Sensors & Transducers Journal, Vol. 99, Issue 12, December 2008, pp. 25-32

Sensors & Transducers

ISSN 1726-5479

http://www.sensorsportal.com

An Inter-digital Capacitive Electrode Modified as a Pressure Sensor

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Received: 22 October 2008 /Accepted: 22 December 2008 /Published: 30 December 2008

Abstract: Inter-digital capacitive electrodes working as electric field sensors have been developed for touch panel applications. Evaluation circuits to convert variations in electric fields in such sensors into computer compatible data are commercially available. We report development of an Interdigital capacitive electrode working as a sensitive pressure sensor in the range 0-120 kPa. Essentially it is a touch/proximity sensor converted into a pressure sensor with a suitable elastomer buffer medium acting as the pressure transmitter. The performance of the sensor has been evaluated and reported. Such sensors can be made very economical in comparison to existing pressure sensors. Moreover, they are very convenient to be fabricated into sensor arrays involving a number of sensors for distributed pressure sensing applications such as in biomedical systems. *Copyright © 2008 IFSA.*

Keywords: Inter-digital capacitive electrode, E-field sensors, Touch/proximity sensors, Distributed pressure sensors

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1. Introduction

A wide variety of pressure sensors for different applications, employing different transduction principles, have been developed. A good number of pressure sensors for various applications are now commercially available. They employ different physical effects such as piezoelectric effect, piezoresistive effect, variation of inductance/capacitance with pressure, variation of electrical resistance with pressure, various pressure induced effects etc. Pressure sensors have wide ranging applications in diverse areas such as automotive sector, biomedical systems, gas flow systems, industrial systems etc. These commercial pressure sensors use one of the well-known principles cited above and are available in different sizes and shapes depending on the application. Different pressure sensors working in different ranges have been developed. These differ in their sensitivity, dynamic range and physical size. Pressure sensors for most applications are now commercially available. Even integrated sensors, which can be interfaced directly to electronic circuits, are also commercially available.

The principles and technology of Inter-digital Capacitive Electrodes (ICE) working as electric field (E-field) sensors is now well established [1]. Such electrodes are extensively used as touch/proximity sensors in a good number of electronic systems. Touch sensors use Inter-digital capacitive electrodes made of transparent conductors. Proximity of an external body such as finger tip induces or modifies the e-field across the electrodes and the variations in e-field are amplified with suitable charge amplifiers and processed. However, such touch sensors based on e-field sensing are, in general, digital in nature. Such touch sensors are extensively used in touch screen systems.

Inter-digital capacitive sensors that can sense chemicals have also been developed, which are made of an inert substrate over which two comb electrodes are deposited [1]. A chemically sensitive layer, usually a polymer, is then deposited over the electrodes so that the layer material fills the gap between the electrode patterns. The chemical vapour to be sensed is absorbed or adsorbed into the polymer layer and modifies the dielectric permittivity of the layer, which correspondingly changes the electric field across the electrodes. Specific polymers have been used for organic vapor sensing as they exhibit rapid reversible vapor sorption and can easily be applied as thin or thick films following different techniques. The polymer layer can be chosen depending on its affinity to specific molecules to be detected. If different sensors with different polymer layers are configured to make a sensor array, it is possible to sense organic vapors containing different components. Such sensor arrays can be the part of an electronic nose for specific applications, depending on the sensitive layers chosen. It is also possible to develop multi-parameter sensor arrays made with ICE s.

An E-field sensor is essentially a fringing field dielectrometry sensor that has more or less the same principle of operation as a conventional parallel-plate or co-axial cylinder dielectric sensor cell. A voltage is applied to the electrodes, and the impedance across the electrodes is measured. The electric field lines pass through the medium between the electrodes; therefore the capacitance and conductance between the electrodes vary with the dielectric properties as well as the electrode geometry. Inter-digital dielectrometric sensors rely on the measurement of the dielectric properties of the insulating medium between the electrodes. A review article discussing various aspects of inter-digital sensors and transducers can be found in literature [1]. The references therein give the various applications for which such sensors are generally used. An analytical expression for the capacitance between two comb electrodes of a periodic inter-digital capacitive sensor, based on conformal mapping technique, has been obtained by Igreja and Dias [2]. Their model is a general one and can be applied to any space and finger width as well as for any number of layers with different thickness and permittivity. The capacitance for a sensor configuration is a function of the dielectric permittivity of the medium and the geometrical parameters of the fingers. Jia *et. al.* has reported the design and characterization of a passive wireless strain sensor which employs a planar inductor with a series connected inter-digital capacitor of the type outlined above [3].

Several semiconductor device manufactures make evaluation circuits which can be interfaced directly to E-field sensor electrodes. Such circuits provide computer compatible digital output in standard formats, which are easy to process further with a computer.

In this work we report the development of a pressure sensor by modifying an Inter-digital capacitive electrode working as an E-field sensor. The modification involves introduction of a suitable buffer medium above the electrode pattern and applying the pressure over to it. Application of pressure modifies the dielectric constant of the medium across the electrode structure and correspondingly varies the electric field across it. It is demonstrated that the e-field increases exponentially with applied pressure over a defined pressure range, which makes the system a very sensitive pressure sensor. The principle of the technique, configuration of the sensor and its characteristics are described below. The areas of application of such sensors are discussed. It is demonstrated that such sensors made into an array are very convenient for use in differential pressure sensing in biomedical instrumentation systems such as plantar foot pressure measurement systems, human back pressure monitoring systems etc.

2. Sensor Configuration and Modeling

The design of any Inter-digital Capacitive Electrode sensor requires closed form expressions for the computation of the effective capacitance, based on the geometry of the sensor pattern and the dielectric properties of the medium between the electrodes. Consider an electrode pattern of the form shown in Fig. 1.

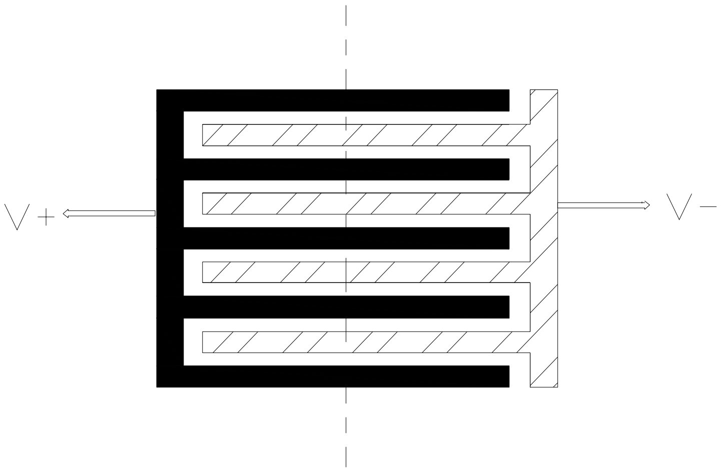

Fig. 1. Typical electrode pattern for an Inter-digital capacitive sensor (Top view).

It is shown that this electrode pattern can be converted into a pressure sensor by placing a soft elastomer sheet over the electrode pattern and applying pressure above it. A side view of the layout of the electrode configuration, imagining the electrode pattern to be cut along the dotted line shown in Fig. 1, is shown in Fig. 2.

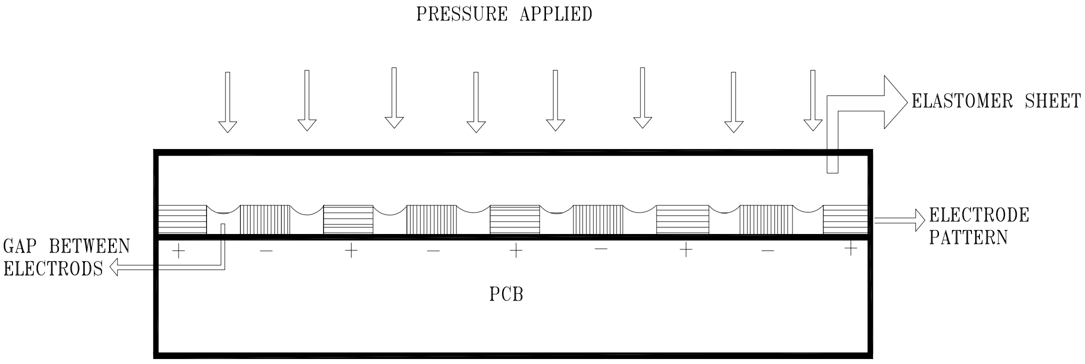

Fig. 2. Side view of the electrode pattern with the elastomer sheet placed above the electrode.

The electrode pattern, made of conductive copper, is fixed on a printed circuit board (PCB) following photolithographic and etching process. The elastomer sheet of appropriate thickness and shore-A hardness is cut to the same area as the electrode pattern so that a uniform pressure applied above the elastomer sheet uniformly varies the permittivity of the medium between the electrodes. The pressure applied over the elastomer sheet can change the electric field across the positive and negative electrodes due to the following reasons.

i) The dielectric permittivity of the elastomer medium changes with applied pressure due to the high compressibility of the medium and hence changes the electric field across the electrodes.
ii) Application of pressure can make the elastomer medium penetrate into the gap region between the electrodes, shown as blank gap in the electrode pattern shown in Fig. 2, which in turn changes the permittivity and hence the electric field across the electrodes.

Experimentally one sees an effective change in electric field as a result of the combined effect of the two mechanisms listed above.

In order to establish the relationship between the applied pressure and the effective dielectric permittivity of the medium between the electrodes, we can follow an approach adopted by several previous workers. They have followed a method of calculating the effective capacitance of the inter-digital electrodes from a conformal mapping based on the transformation of two-dimensional analytical function in the complex domain [2]. Conformal mapping transformation transforms the ICE into an equivalent parallel plate capacitor, whose capacitance can be estimated directly. The general expressions used for the estimation of multilayer inter-digital electrode capacitance can be found in literature [4]. It is of the form,

$$C_S = L\,[(N-3)\,C_I/2 + 2\,C_I C_E/(C_I+C_E)],\ N > 3, \tag{1}$$

where C_I being half the capacitance of one interior electrode relative to the ground potential and C_E the capacitance of one outer electrode relative to the ground plane next to it .It is assumed that the length L of the each sector of the electrode is infinitely long compared to its width W. Once all other electrode parameters are fixed, the total capacitance between the negative and positive electrodes of ICE, Cs will be directly proportional to the relative dielectric permittivity of the medium between the electrodes, and hence to the uniform hydrostatic pressure applied over the elastomer medium placed over the electrode.

If p_0 is the atmospheric pressure, the enhanced density of the compressed elastomer medium, ρ_r with applied pressure p is given by [5]

$$\rho_f = \frac{\rho_r (p/p_0)}{(\rho_r/\rho_0 - 1) + (p/p_0)}. \tag{2}$$

Here ρ_r is the density of the compressible component in the elastomer medium (like rubber content in foam rubber) and ρ_0 is the initial density of the elastomer material. For simplicity this expression can be rewritten as

$$\rho_f = \frac{k_1 p}{k_2 + k_3 p}, \tag{3}$$

where, $k_2 = \frac{\rho_r}{\rho_0} - 1$ and $k_3 = \frac{1}{p_0}$.

The relation between material density and dielectric permittivity for a compressible medium is given by the Claussius-Mossoti equation, given by [6]

$$\frac{(\varepsilon_r - 1)}{(\varepsilon + 2)} \frac{M}{\rho_f} = \frac{N_A \alpha}{3\varepsilon_0}, \tag{4}$$

Here ε_r is the relative permittivity of the medium, M is the molecular weight of the monomer of the medium, N_A is the Avogadro's number and α is the polarizability of the medium. Equation (4) can be rewritten as

$$\rho_f = \frac{3\varepsilon_0 M}{N_A \alpha} \frac{(\varepsilon_r - 1)}{(\varepsilon_r + 2)}, \tag{5}$$

This equation implies that the density of the compressible medium is directly proportional to the dielectric factor $\frac{\varepsilon_r - 1}{\varepsilon_r + 2}$

$$\frac{(\varepsilon_r - 1)}{(\varepsilon_r + 2)} = k\rho_f, \tag{6}$$

where $k = {N_A \alpha} / {3\varepsilon_0 M}$ is called molar refraction per repeat unit.

Combining equations (3]) and (6), one gets

$$\varepsilon_r = \frac{(2kk_1 + k_3)p + k_2}{k_2 + (k_3 - kk_1)p}, \tag{7}$$

This expression connects the relative permittivity (or dielectric constant) to the applied pressure for the sensor configuration of the type shown in Fig. 2.

It is rather difficult to separate the contributions from the two effects listed earlier. However, since the thickness of the electrode pattern is very small (a few microns only), it is very reasonable to assume that the contribution from effect (i) (variation in dielectric permittivity with pressure) is much larger than the contribution from effect (ii) (variation in permittivity due to penetration of the elastomer into the gap across electrodes). Obviously, equation (7) takes into account effect (i) only.

3. Test Results and Discussion

We have configured a single sensor of the type shown in Fig. 2, with an elastomer medium kept above the electrode array. A calibrated dead weight tester was used to apply known pressures on to the top of the sensor and the output is amplified and measured with standard electronics employing an e-field evaluation board. A block diagram of the electronics used to test the sensor is shown in Fig. 3.

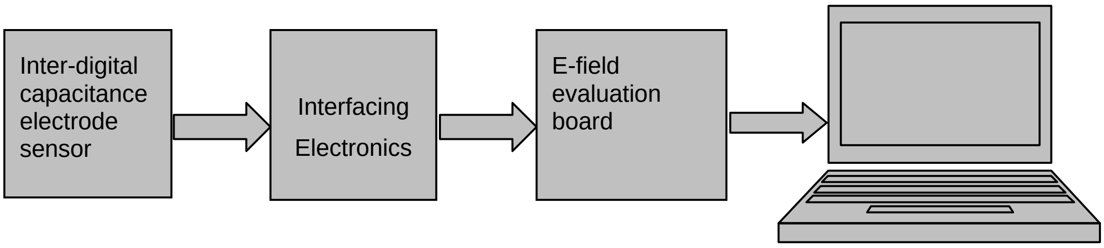

Fig. 3. Block diagram of the Experimental configuration used to record the pressure sensor response.

The response of the sensor to applied pressure is shown in Fig. 4. The measured responses are indicated by triangular points in the figure. The corresponding best fit curve is also shown in the figure as short dotted line.

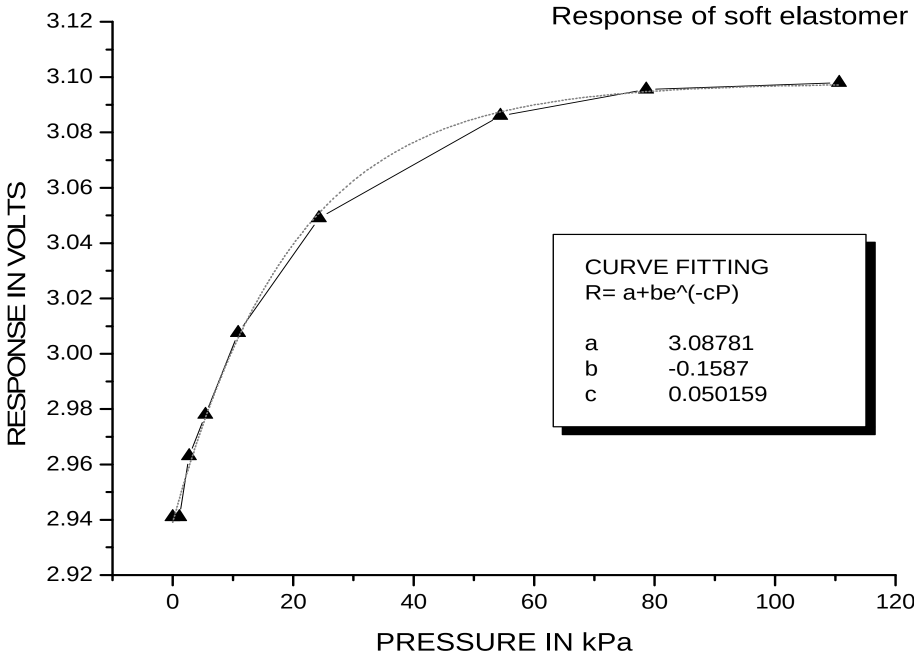

Fig. 4. Response of a typical sensor, configured as described in the text pattern.

The nonlinear response of the sensor to applied pressure is in tune with the variation of the relative permittivity with pressure given in equation (7). The sensor response has been measured several times, and it is found that the reproducibility of the measurement is very good. The drift in the output voltage during repeat measurements is less than 0.48 %.The zero stabilization of the sensor can be ensured by fixing the elastomer sheet tightly on to the electrode pattern. The voltage output from the sensor increases exponentially with applied pressure up to about 110kPa .The variation in the sensor output R with applied pressure P follows the relation

$$R = a + b * e^{-cP} \tag{8}$$

Here *a*, *b* and *c* are parameters that determine the nature of the variation of the output signal with applied pressure. The curve that fits best with the experimental curve gives the following values for these parameters: *a* =3.08781; *b* = -0.1587; *c*=0.050159.

As is evident from Fig. 4, the sensitivity of the sensor is nonlinear, with high sensitivity up to a pressure of about 75 kPa and then decreasing gradually for higher values of pressure. Up to an applied pressure of about 75 kPa the sensitivity is approximately 1.53 mV/ kPa. Experiments show that the response curve and sensitivity of the unit, as well as the dynamic range of the sensor strongly depend on the compressibility (elastic modulus) and thickness of the elastomer sheet placed above the electrode. We have optimized these with a proper choice of the elastomer sheet and its thickness so that it works well in the pressure range 0-120 kPa. The sensor response is optimized for this range as this is the pressure range of interest for many biomedical pressure sensing systems such as plantar foot pressure measurement units, where multiple sensors (typically 48 sensors) share the load. The elastomer sheet parameters can be suitably modified for other pressure ranges and applications.

The nonlinear response of the sensor is not a disadvantage as long as the repeatability and reproducibility are good. The sensor response can be stored in the computer memory as a look up table and the output corresponding to any applied pressure read from it. The present types of sensors are envisaged to be used as sensor arrays for distributed pressure sensing, where the systems are nowadays designed to work under microcontroller/microcomputer control for data acquisition and analysis. The look-up table can be stored into memory of the systems and the output corresponding to applied pressure to each sensor read from it.

The main advantage we see for this sensor configuration is that it is easy to configure multiple sensors for distributed pressure sensing applications. Since any number of sensors can be organized in a single process, with just one elastomer sheet of sufficient area, the sensor pattern can be made very cheap. We envisage such sensor arrays to find applications for distributed pressure sensing in bio-medical systems such as plantar foot pressure measurement systems, human back pressure monitoring systems etc.

4. Conclusions

We have successfully developed a modified inter-digital capacitive pressure sensor with a sensitive elastomer sheet acting as the pressure transmitter element, suitable for distributed pressure sensing applications such as plantar foot pressure measurement, human back pressure measurement etc. Analysis of the performance of the sensor configuration reveals that it is convenient, sensitive, reproducible and economical for use in many applications, particularly biomedical pressure sensing applications.

Acknowledgements

Work supported by Kerala State Council for Science, Technology and Environment (Grant No. 010/STP/ETP-2/2006/CSTE). One of the authors (TJG) acknowledges the financial support by Council of Scientific & Industrial Research (CSIR), Government of India.

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- Sensor instrumentation;
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