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Simultaneous measurement of particle charge, distance and size using coaxial induction probe

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Abstract. A novel probe for charge measurements was simulated, designed and tested. It consisted of two coaxial induction probes which were grounded via a current sensing circuit. As a charged spherical object passed the probe, data was collected and analyzed using a PC running a program compiled with LabVIEW. Two simultaneous current signals were integrated to obtain induced charges as a function of time. Then, Gaussian curves were fitted to the data and widths and amplitudes were collected for further processing. According to simulations performed with Comsol MultiPhysics, object charge, distance from the probe and size could be calculated using the above mentioned Gaussian peak parameters. The probe was calibrated and tested using induction charged water droplets and frictionally charged insulating spheres.

1. Introduction.

There is a variety of different methods for measurement of particle charge [1-3]. For single objects or for an amount of powder, traditional Faraday pail is a good and reliable option. However, using Faraday pail requires sampling and in some cases sampling may cause additional charging or it may be inapplicable for other reasons. For online charge measurement different methods based on induction are widely used. In the most simple induction measurement, a probe, which can be a conducting rod or just a piece of wire, is placed near a charge to be measured. The probe can be set to measure either potential or current. If potential is measured, the potential depends on the capacitance of the probe and electronics. If, on the other hand, current is measured, the probe potential is maintained at zero and a bipolar signal is recorded as a charged object passes the probe.

If we consider a charged object passing the probe, signal obtained using a single induction probe is a function of object's charge, distance from the probe, size, speed and shape. To get an accurate value of some of the parameters listed above, some other parameters need to be fixed. As an example, an open-ended Faraday pail can be considered as a single induction probe. When a charged object passes through the probe, an accurate value of charge (and speed to some extent) can be obtained. However, this setup does not give information about the location or size of the object. If another probe with different geometry is added, more data can be obtained and more object parameters can be calculated. As far as authors are aware, a system which would allow a measurement of charge, location and size simultaneously has not been presented.

In the present work, induction method in current mode was used. Instead of one induction probe, two concentric probes were used. Due to current mode, both probes were kept in zero potential which means that an induced charge on one of the probes does not interfere with the other. Recently, somewhat different two probe system in a two dimensional fluidization column has been proposed by



He et al. [4]. A concentric geometry was chosen because that enables quite easy selection of right induction signal peaks from possibly noisy data and many passing charges. In other words, the recorded peaks from both probes are exactly simultaneous for same passing object. The probe was manufactured and assembled perpendicular to a grounded steel pipe so that the probe surface was in the same plane as the inner surface of the pipe.

The system was modeled and simulated using COMSOL multiphysics. It was observed that particle size, location and charge affect the signal properties. Using the simulated results, it was possible to write equations into measurement program which gives particle distance, size and charge as a result.

2. Simulations

The probe and the pipe assembly were modeled using COMSOL Multiphysics 4.3b and the model was identical to the actual probe. In the simulations, spherical particles were used. Radius of the particles was varied from 1 mm to 7 mm. Distance between the probe and the particle was varied between 1 mm and 14 mm. Total charge which was spread uniformly either over surface or within volume, was varied from 0 nC to 1 nC.

Inner probe had a radius of 1 mm. It was separated from outer probe by 1 mm thick insulator. Outer electrode was cylindrical and its thickness was 1 mm. Outer probe was again surrounded with an insulator. The probe was attached to a grounded steel pipe (inner diameter 35 mm). Figure 1 presents a screenshot from COMSOL Multiphysics. In the figure, a positive particle is shown in front of the probe, a few millimeters below the probe axis. Grayscale image shows the surface charge density on the conducting surfaces. Insulating rings between the probes have been set transparent so that surface charge density in these probe regions can be seen.

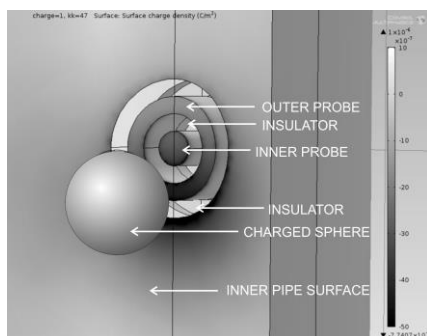


Figure 1. Snapshot from the simulation showing the geometry of the probe and surface charge density on the probe surfaces.

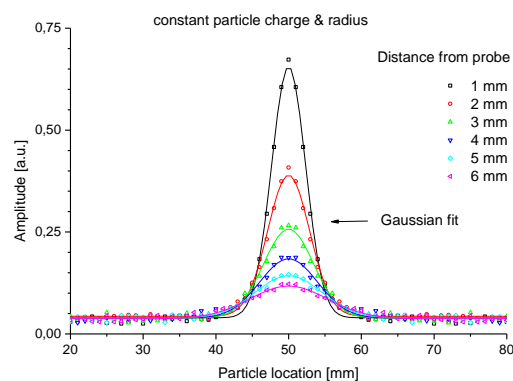


Figure 2. Induced charge on inner probe as a function of height of the particle (50 mm = probe height).

In the simulations, particle was set to move vertically along the pipe at 1 mm steps. Induced charge was calculated by integrating surface charge density over probe surfaces. The shape of the induced charge curve as a function of particle height was of interest and is shown in Figure 2. It was noticed that a Gaussian function fits to the datapoints very well, and it was used in calculations.

In the simulations, particle parameters: size, distance from the probe and charge were varied as mentioned above. Gaussian peaks were fitted to each data and peak parameters: amplitude and width were collected. For further analysis, also amplitude ratio ($A_{\text{outer}} / A_{\text{inner}}$) and width ratio ($W_{\text{outer}} / W_{\text{inner}}$) were calculated. Based on the computer simulations, above mentioned peak parameters were mathematically expressed as a function of particle parameters. The constants in these equations were then refined using experimental data.

3. Probe structure and experimental methods

Dimensions of the probe were same as in the computer model. The induction probes were made of brass and the insulator was non-conducting epoxy. Current from the probes was measured using LMC662 CMOS dual operational amplifiers (National Semiconductor) with 1 G Ω feedback resistors.

The circuit was powered with 9 V battery and was shielded inside a grounded case. Amplified signals from both probes were recorded using NI USB-6008 data acquisition system (National Instruments) at sampling rate of 1 ms.

At the present, charged objects which were dropped through the vertical pipe were either induction charged water droplets (diameter 3.5 mm) or frictionally charged insulating spheres (diameters 2, 6, 10 and 13 mm). The charge on water droplets could be continuously adjusted. It is important to note that at the present the system is not capable to analyze particles with different velocity. Higher velocity would narrow the peaks but would not change the amount of induced charge on the probe surfaces. Thus, all particles were dropped under gravity from the height of 30 mm with zero initial velocity. Particles were collected directly in a Faraday pail connected to an electrometer (Keithley 6517A, Keithley Instruments).

Data was collected and analyzed using a virtual instrument (VI) compiled in LabVIEW 2009. The VI scanned both signals and when concurrent peaks occurred, signals were integrated. Next, Gaussian curves were fitted to the signals, and amplitudes and widths were taken to further processing.

4. Calculation of particle charge, distance and size

4.1. Induction charged water droplets

Expressions obtained using simulations could be verified using induction charged water droplets. Figure 3 presents Gaussian amplitudes measured from outer and inner probes (A_o and A_i respectively) and amplitude ratio as a function of distance from the probe. In this experiment, charge was kept constant (169 pC) but the distance from the probe was varied.

Figure 4 proves that amplitude increased linearly as a function of water droplet's charge which was measured using a Faraday pail and an electrometer. In Figure 4, the distance was kept constant at 6 mm from the probe. From the same figure, it can also be noticed that the widths of Gaussian peaks did not vary with charge. All datapoints in Figs 3 and 4 are mean values of 10 measurements. Standard deviations are too small to notice except in Figure 4 (widths), where SD's are significant especially, when the charge was small and signal quite noisy.

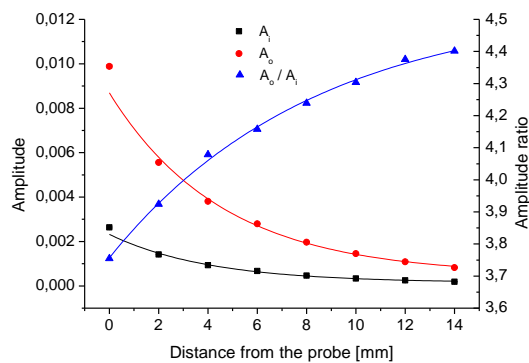


Figure 3. Gaussian peak amplitudes fitted to outer and inner probe signals (A_o and A_i respectively) and amplitude ratio (A_o / A_i) as a function of distance from the probe.

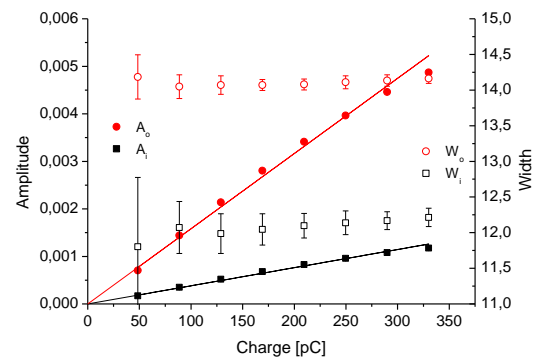


Figure 4. Gaussian peak amplitudes fitted to outer and inner probe signals (A_o and A_i respectively) and fitted widths (W_o and W_i) as a function of droplet charge.

Situation was quite easy with induction charged water droplets which had constant diameter and velocity. The distance from the probe could be calculated from the amplitude ratio and when the distance was known, charge of the droplet could be calculated from either amplitude. So, in case of water droplets, only amplitude information was needed to evaluate both charge and distance.

4.2. Frictionally charged insulating particles

Variable size of the particles brought another parameter to be solved from the signals. Additionally, charge distribution along the sphere surface was probably not uniform. Thus, more measurements

were required to get some statistics. Different sized particles were frictionally charged, passed by the probe at different distances, and their charges were measured using the Faraday pail.

Figure 5 shows a good correlation between simulated and measured data. Both amplitude ratio and width were functions of particle distance d and size r . These two equations (Equations 1 and 2) were defined using experimental data and written into the VI. VI measured the values of (A_0 / A_i) and W_0 and solved these equations simultaneously to get particle radius and distance. Once these were solved, charge q could also be solved using A_0 (Equation 3). Amplitude A_0 was a linear function of particle charge but the slope was actually a function of particle size and distance. The (exponential) dependence of the slope on the particle radius and distance was verified experimentally and the resulting equation was written into the VI.

$$\frac{A_0}{A_i}(r, d) = 4.7 + (0.194 \cdot r - 2.012) \cdot e^{-(d / (0.2122r + 6.333))} \quad (1)$$

$$W_0(r, d) = 0.61655 \cdot d + 0.64564 \cdot r + 4.39215 \quad (2)$$

$$q = \frac{A_0}{5.6 \cdot 10^{-4} \cdot e^{-r / 1.4} + 5.8 \cdot 10^{-5} \cdot e^{-d / (0.7 \cdot r + 3.1)}} \quad (3)$$

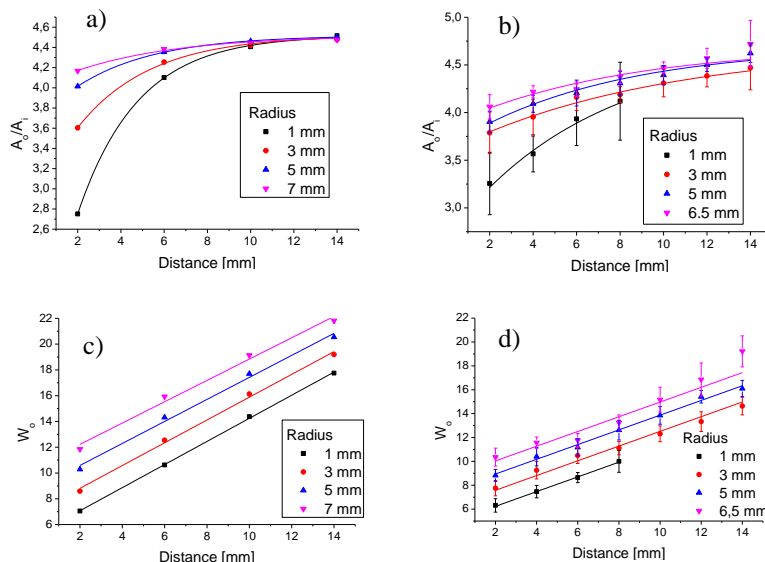


Figure 5. Simulated (a) and measured (b) amplitude ratios and simulated (c) and measured (d) outer probe widths for different sized particles as a function of the distance from the probe.

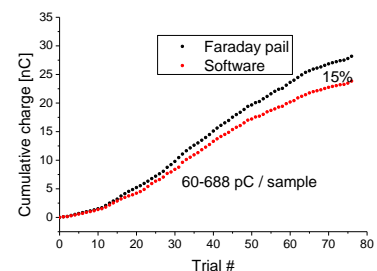


Figure 6. Cumulative charge of 3 mm radius spheres measured with Faraday pail and by coaxial probe. Particle's charge and the distance from the probe were randomly varied from 60 to 688 pC and 1 to 10 mm respectively. Difference between measured and calculated charge was 15%. Average calculated radius was 3.7 mm.

5. Results and conclusions

Figure 6 shows example data measured using spheres of 3 mm radius and random charge and distance. Although a single measurement might have some error, cumulative charge graph shows that on average, the system was able to measure charge reasonably well. Measurements performed with the coaxial probe agree well with computer simulations. By measuring current signals simultaneously from both probes and performing necessary signal analysis, it was possible to determine particle size, charge and distance from the probe when the particle velocity remained constant. Ongoing work includes gathering more calibration data to improve the calculation accuracy. Also, probe geometry is being changed in order to get the velocity data as well.

6. References

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