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Spatial filtering characteristics of electrostatic sensor matrix for local velocity measurement of pneumatically conveyed particles

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ABSTRACT

The accuracy of local particle mean velocity measurement with spatial filtering method based on an electrostatic sensor matrix (ESM) is closely related to its sensitivity and spatial filtering characteristics. In this paper, the three-dimensional electrostatic field generated by a point charge in the sensing zone of the ESM is solved by using a finite element method to obtain the spatial sensitivity distributions of the ESM. Further a dimensionless calculation model for the sensitivity of the ESM is suggested based on a Cosine function. The numerical results demonstrate that the spatial sensitivity has a periodic distribution along the axial direction and its spatial periodicity is determined by the axial spacing between two adjacent electrodes. The sensitivity over the central cross-section is localized. The spatial filtering characteristics of the ESM are also investigated and verified by experiments on a gravity-fed rig. These results provide a basis for the optimized design of the ESM.

1. Introduction

Charge is generated on the particles due to collisions between particles and pipe wall in a gas–solid flow system [1]. Particle charging is a comprehensive interaction result of gas–solid two-phase flow dynamics such as the flow characteristics, the regime and the energy exchange, material and configuration of the pneumatic conveyor and the particle properties (particle size and shape, work functions, impurities, particle surface roughness, moisture content of particle, volume resistivity, permittivity etc.) [2–4]. Thus, the charge carried by particles in the gas–solid flow contains rich flow information on particles movement, individual particle sizes, collisions between particles and pipe wall, clusters or agglomerates (temporary or persisting) of particles and equipment-dominated structures such as "stratified stream" overall particle flow patterns. In recent years, a variety of electrostatic sensors for measuring particle velocity have been developed based on particle charging with advantages of simple structure, high sensitivity, low cost and being non-contact and suitable for harsh industrial fields [5–16].

Electrostatic sensor acts not only as a detector, but also a spatial filter in the spatial frequency domain [8]. Due to the spatial filtering effect, its output signal is the weighted average of the electrostatic flow noise by the spatial sensitivity distribution function of the electrostatic sensor. The power spectrum characteristics of the output signal of the electrostatic sensor can be expressed as the product of the power spectral density function of the electrostatic flow noise and the power spectrum characteristics of the sensor [8,9,15,19]. Studies have indicated that the electrostatic flow noise is a white noise with a limited bandwidth

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in the space domain [8], thus the power spectrum characteristics of the output signal of the electrostatic sensor depend entirely on the spatial filtering characteristics of the electrostatic sensor. If an electrostatic sensor has a special spatial sensitivity function by properly designing its configuration, then special flow information can be obtained from the gas–solid flow system. Xu et al. proposed a spatial filtering method for the particle velocity measurement with a circular electrostatic sensor [9]. However, due to the broad spectral bandwidth at its central frequency, the circular electrostatic sensor has a low selection. It results in low signal-noise ratio and reduces the accuracy of the particle velocity measurement. To improve the spatial selectivity of the spatial filter based on electrostatic induction principles for particle velocity measurement, a multi-ring linear electrostatic sensor array has been proposed to measure particle mean velocity [10,15]. On this basis, an ESM has been designed to measure local particle mean velocity in a pipeline [16]. The peak frequency of the output signal from each linear sensor array of the ESM is proportional to the particle velocity and the method has been verified by some experiments on a gravity-fed rig. As each linear sensor array of the ESM has its own sensing zone over the cross-section of the pipeline, the local mean velocity in different sensing zones can be obtained respectively. The sensitivity and spatial filtering characteristics of the ESM are determined by the arc electrode arrangement and geometric size. Therefore, it is of great significance to study their effect on the spatial filtering characteristics and the optimized design of the ESM.

The objective of the present study is to study the spatial selectivity and spatial filtering characteristics of the ESM. A three-dimensional mathematical model of the induced charge on the ESM due to a single charged particle with a unit charge is presented in this paper and a computational function of the sensitivity of the ESM is suggested based on a fitted Cosine function from the finite element results. The effects of the electrode width, spacing and angle on the sensitivity and the filtering characteristics are analyzed quantitatively. Furthermore, the spatial filtering effect of the ESM is analyzed. Finally, experimental results for the validation of the mathematical model and the temporal frequency characteristics of the ESM are presented.

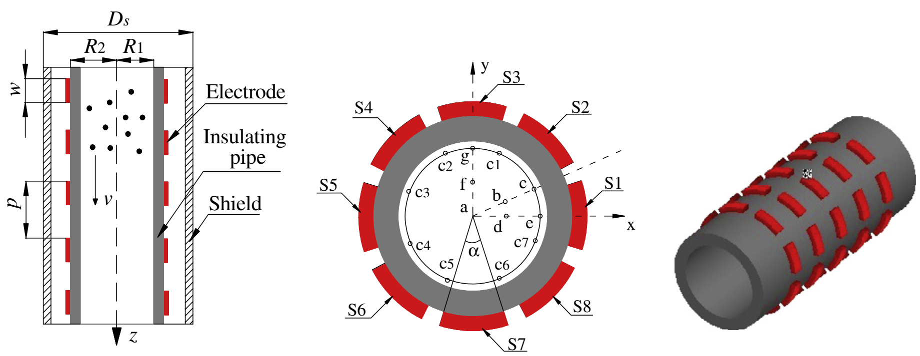
2. Electrostatic sensor matrix configuration

A schematic diagram of the ESM is shown in Fig. 1. It consists of a 40-electrode matrix, an insulating pipe and a metal shield. The electrodes of the ESM are evenly mounted on the outer surface of the dielectric pipe. Each 5 arc electrodes along the pipe axial direction are connected by an electrical wire to form a linear sensor array, and hence there are totally 8 linear sensor arrays (S1–S8). As shown in Fig. 1, w is electrode width; R_1 and R_2 denote the inner radius and the outer radius of the insulating pipe, respectively; D_s is the shield diameter; p is the axial spacing between two adjacent electrodes, and α denotes the electrode angle. The electrode number of each linear sensor array is denoted by n.

At present, there is no access to the analytical solution of the induced charge on the sensor electrode for the dynamic process that a charged particle moves within electrostatic sensor. A mathematical model for electrostatic sensor has been established to explore its sensing characteristics, which treats the interaction between the moving charge and the electrodes as an electrostatic field [10,17]. This model is used to investigate the characteristics of the ESM in this paper. The ESM is symmetrical, and thus the eight linear sensor arrays have the similar sensing field distribution. According to the strategy of simulation adopted by Xu et al. [17], only Several typical flow streamlines denoted by a, b, c, d and e are selected to represent the axial sensitivity distribution of the ESM in the paper, as shown in Fig. 1(a). The radius of the flow streamlines are 9 mm, 4.5 mm, and 0 mm, and their angles θ are 0° and 22.5° over the cross-section of the pipe. In simulations, the structure parameters of the ESM are set as follows: $R_1 = 9.5$ mm, $R_2 = 12.5$ mm, $D_s = 25$ mm, $p = 20$ mm, $\alpha = 40^o$ and $n = 5$.

3. Spatial sensitivity distribution of the ESM

The spatial sensitivity of an ESM can be defined as the induced charge on the electrode of the ESM when a unit point charge is positioned at various space coordinate (r, θ, z) in the sensing zone of the ESM. Therefore, the spatial sensitivity can be represented by the following dimensionless parameter $S(r, \theta, z)$ [10,17]:



(a) Sectional view (b) Three-dimensional view

Fig. 1. Schematic diagram of the ESM.