PTL APPLICATION NOTE AN3

ENGINEERING DESIGN RULES FOR ECT SENSORS

Issue 4

March 2001

ABSTRACT

This Application Note explains how the design of a capacitance sensor for use with an Electrical Capacitance Tomography (ECT) system influences the performance of the system. A set of engineering rules are developed which allows successful working ECT sensors to be designed for use with specific materials.

PROCESS TOMOGRAPHY LTD

64, Courthill House, Water Lane, Wilmslow, Cheshire. SK9 5AJ United Kingdom.

Phone/Fax 01625-418722
(From outside UK +44-1625-418722)
email: enquiries@tomography.com Web site: www.tomography.com

Registered in England No. 2908507. Registered Office 15, Croft Road, Wilmslow, Cheshire. SK9 6JJ United Kingdom.

1. INTRODUCTION

Electrical Capacitance Tomography is a technique for obtaining information about the contents of vessels, based on measuring variations in the dielectric properties of the material inside the vessel. The basic idea is to fit a number conducting plates (electrodes) around the periphery of the vessel and to measure the capacitance variations which occur between combinations of electrodes when a dielectric material is introduced inside the vessel.

An important step in planning a successful ECT application is the design of the capacitance sensor unit, as this will normally be unique for each new application. This note explains how the various design parameters of ECT sensors interact and affect the overall sensor performance, and develops a set of design rules which allow an effective ECT sensor to be constructed for a specific application. The Application Note concentrates on the design of sensors for use with vessels having circular cross sections (although many of the comments apply to vessels of any cross section).

The design of ECT sensors is closely linked to the capabilities of the capacitance measuring equipment to be used with the sensor. An ideal capacitance measuring system will have a very low noise level, a wide dynamic measurement range, high immunity to stray capacitance to earth and be able to carry out measurements at high speed. The information given in this paper is largely based on the capabilities of the PTL DAM200 Data Acquisition Module which can measure capacitance in the range 0.1 to 2000 fF with an rms noise level around 0.07 fF.

The sequence of electrode excitation is fixed in the DAM200 unit and only one electrode can be a SOURCE electrode, excited at a potential above that of earth, at any one time. The remaining electrodes are set to be DETECTOR electrodes and are maintained at virtual earth potential. This is not the only possible mode of operation of an ECT system but is the one on which most experience has been gained to-date and this note will therefore be restricted to a discussion of sensors suitable for use with single electrode excitation ECT systems of this type.

2. OVERVIEW OF SENSORS FOR ECT SYSTEMS

2.1 Sensors with external electrodes

Capacitance sensors for use with vessels of circular cross-section are normally customised modules which are individually designed for each specific application and can take one of two basic forms. The simplest arrangement from a constructional viewpoint consists of a non-conducting section of pipe surrounded by an array of equally-spaced capacitance electrodes with an overall outer earthed screen as shown in figure 1(a). A simple sensor of this type is shown in figure 2. This arrangement has the advantage that contact with and possible contamination of the electrodes by the fluid inside the pipe is avoided and the measurement is therefore non-invasive. However, sensors with electrodes on the outside of the vessel wall can exhibit considerable non-linearity in their response to dielectric materials introduced inside the sensor. This effect is caused by the presence of the sensor wall, which introduces an additional (and unhelpful) series coupling capacitance into the measurement of the inter-electrode capacitances.

2.2 Sensors with internal electrodes

An alternative arrangement is to fit the electrodes inside the vessel as shown in figure 1(b). In the case of a metal-walled vessel, this requires the use of some form of insulated liner supporting the electrodes, which then is placed inside the vessel. Although it is more difficult to design and construct this type of sensor from a mechanical viewpoint, sensors with electrodes inside the vessel do not suffer from the non-linearity problems exhibited by sensors with external electrodes and if the highest accuracy is required, this type of sensor should be used in preference to a unit with external electrodes.

2.3 Screening arrangements

For both types of sensor, the inter-electrode capacitances are typically fractions of a picoFarad and an earthed screen must be placed around the electrodes to eliminate the effects of extraneous signals and variations in the stray capacitance to earth, which would otherwise predominate and corrupt the measurements. ECT sensors must have a high level of mechanical stability, as any small movement between electrodes will change the values of inter-electrode capacitances. The electrodes are connected to the capacitance measuring system by individual coaxial connecting leads.

The capacitance measuring system normally imposes an upper limit on the allowable capacitance between each sensor electrode and earth. In the case of the PTL DAM200 unit, this value is 200 pF and this figure includes the capacitance of the coaxial connecting leads (typically 100pF/metre) as well as the capacitance between each measurement electrode and the external sensor screen.

2.4 Guard electrodes

If the sensor electrodes are short compared with the diameter of the sensor, extra axial guard electrodes will normally be required at each end of the measuring electrodes. The purpose of the guard electrodes is to maintain a parallel electric field pattern across the sensor in the region of the measuring electrodes, by preventing the electric field lines from from spreading axially at the ends of the measuring electrodes. This improves both the axial resolution and the sensitivity of the sensor. The guard electrodes are connected to guard driving circuitry in the capacitance measuring unit. Earthed axial electrode tracks may also be needed between adjacent measuring electrodes to reduce the standing capacitance between adjacent electrodes to a value low enough to avoid overloading or saturating the capacitance measuring system. These earthed tracks can also be extended radially out to the earthed outer screen to further reduce the adjacent electrode capacitances.

2.5 Number of electrodes

The choice of the number of electrodes around the circumference of the sensor is a tradeoff between axial and radial resolution, sensitivity and image capture rate. Existing PTL ECT systems can be used with sensors having 6, 8, or 12 electrodes. The electrodes normally occupy most of the circumference of the sensor and as the measurement sensitivity depends on the surface area of the sensor electrodes, the same sensitivity can be achieved with either a small number of short electrodes or a larger number of longer electrodes. If the number of electrodes is increased, the radial resolution will be improved, while a reduction in the length of electrodes will give better axial resolution. As measurements are made between each electrode and every other electrode, there are N(N-1)/2 possible unique capacitance measurements per image for a system with N measuring electrodes (corresponding to 66 individual measurements for a 12 electrode sensor). It follows that more measurements will be required to collect data for each image as the number of electrodes is increased, and hence the speed of data capture will be reduced as the number of electrodes is increased.

2.6 Electrode Numbering Convention

By convention, electrodes are numbered anticlockwise, starting in the first quadrant above the horizontal. So for a 12 electrode system, electrode 1 lies in the sector from 0 to 30 degrees, electrode 2 in the sector from 30 to 60 degrees and so on as shown in figure 1.

2.7 Typical Inter-Electrode Capacitance Values

The values of measured inter-electrode capacitances for a typical 12-electrode sensor containing air are shown in figure 3. These figures were measured using a 50 cm diameter sensor having relatively long external measurement electrodes (10 cm). The sensor did not contain driven guard electrodes. Although there are 66 possible unique values of inter-electrode capacitance, these reduce to a set of 6 generic capacitances (C1-2, C1-3. ......C1-6) as long as the sensor is symmetrical and is either empty or is filled with a uniform material. Note that C1-2 means the capacitance measured between electrode 1 and electrode 2 etc..

From the results shown in figure 3, it can be seen that there is a wide range of values for the inter-electrode capacitances, ranging from a high figure of 500fF for adjacent electrodes to a low value of 10fF between opposite electrodes. These values were measured with the sensor containing air and will normally increase if any other dielectric material is introduced into the sensor.

Note that an assymetrical capacitance distribution has occurred because the sensor measured used a pcb foil construction (see section 2.8) with the join between electrodes 1 and 12. Small errors in the inter-electrode gap cause large errors in inter-electrode capacitance values and it is therefore preferable to locate the join along the centre of an electrode for this reason.

This wide range of standing capacitances causes problems for the capacitance measuring unit, which will normally have an upper and lower limit for the range of measurable capacitances (Cmax and Cmin). In the case of the PTL DAM200 unit, the upper measurement limit Cmax is 2000fF and the lower limit Cmin is approximately 0.1fF.

The value of the standing capacitance between adjacent electrodes can be reduced either by simply increasing the spacing between the electrodes (at the expense of reducing the capacitance between all electrodes per unit length) or by the combined effects of an earthed axial screening track placed between the electrodes and the presence of an external circumferential earthed screen. Experience has shown that for typical sensors, with an earthed axial screening track and an outer screen located approximately 0.5cm from the electrodes, the capacitance between adjacent electrodes is approximately halved compared with the value in the absence of the screens. However, this produces little effect on the capacitance between non-adjacent electrodes.

Typical capacitances for a 12 electrode sensor with suitable driven guard electrodes (see design rules 4.4 and 4.5) are approximately 100fF per cm of electrode length (K1) between adjacent electrodes and 1 fF/cm (K2) between opposite electrodes. For an 8 electrode sensor, the capacitance per unit length between adjacent electrodes is similar to that for 12 electrode sensors, ie around 100fF/cm, however, the capacitance per unit length for opposite electrodes increases to around 2 fF/cm.

2.8 Electrode fabrication

A typical electrode arrangement for a single plane 8 electrode sensor with driven guard electrodes is shown in figure 4. The electrodes are fabricated using photolithography techniques from flexible copper-coated plastic laminate which is etched with the required electrode pattern and then wrapped around the outside of the pipe or vessel. Figure 4 shows a negative image of an unrolled electrode laminate. The white areas are copper foil and the black lines represent insulating gaps between the electrodes. The 8 measurement electrodes are in the centre of the sensor and driven guard electrodes are located at each end of the measurement electrodes. Axial conducting strips separate the sets of electrodes and are connected to earthed areas at each end of the sensor.

The laminate is attached to the outside of an insulating pipe with the copper foil on the outside and connections are soldered to the measurement electrodes and guard electrodes using coaxial connecting leads. The two sets of guard electrodes must be interconnected using lengths of insulated wire which pass over each measurement electrode. Further detailed information about sensor fabrication is given in Appendix 1.

2.9 Lengths of Measurement and Guard Electrodes

The image produced by an ECT system is derived from the capacitances measured between the sensor electrodes. As these capacitances are proportional to the surface area of the electrodes, the measurement electrodes must have a finite length Lm. The image is therefore derived from capacitance measurements averaged over the length of the electrodes and it follows that an ECT system can not produce images with very high axial resolution because of the need to have electrodes of finite length.

In an ideal ECT sensor, the electric field lines will be normal to the sensor axis. However, if electrodes are used which are short compared with the diameter of the sensor, the field lines will spread out at the ends of the measuement electrodes. This will have two consequences:

1. The capacitance measured between electrodes will be reduced and hence the measurement sensitivity will also be reduced.

2. The axial resolution of the sensor will be degraded because of the axial spreading of the field lines at the end of the sensor.

This problem can be virtually eliminated by the use of driven guard electrodes at each end of the measuring electrodes as described previously. Experiments have been carried out to establish the required length for guard electrodes Lg. Figure 5 shows how the length of guard electrodes increases the capacitance measured between two electrodes of length 1cm in an 8 electrode sensor of diameter 15 cm, with driven guard electrodes of equal length Lg at each end of the measurement electrodes. It can be seen from figure 5 that when Lg equals the sensor radius, the capacitance measured between opposite electrodes is approximately 60% of the maximum possible value (which can only be realised with infinitely long guard electrodes).

2.10 Electrostatic charge precautions

As ECT sensors often contain dielectric materials which are in motion, there is a high probablility of electrostatic charge accumulating on the measuring electrodes, resulting in the development of high voltages between the electrodes and earth. These voltages could easily damage the sensitive electronic circuitry in the capacitance measuring unit and precautions must be taken to prevent excessive voltages from becoming established on individual electrodes. This is done in practice by connecting discharge resistors (of value 100K - 10M Ohm) between each individual measuring and guard electrode and earth. The discharge resistors must be integrated into the sensor itself (not the capacitance measuring unit).

2.11 Sensor Calibration

The standard method currently in use for calibrating ECT systems and sensors is to measure the inter-electrode capacitances when the sensor is filled with dielectric materials having permittivities at the extreme ends of the measurement range of interest. Hence the sensor will first be filled with a material having a low dielectric constant, emptied, and then refilled with a second material having a higher dielectric constant. These sets of inter-electrode capacitances are then normalised to values of 0 at the lower permittivity calibration point and 1 at the higher permittivity calibration point. From these capacitance measurements, images are constructed in which the image pixels have nominal values between 0 (corresponding to the lower permittivity material) and 1 (corresponding to the higher permittivity material).

2.12 Sources Of Image Distortion

ECT is a so-called soft-field measuring technique. The object space is interrogated by electric field lines, which can be envisaged as curved lines running between the measuring electrodes. If a uniform dielectric material is introduced inside an ECT sensor with internal electrodes, so that the material completely fills the sensor, then the pattern formed by the electric field lines inside the sensor will be the same, irrespective of the permittivity of the dielectric material. However, if the space inside the sensor is only partially filled by dielectric, or if the dielectric material is non-uniform, the pattern of the electric field lines will be changed by the material inside the sensor. The effect will be to distort any image obtained from the measurements of the inter-electrode capacitances. This is analogous to the distortion of an optical image by an imperfect lens. Further image distortion is introduced by sensors which contain electrodes located outside the vessel wall. As the objective of an ECT system is to obtain an image based on variations in the permittivity of the material inside the sensor, allowance must be made for this distortion in the image reconstruction algorithm if an accurate image is to be obtained.

3. SENSOR PERFORMANCE

3.1 Sensitivity to permittivity perturbations

The sensitivity of an ECT sensor to small changes in permittivity inside the sensor varies with the radial position of the perturbation and is also a function of the size of the perturbation and the magnitude of its permittivity change. Circular ECT sensors have maximum sensitivity near the sensor wall and minimum sensitivity at the centre of the sensor.

3.2 Axial and Orthogogonal Resolution.

Provided that adequate driven guard electrodes are used, the axial resolution achievable with a given sensor will be approximately equal to the axial length of the measuring electrodes.

It is more difficult to define the orthogonal resolution (ie the resolution across a diameter) because the sensitivity of the sensor to a minor perturbation in permittivity varies along the diameter as described in the previous section. As a rule of thumb, the orthogonal resolution will be approximately equal to D/N where D is the diameter of the vessel and N is the number of measurement electrodes placed around the circumference of the sensor.

4. SENSOR DESIGN RULES

4.1 Internal or external electrodes

If the vessel wall is metallic, internal electrodes must be used. If the vessel wall is made of an insulating material, the electrodes can be placed either inside or outside the vessel wall. A sensor with internal electrodes will normally have superior electrical performance to one with internal electrodes, but the design and construction of sensors with internal electrodes is considerably more complex than that for sensors with external electrodes.

4.2 Number of electrodes.

The maximum number of electrodes (12) should be used wherever possible, provided that sufficient measuring sensitivity and axial resolution can be achieved. For the best axial resolution, a small number of short measurement electrodes should be used. The axial resoultion will be approximately equal to the length of the measurement electrodes. For the best resolution across the image plane, a large number of longer measurement electrodes should be chosen. The orthogonal resolution will be approximately D/N where D is the sensor diameter and N is the number of measuring electrodes.

4.3 Maximum and minimum inter-electrode capacitance values..

For a sensor to be able to image materials having permittivities in the range from a lower value of E1 to an upper value of E2, with a measurement system which can measure capacitance over a range from Cmin to Cmax, the sensor should be designed so that:

- The capacitance measured between **adjacent** electrodes, with the sensor containing the **lower permittivity material** (E1), must be less than **Cmax.(E1/E2**). This is necessary to allow the capacitance when the sensor is full of the higher permittivity material (E2) to be less than the maximum measurable value Cmax.

- The capacitance measured between **opposite** electrodes with the sensor containing **the lower permittivity material** must not be less than **K.Cmin**, where K is a constant (typically 50) This ensures that a relatively noise-free measurement of the opposite electrode capacitance can be made.

These capacitance values can be translated into equivalent electrode lengths using the typical figures for capacitance per unit length for adjacent and opposite electrodes (K1 and K2) given in section 2.7.

4.4 Total electrode length

The total electrode length Lt (including the measurement and driven guard electrodes, but excluding the earthed end regions) should normally be at least equal to the diameter of the vessel to be imaged as discussed in section 2.9. A larger value for Lt will further increase the sensitivity of the sensor.

4.5 Lengths of measurement and guard electrodes

The minimum usable length of measuring electrodes is Lmin = Cmin/K2 and the maximum length Lmax is Cmax/K1, where Cmin and Cmax and the values for K1 and K2 are those given in section 2.7. This will define the range of possible lengths for the measurement electrodes. The final choice will need to be made on the basis of the required axial resolution and measurement sensitivity.

Once the length of the measurement electrodes has been chosen, the length of the guard electrodes can be evaluated using the following equation:

$$Lt = Lm + 2.Lg \ .$$

where Lt is the total electrode length (section 4.4), Lm is the length of the measurement electrodes and Lg is the length of the driven guard electrodes.

4.6 Screening arrangements

The measuring electrodes must be completely surrounded by an earthed, metal screen and the measuring and guard electrodes must be connected to the measuring unit by screened coaxial connecting leads. For the PTL DAM200 unit, the maximum capacitance between any measuring electrode and the earthed screen should not exceed 200 pF. It should be noted that this figure includes the capacitance of the coaxial connecting leads (100pF per metre length).

4.7 Connecting leads

The measurement and guard electrodes must be connected to the capacitance measuring unit by screened coaxial cables (recommended type RG174), terminated in SMB coaxial connectors. The maximum length of connecting lead should not exceed 1.5 metres. The inner conductor of each coaxial cable should be connected to the pcb electrode and the outer braid of the cable must be connected to an earthed area of the pcb laminate.

4.8 Electrostatic precautions

Each measurement and guard electrode must be connected to an earthed area on the sensor laminate by an individual discharge resistor. Suitable values of resistor are 1Mohm, 0.25 Watts.

5. PRACTICAL VALUES

From experience gained to-date with the PTL300 ECT system, we suggest the following minimum lengths should be used for measurement and guard electrodes:

No of electrodes	**Minimum length of measurement electrodes cm**	**Total electrode length including guard electrodes cm**
6	**2.5**	**D**
8	**3.5**	**D**
12	**5**	**D**

where **D** is the diameter of the sensor. Improved sensitivity will occur by increasing either the length of the measurement or gurad electrodes or both of these.

APPENDIX 1

SENSOR FABRICATION

A1.1FLEXIBLE COPPER-COATED LAMINATE

One flexible laminate material which has been used successfully by PTL to fabricate sensors is GTS77012ED copper polymide (Kapton) laminate. This material is available in rolls of 610mm width and consists of a 50 micron film of plastic coated with a 35 micron layer of copper. The material can be soldered without damage at a temperature of 300 degrees centigrade.

The UK supplier is:
GTS Flexible Ltd.,
41 Rassau Industrial Estate,
Ebbw Vale,
Gwent.
NP3 5SD,
UK.

Phone 01495 307060, Fax 01495 306333.

The electrode pattern is produced using standard printed circuit board design techniques. The electrode pattern must be drawn using a suitable CAD package and plotted by a photoplotting bureau to produce an accurate artwork suitable for pcb manufacture.

A1.2 EXTERNAL SCREEN

This can take a number of forms.

If a metallic tube of a convenient size is available, then this can be used directly.

If a plastic tube is available, it can be used by lining it either internally or externally with a conducting material. For experimental work, self-adhesive copper tape is suitable.

The screen can also be formed from a flexible copper sheet wrapped around the sensor and held in place with cable ties.

In all cases, the external screen must be connected electrically to the earthed region of the sensor foil using a short length of flexible connecting lead.

A1.3 GUARD ELECTRODE INTERCONNECTION

The driven guard electrodes at the ends of the measurement electrodes must be interconnected by short lengths of insulated wire, connected to each driven guard electrode. The coaxial connecting leads for the guard electrodes then only need to be connected to one electrode of each pair of guard electrodes.

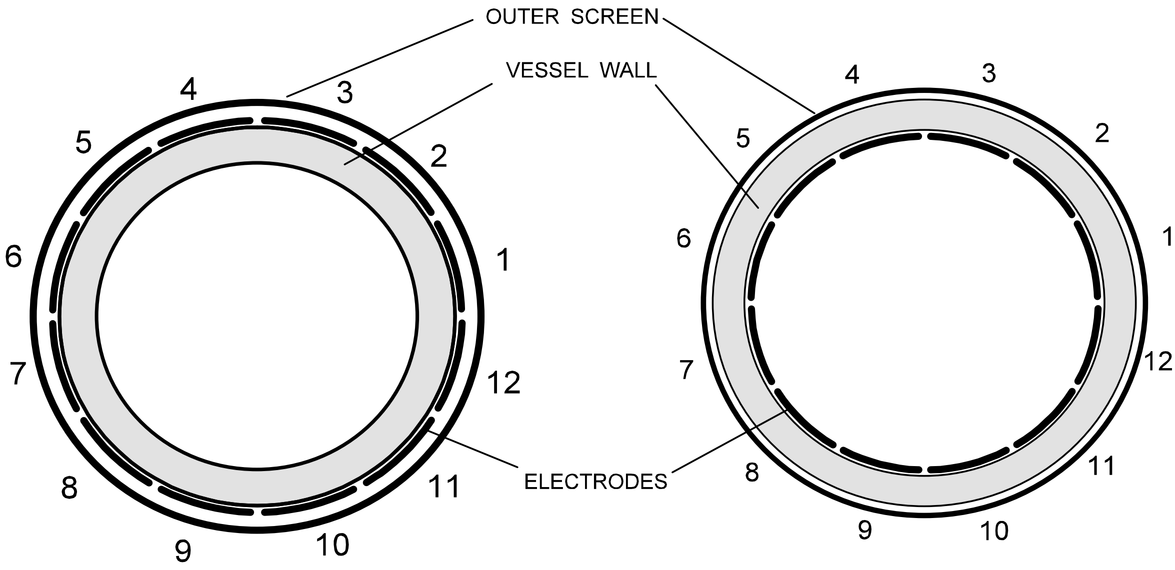


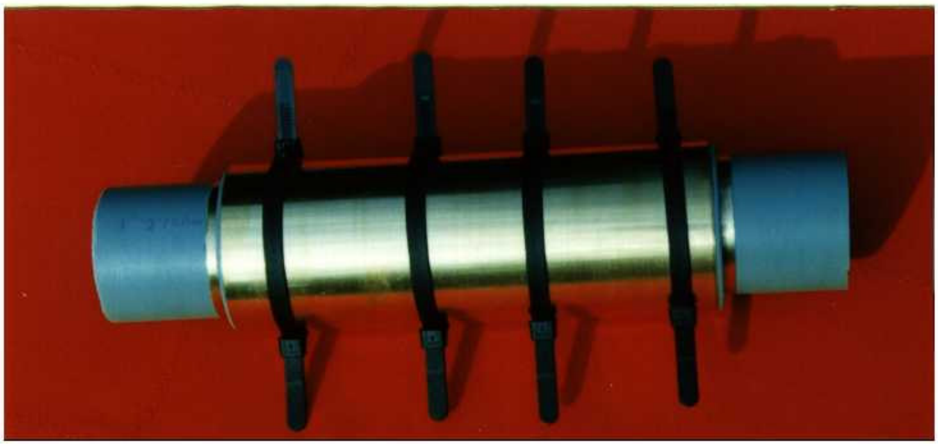
FIGURE 1(a) EXTERNAL ELECTRODES

FIGURE 1(b) INTERNAL ELECTRODES

FIGURE 1. CROSS SECTIONS OF SENSORS WITH INTERNAL AND EXTERNAL ELECTRODES

Pipe with sensor electrodes

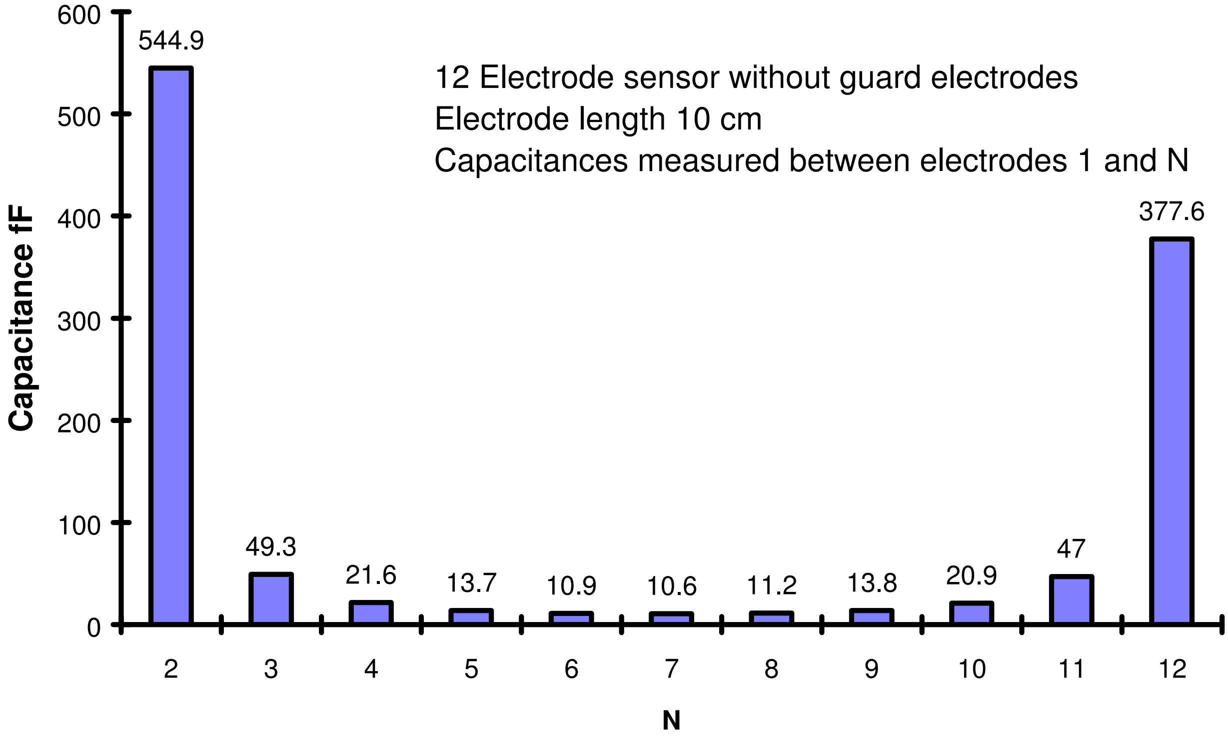
Addition of radial spacers



Addition of outer screen

Figure 2 Views showing construction of Demonstration ECT sensor

FIGURE 3. TYPICAL INTER-ELECTRODE CAPACITANCES C1-N



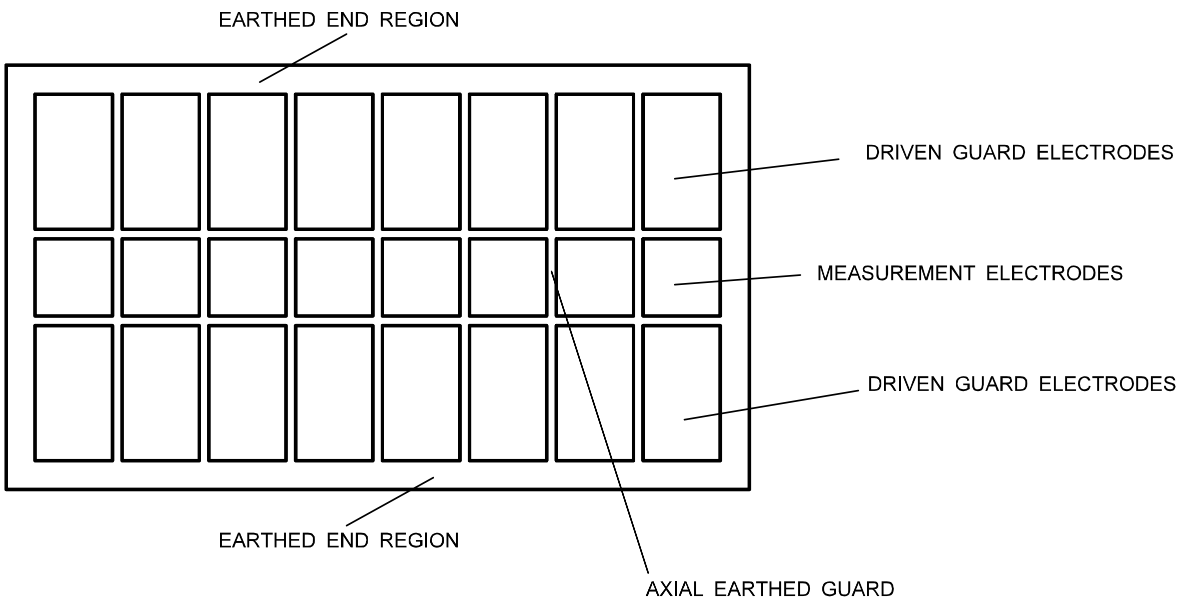


FIGURE 4. ELECTRODE FOIL ARRANGEMENT

Figure 5. Variation of capacitance between opposite electrodes with electrode length