Sensitivity study of ring-shaped electrostatic sensor based on nonparametric estimation

Zhe Kan*, Yuanzhe Li
School of Information and Control Engineering
Liaoning Petrochemical University, Fushun, China
*Corresponding author email: kanzhe@lnpu.edu.cn

Abstract. In this paper, aiming at the problem of the electrostatic sensor signal satisfying the gaussian distribution, the non-parametric kernel estimation method is introduced, and the electrode induction model of the electrostatic sensor is finally fitted by combining the goodness of fit and the simulation data samples. This model satisfies the gaussian distribution and the electrostatic signal satisfying the gaussian distribution is given in the theory. Maxwell simulation software was used to simulate the theoretical sensitivity of the electrostatic sensor and the axial and radial spatial sensitivity characteristics of different sensor parameters were obtained. Within a certain range, the relative permittivity of the insulating tube is also discussed. Finally, an insulating tube with a relative permittivity of 3 is selected as the material of the insulating tube. Finally, the experiment is carried out on the experimental equipment and the conclusions obtained in the article are confirmed.

1. Introduction

Pneumatic conveying process widely exists in chemical process, and a series of researches have been carried out on the measurement of gas-solid two-phase flow parameters. Many scholars in China have also studied electrostatic sensors, and a large number of discussions have been carried out by changing the model structure and other conditions. An electrostatic sensor model is studied with an array of bar electrodes and a square insulated pipe based on electrostatics, as well as the mirror-charge method establishes a mathematical model[1]. The actual results obtained through the experimental device are basically consistent with the simulation results, which indicate that the established analytical mathematical model is correct and effective[2]. In order to overcome the uneven sensor sensitivity distribution, an electrostatic sensor with mesh electrode is designed by COMSOL software. Higher sensitivity is achieved and the sensitivity distribution is more uniform. In 2012, the different flow patterns of two-phase flow is analyzed[3-7], and it is concluded that the uneven sensitivity distribution of the electrostatic sensor is caused by the non-linearity of the electrostatic sensor itself and the design structure model[8]. Therefore, the matrix electrode electrostatic sensor is designed, and the sensitivity distribution is consistent with the reality through simulation, which also provides a direction for the realization of the model optimization of the electrostatic sensor. Electrostatic sensor has a simple structure model, and the price is relatively low. The equipment is simple and convenient to install, and it is suitable for some places with bad environment and other advantages. At present, the main research institutions for electrostatic sensors are Manchester University in the United Kingdom; Greenwich University; Tsinghua University; Southeast University[8-11]; Tianjin University[12]. ABB, PCME and other companies in the UK are developing electrostatic sensors, among which ABB and
the University of Teesside have jointly developed a plug-in electrostatic load detector, which can be used normally in thermal power plants.

When particles collide and rub in the pipe, a large amount of static charge will be generated on the particles and the pipe. Currently, sensors for electrostatic charge measurement can be divided into intrusive and inductive types according to the installation methods. Among them, the flow of intrusive particles is easy to cause electrode wear, which requires frequent electrode replacement to avoid affecting the accuracy of measurement results. While the induction type has no effect on particle flow, and the flow of particles in the pipeline will not cause electrode wear, which mainly includes the ring electrostatic sensor.

2. Electrostatic sensor principle

In the process of pneumatic conveying, there is a wide range of gas-solid two-phase flow state, and the fluid is in a fast flow or jitter. Vibration and other motion state, Collision and separation between solid particles and pipelines make particles carry a considerable amount of static electricity. The electrostatic sensor's schematic diagram is shown in Figure 1.

![Fig.1 electrostatic sensor](image1)

In Figure 1, the annular electrostatic sensor consists of a PVC tube, a metal shield, and a copper electrode ring. Label 1 is the ring electrode, Label 2 is the shielding cover, Label 3 is the insulating tube, Label 4 is the electrostatic signal lead line of the electrode, and Label 5 is the fixing bolt. A metal ring of fixed width b is used as an electrostatic electrode on the outer wall of the insulating tube.

The amplification factor and the electrostatic signal are amplified to 1-5V for the collector to collect. The collector chooses NI acquisition card, and the receiving software of the upper computer adopts LabVIEW software. The laboratory measurement system is shown in Figure 2.

![Fig.2 Sensor experimental system](image2)
3. Theoretical model of electrostatic sensor

3.1 Theoretical model

\[
\begin{align*}
\nabla \cdot \nabla \phi(r, \theta, z) &= -\frac{\rho(r, \theta, z)}{\varepsilon(r, \theta, z)} \\
\phi(r, \theta, z)|_{(r, \theta, z) \in \Gamma_s} &= 0 \\
\phi(r, \theta, z)|_{(r, \theta, z) \in \Gamma_d} &= \text{Cons}
\end{align*}
\]

(1)

Where, \(\phi(r, \theta, z)\) is as electric potential distribution in the field of function. \(\rho(r, \theta, z)\) is charge density of the body for the space, and \(\varepsilon(r, \theta, z)\) of the dielectric is for the space distribution of the dielectric constant. \(\Gamma_s\) and \(\Gamma_d\) are respectively electrode of the space position of shielded enclosure, Cons is a constant.

3.2 Model building

The three-dimensional static sensor model established by Maxwell software is shown in Figure 3. The middle ring of the pipe is the electrode of the static sensor. In the model, Z axis represents the electrode and the axial direction of the pipe, X axis represents the radial direction, and Y axis represents the tangential direction.

Maxwell software is used to draw the electric field intensity vector and cloud maps at different spatial positions in 2D. The electric field vector and cloud maps at the radial space centre position, and adopted the default XY Cartesian coordinate system is as shown in Fig. 4.
In the post-processing process of Maxwell3D, the field calculator is needed to calculate the induced charge on the electrode surface, and the spatial sensitivity characteristics of the electrostatic sensor can be obtained according to the following equation

\[ S = \frac{|q(r, \varepsilon, 0, z)|}{Q} \]  

(2)

Therefore, \( q(r, \varepsilon, 0, z) \) is electrostatic sensor sensing electrode charge, \( Q \) is charged particles take charge of its own.

### 3.3 Non-parametric estimation mathematical model

The advantage of non-parametric function estimation method is that there is no specific assumption on the function model and it avoids the risk of model selection. However, the expression is complex, difficult to explain, and a large amount of calculation is a big problem of non-parameter[13].

The kernel density estimation method is suitable for small and medium-sized data sets and can quickly generate an asymptotic unbiased density estimation. Assuming \( x_1, x_2, ..., x_n \) is the sample of random variable \( x \), and the probability density function of \( x \) is \( f(x) \). Given a kernel function \( K(x) \) and a positive number \( h \) is called "window width," At \( n \to \infty, h \to 0 \), the variable \( x \) of kernel density estimation can be expressed as:

\[ \hat{f}(x) = \frac{1}{nh} \sum_{i=1}^{n} K \left( \frac{x - x_i}{h} \right) \]

(3)

Relative to the kernel function, the choice of the bandwidth on the result of data fitting is bigger. When the \( h \) value, the greater the kernel density estimation function \( \hat{f}(x) \) curve is smooth, but it ignores the more details.

\[ Q(z) = \frac{\sum_{i=1}^{n} [K_h(z - z_i)^*Q_i]}{\sum_{i=1}^{n} K_h(z - z_i)} \]

(4)

Especially, \( K_h(z - z_i) = \frac{1}{\sqrt{2\pi h}} e^{-\frac{(z - z_i)^2}{2h^2}} \)

Based on the theory of nonparametric estimation, the formula of induced charge of electrostatic sensor is determined:

\[ Q(r, \varepsilon, z) = A(r, \varepsilon)e^{-\frac{z^2}{B(r, \varepsilon)}} \]

(5)

Among them, \( Q(r, \varepsilon, z) \) is in the relative dielectric constant of \( \varepsilon \) insulation pipe and charged particles in the radial position \( z \) electrode, and \( A(r, \varepsilon) \) and \( B(r, \varepsilon) \) is a function of \( r \). \( A(r, \varepsilon) \) is decision, and \( Q(r, \varepsilon, z) \) is amplitude. \( B(r, \varepsilon) \) is decision, and \( Q(r, \varepsilon, z) \) is shape. The first-stage charge amplification principle in Figure 3 is used to convert the amount of electrode charge into voltage, and the measurement principle satisfies the expression (2). The electrode charge signal can be converted to 1-5V output through the filtering amplifier circuit, which can be used for collection and analysis by the acquisition card. Finally, the sensitivity formula of electrostatic sensor is determined as follows:

\[ S = \frac{|Q(r, \varepsilon, z)|}{Q} = \frac{A(r, \varepsilon)e^{-\frac{z^2}{B(r, \varepsilon)}}}{Q} \]

(6)
4. Simulation and experiment
Sensitivity is one of the important parameters, and the evaluation of electrostatic sensor is operated characteristics based on the definition of spatial sensitivity. The finite element simulation and calculation of the field calculator can be found that the charged particles lie in the space position of PVC pipes, such as the size of the sensor electrode are related to spatial sensitivity characteristics of electrostatic sensor. Therefore, in order to understand whether the electrostatic sensor has good operating characteristics, it is important to calculate the space the sensitivity parameters.

4.1 Simulation experiment
The electrode width b of the electrostatic sensor is set as 30mm, 40mm, 50mm and 60mm respectively, and the diameter of the pipe D is as 100mm. And the field calculator is used to calculate the amount of induced charge in different axial and radial positions, and it is obtained the sensitivity of the corresponding electrostatic sensor. The simulation figure is as shown in Fig. 5.

From figure 5, it can be seen within a certain range that W/D is the greater the relative sensitivity is higher. Electrostatic sensor is width b the growth, and the probe sensitivity is reduced. And in the axial centre of basic graphics presented, the normal distribution can be seen in the centre of the radial position on either side. When the W/D is 0.5 and 0.6, its change is in surge. When W/D is 0.3, it can be seen that the sensitivity is lower than 0.4 W/D. So W/D 0.4 relative is the most appropriate, it is adopted in this paper pipe. Its diameter is 100 mm width of 40 mm electrode.

![Fig. 5 Effects of different electrode widths on axial and radial sensitivity](image.png)

The axial width of the electrode and the radius of the pipe is given. W/R is as fixed values, when the charged particles radially move along the pipe, the variation trend of the charged particles at different spatial positions is shown in Fig. 6.

![Fig. 6 Simulation results of a particle at the different spatial positions](image.png)

One conclusion can be drawn from Figure 6. The particles are in the axial position 450<Z<550. The larger the radial coordinate is, the larger the r/R is. And the electrode sensitivity is the greater in the axial position 50<Z<450 and 550<Z<950. With the increase of radial coordinates, the sensitivity of
the electrode gradually decreases, which also reflects the inhomogeneity of the spatial sensitivity of the electrostatic sensor.

4.2 Experiments
The experimental equipment mainly includes electrostatic sensor module, signal processing module, signal acquisition and signal display module. The sensor has four signal output lines, and representing the width of the induction electrode is 5mm, 10mm, 20mm and 40mm respectively from bottom to top. The plastic ball is allowed to fall from the same height. The measurement result is shown in Fig. 7.

![Fig.7 Voltage values of a particle under the different electrode widths](image)

From the figure 7 it can also be found, electrode width is wider, and the measured voltage signal amplitude is smaller. Because the balls are at the same speed, the change of the signal amplitude can reflect the uniformity of the pipe inner space sensitivity. Sensitivity is uniform, so the voltage signal size change is slow. The amplitude is the less, and it is consistent with the results of the simulation.

5. Conclusion
The principle of the electrostatic sensor is simply introduced. By a non-parametric kernel estimation method commonly used in statistics, the estimated value of the induced charge at each axial position can be calculated with R programming language. And then the goodness of fit is introduced to judge the effect of the fit, and the results show the advantage that is the kernel function using Gaussian kernel function for the estimated value of the induced charge. The original data reached 0.95 between the goodness of fit. The results provide a certain basis for the sensitivity formula using Gaussian distribution theoretical basis. The greater the electrostatic sensor sensitivity is relatively higher. Within a certain range, the relative dielectric constant insulating tube is larger, and the electrostatic sensor sensitivity is higher. But with the increase of the relative dielectric constant, the sensitivity of the probe is reduced.

Finally, the experimental equipment and experimental result analysis are briefly introduced, and the corresponding relationship of Q-U graph is explained. The experimental results match the results of Maxwell simulation.

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