The real-time monitoring technology of air quantity based on the optimization of air velocity sensors location in mine ventilation network

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***Abstract*—As the monitoring data of air velocity sensor is inaccurate in the mine underground roadway, the index system and the mathematic model of optimal air velocity sensor location is established based on the variable fuzzy theory. The objective functions are the minimum amount of air velocity sensor locations, which can obtain air quantity of each roadway. And the constraints obey the air quantity balance equation of each circuit and node. In order to improving the accuracy of the monitoring data and reduce the disturbance to the measurement and calculating results, the adjustment analysis of redundant air velocity sensor measurement and the standard deviation filter method are put forward. Then, the real-time monitoring technology of mine roadway in mine ventilation network is formed and the air quantity automatic monitoring system of mine ventilation network is established. The application shows that, this technology can achieve the real-time monitoring in the underground roadway. In addition, it effectively improves the air quantity accuracy of monitoring data and provides an important basis data for management decisions of mine ventilation system.**

Keywords*—air quantity; air velocity sensor; monitoring; ventilation network

I. INTRODUCTION

The air quantity of underground mine roadway, which is the main parameters of mine ventilation system, is indirectly calculated by the air velocity and the area of cross section. However, due to the roadway center is larger than the roadway edge, the air quantity is unevenly distributed in the roadway section (Luo et al., 2015; Zhao et al., 2012a). The air quantity of roadway often means the average value of air quantity in the mine ventilation roadway (Si et al., 2014; Petar et al). The air quantity is changed with the main fans, the ventilation regulation facilities, the mine car, the pedestrian movement and so forth. The traditional manual method has poor timeliness of data, and it cannot realize the real-time measurement of air velocity (Hubiao et al., 2011). The modern method uses the air velocity sensor to monitor the velocity value in mine safety monitoring system (Belle, 2013). Due to the huge number of roadway in mine ventilation system, it spends large investment costs if installing the air velocity sensor in every roadway. According to the graph theory and mine ventilation theory, the branch airflow parameters obey the Kirchhoff's current law and Kirchhoff's voltage law. As the independent variable of air quantity is less than the number of branches, it is not necessary to install air velocity sensor in each branch (Biagetti et al., 2004; Hasan, 2015). In addition, because the air velocity sensor can only monitor the point air velocity of the roadway, the monitoring result needs to be revised (Masuo et al., 2017).

In order to obtain the actual monitoring data, the ultrasonic vortex joint technology is developed, and the new air velocity sensor which has the higher accuracy and sensitivity is produced (Cohen et al., 2008). However, it does not fundamentally solve the actual error problem merely improve the monitoring accuracy of air velocity sensor. The computer simulation analysis method accurately calculates the distribution of air velocity field according to the computational fluid dynamics method, and determines the correction factor by the simulation data (S. Torno, 2010; Wang et al., 2013). This method has the advantages of better economy, shorter time consuming, better simulated ability, and it also can avoid measurement errors caused by manual. Using 3D model of CFD software to simulate the air velocity field, the correction factor is calculated under the condition that the roadway has the fixed size, different air velocity and different section shape (Hao et al., 2011; Wang et al., 2013). Furthermore, one-dimensional linear regression equation method is used to establish the approximate linear equation between the monitoring data and the average value of air velocity (Zhao et al., 2012b). The monitoring data accuracy of air velocity sensor is related to the design discipline, hanging position and correction method of monitoring data, some scholars analyze the monitoring data by using the average repeated monitoring data, percentage of measured values deviated from the mean value, and so forth, whereas, these methods merely correct the error of the sensor itself, it cannot eliminate the error of the average velocity, thus they still unable to satisfy the monitoring requirements of ventilation network.

As the monitoring data of air velocity sensor is inaccurate in the underground roadway, on the basis of studying the air velocity sensor location and monitoring data processing method, this paper puts forward the real-time monitoring technology of mine roadway in mine ventilation network, and establishes the air quantity automatic monitoring system. It provides an important basis data for the management decisions of mine ventilation system.

II. THE AIR VELOCITY SENSOR LOCATION BASED ON THE VARIABLE FUZZY THEORY

A. Independent variables of mine ventilation network

The air quantity of each node obeys the Kirchhoff's current law in mine ventilation network,

$$\sum_{j=1}^{B} I_{ij} Q_j \rho_j = 0 \tag{1}$$

where, I_{ij} is the basic correlation matrix; i is the node number, i=1,2,…,N; j is the branch number, j=1,2,…,B; Q_j is the air quantity of branch, m^3/s; ρ_j is the branch density, kg/m^3.

According to the topology of mine ventilation network, it can solve N-1 branches of air quantity from formula (1). So (B-N+1) air quantity equations must be increased, which is equal to the circuit number M. From air quantity relationship of branches and cotrees,

$$Q_j \rho_j = \sum_{i=1}^{M} C_{ij} Q_{yi} \rho_{yi} \tag{2}$$

where, C_{ij} is the fundamental circuit matrix; Q_{yi} is the air quantity of cotree in circuit i, m^3/s.

Consequently, the number of independent variable is equal to the number of circuit in mine ventilation network, and the air quantity of all the branches can be calculated from one set of cotree branches.

B. Factor index system of air velocity sensor location

By installing the air velocity sensor in one set of cotree branches, the air quantity of branch is calculated by the cross-sectional area and formula (2). Then it can realize the real-time monitoring of air quantity in mine ventilation network. Considering the existing mine air quantity sensor, the main influence factors which effect the air quantity sensor location are screened from the economy and rationality of the mine monitoring system design. Fig.1 illustrates the factor index system structure of air velocity sensor location.

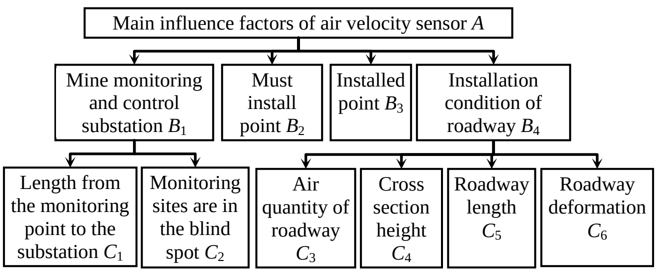

Fig.1 Factor index system of air velocity sensor location

- Mine monitoring and control substation B_1. If the distance between the monitoring point and substation exceeds the upper limit, it cannot receive and process sensor data, and the monitoring point is the blind spot. Therefore, the more substations should be installed or monitoring points should be rearranged.
- Must install point B_2. It includes the main intake and return air shaft, coal working face, and return airway. The air velocity sensor should be installed in the airflow measuring station. The 1 and 0 are used to indicate the must install point and not need install point of air velocity sensor, respectively.
- Air velocity sensor installed point B_3. 1 and 0 are used to indicate the installed point and not installed point, respectively.
- Installation condition of roadway B_4. The installation condition of air velocity sensor is obtained by the actual situation of the roadway near the monitoring point, which mainly includes the air quantity of roadway C_3, cross section height C_4, roadway length C_5 and roadway deformation C_6.

a) Air quantity of roadway C_3. The air velocity sensor has its reasonable monitoring range. If the air quantity is too small, the measurement error will relatively large.

b) Cross section height C_4. C_4 is determined by the cross section of the sensor installation point. As the air velocity distribution is uneven, at least there has 1 monitoring data near the center of the monitoring section theoretically, which can be used to replace the average air velocity of the roadway.

c) Roadway length C_5. As the distribution of airflow is not balanced in the short airway, it is easy to be influenced by vortex and turbulence.

d) Roadway deformation C_6. The serious deformation, the general deformation and the no deformation are adopted to evaluate the deformation degree of the roadway. The 1, 0.5 and 0 are used to indicate the serious deformation, the general deformation and the no deformation, respectively.

C. Mathematical model of air velocity sensor location

Suppose $\mathbf{\Gamma} = \{\Gamma_{ij}\}, i = 1,\cdots,B, j = 1,\cdots,Y$ is the index set of B branches and Y evaluation indexes. Using the relative membership degree to eliminate the non public degree of different dimensions, the reasonable weight of each branch is evaluated by the membership degree of superior index u_{1i}, which provides the weight information for optimizing the air velocity sensor location.

$$u_{1i} = \left(1 + \sum_{j=1}^{Y} (\omega_j (gr_j - \Gamma r_{ij}))^2 / \sum_{j=1}^{Y} (\omega_j (\Gamma r_{ij} - br_j))^2 \right)^{-1} \tag{3}$$

where, u_{1i} is the membership degree of superior index; ω_j is the weight of each factor; Y is the factor index number; g_r is the standard superior degree of membership; b_r is the standard inferior degree of membership.

D. Redundant air velocity sensor location method

In order to ensure the accuracy of the monitoring data of the air velocity sensor, the redundant sensor is often used tocomparing the different data, which can detect the sensor failure just in time and improve the accuracy of the sensor.

From the above mathematical model, the air velocity sensor is installed in one cotree set of the ventilation network. In order to improve the reliability of the monitoring data and reduce the initial investment of the mine monitoring system, the redundant air velocity sensor is installed in the branches which have the high frequency in the circuit. In addition, there is at least 1 branch in each circuit to install the redundant air velocity sensor. Based on the depth first search method, the flowchart of redundant air velocity sensor location algorithm is determined, which is shown in Fig.2.

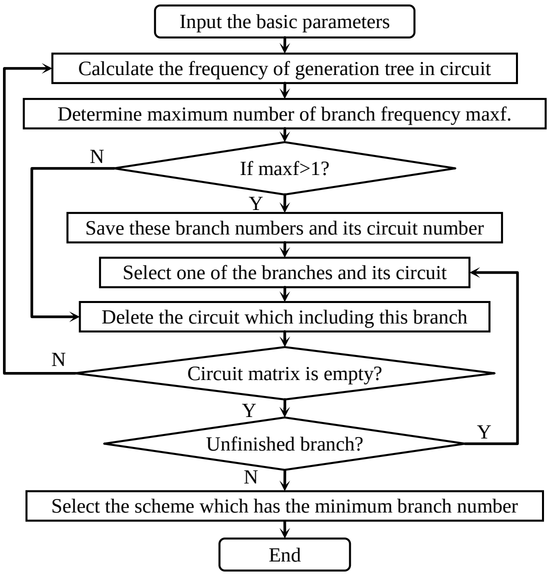

Fig.2 Flowchart of redundant air velocity sensor location algorithm

- Step 1: Input the basic parameters, including the circuit information of mine ventilation network, branch information, etc;
- Step 2: Calculate frequency of generation tree in circuit;
- Step 3: Determine the maximum number of branch frequency maxf. If maxf>1, save these branch numbers and its circuit number, and then execute step 4; if maxf=1, then execute step 5;
- Step 4: Select one of the branches and its circuit, and then execute step5;
- Step 5: Delete the circuit which including this branch. If the circuit matrix is empty, then execute step 2; if the circuit is empty and there still have an unfinished branch, then execute step 4; if the circuit is empty and all the branches has been traversed, select the location scheme of the redundant air velocity sensor which has the minimum branch number.

III. MONITORING DATA PROCESSING TECHNOLOGY OF MINE VENTILATION NETWORK

A. *Filter analysis technology of monitoring data*

Mine ventilation system is a dynamic and complex system. Because of the influence of coal mining, driving, transportation and other production activities, the airflow is always change, which seriously affect the accuracy of the monitoring data. In order to reduce the impact of disturbance on the measurement data, on the basis of the multiple sampling calculation of monitoring system, the filter analysis technology of monitoring data is used to remove noise and improve the accuracy of monitoring data.

Suppose m_t is the monitoring value of monitoring parameter m at time t, the average sample value of the monitoring parameter is:

$$\overline{m} = \frac{\sum_{t=1}^{n} m_t}{n} \tag{4}$$

where, n is the total number of monitoring samples; $\overline{m}$ is the mean value of n air velocity sample, t=1,2,…,n.

By calculating the standard deviation of the monitoring parameters, the dispersion degree of the sample data is determined. The formula is:

$$\sigma = \sqrt{\frac{1}{n}\sum_{t=1}^{n}(m_t - \overline{m})^2} \tag{5}$$

where, σ is the standard deviation for monitoring parameter sample.

From formula (5), the greater σ, the greater difference between the monitoring value and the average value of the monitoring parameters. Finally, the greater fluctuation of the monitoring data should be removed.

TABLE I. AIR QUANTITY MONITORING DATA AND STANDARD DEVIATION FILTER

Sample	Monitoring data /$m^3 \cdot s^{-1}$	Relative error /%	Filtering data /$m^3 \cdot s^{-1}$	Relative error /%
1	5.35	0.31	5.35	0.35
2	5.34	0.51	5.34	0.54
3	5.40	0.73	5.40	0.7
4	5.39	0.42	5.39	0.39
5	5.69	6.07	-	-
6	5.20	3.04	5.20	3.08
7	5.55	3.34	5.55	3.31
8	5.40	0.61	5.40	0.58
9	5.03	6.33	-	-
10	5.31	0.99	5.31	1.02
Mean value	5.37	-	5.37	0.008
Standard deviation	0.1695	-	0.0907	

Assuming that the 10 monitoring data of air quantity of one branch are illustrate in Table 1, the mean value $\overline{m}$ =5.37, σ=0.1695. According to the relative error between the monitoring data and the mean value, because the relative error of sample 5 and sample 9 is exceeding 5%, they are removed. Calculating the standard deviation is σ=0.0907, so the discrete degree is small after filtering the data.

B. *Adjustments analysis of air quantity in mine ventilation network*

In mine ventilation network, most resistance of the mine roadway can be considered as a constant in a short period time excepting tunneling driving and the cross heading roadway. Under the premise of ensuring the normal use of the instrument and apparatus, the monitoring data error is a random error, which often obeys the normally distributed. The adjustments analysis of air quantity is often used to eliminate these errors.

According to the adjustments analysis of air quantity in mine ventilation network,

$$Q_m^{'} = Q_m + W_q^{-1} A^T \left(A W_q^{-1} A^T \right) E \qquad (6)$$

where, Q'_m is the arithmetic mean value vector; Q_m is the mass flow vector of branch; $W^{-1}{}_q$ is the weight matrix of the measurement accuracy, which is the reciprocal of the measured value; A is the incidence matrix; E is the measured unbalance error vector.

Because the air velocity sensor is only installed in parts of the roadway, the Q_m is constituted by the calculating air quantity of the no installed sensor roadway.

IV. Automatic Monitoring System of Air Quantity in Mine Ventilation Network

According to the real-time monitoring technology of mine roadway in mine ventilation network, the automatic monitoring system of air quantity is established. Fig.3 illustrates the structural representation of the automatic monitoring system, including data acquisition system, data processing system and display system. The data acquisition system mainly includes the substation, the air velocity sensor and the air density sensor. The air velocity sensor monitors the air velocity of one cotree set branches and some main intake ventilation roadway; the airdensity sensor monitors the air density of the air velocity sensor installation position. The monitoring data of all the sensors will be collected by the substation, and then transmitted to the data processing system uniformity.

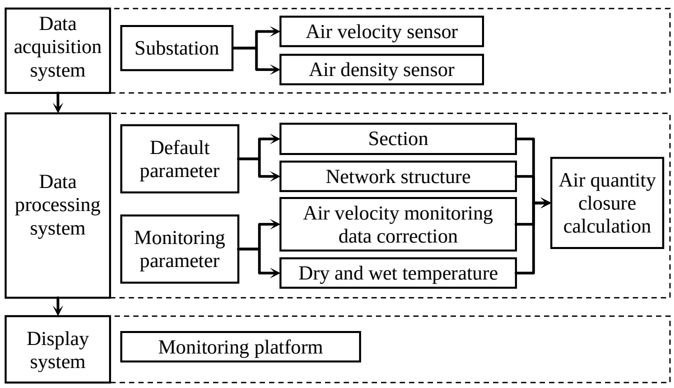

Fig. 3 Structural representation of the automatic monitoring system of air quantity in mine ventilation network

The specific implementation steps are as follows:

- According to the monitoring data of the air velocity sensor, the average air velocity of the roadway is calculated by using the formula of the fixed velocity of the non uniform flow field;
- The average air quantity of the roadway is calculated by the cross-sectional area of the air velocity sensor installation position and the monitoring data of the air density sensor;
- The air quantity of the non cotree branches is calculated by the equation of air quantity balance of each circuit and node;
- According to the data closure principle and regression analysis method, the redundancy data is used to correct the monitoring data and improve the monitoring accuracy of mine ventilation network.

V. Case Study

Using the complex ventilation network with exhaust fan as an example (Fig.4), the node number N=13, the branch number B=19, the circuit number M=7, e represents the branch, v represents the node, e_{18} represents the fan branch, e_{19} represents the virtual atmosphere connected branch. The basic parameters of each branch is illustrate in Table 1.

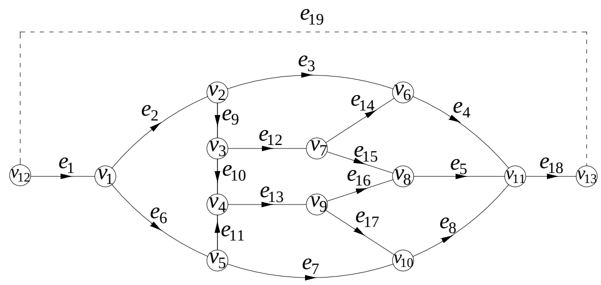

Fig.4 Sketch map of mine ventilation network

Select a set of basic circuit, the circuit is shown in Table 2.

TABLE II. Basic circuit of mine ventilation network

Cotree branch	Generation tree branch
5	-8,-17,16
3	4,-8,-17,16,-15,-12,-9
7	-17,16,-15,-12,-9,-2,6
13	16,-15,-12,-9,-2,6,11
14	4,-8,-17,16,-15
10	-11,-6,2,9
18	19,1,2,9,12,15,-16,17,8

The air velocity sensor and air density sensor are installed in cotrees of e_3, e_5, e_7, e_{10}, e_{13}, e_{14}, e_{18}, and main pathway of e_1, e_2, e_6. The sensor data collected at a certain moment is shown in Table 3.

TABLE III. Collected monitoring data of ventilation network

Sensor	Branch	Air velocity $/m\cdot s^{-1}$	Density $/kg\cdot m^{-3}$	Cross section area $/m^2$	Air velocity correction $/m\cdot s^{-1}$	Mass flow $/kg\cdot s^{-1}$
1	3	2.68	1.15	12.40	2.57	36.65
2	5	1.99	1.24	15.50	1.91	36.71
3	7	1.93	1.09	18.40	1.85	37.10
4	10	0.40	1.1	12.20	0.39	5.23
5	13	2.53	1.15	13.20	2.42	36.74
6	14	0.64	1.18	11.80	0.62	8.63
7	18	6.54	1.25	18.50	6.26	144.76
8	1	8.15	0.98	19.00	7.80	145.24
9	2	4.49	0.99	18.50	4.30	78.75
10	6	3.24	1.1	19.50	3.10	66.50

The air velocity sensor is installed in the 0.8 times relative height from the bottom border. The correction curve is as follows:

$$v^{'} = 0.9573 v_m + 0.0027 \qquad (7)$$

where, v' is the corrected air velocity, m/s; v_m is the measured air velocity, m/s.

The corrected air velocity is calculated by formula (7), which is illustrated in the corrected air velocity column of Table 3.

According to the monitoring data correction of the air density sensor and the air velocity sensor, as well as the cross section parameters, the mass flow of the monitoring branches is calculated. The other branches are calculated by Kirchhoff's current law of mine ventilation network. Because the redundant branch e_1, e_2 and e_6 have two mass flow data, one is calculated by the sensor data, another is the calculated by the cotree branches, the mass flow of the redundant branches are the average value of these two data, which is illustrate in redundant correction column of mass flow.

Using the adjustment analysis of ventilation network (formula (6)), the correlation matrix A is obtained by the relationship of nodes and branches, E=[-0.08,1.24, -0.02, -0.09, -0.95, 0.09, 0, 0.09, 0.11, -0.02, -0.17, 0.08, -0.28]^T, then the mass flow of each branches is calculated and illustrate in the adjustment analysis column of mass flow in Table 4. From the relationship between the mass flow and air quantity, the air quantity is calculated and shown in corrected air quantity column in Table 4. At this point, if there is no air density sensor in the branch, then the corresponding data should be manually measured and set in the default parameters.

TABLE IV. AIR QUANTITY CORRECTION OF BRANCHES

Branch	Mass flow /kg·s^{-1}			Corrected air quantity /m^3·s^{-1}
	Calculated by the circuit	*Calculated by redundant correction*	*Calculated by adjustment analysis*	
1	144.68	144.96	145.00	147.96
2	76.19	77.47	77.79	78.58
3	36.65	36.65	36.24	31.51
4	45.19	45.19	44.94	36.84
5	36.71	36.71	36.58	29.50
6	68.64	67.57	67.37	61.25
7	37.10	37.10	37.36	34.27
8	62.69	62.69	62.73	51.00
9	39.58	39.58	39.07	37.21
10	5.23	5.23	4.66	4.23
11	31.42	31.42	31.91	29.55
12	34.37	34.37	34.46	30.49
13	36.74	36.74	36.75	31.95
14	8.63	8.63	8.88	7.53
15	25.74	25.74	25.57	21.67
16	11.06	11.06	11.19	9.56
17	25.57	25.57	25.34	21.84
18	144.76	144.76	144.60	115.68
19	145.04	145.04	145.16	148.12

VI. CONCLUSIONS

The mathematic model of optimal air velocity sensor location is established based on the current mine monitoring system. The objective functions of the model are the minimum amount of air velocity sensor locations, and it should realize the real-time monitoring of whole ventilation network; the constraints obey the air quantity balance of each circuit and node.

Using the adjustment of redundant air velocity sensor measurement and the standard deviation filter method, the real-time monitoring technology of mine roadway in mine ventilation network is formed. It can effectively improve the air quantity accuracy of monitoring data in the roadway and provide an important basis data for the management decisions of mine ventilation system.

The air quantity automatic monitoring system of mine ventilation network is established, which can be combined with the mine safety monitoring and control system, and greatly improve the accuracy of mine safety monitoring and monitoring system in the airflow monitoring. It has a good popularization and application value in the future.

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