Local solid particle velocity measurement based on spatial filter effect of differential capacitance sensor array

Gao Heming1, Deng Huiwen1, Min Yingxing2, Wang Bing3, Fan Bingyan1

1 School of Mechanical and Precision Instrument Engineering, Xi’an University of Technology, Xi’an 710048, People’s Republic of China
E-mail: 313423109@qq.com

Abstract: This study proposes a novel velocity measurement method based on a differential capacitance sensor array (DCSA) for the solid particles in gas-solid flow. Firstly, the DCSA is modelled by the finite-element software ANSOFT, and its sensitivity characteristic is acquired. Additionally, the spatial filtering effect of DCSA is theoretically investigated, which validates the feasibility of particle velocity measurement based on DCSA. By measuring the frequency bandwidth (cut-off frequency) of the DCSA’s output capacitance signal, the velocity of the local particles in the pipeline can be calculated. Further through the form of differential detection, the cut-off frequency can be accurately converged. Finally, a novel solid particle velocimeter based on DCSA is developed and tested on a gravity-delivery particle experimental device. The results indicate that the method has the feasibility for the velocity measurement and its repeatability is within 11% over the velocity range of 1–3 m/s.

1 Introduction

Pneumatic conveying is widely used in industrial processes to transport powdered and granular materials, including chemicals, energy, electricity and so on. The velocity of solid particles during gas-solid two-phase flow is one of the important parameters describing flow characteristics and state. In order to effectively utilise energy and raw materials and optimise particle handling and control process, an accurate, reliable, real-time, non-invasive and continuous measurement methods of the particle velocity in the conveying pipeline becomes increasingly important [1, 2]. As a typical example, the pneumatic conveying process of pulverised coal particles requires optimisation of the conveying speed. In the case of excessive particle velocity, the particle degradation, energy consumption and severe pipeline wear will be severed. On the contrary, in the case of insufficient particle velocity, the pipeline blockage and unstable flow state always happen [3]. Thus, the accurate measurement of particles velocity is critical for the pneumatic conveying processes.

To achieve the velocity measurement of solid particles, many efforts and attempts have been made such as laser Doppler velocimetry [4], particle tracing velocimetry [5], cross-correlation method [6], spatial filtering velocimetry [7] and so on [8, 9]. One of them is the optical spatial filtering method, which was proposed by Ator in the 1960s [10]. Although the method has low spatial frequency resolution, it also has the advantages of a stable optical and mechanical system and relatively simple data processing algorithms [11]. Therefore, it has attracted great attention. Recently, the physical implementation of spatial filters has extended from optical filters to capacitance transducer probes, because of its low-cost, fast response, non-invasiveness and electrode design flexibility [12, 13]. As capacitive sensors have the ability to detect changes in particle concentration, this measurement method can be used to detect mass flow rate of particles. However, research work on the structure of capacitive sensors has mainly focused on annular or semi-annular shapes, and is mainly applicable to detecting the flow state of particles over the cross-sectional area of pipe. The output signal of the sensor contains the distribution information of all the particles over the cross-sectional area of pipe [13–16]. Practically, the particle velocity and concentration distribution over the cross-section of the pipe is uneven, depending on the direction in which the pipe is arranged (vertical or horizontal), the gas velocity (high or low velocity), the solid material properties and so on. Thus, the local velocity measurement of the particles distributed in the different sections over the cross-section of the pipe is helpful to regulate the flow state of the particles conveyed in the pneumatic conveying system.

The purpose of this study is to design and investigate a novel spatial filter based on differential capacitance sensor array (DCSA), which is able to measure the velocity of particles close to the pipe wall. The spatial sensitivity distribution of the DCSA is analysed by the finite-element method, and the velocity measurement method based on its spatial filtering effect is also investigated. Through theoretical deduction, the quantitative relationship between the amplitude–frequency characteristic of the output signal of DCSA and the particle velocity is obtained. Then a novel particle velocimeter based on the DCSA is further developed, and its performance is evaluated on a gravity-delivery particle experimental device.

2 DCSA configuration and measurement principle

2.1 DCSA configuration

Fig. 1 is a schematic diagram of the DCSA. The DCSA consists of three parts including electrode array, insulated pipeline and metal shield. The electrode array consists of 16 arc-shaped receiver electrodes and 1 ring-shaped transmitter electrode and 2 axial protection electrodes. The metal shield covers the electrode matrix to eliminate the electromagnetic interference. The axial protection electrode limits the electric field line divergence along the pipeline, and is used to obtain a well-defined axial sensitive region. The receiver electrodes are symmetrically distributed on both sides of the ring-shaped transmitter electrode, forming two-layer arrays along the axial direction of the pipeline. Therefore, there are 16 capacitors in the circumferential direction of the pipeline, marked as \( C_1 \) and \( C_{2n} \) respectively \((i = 1, 2, 3 \ldots 8)\). According to the principle of ‘Fringe Electric Field’ detection based on planar capacitance, the pipeline cross-section will be meshed into eight fan-shaped sensitive regions \( S_i(= 1, 2, 3 \ldots 8) \). The inner radius \( R_1 \) and outer radius \( R_2 \) of insulated pipeline are 11 and 12.5 mm, respectively. The electrode axial length \( w \) is 10 mm, and the axial length \( s \) of the ring protection electrode is 5 mm, the spacing \( d \) between the transmitter electrode and the receiver electrode is 1 mm. The covering angle of detection electrodes \( \alpha = 42^\circ \).
2.2 Axial sensitivity characteristics of DCSA

The concentration and velocity of particles in different positions in the pneumatic conveying pipeline are generally non-uniform. In order to understand the operating characteristics of the DCSA, the axial sensitivity distribution of the DCSA is investigated by the simulation. The three-dimensional finite-element model of the DCSA was established using ANSOFT software, whose structural parameters are the same as Section 2.1 and the coordinate origin \( O \) is in the sensor centre. The axial sensitivity in DCSA is defined as [11, 12]

\[
sij(z) = \frac{C_{ij}(z) - C_{el}}{C_{el}} \times 100\% \quad (1)
\]

where \( sij(z) \) is the axial sensitivity distribution function of DCSA, \( C_{el} \) and \( C_{sh} \) are the capacitance values of \( C_{ij} \) when the sensor is empty and full of test particles, respectively. \( C_{ij}(z) \) is the capacitance value when the test particles are located at the axial position \( z, i = 1, 2 \) and \( j = 1, 2 \ldots 8 \).

As DCSA is a three-dimensional sensor, taking into account the structural symmetry and time consumption of the three-dimensional finite-element analysis, only several typical positions denoted by \( a, b \) and \( c \), were chosen to calculate the axial sensitivity distribution of the DCSA as shown in Fig. 2. The chosen positions correspond to the radius \( r = 0, 5, 10 \) mm, the angle \( \theta = 22.5^\circ \). The sensitivity distribution of the capacitors \( C_{11} \) and \( C_{21} \) along the axial direction of pipe. As can be seen from Fig. 3, the overall DCSA axial sensitivity exhibits a double-peak variation. The two peaks are located at the centre between the transmitter and receiver electrodes and the axial distance is \( w + d \) (\( w \) is the axial length, \( d \) is the electrode spacing). The axial sensitivity distributions of capacitors \( C_{11} \) and \( C_{21} \) are approximately Gaussian function. In addition, the closer to the inner wall of the pipe, the greater the change in sensitivity. The sensitivity of the position in the centre of the pipeline and the position away from the electrode is small, and it can be considered that the particles at this position have no influence on the output signal of the sensor. Therefore, the sensitive area of DCSA is the local zone between the adjacent transmitter and receiver electrode. Therefore, each capacitance of DCSA is equivalent to a local spatial transducer probe.

2.3 Spatial filter velocity measurement principle

In the process of gas-solid two-phase flow, the particle distribution in the conveying pipeline is a function of spatial coordinates \( (r, \theta, z) \) and time \( (t) \), and can be expressed as \( \rho = \rho(t, r, \theta, z) \). Since the gas-solid flow regime is unstable and randomly changing, the particle distribution function is a random function about \( (t, r, \theta, z) \), which is defined as ‘flow noise’. The change of capacitance signal caused by moving particles is represented by \( \Delta C(t) \) and can be calculated as

\[
\Delta C(t) = k_0 \int \int \int \rho(t, r, \theta, z) \cdot s(r, \theta, z) \cdot r \, dr \, d\theta \, dz \quad (2)
\]

where \( k_0 \) denotes a constant associated with particle dielectric properties and size. As shown in (2), the output capacitance signal is a random signal, because it is a weighted average of the spatial sensitivity functions \( s(r, \theta, z) \) and a random function \( \rho(t, r, \theta, z) \) which represents the distribution of the particle’s spatial position.

In the actual measurement, since the erratic movement of the particles and an uneven distribution of the electric field, the DCSA output signal over time is constantly changing. For better calculations, it is assumed that only the axial movement velocity of the particles is considered, that is, the presence of the axial movement velocity of the particles only at a given radial and circumferential position \( (r, \theta) \). Previous studies have shown that gas-solid two-phase flow is random noise with limited bandwidth.
\[ S \Delta C(f) \approx k_1 \frac{1}{\sqrt{\pi Z/2}} \left| \int_{-Z}^{Z} s(z) \, dz \right| \]

where \( k_1 \) is constant, \( S(f) \) represents the spatial Fourier transform of the spatial sensitivity function \( s(r, \theta, z) \), \( f_2 \) is the spatial frequency of the axial direction and \( f \) is the temporal frequency with \( f = f_2 v_z \). Equation (3) shows that the output signal power spectral density of each capacitor of the DCSA absolutely depends on its spatial filtering characteristics. Therefore, if a suitable sensor structure is designed, the desired spatial sensitivity function can be obtained, and then the velocity of the particle can be accurately obtained from the complex gas solid flow.

According to the characteristics of the axial sensitivity distribution in Fig. 3, sensitivity along the axial distribution is similar to that of a Gaussian curve, which can be expressed as

\[ s_i(z) = a e^{-b(z-c)^2} + d e^{-g(z-m)^2} - Z/2 \leq z \leq Z/2 \]

where \( a, b, c, d, g \) and \( m \) are all fitting coefficients, which are associated with the geometry parameters of the DCSA and the spatial position \( (r, \theta) \) of the particles.

At a fixed radial position, the solid phase particles are allowed to move in the axial direction at a certain velocity. In this case, the sensitivity change caused by the uneven distribution of the solid particle can be considered as being generated by the unit impulse signal \( \delta(z - v t) \). The unit impulse response of the sensor axial sensitivity can be expressed as

\[ h(t) = \int \delta(z - v t) \, s(z) \, dz \]

Perform a Fourier transform on (5) and take its absolute value. The amplitude–frequency characteristic function \( |H(f)| \) of the unit impulse response \( h(t) \) can be derived and expressed as

\[ |H(f)| = \int h(t) \exp(-j2\pi f t) \, dt \]

\[ = \frac{a e^{-\frac{b}{v_z}}}{\sqrt{b}} \exp \left( -\frac{\pi^2 f^2}{v_z^2} \right) + \frac{d e^{-g}}{\sqrt{v_z g}} \exp \left( -\frac{\pi^2 f^2}{v_z^2} \right) \]

From (6), it can be seen that the DCSA has low-pass filter spectrum characteristics in the time–frequency domain. This is because when the flow of a solid particle causes a change in capacitance, the sensor will average this ‘flow noise’ under a certain spatial weight function, and this noise cannot be completely transferred to the sensor. Therefore, the velocity information can be obtained by extracting the frequency bandwidth (cut-off frequency) characteristics of the sensor output capacitance signal.

In the frequency response curve, when the amplitude–frequency characteristic decays to zero, that is, when the derivative of the above equation is zero, the equation is as follows:

\[ \frac{a}{\sqrt{b}} \exp \left( -\frac{\pi^2 f^2}{v_z^2} \right) \times \left( 1 - \frac{2f^2}{v_z^2} \right) + \frac{c}{\sqrt{v_z g}} \exp \left( -\frac{\pi^2 f^2}{v_z^2} \right) \times \left( 1 - \frac{2f^2}{v_z^2} \right) = 0 \]

If a structural characteristic constant \( g_s \) is introduced at spatial position \( (r, \theta) \), the solution of the above equation can be expressed as

\[ \sqrt{v_z g} = g_s \]

where \( g_s \) is the structural characteristic constant, which is related to the sensor structure and the spatial position; \( f_m \) is the cut-off frequency of the spectrum of the capacitor output signal.

From (10) and Fig. 4, it can be seen that the output capacitance signal is linear with the bandwidth, and the velocity information can be obtained by measuring the cut-off frequency. However, in the actual measurement, the cut-off frequency in the spectrum is always difficult to accurately converge, and the structural characteristic constant \( g_s \) is difficult to calibrate. Therefore, in order to improve the measurement accuracy, on the basis of the spatial filtering method, the differential detection technology is adopted to overcome the inaccurate convergence of the cut-off frequency. According to (4), the differential sensitivity function of the axially adjacent capacitors \( C_{11} \) and \( C_{21} \) is theoretically given by

\[ s d(z) = s 1 j(z) - s 2 j(z) = s 1 j(z) - s 2 j(z + (w + d)) \]

where \( w \) is the axial length and \( d \) is the electrode spacing.

Perform a Fourier transform on (9) and take its absolute value, the amplitude–frequency characteristic function of (9) can be deduced as

\[ |Sd(f)| = \int s d(z) \exp(-j2\pi f z) \, dz \]

\[ = |H(f)| - \exp(-j2\pi f)| \]

\[ = 2|H(f)|\sin(\pi(w + d) f) \]

From (10), after the differential operation, \( H(f) \) is modulated by sin \((\pi(w + d) f)\). In this paper, sin \((\pi(w + d) f)\) is defined as sine modulation factor. When \((\pi(w + d) f)\) is equal to \(n\pi\), the modulation factor is equal to 0, the following relationship exists:
\[ f_z = \frac{1}{w + d} \]
\[ \Rightarrow v = \frac{w + d}{f_m} \]

From (11) and Fig. 5, the cut-off frequency \( f_m \) is accurately converged, and the proportional coefficient of velocity and frequency bandwidth is determined only with the sensor structure parameters. This implies that measurement errors caused by uneven distribution of the spatial position of the particles can be eliminated, and the velocity measurement range and resolution can be adjusted by optimising the sensor structure parameters.

3 Experimental research and results analysis

3.1 Instruments and experimental system

The DCSA spatial filter particle velocity measurement system is mainly composed of a measuring probe, a capacitance-to-digital conversion circuit based on the PCAP01 chip and a computer data acquisition and processing system, as shown in Fig. 6. The electrode adopts a thin copper sheet with a thickness of 0.1 mm and adheres to the outside of the PVC pipe with permittivity 3.8. The other parameters of the DCSA sensor keep in accordance with the design parameters in the simulation.

Graphical programming software Labview is applied to achieve data analysis, display and storage. The sampling frequency of each capacitor of DCSA is 2.38 kHz. The spectrum analysis is based on the fast Fourier transform method. In the method of measuring the particle flow velocity by the spatial filtering method, the velocity information is obtained by measuring the cut-off frequency of the output capacitance signal. From the theoretical analysis, it can be known that the output signal of the DCSA not only contains the frequency spectrum information of velocity, but also contains the DC low-frequency information, which is called the fundamental frequency information, and is mainly caused by \( C_{ed} \) (the capacitance value of the sensor empty tube), and the basic frequency information is superimposed on the frequency spectrum containing the velocity information the spectrum width will be shifted during signal processing, which will affect the accuracy of velocity measurement. Therefore, this paper will calibrate the empty tube and full tube capacitance values, and normalise the experimental data to the normalised capacitance value as in (1).

Due to the lack of reliable calibration equipment, this paper uses a gravity-delivery particle experimental device and arranges the pipeline at 45° to complete the measurement of local particle velocity. When the pipeline is arranged inclined at 45° angle, the corresponding reference velocities and distances are reported in Table 1. In the gravity-delivery particle experimental device, the conveyed material in the test is the resin particle and glass particle, and the material parameters are reported in Table 2.

3.2 Results and analysis

When the pipes are arranged at an angle of 45°, the particles can be controlled to flow through the sensitive space of \( C_{11} \) and \( C_{21} \) along the bottom of the pipes. Set the acquisition time of measurement to 1 s. Fig. 7 shows the output capacitance signals of capacitor \( C_{11} \) for resin particles falling from the different distance in the inclined pipeline. When the single particles pass through the sensor sensitive area in the axial direction, the output signal of the DCSA is approximately a continuous Gaussian pulse, which is mainly determined by the sensitive mechanism of the 'edge electric field' detection of DCSA, and the spatial structure of the electrodes. However, as shown in Fig. 7, the output signal is a superposition of a series of pulses that amplitude and phase fluctuate randomly, which are mainly attributable to the random particle concentration and velocity distribution in the pipeline. The main cycle of the included pulse signal is the same. As shown in Fig. 7, with the increase of particle velocity, the pulse density of the output signal is enhanced (the number of pulses increases), and the randomness of the fluctuation is obvious. This is due to that the particles flow state becomes unstable as the height increases and more particles pass through the DCSA sensitive zone in the same acquisition time.

Fig. 8 shows the spectral characteristics corresponding to the output capacitance signals of Fig. 7. In order to improve the precision and stability of the velocity measurement, and eliminate the interference of the noise signal due to the mechanical vibration, electromagnetic interference and the internal thermal noise of circuit, the polynomial fitting method is adopted to determine the trend of frequency spectrum in the paper (red solid line shown in Fig. 8). From Fig. 8, it can be seen that as the particle velocity increases, the spectrum width of the output signal of the capacitor increases significantly, but the amplitude decreases, which is consistent with (7). In addition, with the particle velocity increase, the frequency bandwidth is wider (the cut-off frequency is greater), as shown in Fig. 8.

However, as shown in Fig. 8, the cut-off frequency in the spectrum is always difficult to accurately converge due to noise and random disturbance of the particles. According to (10) and (11), the differential capacitance \( C_{11} \) (\( C_{11} = C_{11} - C_{21} \)) signals and

![Graphical Programming Software Labview](http://labview.com)

![Gravity-Delivery Particle Experimental Device](http://particledevice.com)

**Table 1** Distance and reference velocity of particles flowing through the pipe when installed in a 45° pipe

| Distance \( d \), m | 0.07 | 0.29 | 0.65 |
|-------------------|------|------|------|
| reference velocity \( v_r \), m/s | 1    | 2    | 3    |

**Table 2** Conveying material characteristic parameters

| Material   | Diameter \( d_m \), mm | Density \( \rho_m \), kg m\(^{-3} \) | Permittivity \( \varepsilon_r \), F m\(^{-1} \) |
|------------|------------------------|----------------------------------|----------------------------------|
| resin particles | 6                      | 1410                             | 8.35                             |
| quartz     | 6                      | 2760                             | 4.2                              |
| particles  |                        |                                  |                                  |
spectra are shown in Figs. 9 and 10. From Fig. 10, the spectrum is exactly converged at 90, 180, 270 Hz, which is in agreement with (11). By comparing Figs. 8 and 10, after the difference operation spectrum, the cut-off frequency can be accurately converged, so the velocity measurement is more accurate.

Fig. 11 shows the results of continuous local velocity of resin particles measured by the differential capacitance $C_{d1}$ in inclined pipeline. It can be seen that at the same distance, the consistency of velocity measurement results is better. Under the test conditions given in the paper, the repeatability error of the resin particle velocity measurement is within 4.2–10.3%. Therefore, in order to accurately obtain the local velocity of the particles, when actually designing the measurement system, noise interference should be minimised, and parasitic capacitance and stray capacitance should be effectively compensated. In addition, due to the influence of air resistance and the collision and friction between the particles and the pipe wall, the average actual measurement velocity of the pellets is lower than the reference velocity, and with the increase of the drop distance, the friction and resistance of the pellets are increased. The difference between the actual measurement velocity average and the reference velocity increases, which are consistent with the results shown in Fig. 11. Uniform experimental results were observed under different drop heights and material particles. Therefore, the DCSA has local sensitivity characteristics and can measure the local velocity of solid particles.

4 Conclusion

In this paper, based on the local sensitive properties of DCSA and the spatial filtering effect, a spatial filtering measurement method for particle local velocity of gas-solid two-phase flow is proposed. Each electrode pair of the DCSA has a different sensitive area. Using the symmetry of its spatial structure, the local average velocity information of particles can be accurately obtained by detecting a single capacitance signal or an adjacent symmetrical capacitive differential mode signal, the measurement of the local velocity of solid particles is achieved. The experimental results show that the repeatability of the test system is better than 11%. It provides theoretical and technical support for the design of the DCSA spatial filter to measure the velocity of solid particles.

5 Acknowledgments

This work is supported partly by National Natural Science Foundation of China under grant nos. 51406164 and 41575035, and Special Funds for Natural Science Basic Research Projects of Shaanxi province under grant no. 2017JM5092.

6 References

[1] Arakaki, C., Ghaderi, A., Datta, B.: ‘Non-intrusive mass flow measurements in pneumatic pneumatic transport’. 5th Int. Conf. for Conveying and Handling of Particulate Solids, Sorrento, Italy, August 2006, pp. 27–30
[2] Shao, F., Lu, Z., Wu, E., et al.: ‘Study and industrial evaluation of mass flow measurement of pulverized coal for iron-making production’, Flow Meas. Instrum., 2000, 11, pp. 159–163
[3] Yan, Y.: ‘Mass flow measurement of bulk solids in pneumatic pipelines’, Meas. Sci. Technol., 1999, 7, pp. 1687–1706
Li, Y.Z., Li, T., Zhang, H.T., et al.: ‘LDV measurements of particle velocity distribution and annular film thickness in a turbulent fluidized bed’, Powder Technol., 2017, 305, pp. 578–590.

Yan, F., Rinoshika, A.: ‘Characteristics of particle velocity and concentration in a horizontal self-excited gas-solid two-phase pipe flow of using soft fins’, Int. J. Multiph. Flow, 2012, 41, pp. 68–76.

Yan, Y., Byrne, B., Woodhead, S., et al.: ‘Velocity measurement of pneumatically conveyed solids using electrodynamic sensors’, Meas. Sci. Technol., 1995, 6, pp. 515–553.

Petrak, D.: ‘Simultaneous measurement of particle size and particle velocity by the spatial filtering technique’, Part. Part. Syst. Charact., 2002, 19, (6), pp. 391–400.

Zheng, Y., Liu, Q.: ‘Review of techniques for the mass flow rate measurement of pneumatically conveyed solids’, Measurement, 2011, 44, pp. 589–604.

Zhu, J., Li, G., Qin, S., et al.: ‘Direct measurements of particle velocities in gas-solids suspension flow using a novel five-fiber optical probe’, Powder Technol., 2001, 115, pp. 184–192.

Ator, J.: ‘Image-velocity sensing with parallel-slit reticles’, J. Opt. Soc. Am., 1963, 53, pp. 1416–1422.

Aizu, Y., Asakura, T.: ‘Principles and development of spatial filtering velocimetry’, Appl. Phys. B, 1987, 43, pp. 209–224.

Hammer, E., Green, R.: ‘The spatial filtering effect of capacitance transducer electrodes (flow measurement)’, Phys. E, Sci. Instrum., 1983, 16, pp. 438–443.

Holler, G., Hrach, D., Fuchs, A., et al.: ‘Application of a combined capacitive flow velocity and density sensor for the measurement of liquid hydrogen mass flow’. Proc. IEEE Int. Instrumentation and Measurement Technology Conf. (I2MTC 2009), Singapore, 5–7 May 2009, pp. 1444–1448.

Hrach, D., Fuchs, A., Zangl, H.: ‘Capacitive flowmeter for gas-solids flow applications exploiting spatial frequency’. IEEE Sensors Applications Symp. (SAS 2008), GA, USA, Atlanta, 12–14 February 2008, pp. 26–30.

Hrach, D., Fuchs, A.: ‘Investigation of field electrode geometries in capacitive flow measurements’. IEEE Sensors Conf., Lecce, Italy, 2008, pp. 17–20.

Ismail, B., Ahmed, W.: ‘Innovative techniques for two-phase flow measurements’, Recent Pat. Electr. Eng., 2008, 1, pp. 1–13.