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Design of fan beam optical sensor and its application in mass flow rate measurement of pneumatically conveyed solids

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Abstract: The fan-beam optical sensor is made up of many semiconductor lasers and detectors fixed around the wall alternately at a cross section of pneumatically conveying pipe. When the sensor works, a scanning light source emits a 50° lamellar fan-beam through the gas-solid two phase flow, and the projection data resulting extinction effect of solid particles are detected at the same time. With the projection data, the flow rate mass can be calculated, and then the flow image can be reconstructed. In this paper, the design of the sensor including spatial arrangement of the structural parts, basic principle and measurement sensitivity distribution are introduced. The mathematical measurement model of solid mass flow rate is presented together with the testing results.

Key words: Optical sensor, Fan-beam laser, Pneumatic conveyor system, Mass flow rate of solids
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INTRODUCTION

Measurement technology for gas-solid two phase flow has important applications in fields such as process measurement, forecast and control in industry (Teng *et al*., 2002). At present, most optical measurement methods, such as LDV (Laser Doppler Velocimetry), Laser Dust Particles Measurement Device, use an optical sensor probe that only yields information on a single point or a partial area in the flow field and cannot yield instantaneous multi-orientation flow states.

In recent years, many scholars tend to adopt the optical array sensor for measuring gas-solid two-phase flow. For example, Ibrahim and Green (2002) (Sheffield Hallam University of UK) measured the flour dust concentration distribution in an experimental tube (∅80 mm) by adopting halogen lamp- house and optical fiber probe (15 lamp-houses×15 detectors), together with a back projection algorithm; McMackin *et al*.(1999) of the Air Force Laboratory used array optical sensor consisting of semiconductor lasers and CCD to reconstruct the spraying airflow density distribution of jet aircraft. Li *et al*.(2003; 2004a) measured the mass flow rate of solids and reconstructed flow images by using a self-manufactured 15×5 equal-angle fan-beam optical sensors. The above sensor's design, including spatial arrangement of the structure, basic principle and measurement sensitivity distribution are given in this paper together with the mathematical measurement model of solid mass flow rate and testing results.

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DESIGN OF FAN-BEAM OPTICAL SENSOR

Spatial arrangement structure of sensors

The familiar fan-beam optical sensors can be grouped into equal-angle fan-beam optical sensors (arc detectors) and equal-distance fan-beam optical sensors (linear detectors). Fig.1 shows the geometry of the equal-angle fan-beam optical sensor used by the authors. The fan-beam optical sensor is made up of many semiconductor lasers and detectors fixed around the wall alternately at a cross section of the pneumatic conveying pipe. There are *n* semiconductor lasers and *n* detectors. When one semiconductor laser works, the beam focuses on *m* detectors after shining through the test area. So, if every semiconductor laser works, there are $n \times m$ projection data gathered by detectors at $n \times m$ orientation angles. Accordingly, the fan-beam optical sensors have more projections and more orientation angles of scanning beam, and higher spatial resolution than the parallel beam optical sensors.

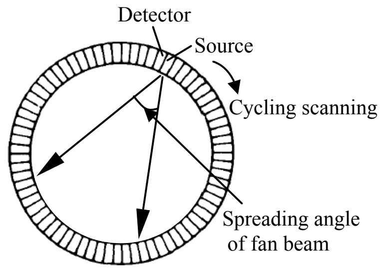

Fig.1 Geometry of equal-angles fan-beam optical sensors

The practical photograph of equal-angle fan-beam optical sensors is shown in Fig.2. It has 15 semiconductor lasers and 15 detectors arranged around the wall of the 80 mm experimental tube. In this experimental system, a semiconductor laser with 650 nm wavelength, 4 mW output power, a collimating lens and an APC circuit is employed. Cylindrical lens embedded in front of a collimating lens transfers the light beam into a 50° lamellar fan-beam with 2.5 mm thickness in turn through the gas-solid two phase flow. Silicon photodiodes (2CU) are used as photoelectric detectors with maximum operating voltage of 40 V, sensitivity >0.5 μA/μW, photoelectric current >30 μA, and response time of 0.1 μs.

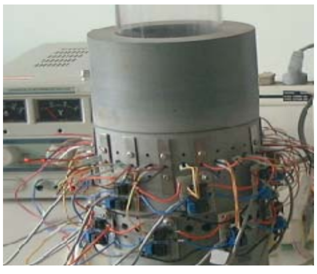

Fig.2 Practical photograph of equal-angle fan-beam optical sensor

The working procedure of the optical sensor is as follows: Every source emits a fan scanning beam which is received by the opposite 5 photodiodes, the signal is inputted into the computer memory by a data acquisition system after photo-to-electricity conversion and signal processing.

In the design of the optical sensor, it is difficult to compromise between spreading sensing field volume and improving spatial resolution; between adding the number of projections and being real time. At present, the better method is to split the difference.

Principle

The principle of fan-beam optical sensor is based on light extinction theory and light scanning property.

The light will attenuate due to absorption and scattering when it propagates through the medium. Absorption of light occurs when it changes into other form of energy such as that due to the thermal motion of molecules, etc., scattering of light is the change of space distribution of light energy. Based on extinction theory, when a parallel homochromous beam is transmitted through homogeneous medium, attenuation of the light intensity can be described by lambert-bear theory as (Modica *et al*., 1970):

$$-\ln(I/I_0) = E(\lambda, m, D_{32})LN\sigma \qquad (1)$$

where I is the transmission intensity; I_0 is the incidence intensity; L is the length of light pass through the test area; N is the quantity concentration of particles; M is the relative refractive index of particles; D_{32} is the average diameter of particles; λ is the light wavelength; σ is shadow area of a particles, $\sigma = \frac{\pi}{4}D_{32}^2$; $E(\lambda,m,D_{32})$ is the particles extinction coefficient, a complex function involving wavelength λ of incidence light, average diameter of particles D_{32} and relative refractive index m of particles.

If the particle medium distribution is homogeneous, Eq.(1) changes into Eq.(2):

$$-\ln(I/I_0)\big|_g = k\int_g N(x,y)\mathrm{d}s \qquad (2)$$

where, $k = \frac{\pi}{4}D_{32}^2 E(\lambda, m, D_{32})$, $N(x,y)$ is the 2D concentration distribution function of measured particles,

g is some different light path.

Let $p_g=-\ln(I/I_0)|_g$, then

$$p_g = k\int_g N(x,y)\mathrm{d}s \tag{3}$$

where p_g is defined as the light projections.

According to Radon Inverse Transform, $N(x,y)$ can be calculated inversely by using the light projections, this method is called optical tomography (OT). But we cannot get the concentration distribution function $N(x,y)$ by only several scanning lights. The way to obtain $N(x,y)$ requires scanning of the area of interest at multiple azimuths, and various angles, and setting up the following Eq.(4), so that the solution of $N(x,y)$ can be achieved.

$$\begin{cases} P_{g1} = k\int_{g1} N(x,y)\mathrm{d}s \\ P_{g2} = k\int_{g2} N(x,y)\mathrm{d}s \\ \cdots \\ P_{gR} = k\int_{gn} N(x,y)\mathrm{d}s \end{cases} \tag{4}$$

Eq.(4) should be independent of each other, in that every path of scanning light is different, and the interval of the light and visual angles should have certain spatial uniformity. Due to the necessary image resolution, it is necessary to establish large numbers of scanning lights at multiple azimuths and various angles. For example, suppose the minimal resolution interval is Δx and the explorative range is $(0, D)$, then the number of grid cells in the test area is $(D/\Delta x)^2$ (corresponding to image resolution), so the total number (corresponding to the number of equations) of independent projection data $\geq(D/\Delta x)^2$. For example, if the explorative range is (0, 80) and the minimal resolving interval is 1 mm, then the image resolution is 6400 pixels, with each beam having to go through all grid cells.

Sensitivity distribution map of sensor

Spatial sensitivity distribution is an important sensor parameter that can be defined as the projection signal sensitivity relative to change of particles concentration under the stimulating light field. The sensitivity distribution relates with the light wavelength, the extinction capability of medium and the spatial structure of array sensors, and mainly reflects the density and spatial uniformity of scanning lights in the test area. According to (Yan *et al.*, 1995), this paper calculates the sensitivity distribution of 15×5 equal-angle fan-beam optical sensors shown in Fig.3.

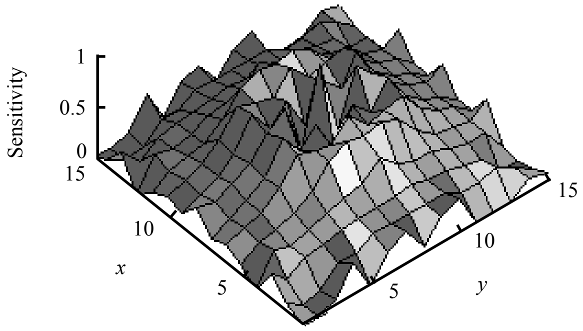

Fig.3 sensitivity distribution of 15×5 equal-angle fan-beam optical sensor

MEASUREMENT MODEL OF MASS FLOW RATE OF SOLIDS

The mass flow rate of solids can be described as

$$q_m = \iint_\sigma c(x,y)v(x,y)\mathrm{d}x\mathrm{d}y \tag{5}$$

where, $c(x,y)$ is the concentration distribution function of particle flow, $v(x,y)$ is the vertical velocity distribution function of particle flow, σ is the cross section of the tube.

Theoretically, if $c(x,y)$ and $v(x,y)$ are known, the mass flow rate of solids can be calculated. But at present, optical tomography cannot provide enough precision for reconstructing concentration distribution and velocity distribution of the particle flow. There exist some primary problems: (1) array sensors cannot provide enough projections and high spatial resolution under a transitory scanning period; (2) the sensitivity distribution is non-uniform; (3) the flow state of particles changes at any moment and the vertical velocity distribution is non-uniform. So it is difficult to calculate the instantaneous mass flow rate of solids based on optical process tomography.

According to mathematical statistics, mass flow rate of solids can also be described as

$$q_m = \bar{c} A \bar{v} \tag{6}$$

where, $\bar{v}$ is the average velocity of particles, $\bar{c}$ is the average mass concentration of particles, and A is the cross section of the tube.

Where,

$$\bar{c} = \frac{\pi}{6} D_{32}^3 \rho \bar{N} \tag{7}$$

where, D_{32} is the average diameter of particles; ρ is the density of particles; $\bar{N}$ is the average quantity concentration of particles which can be weighted by the measurement sensitivity distribution $S(x,y)$.

$$\bar{N} = \frac{\iint_\sigma S(x,y) N(x,y) \mathrm{d}x\mathrm{d}y}{\iint_\sigma S(x,y) \mathrm{d}x\mathrm{d}y} \tag{8}$$

According to the approximate calculation of sensitivity distribution (Yan *et al.*, 1995), Eq.(8) becomes Eq.(9) as

$$\bar{N} \approx \frac{\iint N(x,y) \sum_1^M \delta[r\cos(\phi-\theta)-l] \mathrm{d}x\mathrm{d}y}{\iint \sum_1^M \delta[r\cos(\phi-\theta)-l] \mathrm{d}x\mathrm{d}y} = \frac{1}{kL} \sum_j^M p_\theta(l) \tag{9}$$

where, $r\cos(\phi-\theta)-l=0$ is the light path, (r, ϕ) is polar coordinates of the test area, (l, θ) is Radon coordinates, l is the vertical distance from origin of coordinates of object space (r, ϕ) to scanning beam, θ is the projection angle of scanning beam, $p_\theta(l)$ is the light projection, and the number of $p_\theta(l)$ is M, which correspond to the M scanning beams, L is the total length of all beams.

According to Eqs.(6), (7) and (9), we have

$$q_m = \frac{\pi}{6} D_{32}^3 \rho \bar{v} A \frac{1}{kL} \sum p_\theta(l) \tag{10}$$

for $k = \frac{\pi}{4} D_{32}^2 E(\lambda, m, D)$, mass flow rate of solids can be calculated as

$$q_m = \eta \bar{v} \sum p_\theta(l) \tag{11}$$

where, $\eta = \frac{2}{3} \frac{D_{32} \rho A}{L E(\lambda, m, D)}$.

If the structure of optical sensors is given, the total length L is fixed; suppose that physical chemistry trait of particles is also invariable, then ρ, D_{32} are constant, extinction coefficient $E(\lambda,m,D)$ is approximately constant too, so η is a constant.

Therefore, if $\sum p_\theta(l)$, namely the sum of measured projection data, and the average velocity of particles $\bar{v}$ are measured, the mass flow rate of solids can be obtained.

EXPERIMENTAL RESULTS

The experimental research was carried out with a simulating gas-solids two phase flow, the diameter of tube is ∅80 mm. The quartz particles are put into a hopper blower which is then put into the vertical tube (Li *et al.*, 2004b). The quartz particles fall freely to the tube cross section, with distance of fall being h=255 mm, the vertical velocity is $v=\sqrt{2gh}$=2.1 m/s cross sectional area of the tube is $A=\pi r^2$=0.005 m^2, density of quartz particles is ρ=1500 kg/m^3, the total length of all the beams is L=14.35 m.

The experiment data on mass flow rate and sum of projections is shown in Table 1, where mass flow rate of solids is q_m and $\sum p_\theta(l)$ is the sum of projections.

Table 1 Experiment data on mass flow rate and sum of projections

q_m (g/s)	$\sum p_\theta(l)$ (No dimension)	q_m (g/s)	$\sum p_\theta(l)$ (No dimension)
6.10	6.90	24.03	25.03
12.51	14.78	28.21	31.00
18.97	17.68	33.77	36.02
20.10	20.12	34.20	37.82
21.83	23.21		

Let $x=\sum p_\theta(l)$, $y=q_m$, then the measurement data model is

$$y_t=\eta x_t+\varepsilon_t \quad t=1, 2, \ldots, N \tag{12}$$

where, ε_t is error of measurement, N is the number of measurements, N=9.

The linear regression model is:

$$\hat{y} = \eta x \tag{13}$$

Hereinto, k is an undetermined coefficient. Let

$$\boldsymbol{Y} = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_9 \end{bmatrix}, \ \boldsymbol{X} = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_9 \end{bmatrix}, \ \boldsymbol{V} = \begin{bmatrix} v_1 \\ v_2 \\ \vdots \\ v_9 \end{bmatrix} \tag{14}$$

then the residual error equation is:

$$\boldsymbol{V} = \boldsymbol{Y} - \eta \boldsymbol{X} \tag{15}$$

Selecting y_t based on equal precision measurement, according to the principle of Least Squares, content η is

$$\eta = (\boldsymbol{X}^{\mathrm{T}}\boldsymbol{X})^{-1}\boldsymbol{X}^{\mathrm{T}}\boldsymbol{Y} = 0.9352 \tag{16}$$

The linear regression equation is $\hat{y} = 0.9352x$.

The prediction accuracy of the regression equation is shown below:

U and Q denote regression sum of squares and residual sum of squares respectively,

$$U = \sum_{t=1}^{N} (\hat{y}_t - \bar{y})^2 = 714.895$$

$$Q = \sum_{t=1}^{N} (\hat{y}_t - \bar{y})^2 = 11.814$$

Therefore, residual standard deviation σ and check F value are respectively:

$$\sigma = \sqrt{\frac{Q}{N-2}} = \sqrt{\frac{11.127}{9-2}} = 1.299\,(\text{g/s}) \tag{17}$$

$$F = \frac{U/\gamma_u}{Q/\gamma_Q} = \frac{U/1}{Q/(N-2)} = 423.595 \tag{18}$$

γ_u and γ_Q are the degrees of freedom of regression sum of squares and that of residual sum of squares respectively, γ_u=1, γ_Q=N−2=7.

From the statistical F distribution table, we have

$$F \geq F_{0.01}(1, N-2) = 12.25 \tag{19}$$

CONCLUSION

Fan-beam optical sensors have some advantages, such as high spatial resolution, multiple scanning angles and multiple projection data, which can be used to measure instantaneous mass flow rate of solids, and can overcome the disadvantage of single-point measurement by other sensors. Experiment results showed that it is accurate in measurement of solid mass flow rate and does not destroy the flow field.

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