection systems are in the area of high sensitivity or wide capacitance of lower detection value range. For example, in application such as mobile communication like the capacitive touch screen (Morris, Rivens, Shaw & Haar, 2008) that enables new applications like virtual keyboards and handwriting without a stylus pen (Kolokowsky & Davis, 2010). A small capacitor between the sensors and the finger will be created whenever a finger or other conductive object comes near to the screen. According to (Kolokowsky & Davis, 2010), the created capacitance value is small compared to the others in the system which is about 0.5 *p*F out of 20 *p*F. Meanwhile, a finger capacitance value is usually in the order of *pico* Farad (*p*F), whereas the associate background capacitances value is in the order of 10 *n*F. Chapter 2 will highlight more information about lower value of capacitance range.

Previous research covers a range of frequency less than 100 *k*Hz in their method of switch capacitor in their previous design. This work must be improved as high frequency range output are becoming more advantageous for application in biomedical field like ultrasound (Morris, Rivens, Shaw & Haar, 2008) and in a communication application of miniature ultrasonic hydrophones (Harris, Maruvada & Gamme, 2004), radio transmission, accelerometers and many more. To meet those demands, a range frequency of 100 *k*Hz to 2 MHz should be studied and carefully designed to reach an error free result and sensitive sensor. Highly integrated capacitance-to-digital converters allow capacitive-sensor system designers to benefit from recent mixed-signal technology advances that integrate high-performance analog front ends with low-power, high-resolution sigma-to-delta converters.

Silicon technology can offer interesting perspectives for sensor development. However, the transmission itself is also a key element in terms of power consumption or dissipation, such that sensor interfacing, signal processing, data handling and data transmission also become key parameters in the total system design. In (Chiang, Wang, & Huang, 2008) the transistor size has been reduced to 0.35 μm from the previous work of 4 μm and was successful in achieving maximum frequency range of 500 *k*Hz but consumed more voltage supply in the circuit which is about 3.2 V. This is undesired as more power is used for a smaller size of chip area, although the supply voltage is quite low which is below than 10 V. It is emphasized that both low power consumption and transmission need to be thoroughly matched.

When technology has already moved into *nano* meter, *n*m range especially in CMOS design technology, short channel effects need to be taken into account. Referring to (Baker, 2008) and (Sedra & Smith, 2004), normal channel lengths of a modern CMOS transistors is less than 1 μm.

1.4 RESEARCH OBJECTIVES

The main objective of this research work is to improve the existing work of monolithic complementary metal-oxide-semiconductor (CMOS) auto-compensated sensor transducer (Chiang, Wang, & Huang, 2008) in order to obtain a wide, lower and linear detection range of a capacitance-to-voltage converter that is able to reduce power dissipation and voltage supply. Useful alterations using the existing circuit are made by considering all the design specification. In order to meet the requirement of a good transducer and to overcome the problem mentioned earlier, this research work aims at achieving the following objectives:

1. Implementation of capacitance-to-voltage converter using CMOS 0.13 μm technology for transducer's measurement system according to the specifications.
2. Optimization of design parameters to attain a lower and wider capacitance detection range with better sensitivity and improved linearity.
3. Evaluation and validation of the designed system.

1.5 RESEARCH METHODOLOGY

For research purpose, the technique of switched-capacitor as suggested in (Chiang, Wang, & Huang, 2008) is used by modifiying the previous method using 0.13 μm CMOS technology to support a high speed application system. In order to solve issues in the problem statements and achieve the objectives stated above, the methods taken in this dissertation may be listed as below and simplified as in Figure 1.1

1. Explore related research and existing method available by studying the weakness in the design layout.

2. Development of specification using 0.13 μm technology for the CVC and the operational amplifier (Op-amp).
3. Consideration over wider detection in high frequency range is emphasised for better resolution and lower power consumption.
4. Evaluation and validation by comparing calculation with the specification made to check the end result.
5. Implementation by developing, simulation and testing using the software tool of PSpice.
6. Attaining a linear relationship between the capacitance to be measured and the output voltage to be obtained.
7. Discussion of results by using analytical evaluation and simulation approach.
8. Comparing design with previous reported work.

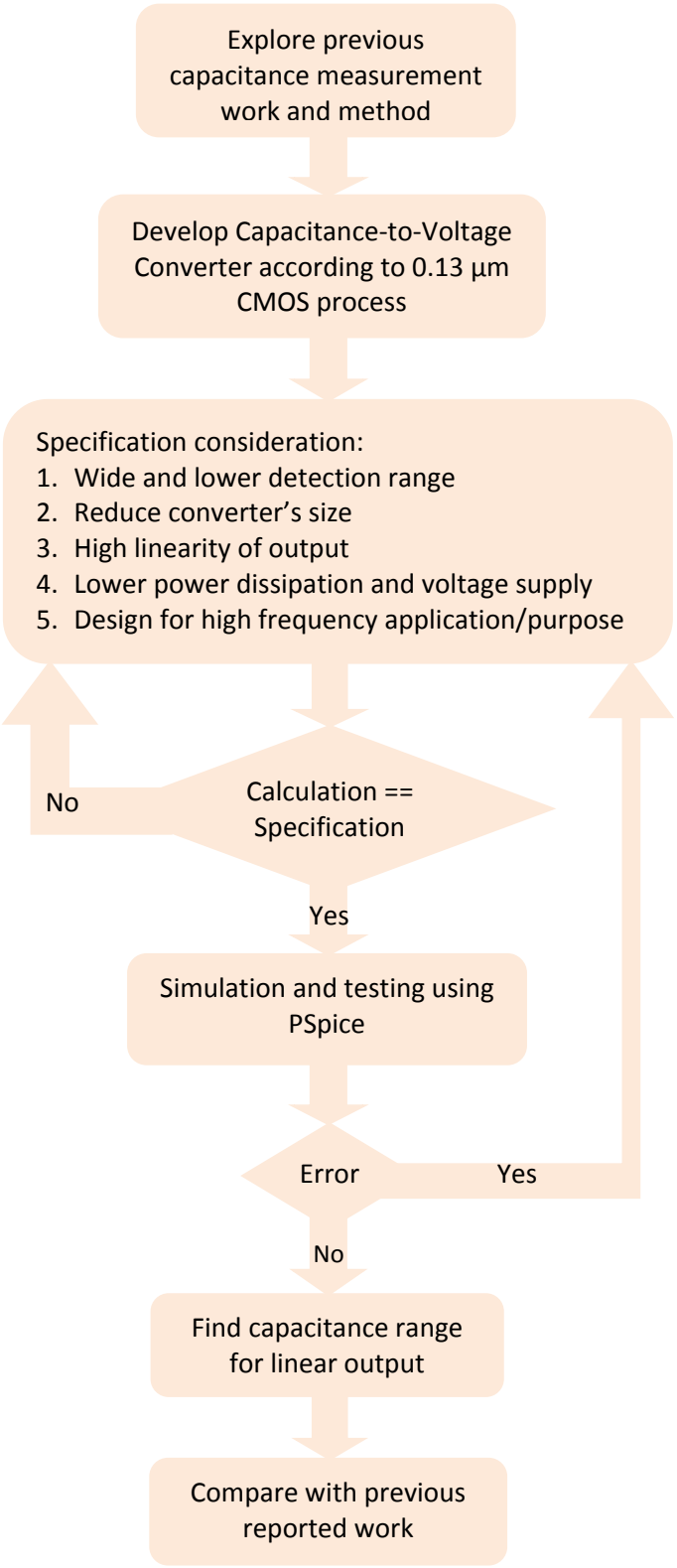

Figure 1.1: Flowchart of Research Methodology

1.6 DISSERTATION ORGANIZATION

The first chapter of this dissertation introduces the concept of capacitance measuring system. It presents the problem statements and its significance, research objectives, research methodology and research scope. The rest of the thesis is organized as follows:

Chapter 2 gives further explanation about the capacitance measurement technique available in the market and previous related research work. The fundamental theory behind capacitance measurement systems, existing similar trends and applications of lower capacitance detection range are also listed and discussed. Lastly, it presents literature review and related works in the area of capacitance measuring system and introduces the proposed CVC and briefly explains the operation.

Chapter 3 discusses on the CVC and the Op-amp design. Details of selection transistor switch and the CVC operation are explained. It presents in details the CMOS 0.13 μm technology selection, design specification, procedural outline of the design, schematic of the circuit and calculation using mathematic tools of MatchCAD with simplified design calculations and alterations. Consideration over error contribution is explained in details while designing the circuit system.

Chapter 4 provides the results and analysis of the converter's system using analytical evaluation and simulations approaches. Discussion is made based on the CVC requirement and the Op-amp's characteristic. This chapter also presents the performance analysis undertaken to analyze the design circuit and results are shown. It then compares the designed capacitive sensor with the previous reported research.

Finally Chapter 5 concludes this dissertation and recommendation for further work is presented.