



New technique to measure particle size using electrostatic sensor



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ARTICLE INFO

Article history:

Received 9 February 2013

Received in revised form

27 November 2013

Accepted 28 December 2013

Available online 9 January 2014

Keywords:

Ring electrode

FEM simulator

Sensitivity

Frequency spectrum

Peak's frequency

Signal conditioning circuit

ABSTRACT

A new technique is proposed to measure the particle mean size using an electrostatic sensor in frequency domain. This paper starts with a finite-element modeling simulator to model the induced electric charge of a ring electrode and to find the electrode sensitivity. The mathematical modeling was used to extract particle size information from the simulated signal in frequency domain. The method is applied in an experimental test where a low-noise signal conditioning was designed with a ring electrode as the electrostatic sensor. The method can be used to establish a cost effective size measurement system using electrostatic sensor.

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1. Introduction

One of the interesting areas to develop a reliable and cost effective instrumentation in particle and powder industries have been designing the measurement systems by using electrostatic sensor, which led to a lot of research and development on it. Particle movement in a pipeline or a conveyor can produce a small amount of electric charge on the particle surface due to particle to particle and particle to pipe wall friction and collision. The electric charge on the particle's surface can be detected using electrostatic sensor. Analysis of the sensor's output signal can provide information about the flow parameters. For instance, the velocity of the moving particle can be measured using the cross-correlation technique [1] or spatial filtering method [2]. Particles' mass flow rate measurement in direct method [3], concentration and charge distribution profile-map by utilizing process tomography method [4,5] and particle mean-size measurement [6,7] are some other studies that used the electrostatic sensor capabilities.

Particle size measurement using electrostatic sensor is studied by Zhang and Yan [7] to measure the mean size of particles in a mass flow in the conveyor. A direct method is used in which the magnitude of the output signal is directly related to the mean size of the particles in the conveyor. It is proposed that, from the statistical perspective the larger particle carries more charge than

smaller one, and that has been the fundamental basis for the proposed method. However, It depends on the conditions, e.g., under a constant mass flow rate, based on this theory, signal level should decrease [8].

The mean size measurement of a single particle is challengeable using the direct method. At the first, hardly two particles with the same size, material type and density can get an equal amount of electric charge on their surface. As a result, they induce a different level of electrostatic noise to the sensor, so the measurement system produces different results for the two the same size particles. Second, if two different size particles have an equivalent amount of electric charge on their surface, the measurement system will show identical results for the two particles with different sizes.

Based on the above, the purpose of this study is to measure the mean size of a single particle by applying a magnitude independent method in frequency domain using the electrostatic sensor. The solution involves the simulation results and mathematical modeling, where a logical relation was established between particle size and the frequency at the peak of the frequency spectrum (PFS) of the detected electrostatic noise. In the end, the experiments were conducted, and the experimental results were compared to that obtained from the simulation.

The rest of the article has four parts: a brief background of the electrostatic sensor and detail explanation of the charge induction process to the electrode with its related simulation results, the methodology using the simulation results and mathematical modeling, electrostatic sensor design with a test rig and in the end, the discussion on results.

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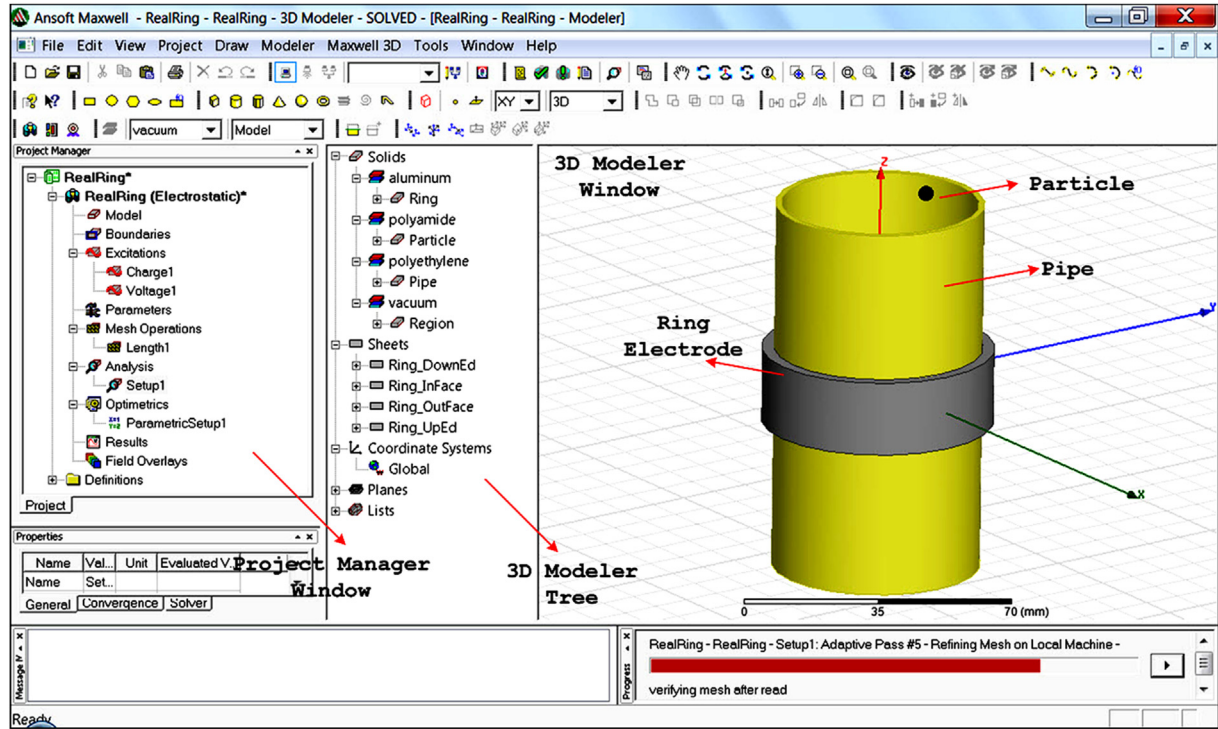


Fig. 1. Maxwell Ansoft interface and the schematic representation of the ring electrode.

2. Electrostatic sensor

Electrostatic sensor consists of two main parts, sensor electrode and signal conditioning circuit. A signal conditioning circuit collects the induced charge to the electrode and amplifies it to a desired level. In the signal conditioning circuit, the electric charge on the electrode either can be collected as the original shape of electrostatic noise using a capacitor [9], or it can be collected as voltage or current using a resistor [10].

The electrode is the main part of the sensor, and its physical properties affect the sensitivity and the frequency bandwidth of the sensor. Depend on the application, the electrode can get different shapes such as ring electrode, pin electrode and plate electrode. The spatial filtering effect or spatial filtering property of the electrode is a terminology that refers to the relation between frequency properties of the sensor's output signal and geometrical size and shape of the electrode. Hammer and Green [11] discussed that the cutoff frequency of a capacitance sensor, which is functionally similar to the electrostatic sensor, depends on the length of the ring shape electrode. Later, the method is used by Gajewski [12] and Yan et al. [1] to model the frequency response of the electrostatic sensor. Zhang in his thesis [13] and Zhang and Coulthard [10] have modeled spatial sensitivity of the electrode by utilizing the FEM analysis; the method later followed by C. Xu et al. [14,15]. To design any measurement system based on electrostatic sensor, the electrode modeling comes as its first importance.

2.1. Charge detection

An electrostatic sensor can detect electrostatic flow noise from a moving particle passing through electrode detection area. Amount of induced charge depends on flux density passing through the electrode and electrode surface area. In this study, a ring electrode as shown in Fig. 1 was used to detect the electrostatic noise from a single particle passing inside a pipe. To find the induced charge to

the electrode, an analytical solution is started by Gauss's law. According to Gauss's law, the charge enclosed at any surface is equal to the flux passing to that closed surface [16,17].

$$q = \int_s \vec{D} ds \quad (1)$$

In Equation (1), $\vec{D}$ is electric flux and q is the charge in the electrode surface. The electric flux is proportional to electric field and subsequently to electric potential as given in Equations (2) and (3).

$$\vec{D} = \epsilon_0 \cdot \epsilon_r \cdot \vec{E} \quad (2)$$

$$\vec{E} = -\nabla \phi \quad (3)$$

Where $\vec{E}$ is the electric field; $\vec{\nabla} = \hat{i}\partial/\partial x + \hat{j}\partial/\partial y + \hat{k}\partial/\partial z$ is called Del operator; $\phi(x,y,z)$ is the electric potential at any point and $\epsilon_r(x,y,z)$ is relative permittivity, and can be a function of position; $\epsilon_0 = 8.854 \times 10^{-12}$ F/m is vacuum permittivity. According to Poisson's equation, divergence from the vector field of the electric potential gradient $\nabla \phi$ produces a value in scalar field, which is proportional to the total volume charge density $\rho_v(x,y,z)$ as given in Equation (4).

$$\vec{\nabla} \cdot (\epsilon_r \cdot \epsilon_0 \vec{\nabla} \phi) = -\rho_v \quad (4)$$

If the volume charge density on the electrode is known, the Equation (4) can be solved for electric potential and after that the electric field, electric flux and charge on the electrode surface can be measured respectively. Equation (4) is a second-order differential equation where in complex geometries such as a sensor electrode, it is difficult to be solved. A numerical method called finite-element analysis can be hired to solve this problem. In finite

analysis method or FEM, the complicated problem is broken up to small elements where the solution can be found by assembling the response of each element. FEM has been applied in a number of researches to simulate induction to the electrostatic sensor electrode where a point-charge is used to represent a charged particle [15,18].

An FEM simulator called Maxwell Ansoft was used in this study. The simulator has 3D CAD facilities, and it can give the solution for an electric field analysis in both 2D and 3D. The design properties are important to be known where they affect the simulation results. The simulator interface is shown in Fig. 1, where its three main parts are modeler window, modeler tree and project manager window. The modeler window includes a ring electrode, pipe and a single particle. The ring was made from aluminum with dimensions 55.6 mm diameter, 3.2 mm thickness and 20 mm length. The pipe was made from polyethylene with dimensions 55.6 mm outside diameter, 1.5 mm thickness, 52.6 mm inside diameter and 80 mm length. A polyamide particle with 1 mm of diameter was used as the source of electric charge. The simulator solves the problem in a finite region so a vacuum region was defined for the design in a way that it surrounds all parts. The region becomes invisible so it can't be seen in Fig. 1. The properties of designed geometry can be found and edited in the modeler tree. The sum of electric charge on faces with the same charge polarity on their surface, for instance positive charge, represents the total charge induced on the electrode.

The FEM properties and project structure, including boundary conditions, excitation, mesh operation, field structure, etc. can be decided in the project manager window which is the leftmost window in Fig. 1. Boundary conditions should be selected to model the electric field behavior on boundaries. Natural-boundaries are chosen for the interfaces between objects, and Neumann-boundaries are selected for the outside edge of the problem region. In Natural-boundaries, the tangent components of $\vec{E}$ are continuous and the normal component of the flux changes with the amount of surface charge density. In Neumann-boundaries condition, $\vec{E}$ is tangential to the boundary and flux cannot pass over the boundary.

The particle was assigned $-1 \mu\text{C}$ charge and Region was excited with 0 V as the reference for electric potential computation. The length-based mesh refinement with the maximum 4 mm of the element length was selected for the surface of the ring electrode. When a length-based mesh refinement is selected, the field simulator refines the length of tetrahedral elements until they reach below the defined value. The tetrahedron's length is specified as the length of its longest edge [19].

In all experiments, the particle movement was considered in two axes (r, z), the z axis is the particle's movement direction, and r axis or radial axis is perpendicular to particle movement direction. As it is shown in Fig. 2, radial axis is located in xy coordinate and it is bounded to the length of ring radius r .

In the first simulation, the particle was moved along z axis at $r = 0$, and the induced charge to the electrode was measured from 100 mm top of the ring to 100 mm below the ring in every 2 mm. In Fig. 2, the particle is located at (0, 20) and the ring is positioned at (0, 0). The charge density distribution and its polarity on the ring surface are shown in colors where each color represents a value in C/m^2 . As it is shown in Fig. 2, the field from the negative charges of the particle induces positive charge to the inside surface and as well as in the upper edge of the ring. In thick rings, the amount induction to the edge is noticeable and should be taken into account.

The results are symmetry from the center of the ring, so the simulations were just conducted from 100 mm top of the ring to the center of the coordinate system. To get only one particle's induction curve as it is depicted in Fig. 3 the simulation was conducted for 51 points.

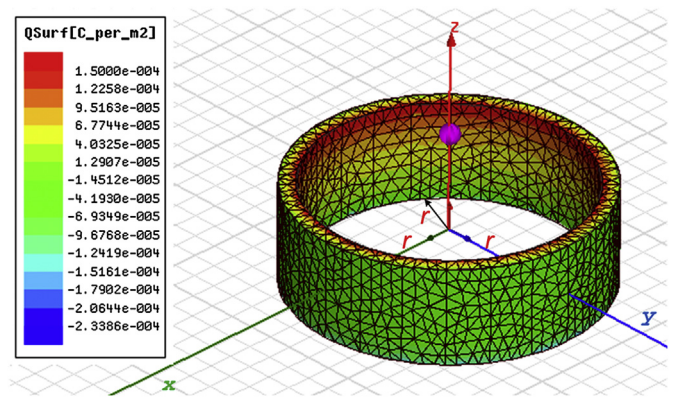


Fig. 2. Charge density distribution on the ring surface.

Fig. 3 shows a particle with $-1 \mu\text{C}$ charge induces up to $0.4 \mu\text{C}$ charge to the electrode surface when it passes through the center of the electrode.

2.2. Sensitivity of the sensor

The sensitivity of the sensor highly depends on the physical shape, size and material type of the electrode and the particle position on electrode's detection area. The sensitivity of the sensor can be estimated using the following equation [1]:

$$S(r, z) = \left| \frac{q(r, z)}{Q} \right| \quad (5)$$

In the Equation (5), $q(r, z)$ is the amount of induced charge from the particle to the electrode, and Q is the entire charge on the particle. Here, the total charge on the particle is $-1 \mu\text{C}$. The induced charge to the electrode, when the particle moves only in z axis, is given as an induction curve in Fig. 3. From Equation (5), the sensitivity of the electrode in z axis is computed and shown in Fig. 4.

The sensitivity curve in Fig. 4 shows that electrode has the highest sensitivity when the particle reaches to the center of the electrode. Fig. 5 provides the results for sensitivity measurement in radial axis.

The sensitivity in radial axis was measured in every 2 mm from $(-25.8, 0)$ to $(25.8, 0)$ where the particle is tangent to the pipe wall. According to the sensitivity curve, the electrode has its highest sensitivity near its wall where it can detect about 70% of the electric field strength induced from the particle.

2.3. Current and power spectrum density

In the signal conditioning circuit, the electric charge on the electrode is collected as the voltage or current signal. The electric

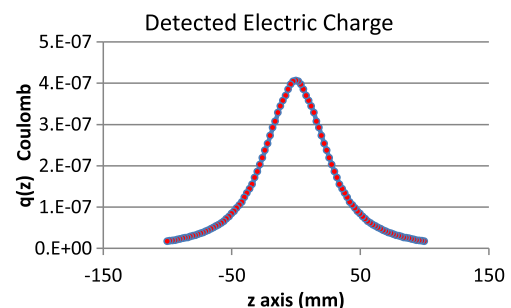


Fig. 3. The charge induction curve from a single particle to a ring electrode at $r = 0$.

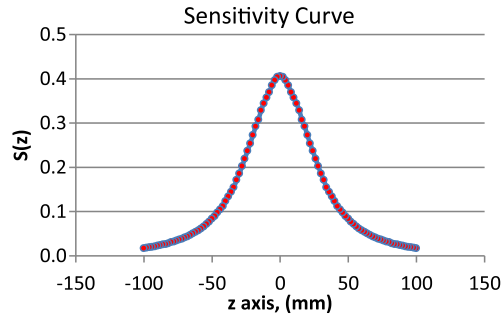


Fig. 4. The sensitivity of the electrode in z axis at $r = 0$.

current in the sensor shapes as the rate of electric charge on the surface of the electrode, which can be represented by the following equation:

$$i(t) = \frac{dq(t)}{dt} \quad (6)$$

To find the electric current, the induced charge curve in Fig. 3 should be rescaled to its equivalent time domain. In experimental test that is explained in the next parts of this paper, the particle passes the ring with a constant velocity of 3.019 m/s which is calculated when the particle drops about 465 mm distance from the top of the electrode with the Zero initial velocity. The particle takes about 67 ms to pass the 200 mm of distance in z axis over the electrode's charge detection area. The curve $q(z)$ in Fig. 3 is rescaled to $q(t)$ and after implementing the Equation (6) on it the electric current signal can be resulted as it is shown in Fig. 6.

The current graph in Fig. 6 shows that the particle induces a current less than 30 μA to the electrode. Fig. 7 shows the normalized frequency spectrum of the induced current to the electrode.

The frequency spectrum shows that the induced current to the electrode has frequency components from 0 to about 50 Hz.

3. Particle size effect on frequency spectrum

According to coulomb's law, the electric field from a uniformly charged insulating sphere with the radius of r_0 and the electric charge of Q with distance r from the particle center can be given as [16]:

$$\vec{E} = \frac{1}{4\pi\epsilon_0} \frac{Q}{r^2} \hat{r} \quad (7)$$

where $r > r_0$ and ϵ_0 is the electric permittivity for free space. From the Equation (7), it can be seen that, r_0 or the particle's radius doesn't have any role on electric field strength. Thus, it does not affect the level and frequency component of detected signal.

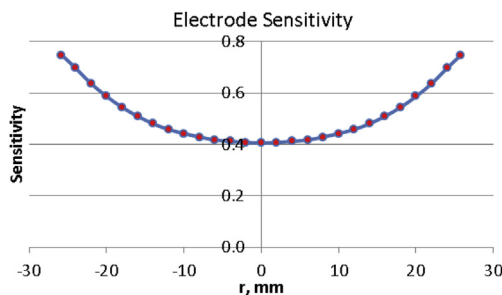


Fig. 5. The sensitivity of the electrode in radial axis at $z = 0$.

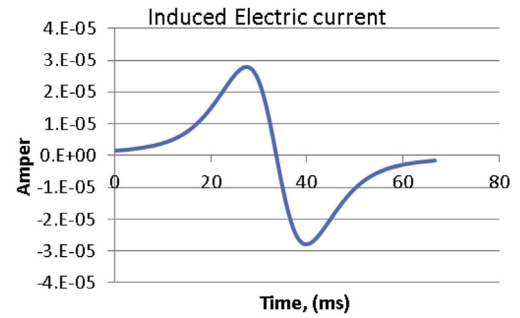


Fig. 6. The induced electric current to the electrode at $r = 0$.

To prove that, a test was conducted by utilizing the field simulator. As it depicted in Fig. 8 three sphere particles with the size of 1 mm, 2 mm and 4 mm with $-1 \mu\text{C}$ electric charge on their surface are dropped at the same point at (24.3, z) inside the ring electrode.

Fig. 9 shows the frequency spectrums of the electric current which was produced by three different size of particles' induction to the electrode. The results show that the curves are coincided to each other.

The frequencies at PFSs shown in Fig. 9 are happened at 39 Hz for all three different sizes of particles. In fact, the electrode sees the sphere particle as a point charge located in the center of the particle, and the particle size doesn't have any effect on the induction level to the electrode and subsequently to the frequency of the output signal.

4. Measurement principle

The illustration for the measurement principles can be started by the investigation on the frequency spectrum properties of the ring electrode when a particle drops in different radial positions. According to a study conducted by Zhang [13] and Zhang and Coulthard [10] on spatial filtering properties of an electrostatic sensor with a ring electrode, dropping a particle at the center of the ring has different frequency components from when the particle is dropped close to the pipe wall. The temporal frequency response of detected electric signal from two different drop positions on radial axis shows different frequency at the PFS for each radial position.

The effect of particle radial position on the FPS was investigated for the ring electrode using a 1 mm sphere particle with $-1 \mu\text{C}$ electric charge. The particle was dropped in 17 different radial positions from $r = 0$ to $r = 25.8$ mm where the particle is tangent to the pipe wall. The simulation results are shown in Fig. 10.

From Fig. 10, when particle drops close to the electrode wall, frequency at the PFS has a higher value as compared to when the particle drops around the center of the ring electrode. It is a result of

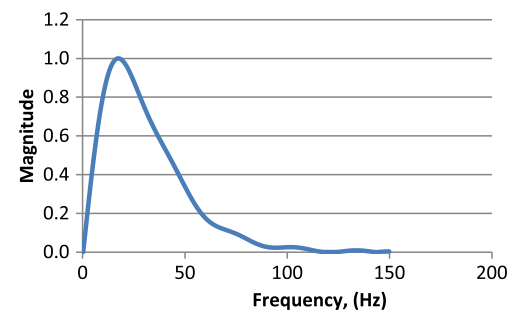


Fig. 7. Frequency spectrum of induced current to the electrode.

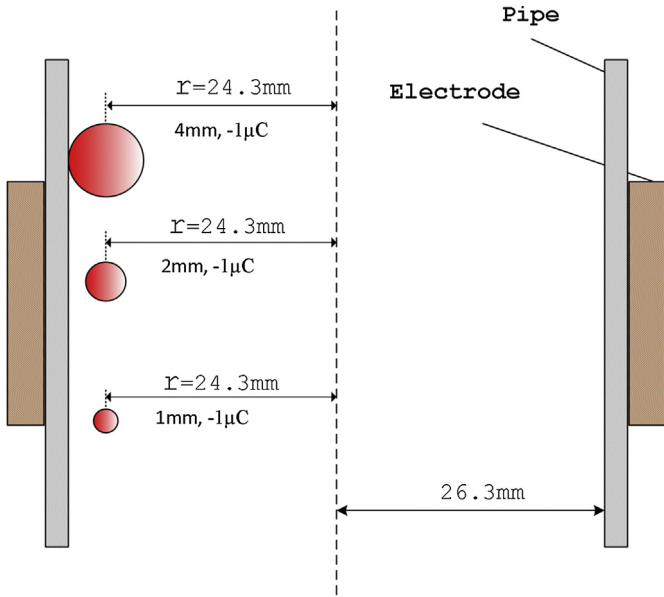


Fig. 8. Three sphere particle with different sizes dropped at the same radial position.

electrode's sensitivity properties, when the particle drops into the middle of the ring, the electrode covers a bigger area of electric field, and the induction occurs for a longer period and subsequently gives smaller frequency. When the particle drops near to the electrode wall, it induces the current in a very shorter period of time and with a higher frequency.

According to C. Xu et al. [14,20] the induced charge to the electrode from a moving particle, which is falling with the velocity v in a known radial axis inside a ring electrode, can be given as:

$$q(t) = \int i(z + vt) \cdot s(z) dz \quad (8)$$

In the Equation, $i(z + vt)$ is the charge distribution function of the particle, and $s(z)$ is the sensitivity of the electrode. The $i(z + vt)$ produced by a particle can be substituted with an unit impulse signal $\delta(z + vt)$ which is the Dirac function [20]. Equation (8) can be written as:

$$q(t) = \int \delta(z + vt) \cdot s(z) dz \quad (9)$$

The amount of electric charge that an electrode can detect from a moving charge particle highly depends on the sensitivity of the electrostatic sensor. Equation (5) provides the sensitivity of the electrode which describes the sensor's ability in detection of the

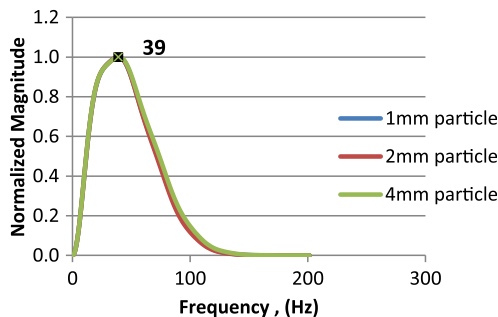


Fig. 9. Frequency spectrums for three different size of particles dropped at (24.3, z) inside the ring.

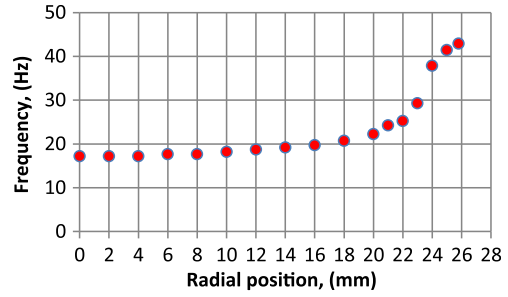


Fig. 10. Frequencies at the PFS's when the particle is dropped at different position in radial axis.

electric charge at any point in its detection area. Fig. 4 shows the sensitivity of the electrode when a particle with 1 mm of diameter was dropped at $r = 0$. The sensitivity curve in Fig. 4 resembles to the Lorentz Peak where its best fit function in general form can be given as:

$$s(z) = a + \frac{b \cdot d}{4(z - c)^2 + d^2} \quad (10)$$

In the Equation (10), a , b , c and d are constant and their values are related to the dropping location of particle on radial axis. A particle with 1 mm of diameter and $-1 \mu\text{C}$ of electric charge was used to find the sensitivity of the electrode in 17 different dropping points from $r = 0$ to $r = 25.8$ mm. Using Least Square algorithm a , b , c and d are approximated for all sensitivity curves and the results are given in the following table with the relative fit standard error.

The effect of constant a and constant c can be approximated with Zero. Substituting the sensitivity function in Equation (9) results:

$$q(t) = \int \delta(z + vt) \cdot \left(\frac{b \cdot d}{4z^2 + d^2} \right) dz \quad (11)$$

That results to:

$$q(t) = \frac{b \cdot d}{4(vt)^2 + d^2} \quad (12)$$

The equivalent circuit for electrostatic sensor could be described as the following circuit in Fig. 11 [13,14], where $q(t)$ represents the source of the charge from the particle and C_s and R_s are the capacitance and resistance of the electrode, C_c and R_c are the capacitance and resistance of the signal conditioning circuit respectively.

In the circuit model the output current can be given as the following equation [20]:

$$i(t) = \frac{dq(t)}{dt} = C \frac{dU(t)}{dt} + \frac{U(t)}{R} \quad (13)$$

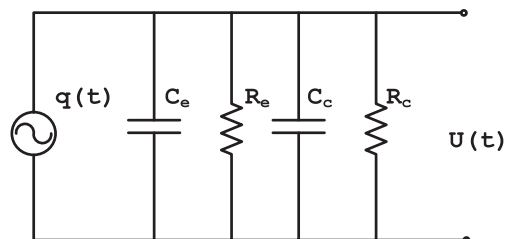


Fig. 11. The equivalent circuit model for electrostatic sensor [13,14].

where $R = (R_s R_c)/(R_s + R_c)$ and $C = C_s + C_c$ are the equivalent resistance and capacitance of the circuit model. Taking the Laplace transform, Equation (13) gives the transfer function between the induced charge to electrode and the output voltage signal as [14,21]:

$$\frac{U(s)}{Q(s)} = \frac{sR}{sRC + 1} \quad (14)$$

The $s = j\omega$, if it is assumed that $sRC \ll 1$, the frequency spectrum of the output voltage can be given as:

$$|U(j\omega)| = R\omega \times |Q(j\omega)| \quad (15)$$

The $Q(j\omega)$ can be found by taking the Fourier transform from $q(t)$ as:

$$F(q(t)) = Q(j\omega) = \int_{-\infty}^{+\infty} \left(\frac{b \cdot d}{4(vt)^2 + d^2} \right) \cdot e^{-j\omega t} dt \quad (16)$$

That results to:

$$Q(j\omega) = \frac{b \cdot e^{-\frac{d\omega}{2v}} \pi}{2v} \quad (17)$$

By substituting the $Q(j\omega)$ in Equation (15), the frequency spectrum can be written as:

$$|U(j\omega)| = R \cdot \omega \times \frac{\pi b \cdot e^{-\frac{d\omega}{2v}}}{2v} \quad (18)$$

At the peak of the frequency spectrum (PFS), the slope is equal to zero, so the derivative of Equation (18) at ω_m is zero.

$$\frac{\pi \cdot b \cdot e^{-\frac{d\omega}{2v}} \cdot R(2v - d\omega_m)}{4v^2} = 0 \quad (19)$$

The solution for Equation (19) establishes a relation between d and ω_m or frequency at PFS as:

$$d = \frac{2v}{\omega_m} \quad (20)$$

d has a direct relation with the particle's dropping position r . From Table 1 using a regression analysis this relation can be obtained as:

$$d = 0.0585 - 0.2629r - 39.176r^2 \quad (21)$$

$\omega_m = 2\pi f_m$, the velocity is known and it is equal to 3.02 m/s. Substituting d in Equation (20) results to a relation between the particle's drop position in radial axis r and the frequency at PFS as:

$$r = -3.35537 + \frac{\sqrt{f_m(-24537.87 + 1504.52f_m)}}{f_m} \quad (22)$$

Fig. 12 shows the comparison between the simulation results and mathematical modeling to find r when the $16 \text{ Hz} < f_m < 43 \text{ Hz}$.

From Fig. 12, it is observed that the mathematical modeling results follow the simulation results, and the small differences are because of curve fitting errors and equation solving assumptions. At the minimum frequency $r = 0$, and at the maximum frequency the particle is dropped tangent to pipe wall.

According to field simulation results shown in Fig. 12, the frequency near the electrode wall has a higher rate of changes compare to the central area where the rate of frequency change is very small. From that it makes sense to use the area close to the electrode wall for better frequency resolution.

Table 1

a , b , c and d for sensitivity curves at different particle's dropping point.

Radial position, (mm)	a	b	c	d	Fit standard error
0	-0.020	0.025	3.18E-07	0.058	0.003
2	-0.020	0.025	3.39E-07	0.058	0.003
4	-0.019	0.025	3.39E-07	0.057	0.003
6	-0.018	0.024	3.18E-07	0.056	0.003
8	-0.017	0.024	3.09E-07	0.054	0.003
10	-0.015	0.024	2.50E-07	0.052	0.002
12	-0.013	0.023	1.89E-07	0.050	0.002
14	-0.011	0.023	1.12E-07	0.047	0.002
16	-0.008	0.023	3.78E-08	0.044	0.002
18	-0.005	0.022	7.76E-10	0.041	0.002
20	-0.002	0.022	1.45E-09	0.037	0.002
21	0.000	0.021	5.10E-10	0.035	0.002
22	0.001	0.021	4.45E-10	0.033	0.003
23	0.003	0.021	9.26E-08	0.031	0.004
24	0.004	0.021	3.94E-07	0.030	0.007
25	0.004	0.021	1.06E-06	0.028	0.011
25.8	0.004	0.021	1.52E-06	0.027	0.016

As a general rule, if the particle passes closer to the electrode wall, it induces the electric current in a higher frequency. This property of the electrode can be used to establish a method to measure the particle size in the frequency domain. It is discussed that, merely the particle size doesn't have any effect to the sensor's output frequency. However, if different sizes of particles drop tangent to the pipe wall, the distance between the center of particle and the electrode wall will change according to particle's size. As it depicted in Fig. 13, the smaller particle would be closer to electrode wall, and it would induce a current with higher frequency to the electrode.

When various sizes of particles are fallen tangent to the pipe, the electrode detects them as the point charges dropping at different locations in the radial axis which results to a unique f_m for each size of particle. From Fig. 13, the particle size can be found as:

$$D_p = 2(r_{\text{ring}} - r) \quad (23)$$

where D_p is the diameter of the particle in millimeters; r_{ring} is the radius of the ring, and r is the particle's radial position which is given in Equation (22).

5. Signal conditioning circuit and test rig

The circuit deals with random and very small range of the electric charge fluctuations. In a pipeline with a mass flow rate between 0.3 and 3 kg/s electric charge density is about 10^{-7} – 10^{-3} (C/kg) [1] where the current is less than 3 mA. For a single particle,

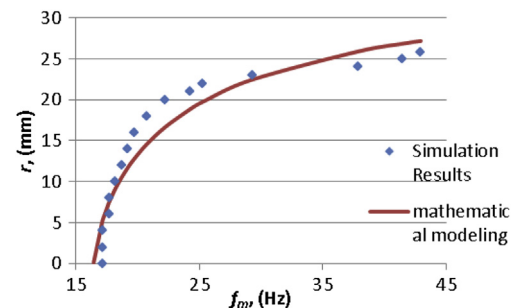


Fig. 12. The relation between particle drop position at radial axis and frequency at PFS (f_m).

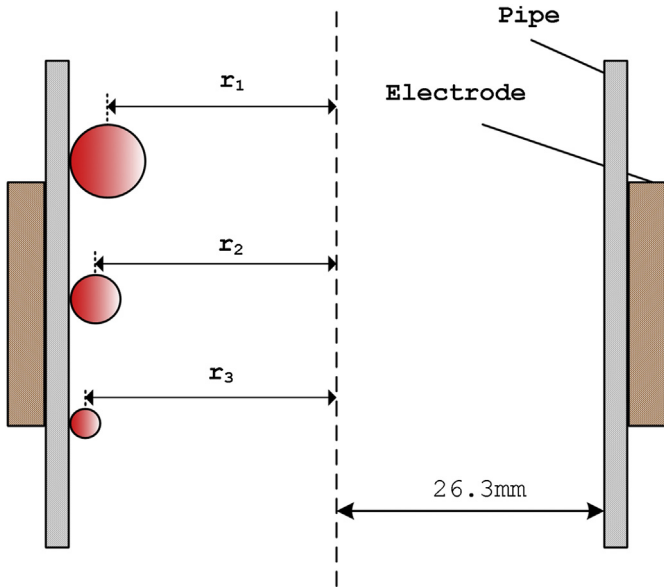


Fig. 13. Different particle sizes are dropped tangent with the pipe wall.

it is about few nano amperes [22]. In this condition, due to high amplification requirements, the noise filtering is very important to be taken into account in the circuit design. Furthermore, the sensor is extremely sensitive to extrinsic noise. A 50 Hz electromagnetic field from a power line near the sensor easily can be detected by sensor electrode and amplified with the signal conditioning circuit which can drown and damage the desired signal. Fig. 14 shows the signal conditioning used for electrostatic sensor.

The circuit consists of two main parts, the signal collector and signal amplifier. The signal collector is a current-to-voltage converter. As an advantage of this circuit, an additional resistor is not required to collect the signal in the circuit's input, as an extra resistor inserts noise and increases the offset voltage in the output of the amplifier. The operational amplifier OPA2604AP and its feedback circuit collect the charge from the electrode and amplify the current form of the signal to $R_1 I_s$ volts in the output. Current I_s shapes on R_1 as given in Equation (6), and C_1 on the feedback provides a low-pass filter which determines the cutoff frequency of the circuit as:

$$f_c = \frac{1}{2\pi R_1 C_1} \quad (24)$$

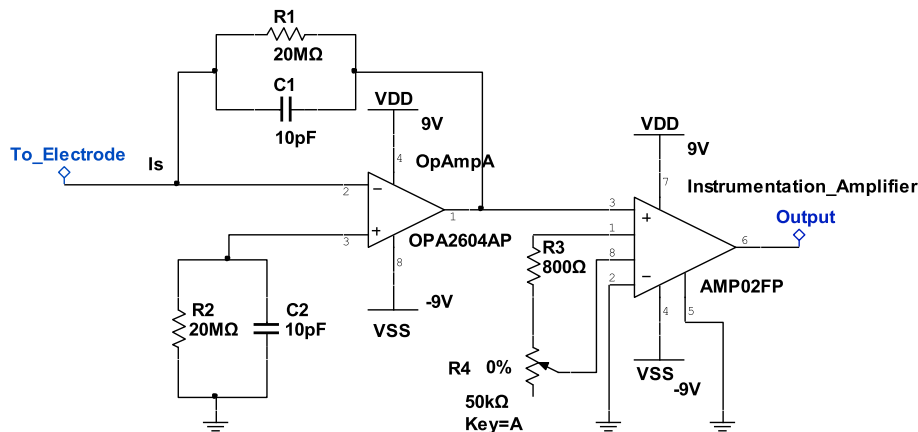


Fig. 14. The signal conditioning circuit for electrostatic sensor.

The cutoff frequency is 796 Hz, which is a suitable bandwidth for electrostatic sensor where the higher-frequency electrostatic noise is not expected.

In the other part of the circuit, a high-accuracy instrumentation amplifier AMP02 is used as the second amplifier which provides an adjustable gain for circuit only using a single external resistor. The adjustability of the gain is necessary when particles with unknown charge are used for measurement. The gain equation for this amplifier is given as:

$$\text{Gain}_{\text{inst}} = \frac{50 \text{ k}\Omega}{R_G} + 1 \quad (25)$$

The R_G in this circuit is the series of $R_3 + R_4$ which R_4 is a 50 KΩ potentiometer. The total gain of the circuit can be given as:

$$\text{Gain} = \left(1 + \frac{50 \text{ k}\Omega}{R_G}\right) \cdot R_1 \quad (26)$$

The total gain of the proposed amplifier is an adjustable value from 39.6×10^6 to 1270×10^6 . To protect the circuit from 50 Hz extrinsic noise, a DC supply using a voltage-converter circuit was used to provide a dual supply of ± 9 V from a single 9-V battery.

Fig. 15 shows the test rig which is utilized for experiments. The signal from an electrostatic sensor was transferred and saved in a PC using a Dewetron data transfer unit.

The pipe and electrode in the experimental test have the same design as it is explained for the simulation setup. Particles dropping velocity and height are the same as they are given in the modeling. The pipe body in the top and below of the ring was covered with a grounded shield to prevent the electric charge induction to the circuit's wiring and connectors. In addition, the shielding discharges the pipe body from the electric charges. Without shielding the pipe, the output signal loses its shape. A particle with unknown charge was fallen to the center of the electrode ($r = 0$). The normalized output of both simulation results and experimental results are compared in following figure.

Fig. 16 shows the output signal in both simulation and experimental result almost coincide to each other with very small differences.

6. Experimental results and discussion

In particle size measurement experiment, five different sizes of particles with the diameters of 4 mm, 6 mm, 8 mm, 10 mm and 14 mm were tested. The particles were dropped tangent to the pipe wall and the frequency at PFS or f_m for each particle was recorded. The following figure shows the results in blue dots.

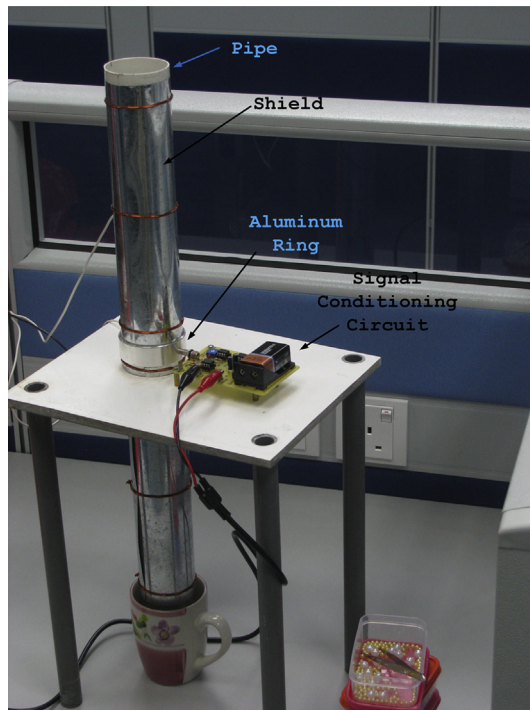


Fig. 15. Test rig for electric charge detection.

The D_p or the particle's diameter is calculated using Equation (23) for each recorded f_m from dropped test particles inside the electrode. The results are plotted in red dots in Fig. 17. The trend lines for the results show a small difference between modeling results and experimental results. In fact, the field simulation design never can be exact the same as to the real component. For example, the real particle has a non-uniform charge distribution on its surface, or the ring electrode is not a perfect ring electrode because it has connector and wiring for connection to the signal conditioning circuit. Furthermore, the particle velocity assumed constant in modeling, however in fact, it increases linearly with gravitational acceleration. In addition, the errors are existed for signal reading from the electrode to the PC. The both modeling and experimental results indicated that an inverse relation between particle size and the frequency at PFS exists, which is independent from the amount of electrical charge on the particle's surface. A measurement system can be established using calibration equation or trend line equation which is shown in Fig. 17.

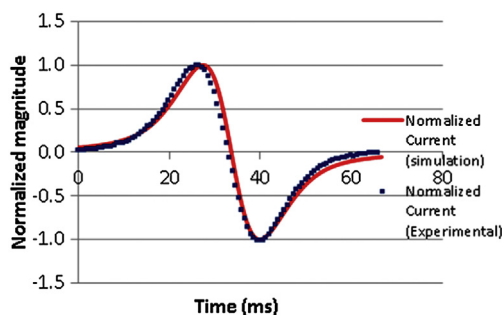


Fig. 16. Comparison between normalized current in simulation and experiment when a particle with unknown size and electric charge was dropped at $r = 0$ in radial position.

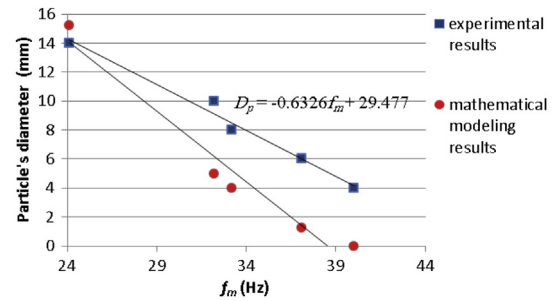


Fig. 17. Experimental results (blue dots) and modeling results (red dots) for particle size measurement. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

7. Conclusion

This study was focused to measure a single-particle mean size using electrostatic sensor independent from the amount of charge on the particle's surface. A ring electrode was designed, and by using a field simulator the charge induction to the electrode was calculated in different positions in the electrode's detection zone. The mathematical modeling was provided, which shows a relation between particle dropping position on radial axis and frequency at the peak of the output signal's frequency spectrum (f_m). From this relation, a new technique was proposed to measure the particle size from the measured f_m . The experimental test was included with the design of a new signal conditioning circuit with adjustable gain, which is suitable to measure the different level of electric charge on particles with unknown charge on their surface. The results from experimental findings follow the modeling results and the proposed method for the particle sizing. However, small differences between experimental findings and modeling results are not deniable, as the real design can't be perfect as it exists in the modeling and simulation. The method is limited to measure the particles within a range of few millimeters; as a future work it can be developed and researched for micron size of particles. In addition, the method can be researched in process tomography area to find the particles moving pattern inside a conveyor.

Acknowledgment

This research is supported by Ministry of Science, Technology and Innovation (MOSTI) Malaysia and Universiti Teknologi Malaysia (UTM) through the Research Grant University Vote number 02H73. The authors are grateful to the Ministry and UTM for supporting the present work and express appreciation to Professor Jalil Ali, Nanotechnology Research Alliance UTM.

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