An electrodynamic sensor for electrostatic charge measurement

M. F. Rahmat and N.S. Kamaruddin
Department of Control and Instrumentation Engineering,
Faculty of Electrical Engineering, Universiti Teknologi Malaysia,
Skudai 81310 Johor Malaysia
Email: fuaad@fke.utm.my

Abstract- Electrodynamic sensors are used in the process industry because they are low cost and robust. Though frequently used very little fundamental work on them has been reported. This paper describes an investigation into characteristics of hemispherically and rectangularly shaped sensors. Two parameters are investigated, the effect of sensor area on sensitivity and the spatial filtering effect of the sensor due to its finite size. Models are proposed and results obtained using them compared with experimental values.

Index terms: Electrodynamic sensor, sensitivity, spatial filtering effect, pneumatic conveyors, process tomography, measurement, mass flow rate

I. INTRODUCTION

Transducers which sense the electrostatic charge carried by dry solids have applications in determining flow parameters in pneumatic conveyors, e.g. the velocity of conveyed materials [1], the solids volume flow rate [2]. The measurement is based on charge being induced into the sensor as the charged particles flow past it. Sensors generally consist of areas of metal insulated from the walls of the conveyor. For process measurement ring electrodes are widely used and have been thoroughly investigated [3, 4].

The transducer is robust and low cost, so it has the potential to be applied for process tomography. In process tomography [5] several (typically 8, 16 or 32) identical transducers are positioned around the vessel being interrogated to provide measurements which are used to reconstruct dynamic images of the movement of the material being monitored. With large numbers of sensors the ring electrode is no longer applicable and small sensors consisting of either rectangular or circular section are more appropriate.

For applications where the process is varying rapidly, e.g. pneumatically conveyed solids, the measurement system parameters should be known. This paper investigates the relationships between sensor size, sensor sensitivity and the frequency bandwidth, termed the spatial filtering effect [6], of the transduced signals.

II. ELECTRODE SENSITIVITY

The electrode sensitivity is modelled for a circular electrode by considering the effect of a single charged particle, q, as it moves vertically downwards at a constant velocity, v.

The assumptions for the model are:

The point charge is travelling in an axial direction parallel to the axis of the pipe, the particle has a constant, finite amount of charge which is not dissipated during the time it travels through the sensing volume, the surface area of the electrode is small compared to the radius of the pipe, the charge acts as a point source and the pipe is of non conducting material.

Then for a single charged particle, assumed to be a point charge of value q, the field is uniformly radial

$$E = \frac{q}{4\pi r_i^2 \varepsilon_0} \quad (1)$$

This point charge induces a potential onto the surface of the small, flat electrode used to sense the change in potential at a point on the wall of a non-conducting or dielectric pipe. It is assumed that there are no other interacting fields on the electrode since there is no surface charge on the pipe wall.

For a given circular sensor, the surface area is πr_e^2 which is considered normal to the flux as shown in figure 1. So the proportion of flux passing through the sensor due to the charged particle at a distance i from it is

$$\frac{\pi r_e^2}{4\pi r_i^2} \quad (2)$$

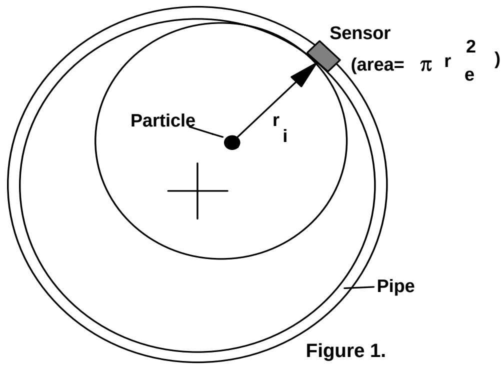

Figure 1.
Positional relationship between particle and sensor

Figure 1. Positional relationship between particle and sensor

The charge induced onto the sensor is proportional to q. Hence,

$$Q_e = \frac{kqr_e^2}{r_i^2} \tag{3}$$

Equation 3 suggests the amount of charge induced onto an electrode depends upon the radius of the electrode squared, i.e. the area of the electrode.

This charge is stored on a capacitor (figure 4) and provides a voltage V_e given by

$$Q_e = CV_e \tag{4}$$

The voltage is amplified, rectified, smoothed and averaged.

The sensitivity of the sensor is defined as $\frac{Q_e}{q_i}$. This value is difficult to determine because the level of the conveyed charge, q_i, is difficult to control. In this paper a series of sensor diameters are compared simultaneously so that the same q_i is detected by them all. Also it is the amplified, rectified and averaged voltage which is measured (section 5.1).

III.   SPATIAL FILTERING

An investigation into the spatial filtering effect arising from capacitance electrodes is described in a paper by Hammer and Green [6], which relates the velocity of flowing discontinuous material to the frequency bandwidth of the sensed signal[8]. This paper extends the concept to electrodynamic sensors. Process tomography using electrodynamic sensors will generally use circular or hemispherical electrodes, however, there may be applications requiring rectangular electrodes [7]. The results from the rectangular electrodes may be compared with the measurements obtained using capacitance electrodes [6].

Assume that a single charged particle moves past the sensor, of diameter or length a, at a distance d, with a velocity v, can be considered as a pulse of charge q(t). This moving charge results in a charge being induced into the sensor (figure 2). The quantity of charge induced into the sensor is described by:

$$\delta q_i(t) = k\frac{v}{a}\int_0^\infty \frac{q(t)}{d^2}dt \tag{5}$$

where q(t) represents the charge pulse provided by the moving particle and k is a constant of proportionality with appropriate dimensions. If the pulse duration is short compared with a/v it may be shown [6] that the response is a 'sinc' function with the effect of a and v on the modulus shown graphically in figure 3.

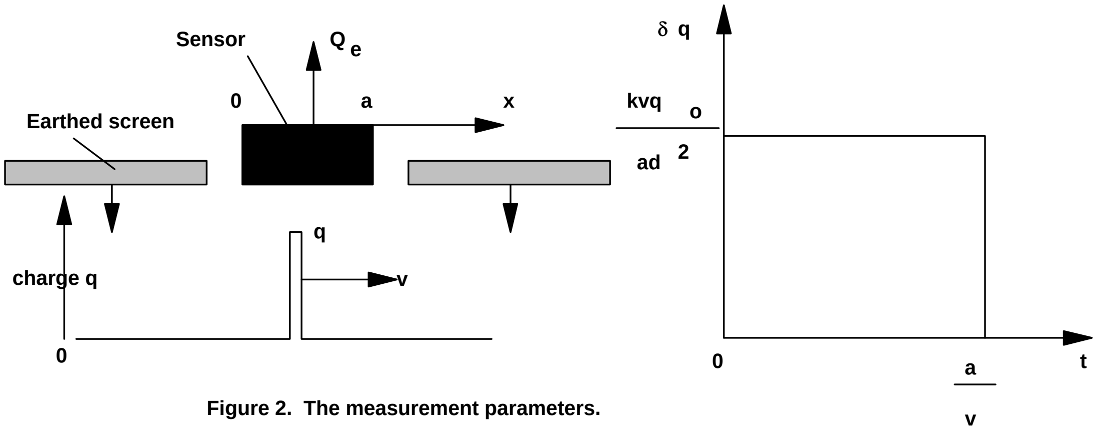

Figure 2. The measurement parameters

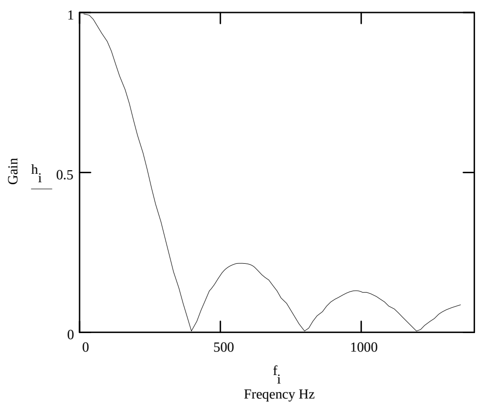

Figure 3. Frequency response for a = 0.005 mm, v = 2.0 m/s

The rectangular electrodes are much longer than the hemispherical ones and recordings of the voltage from the sensor, taken when investigating the spatial filtering effect, are slightly different to those from the hemispherical electrodes (section 5.2). The analysis referred to above requires modifying in order to determine the spatial filtering characteristics of long rectangular sensors.

In the experimental verification of this analysis, the long electrodes are curved to approximately the same radius as the charged bead moves along to ensure the bead electrode gap remains constant as it passes. In this case the charged bead is passing the electrode for a longer period than for the hemispherical sensor. The charge and discharge currents are noticeably spaced in time, as are the corresponding rectified voltages (figure 4). The spatial filtering effect for this system is calculated by considering the system as consisting of two impulses with a time delay separating them. If the pulse duration's are short compared with a/v they may be regarded as two Dirac pulses:

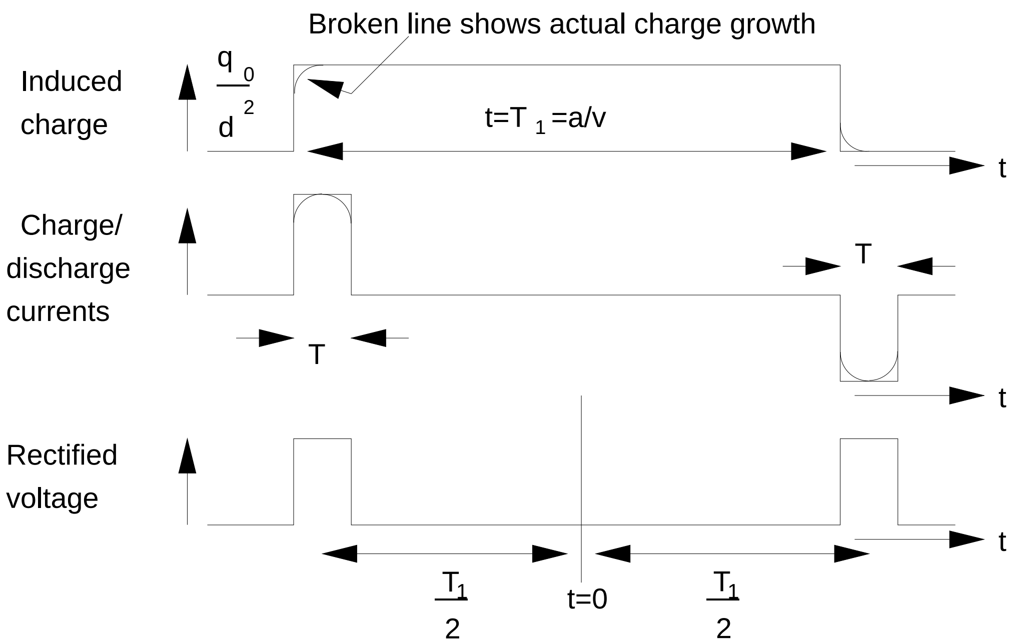

Figure 4. Idealised induced charge and corresponding voltages for the rectangular electrode.

Then the transducer response may be written

$$V_i(\omega) = \int_{-\frac{T_1}{2}-\frac{T}{2}}^{-\frac{T_1}{2}+\frac{T}{2}} k\frac{q_0}{d^2}e^{j\omega t}dt + \int_{\frac{T_1}{2}+\frac{T}{2}}^{\frac{T_1}{2}+\frac{T}{2}} k\frac{q_0}{d^2}e^{j\omega t}dt \qquad (6)$$

where T is the time taken to charge and discharge the electrode. After integration and expansion equation (6) gives

$$\frac{V_i}{q_0} = \frac{4k}{d^2\omega}\cos\frac{\omega T_1}{2}\sin\frac{\omega T}{2} \tag{7}$$

which may be written in the frequency domain as:

The modulus of equation 7 is given by

$$\left|\frac{V_i}{q_0}\right| = \frac{2k}{d^2}\left|\cos\frac{\omega a}{2v}\right|\left|\frac{\sin\frac{\omega T}{2}}{\frac{\omega}{2}}\right| \tag{8}$$

and the effect of a and v on the modulus shown graphically in figure 5.

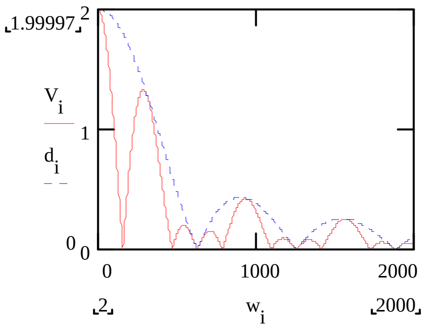

Figure 5. Predicted spatial frequency response for the rectangular electrode.

IV. ELECTRODYNAMIC SENSOR

The circuit diagram of the electrodynamic transducer is shown in figure 6. The sensor consists of a plain metal rod, termed the electrode, which is isolated from the walls of the metal conveying pipe by an insulator, e.g. glass or plastic. This electrode has a capacitance to earth, which is very small (fraction of a pico Farad) but variable due to manufacturing tolerances. To minimise the effect of this capacitance a low value capacitor (several pico Farad) is connected in parallel with it. A resistor is connected in parallel with the capacitors to provide a charge/discharge path.

The charged particles in the pipe flow past the electrode inducing charge into it in the process. The flow of current through the resistor due to this induced charge results in a varying voltage. This voltage is buffered by a unity gain non inverting amplifier whose output provides a driven guard for the input circuitry and is amplified and conditioned by further circuitry.

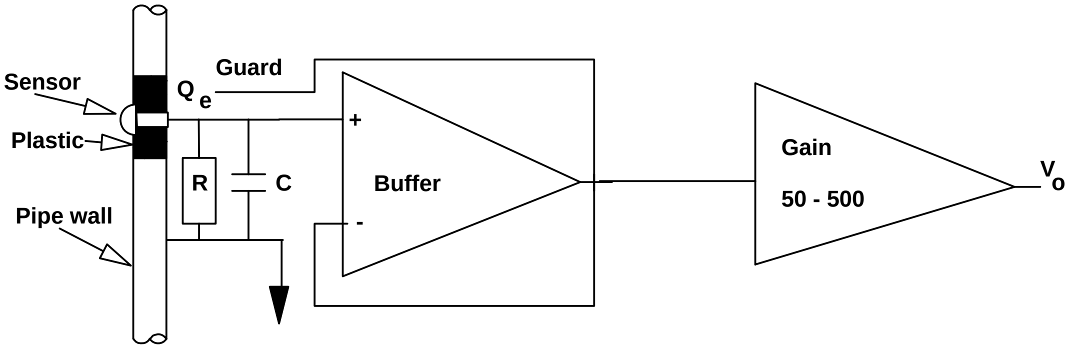

Figure 6. The transducer circuit.

V. MEASUREMENT

Results from two experiments are presented. The first experiment is used to determine the sensitivity of several electrodes at the same time by using an axial array of sensors and flowing sand. The second experiment investigates the spatial filtering effect of the electrodes by using a single, charged bead moving past the electrode at a known velocity.

a.Sensor sensitivity.

The sensitivity is determined by arranging a number of differently sized sensors so that sand flows past each of them in turn as shown in figure 7. The level of charge on the flowing sand is very difficult to quantify, however since the sensors are evaluated at the same time their outputs may be compared directly. The small diameter electrode at each end of the array checks that the flowing sand does not change its characteristics as it traverses the section.

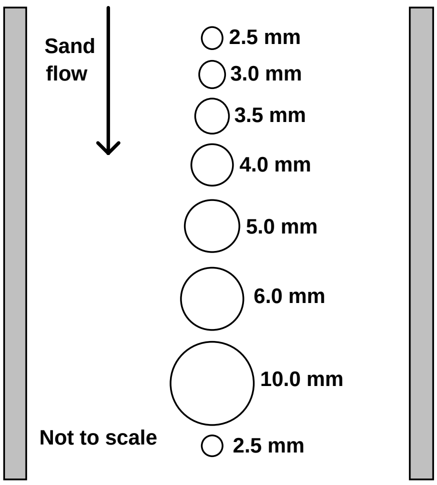

Figure 7. Arrangement of hemispherical electrodes for sensitivity measurements

A series of different sand flow rates are made to pass the electrodes and the resulting outputs determined. Results for the 3 mm diameter electrode are shown in figure 8.

A linear regression line is fitted to the measured values. The gradient of this line provides the overall sensitivity of the sensor (V/gm/s). To obtain the electrode sensitivity, the gain of each electronic amplifier was measured and divided into the overall sensitivity of the appropriate channel. The results are summarised in figure 9 which shows a straight line relationship between electrode sensitivity and electrode area.

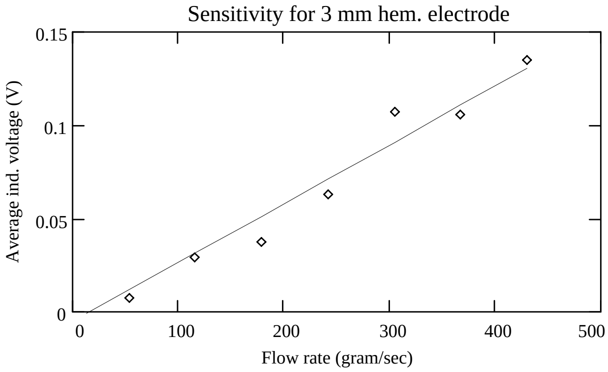

Figure 8. Mass flow rate versus averaged induced voltage for 3 mm hemispherical electrode.

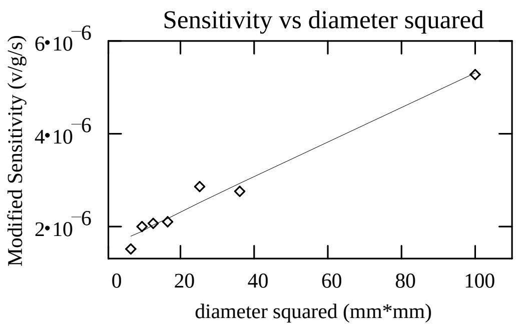

Figure 9. Plot showing sensitivity versus electrode diameter squared (hemispherical sensors).

The tests were repeated using rectangular electrodes 10 mm wide, but with lengths ranging from 20 to 300 mm. Similar analyses were carried out on the results and these are summarised in figure 10.

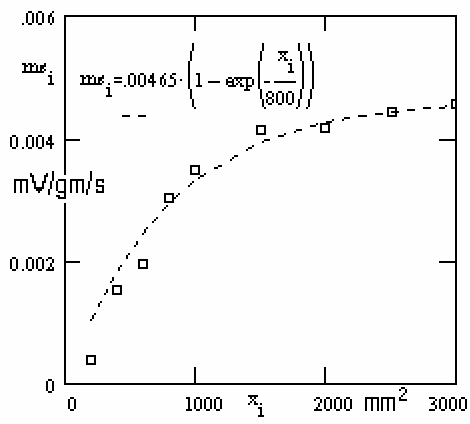

Figure 10. Plot showing sensitivity versus electrode area (rectangular sensors).

b. Spatial filtering.

The spatial filtering was carried out using a plastic ball mounted at the tip of a rod mounted on the shaft of an electrical motor (figure 11). The bead was electrostatically charged by contact with a charged plastic rod. The rod is rotated at a controlled rate and the ball passes the sensing electrode once per revolution. The angular velocity, ω, of the rod is determined from the induced pulse repetition rate. The speed of the bead is then calculated from v = rω, where r is the radius of the rod.

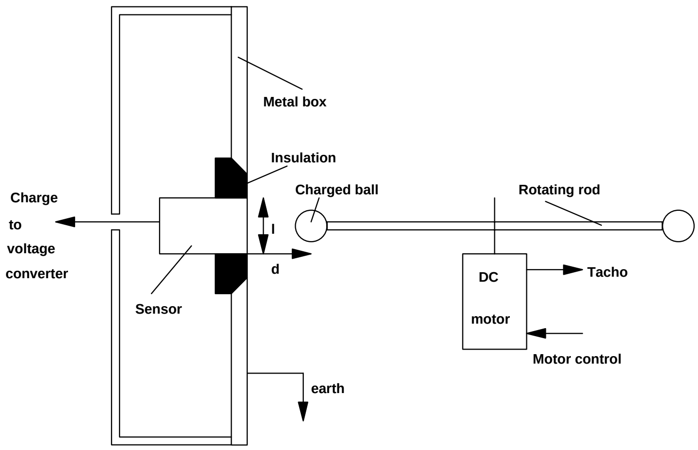

Figure 11. Apparatus for measuring the spatial filtering effect.

Figure 12 shows a typical result obtained using an hemispherical electrode.

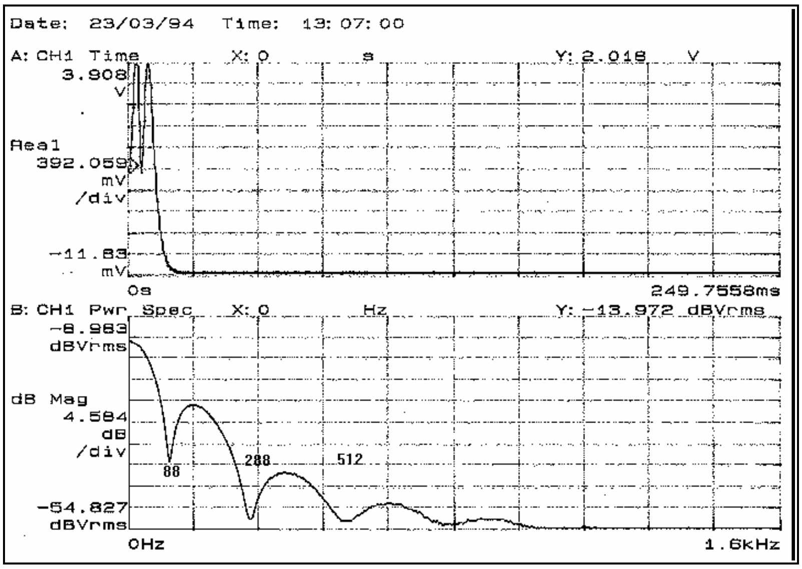

Figure 12. Relationship between effective electrode diameter and actual electrode with ac coupled amplifier. Hemispherical sensor, d = 3 mm, υ = 2.46 m/s, PW =12.5 ms, f_0 = 88 Hz

The electronic amplifiers used for the process tomography measurement system are ac coupled to minimise the effects of off-set drift in the operational amplifiers. However, for the tests on the long electrodes dc coupled amplifiers have been used. Spatial filtering effect results for the hemispherical electrodes are shown in figure 13. Equivalent results for the rectangular electrodes using dc coupled amplifiers are shown in figure 14.

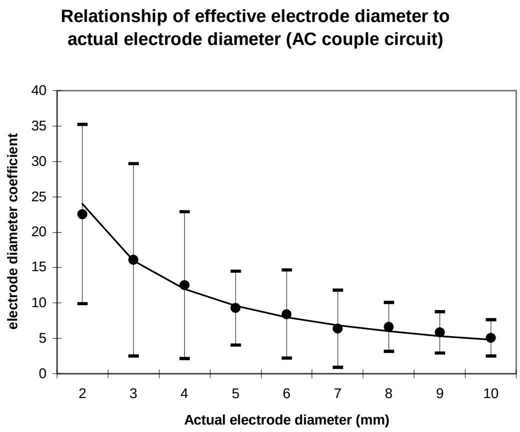

Figure 13. Relationship between effective electrode diameter and actual electrode with ac coupled amplifier.

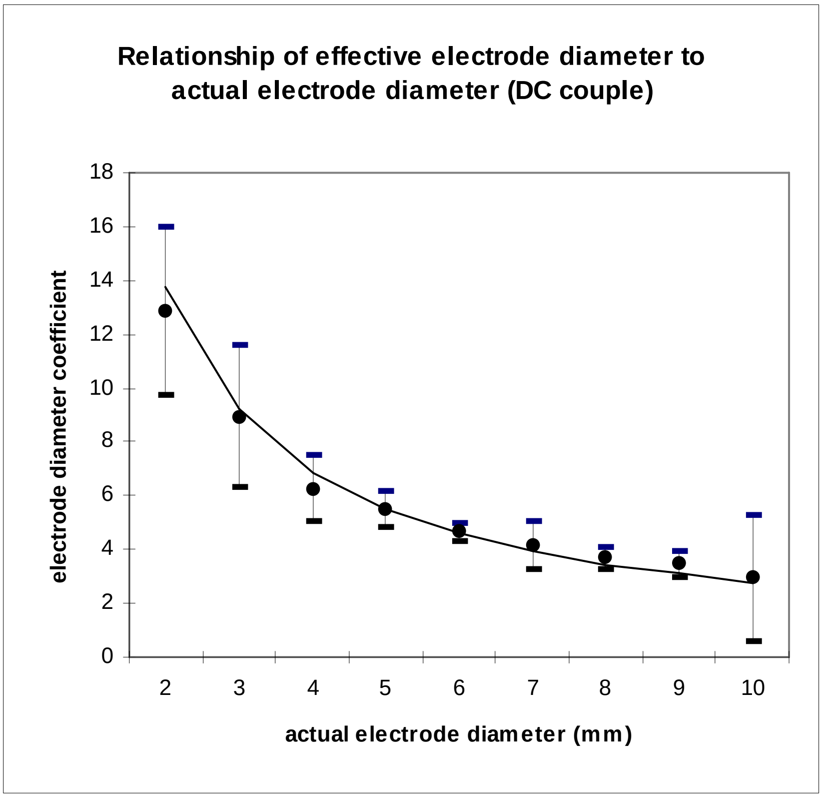

Figure 14. Relationship between effective electrode diameter and actual electrode with dc coupled amplifier.

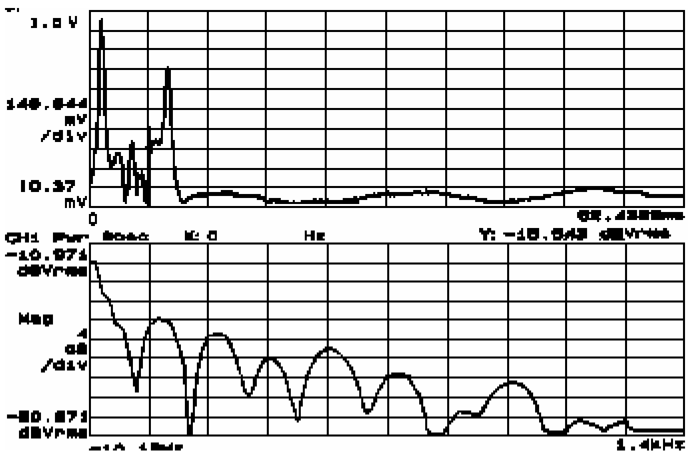

Figure 15. Typical result from rectangular sensor, dc coupled amplifier.

VI. DISCUSSION OF RESULTS

The results shown in figure 9 support the theory that the electrode sensitivity is a linear function of electrode area for the hemispherical sensors. However, figure 10 demonstrates that for long electrodes the sensitivity asymptotically increases to .00465 mV/gm/s with increasing length.

The spatial filtering with hemispherical electrodes produces two significant results. Firstly, the spatial frequency varies with the ratio a/v, however the predicted frequency bandwidth is always wider than the measured bandwidth as shown in figures 13 and 14. Secondly, the bandwidth of the amplifier contributes to the spatial cut off frequency.

The results for the long rectangular electrodes have a frequency characteristic which does appear to be the combination of sinc and cos functions predicted by equation 8. However, the calculated response is a complex relationship between a, v and T making the spatial bandwidth difficult to predict. Figures 5 and 15 show that the first minimum does not occur at the first minimum of the sinc function, but at a lower frequency.

Errors in predicting the spatial frequency probably arise from two assumptions. Firstly, the input consists of a rectangular induced charge whereas the recordings shown in figures 12 and 15 show otherwise. Secondly, the induced charge only exists as the charged particle passes by the electrode, which neglects the electrostatic field surrounding a charged body.

VII. CONCLUSIONS

As a conclusion, from the sensitivity investigation through theory and experimental work, it is found that linear relationship exist between circular or hemispherical size electrode and sensor sensitivity but a non linear relationship exist between rectangular size electrode and sensor sensitivity. For spatial filtering effect investigation, the frequency response characteristics for a circular size electrode give a sinc function response but for a rectangular size electrode give a combination of sinc and cos function response. Both sensor size are suitable to be applied in process tomography and solid particle sizing investigation.

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