Flow-Velocity Measurement for Bulk Granular Solids in Pneumatic Conveyor Pipes Using Random-Data Correlator Architecture

Anton Fuchs, Hubert Zangl, Georg Brasseur, and Emil M. Petriu, *Fellow, IEEE*

***Abstract*—This paper discusses a correlative-measurement technique for the evaluation of the flow velocity of bulk granular solids moving through the pneumatic conveyor pipes in both the dense and dilute phases. Flow velocities are recovered from the cross-correlation functions between the pairs of signals produced by the noninvasive capacitive sensors placed in circular layers at a given distance on the conveyor pipe. A random-data correlator architecture is discussed as a cost-effective solution for the real-time computation of the multiple correlation functions used for the estimation of the cross-sectional tomographic model of the flow-velocity profile in the dilute phase.**

***Index Terms*—Dense phase, dilute phase, particle flow velocity, pneumatic transport of bulk granular solids, random-data correlator architecture.**

I. Introduction

Monitoring the flow velocity of bulk solids moving through pneumatic conveyor pipes is of major practical interest for many industrial applications [1]–[4]. However, this is not a trivial task because of the complexity of the phenomena encountered during this flow. Two clearly distinct flow phases have to be considered separately [5]. In the dense phase, solid particles are not fully dispersed in the pneumatic carrier, and therefore, they are transported at low velocities [2], [6]. This type of flow consists of a sequence of high particle-density sections, interrupted by sections with a very low particle density; the reason for this is sometimes called a plug flow. The dilute phase, on the other hand, is characterized by a relatively lower particle concentration of the bulk solids transported pneumatically through the pipe [7], [8].

The speed and the amount of the pneumatic carrier needed to transport a given amount of a granular material through a pipe are usually higher in the dilute phase than in the dense phase.

Since in the dense-phase flow the conveyor pipe is either filled with material particles of a relatively homogenous high density (granular plug) or not filled at all, the particle velocities are considered to have practically the same value in any given cross section of the conveyor pipe. However, the measurement of the particle velocities in the dilute-phase flow is a more challenging task because of the higher velocities and their nonuniform cross-section distribution.

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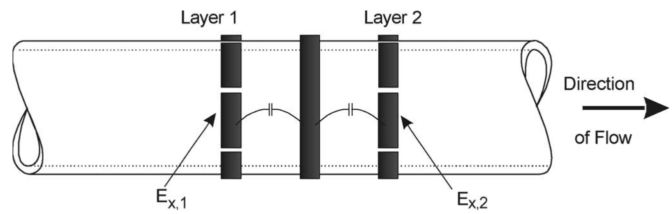

Fig. 1. Rings of capacitive electrodes are placed on the exterior of the nonconductive conveyor pipe. The common collector ring lies in between the two rings of the transmitter segments.

This paper discuses a correlative-measurement technique for the measurement of the particle flow velocities in both the dense and dilute phases. Particle velocities are recovered by calculating the cross-correlation functions between the pairs of signals produced by the noninvasive sensors placed in circular layers at a given distance on the conveyor pipe. We have studied a correlator architecture using a low complexity internal random-data representation that offers a cost-effective solution for the real-time computation of the multiple correlation functions [9], [10].

II. Measurement Setup

The electrical-capacitance methods are routinely used for the nonintrusive monitoring of the powder and granular materials flow in the pneumatic-conveyor systems [2], [11].

Our measurement setup consists of two sensor rings, placed at a distance of 0.03 m, with a common collector ring between them, mounted around the nonconductive conveyor pipe, as shown in Figs. 1 and 2. Each outer ring consists of seven individual capacitive electrodes. The diagram in Fig. 1 shows the capacitive-sensor setup where $E_{x,1}$ and $E_{x,2}$ are the stray capacitances between the two sets of electrodes and the common collector ring (shown as a solid ring in the middle of the sensor setup).

As the granular material flows through the conveyor pipe, it affects the capacitance between the outer-ring electrodes and their middle-ring common collector electrode. Any change in the relative permittivity of the material flow is detected first as a change in the "upstream" capacitance (between the first

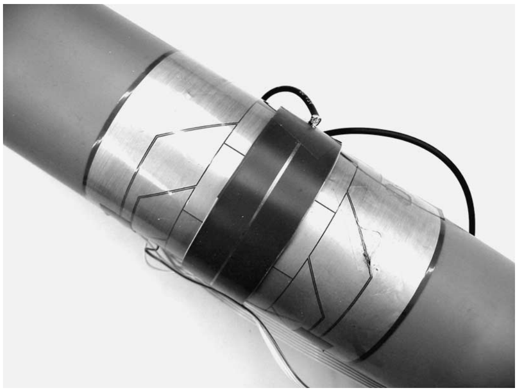

Fig. 2. Physical implementation of the noninvasive capacitive-sensor setup on a conveyor pipe.

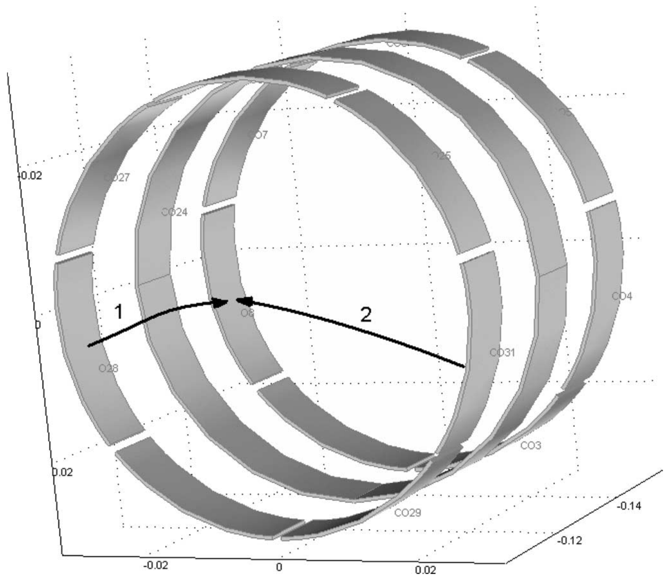

Fig. 3. Three-dimensional (3-D) perspective of the sensor layout. The correlation of signals picked up by the electrodes on the same longitudinal direction, 1) allows the monitoring of a region close to the pipe wall, while the correlation of signals picked up by electrodes in diagonal opposition, and 2) allows the monitoring of a region in the transversal cross section of the pipe.

outer-ring electrodes placed on the pipe and the common ring collector electrode) and then after a delay as a change in the "downstream" capacitance (between the second outer-ring electrodes and the common ring collector electrode).

The signals of the upstream- and downstream-measurement layers usually have similar shapes but different phases due to the time taken by the material to flow between the sensitive areas. These phase shifts can be recovered from the cross correlation of the pairs of signals coming from the different combinations of the upstream and downstream individual electrodes. The cross correlation of the pairs of signals from the electrodes placed longitudinally allows the estimation of the particle-flow-velocity profile in a region close to the wall of the conveyor pipe. The cross correlation of the pairs of signals from the diagonally opposed electrodes, as shown in Fig. 3, allows the estimation of the particle-flow-velocity profile in the cross section of the conveyor pipe.

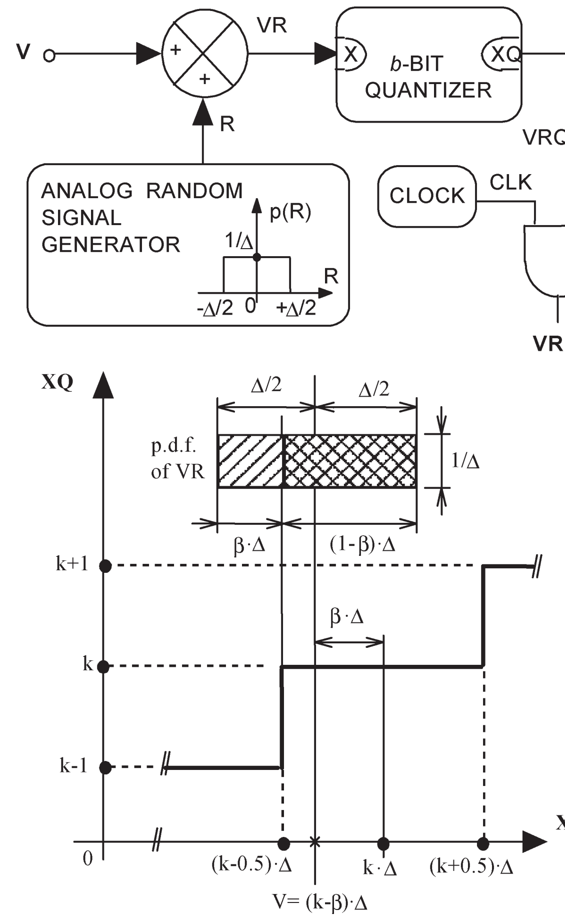

Fig. 4. Multibit analog/random-data conversion (adapted from [9]).

III. Correlator Architecture Using Random-Data Representation

This section summarizes the basis of the random-data representation and its application to the implementation of the hardware correlator architectures as described in [9].

The random-data representation of the analog signals is produced, as shown in Fig. 4, by a multibit dithered quantization. The analog input V, which is supposed to have a relatively low variation rate, is mixed with a random dither R, which is uniformly distributed between $-\Delta/2$ and $+\Delta/2$. The resulting analog signal VR is quantified with a b-bit resolution and then sampled by a clock CLK to produce the random sequence VRD of the b-bit data having amplitudes restricted to two sequential quantized values $k-1$ and k.

The ideal estimation over an infinite number of samples of the random-data sequence VRD can be calculated from the quantization characteristics:

$$\begin{aligned} E[\text{VRD}] &= (k-1)\cdot p\,[(k-1.5)\cdot\Delta \le \text{VR} < (k-0.5)\cdot\Delta] \\ &\quad + k\cdot p\,[(k-0.5)\cdot\Delta \le \text{VR} < (k+0.5)\cdot\Delta] \\ &= (k-1)\cdot\beta + k\cdot(1-\beta) \\ &= k-\beta. \end{aligned}$$

The deterministic component V of the random-data sequence could be estimated as the average V_N^* over the finite set of

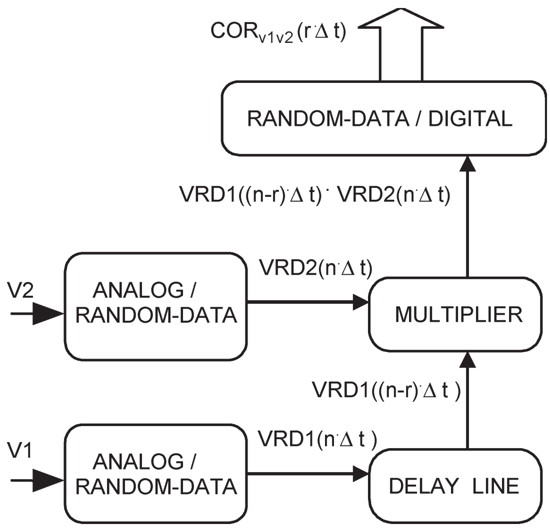

Fig. 5. Correlator architecture using random-data representation (adapted from [9]).

the most recent N random-data $\{\mathrm{VRD}_i/i = 1, 2, \ldots, N\}$. The estimation accuracy depends on the quantization resolution Δ, the number N of averaged samples, and on the statistical properties of the dither signal R.

The random-data representation, which usually is limited to a 2-bit resolution, allows the efficient implementation of the hardware computational complex algorithms because of the remarkable reduced complexity of the circuits needed to implement the individual arithmetic operations with such a low-resolution operands.

Fig. 5 shows the basic architecture of a correlator with two inputs [V1 (an analog signal generated in our case by one of the upstream electrodes) and V2 (an analog signal generated in our case by one of the downstream electrodes)], which are processed internally as the random-data streams $\mathrm{VRD1}(n \cdot \Delta t)$ and $\mathrm{VRD2}(n \cdot \Delta t)$, where Δt is the sampling rate. An r-stage shift register provides the desired $r \cdot \Delta t$ delay for the first data stream. The stream of the product samples $\mathrm{VRD1}((n - r) \cdot \Delta t) \cdot \mathrm{VRD2}(n \cdot \Delta t)$ is finally averaged by the random-data/digital converter producing the correlation-function value $\mathrm{COR}_{\mathrm{V1 \cdot V2}}(r \cdot \Delta t)$.

Table I summarizes the correlator's performance for the different random-data resolutions relative to an ideal analog correlator, when the inputs are statistically independent Gaussian noise signals with amplitudes restricted within $\pm 3\sigma$ [12]. It may be interesting to note that, by increasing the number of the quantization levels from two (as in the case of the random pulses) to three (as in the case of the 1.5-bit random-data streams), the relative error is reduced by a factor of 12.5.

IV. Dense-Phase Measurements

The presence of a material plug in the sensitive layers means an increase of the permittivity between certain electrodes of the two outer rings and the collector ring, resulting in an increase of the evaluated capacitances. Fig. 6 shows the similarly shaped signals provided by the two capacitive sensors for a dense-phase flow, when the granular material forms plugs in the conveyor pipe. These material plugs are easily detected due to a significant increase in the signal amplitude when the plug reaches a sensor layer.

TABLE I
Relative Mean-Square Error of a Random-Data Correlator Function of the Number of Quantization Levels

Quantization levels	Relative mean square error
2	72.23
3	5.75
4	2.75
...	...
8	1.23
...	...
analog	1

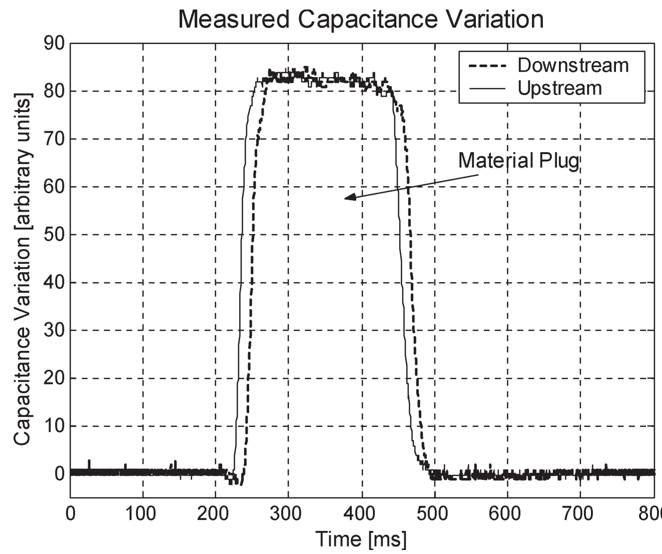

Fig. 6. Capacitive readout for the two electrodes placed upstream and downstream longitudinally on the pipe wall while recording the flow of a granular plug.

Knowing the value of the time delay between the signals detected by the electrodes placed at a given distance on the conveyor pipe allows immediate calculation of the velocity of the material plug traveling through the pipe.

Due to its inherent robustness to noise, the correlation technique is commonly used for the measurement of the time delays in this type of applications [13].

Fig. 7 shows the cross-correlation function of the two analog signals of Fig. 6 picked up by the capacitive sensors placed at a distance of 0.03 m. The peak of this correlation function occurs at a time delay of 14.32 ms, which further yields a flow velocity of 2.095 $\mathrm{m} \cdot \mathrm{s}^{-1}$.

Fig. 7 allows us to compare the shape of the peak of the correlation function calculated directly from the two analog signals [Fig. 7(a)] against those produced by the correlation of the 2-bit random-data signal representations [Fig. 7(b)], 1.5-bit random-data signal representations [Fig. 7(c)], and 1-bit random-data signal representations [Fig. 7(d)]. As it can be easily seen, both the 1.5- and the 2-bit random-data representations yield the same time-delay value for the correlation-function peak as that produced by the cross correlation of the original analog signals.

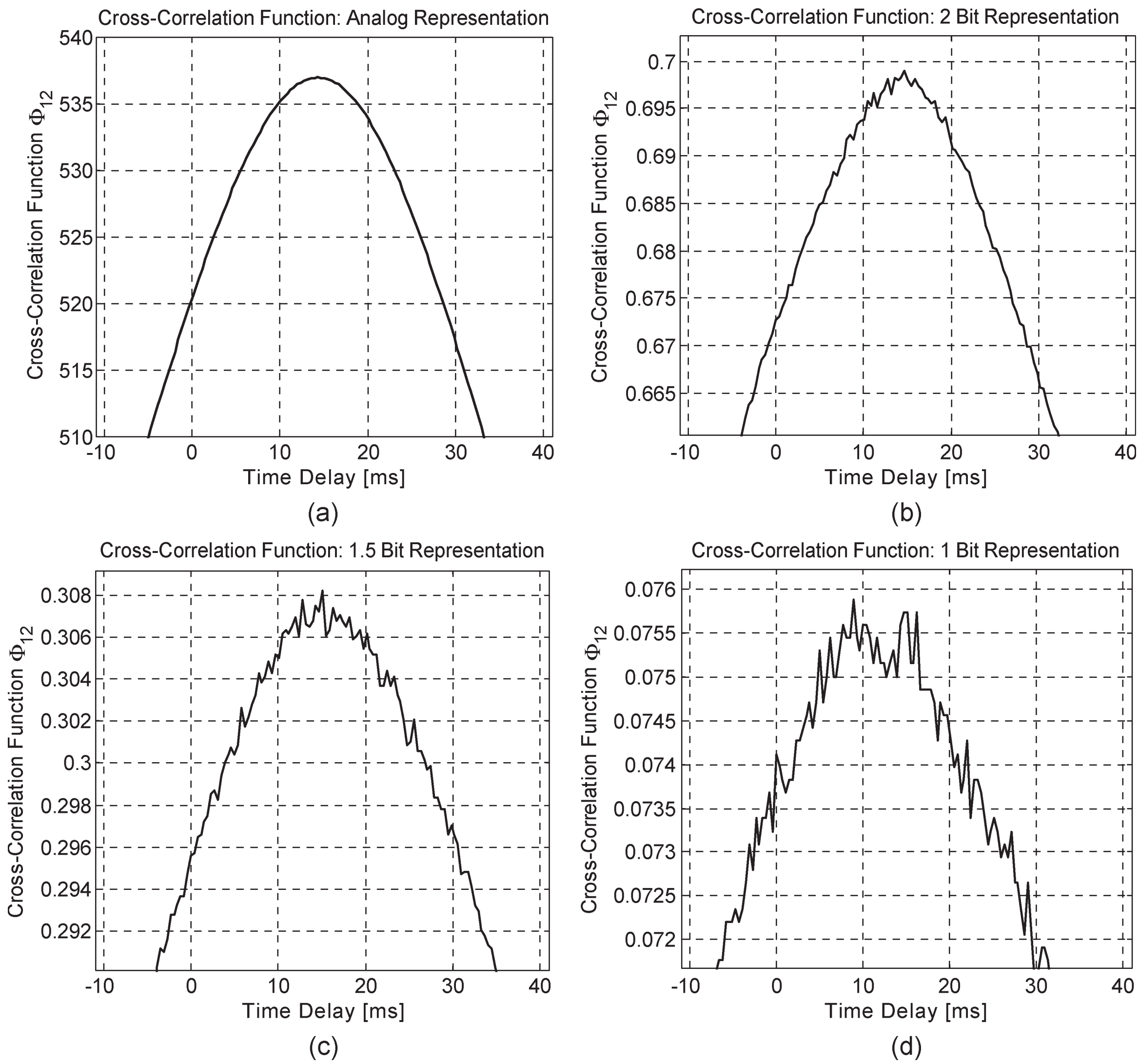

Fig. 7. Cross-correlation function of the two analog signals of Fig. 6 calculated for the different internal data-representation formats. (a) Analog signals. (b) 2-bit random data. (c) 1.5-bit random data. (d) 1-bit random data.

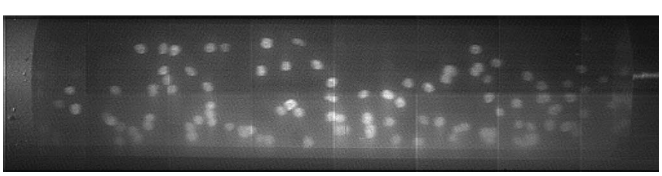

Fig. 8. Dilute-phase flow of the plastic pellets acquired through a transparent pipe section by means of a high-speed camera.

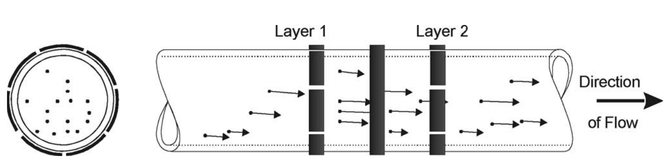

Fig. 9. Measurement setup with the two layers (rings) of capacitive sensors. The particle velocities are the function of the particle trajectories through the pipe.

V. Dilute-Phase Measurements

The plastic pellets, which are frequently used in many industrial processes, are often transported through the pneumatic

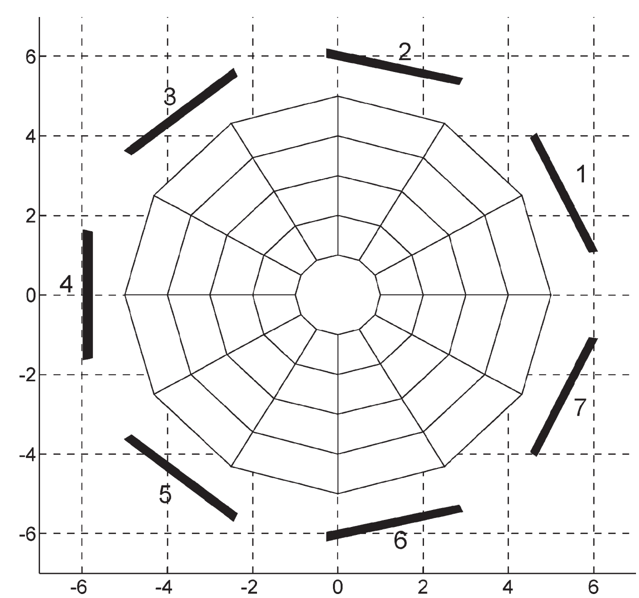

Fig. 10. Segmentation of the pipe cross section with the denomination of the seven electrodes in the upstream ring.

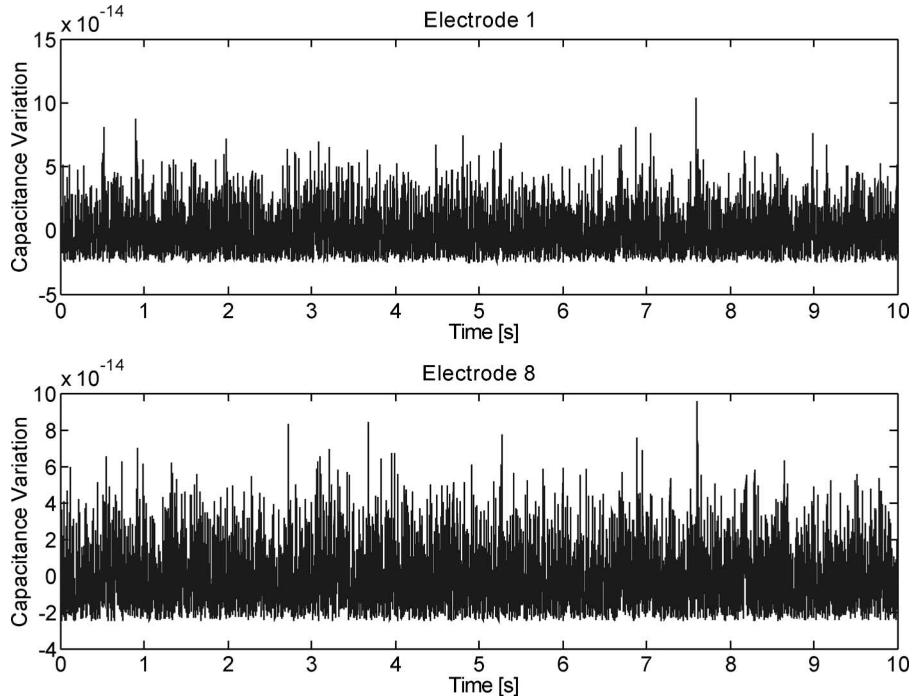

Fig. 11. Analog signals picked up by the two electrodes placed upstream and downstream longitudinally on the pipe wall.

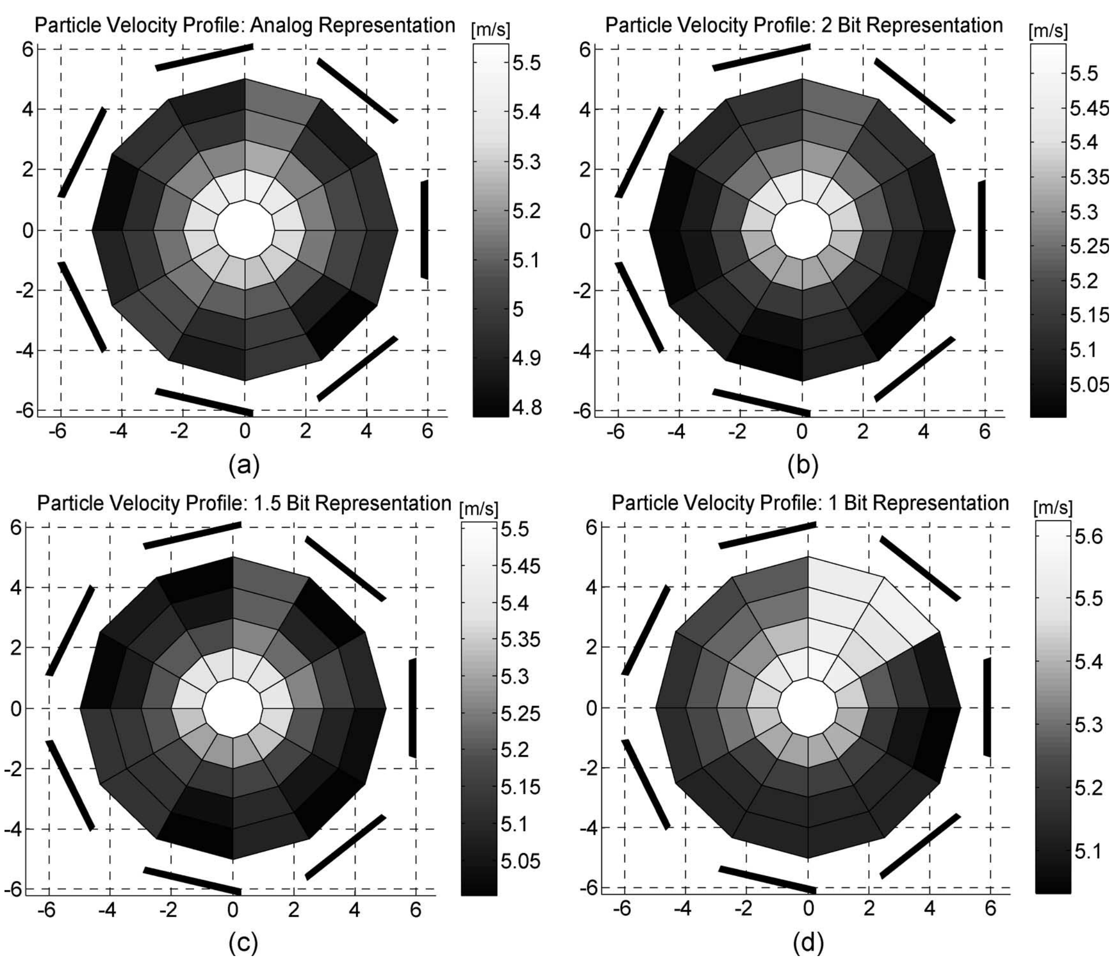

Fig. 12. Comparison of the reconstructed velocity profile in the cross section of the pipe based on the correlation functions calculated using the different data representations. (a) Analog signals. (b) 2-bit random data. (c) 1.5-bit random data. (d) 1-bit random data.

conveyor pipes in a dilute-phase flow. The high-speed-camera snapshot shown in Fig. 8 illustrates the particle distribution in this type of flow. It could be observed that, due to the gravity, the concentration of the particles in a horizontal pipe is higher toward the bottom side of the pipe.

Due to the complexity of the nonlinear phenomena encountered in the dilute-phase case and the limited number of sensors, which can be used in practice, it cannot realistically be expected to recover the velocity of each particle, as shown in Fig. 9. However, the measurement setup shown in Fig. 3, consisting of two sensor rings with seven individual capacitive electrodes per ring, allows for the recovery of an approximate cross-sectional particle-flow-velocity model. The cross sections of this model are divided into 12 radial sectors, which are each subdivided in four regions. There is also a common circular core at the base of each sector, as shown in Fig. 10. The pair of signals illustrated in Fig. 11, produced by an upstream and a downstream electrode, shows a notable variation due to the nonuniform behavior of the particles flowing through the pipe.

We are calculating all the 49 possible cross-correlation functions between the seven signals provided by the electrodes in the first sensor ring and the seven signals provided by the electrodes of the second sensor ring. Fig. 12 shows the cross-sectional tomographic images of the dilute-phase flow-velocity profile recovered from these 49 cross-correlation functions. This allows us to compare the velocity profile based on the correlation function calculated from the analog signals, as shown in Fig. 12(a), against those based on the correlation functions calculated using the internal random-data representations with a 2-bit resolution, shown in Fig. 12(b), a 1.5-bit resolution, shown in Fig. 12(c), and a 1-bit resolution, shown in Fig. 12(d).

It is apparent that the 1.5-bit random-data representation yields the results that are noticeably similar to those obtained from the cross correlation of the pairs of the original analog signals.

VI. Conclusion

The capacitive-sensor technology and the associated correlative-measurement method described in the paper provide a robust solution for the evaluation of the flow velocity of the bulk granular solids moving through the pneumatic conveyor pipes in both the dense and the dilute phases.

The correlator architecture using the low-resolution 1.5-bit random-data representation (corresponding to the three quantization levels) offers a cost-effective solution for the real-time computation of the 49 cross-correlation functions used for the estimation of the cross-sectional tomographic model of the flow-velocity profile in the dilute phase.

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