Dynamic Monitoring Technology of Air Quantity in Mine Ventilation System Based on Optimum Location of Wind Speed Sensors

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Abstract. To improve the accuracy and reduce the disturbance during the monitoring, the index system and the mathematic model of optimal wind speed sensors’ location are established using the variable fuzzy theory. Then the adjustment analysis of redundant wind speed sensor measurement and the standard deviation filter method are put forward. Then, the dynamic monitoring technology in mine ventilation network is formed and the automatic monitoring system of air quantity in mine ventilation network is established. The application in a complex ventilation network shows that, this method only needs 10 wind speed sensors (7 must install points and 3 redundant install points) to obtain the air quantity of 19 branches. And it can achieve the dynamic monitoring in the underground roadway, which provides an important basic data for management decisions in mine ventilation network.

Keywords: Air quantity, wind speed sensor, ventilation network.

1. Introduction

The air quantity of underground mine roadway is generally calculated by the wind speed and the area of cross section. In fact, the air quantity is unevenly distributed in the roadway section [1-2]. The air quantity of roadway is usually represented by the average value of air quantity in the mine ventilation roadway [3-4]. Due to it varied with the change of main fans, the ventilation regulation facilities, the mine car, the pedestrian movement and so on, an accurate measurement for wind speed of underground roadway plays an important role in the subsequent analysis of ventilation system.

In initial time, airflow meters are used to measure the wind speed in each roadway. However, it takes a lot of time to measure all the roadways in a mine ventilation system. Furthermore, the effectiveness of the method of manual measurement is poor, especially in windless and breezy roadways. It cannot realize the dynamic measurement of wind speed [5].

With the development of monitoring technology, the wind speed sensor is used to measure the wind speed data of each underground roadway in real-time. Due to the wind speed sensor can only monitor the point wind speed of a section, which is not present the average velocity of a roadway, so the monitoring result needs to be revised [6]. The ultrasonic vortex joint technology is developed, in addition the new wind speed sensor with higher accuracy and sensitivity is produced [7]. However, it does not fundamentally solve the problem of monitoring accuracy of wind speed roadway in a
ventilation system merely improving the monitoring accuracy of wind speed. Furthermore, as the independent variable of air quantity is less than the number of branches [8-9], it is a waste of money to install wind speed sensors in every roadway of a ventilation system in order to obtain the actual air velocity data of the ventilation network [10], and the processing of multi-sensor data is more complex.

The computer simulation analysis methods are conducted. This method accurately calculates the distribution of wind speed field according to the computational fluid dynamics method, and determines the correction factor by the simulation data [11-12]. This method has the advantages of better economy, shorter time consuming, better simulated performance, and can avoid measurement errors caused by manual measurement method. Besides that, a 3D model of CFD software is used to simulate the wind speed field [13]. The correction factor is calculated under the condition that the roadway has the fixed size, different wind speed and different section shape. Furthermore, a one-dimensional linear regression equation method is used to establish the approximate linear equation between the monitoring data and the average value of wind speed [14].

The monitoring data accuracy of wind speed sensor is related to the design discipline, hanging position and correction method of monitoring data, some scholars analyse 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, they have unable to satisfy the monitoring requirements of ventilation network. To solve this problem, this paper puts forward the dynamic monitoring technology of mine roadway in mine ventilation network, and establishes the air quantity automatic monitoring system to optimize the monitoring locations. It provides an important basis data for the management decisions of mine ventilation system.

2. The wind speed sensor location based on the variable fuzzy theory

2.1. Independent variables of mine ventilation network

The air quantity of each node obeys the Kirchhoff’s current law in mine ventilation network, calculated by:

$$\sum_{j=1}^{B} I_{ij} Q_{j} \rho_{j} = 0 \quad (1)$$

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; $\rho_{j}$ 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, showed in Eq (2),

$$Q_{j} \rho_{j} = \sum_{i=1}^{M} C_{ij} Q_{ni} \rho_{ni} \quad (2)$$

where, $C_{ij}$ is the fundamental circuit matrix; $Q_{ni}$ 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.

2.2. Factor index system of wind speed sensor location

By installing the wind speed sensor in one set of cotree branches, the air quantity of branch is calculated by the cross-sectional area and equation (2). Then it can realize the dynamic monitoring of air quantity in mine ventilation network. For existing mine air quantity sensor, the main influence factors which affect the air quantity sensor location are the economy and rationality of the mine monitoring system design. Figure 1 illustrates the factor index system structure of wind speed sensor location.
Figure 1. Factor index system of wind speed sensor location.

(1) Mine monitoring and control substation $B_1$. If the distance between the monitoring point and substation exceeds the upper limitation, it cannot receive and process sensor data, and the monitoring point is the blind spot. Therefore, more substations should be installed or monitoring points should be rearranged.

(2) Must install point $B_2$. It includes the main intake and return air shaft, coal working face, and return airway. The wind speed 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 wind speed sensor, respectively.

(3) Wind speed sensor already installed point $B_3$. 1 and 0 are used to indicate the already installed point and not already installed point, respectively.

(4) Installation condition of roadway $B_4$. The installation condition of wind speed 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 $C_6$.

2.3. Mathematical model of wind speed sensor location

Suppose $\Gamma = \{\Gamma_j\}, j = 1, \cdots, B, j = 1, \cdots, Y$ 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 wind speed sensor location.

$$u_i = \left[1 + \sum_{j=1}^{Y} (\omega_j (gr_j - g_\Gamma_j))^2 / \sum_{j=1}^{Y} (\omega_j (gr_j - b_\Gamma_j))^2 \right]^{-1}$$  \hspace{1cm} (3)

where, $u_{1i}$ is the membership degree of superior index; $\omega_j$ 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.

2.4. Redundant wind speed sensor location method

In order to ensure the accuracy of the monitoring data of the wind speed sensor, the redundant sensor is often used to compare 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 wind speed 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 wind speed 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 wind speed sensor. Based on the depth first search method, the flowchart of redundant wind speed sensor location algorithm is determined, which is shown in Figure 2.
Figure 2. Flowchart of redundant wind speed sensor location algorithm.

Step 1: Input the basic parameters, including the circuit information of mine ventilation network, branch information and so on;
Step 2: Calculate the frequency of generation tree in circuit;
Step 3: Determine the maximum number of branch frequency \( \text{max}_f \). If \( \text{max}_f > 1 \), save these branch numbers and its circuit number, and then execute step 4; if \( \text{max}_f = 1 \), then execute step 5;
Step 4: Select one of the branches and its circuit, and then execute step 5;
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 have been traversed, select the location scheme of the redundant wind speed sensor which has the minimum branch number.

3. Monitoring data processing technology of mine ventilation network

3.1. 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 always changes, which seriously affects 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:
\[ m = \frac{\sum_{i=1}^{n} m_i}{n} \]  

(4)

where, \( n \) is the total number of monitoring samples; \( \bar{m} \) is the mean value of \( n \) wind speed sample, \( t=1, 2, \ldots, n \).

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

\[ \sigma = \sqrt{\frac{1}{n} \sum_{t=1}^{n} (m_t - \bar{m})^2} \]  

(5)

where, \( \sigma \) is the standard deviation for monitoring parameter sample.

From formula (5), the greater \( \sigma \), 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.

| Sample | Monitoring data/m³·s⁻¹ | Relative error/% | Filtering data/m³·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 |

Table 1 illustrates 10 monitoring data of air quantity of one branch, the mean value \( \bar{m} = 5.37 \), \( \sigma = 0.1695 \). According to the relative error between the monitoring data and the mean value, because the relative error of sample 5 and sample 9 is more than 5%, they are deleted. Calculating the standard deviation \( \sigma = 0.0907 \), so the discrete degree is small after filtering the data.

3.2. 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 tunnelling 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 distribution. 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,

\[ Q'_n = Q_n + W_q^{-1} A^T (A W_q^{-1} A^T)^{-1} E \]  

(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 wind speed 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.

4. Automatic monitoring system of air quantity in mine ventilation network
According to the dynamic monitoring technology of mine roadway in mine ventilation network, the automatic monitoring system of air quantity is established.

Figure 3. Structural representation of the automatic monitoring system.

Figure 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 wind speed sensor and the air density sensor. The wind speed sensor monitors the wind speed of one cotree set branches and some main intake ventilation roadway; the air density sensor monitors the air density of the wind speed 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.

The specific implementation steps are as follows:
(1) According to the monitoring data of the wind speed sensor, the average wind speed of the roadway is calculated by using the formula of the fixed velocity of the non-uniform flow field;
(2) The average air quantity of the roadway is calculated by the cross-sectional area of the wind speed sensor installation position and the monitoring data of the air density sensor;
(3) The air quantity of the non-cotree branches is calculated by the equation of air quantity balance of each circuit and node;
(4) 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.

5. Case study
Using the complex ventilation network with exhaust fan as an example (Figure 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.
Select a set of basic circuit (Table 2). The first column is the cotree branch, and the second column is the spanning tree branch. There are 7 circuits in this ventilation network.

**Table 2. Basic circuit of mine ventilation network.**

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

The wind speed 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 3. Collected monitoring data of ventilation network.**

| Sensor number | Branch number | Wind speed /m·s$^{-1}$ | Density /kg·m$^{-3}$ | Cross section area /m$^2$ | Wind speed correction/m·s$^{-1}$ | Mass flow /kg·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 wind speed sensor is installed in the 0.8 times relative height from the bottom border. The correction curve is as follows:

$$v' = 0.9573v_m + 0.0027 \quad (7)$$

Where, $v'$ is the corrected wind speed, m/s; $v_m$ is the measured wind speed, m/s.
The corrected wind speed is calculated by formula (7), which is illustrated in the corrected wind speed column of Table 3.

According to the monitoring data of the modified air density sensor and the wind speed 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 e1, e2 and e6 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 is the average value of these two data, which is illustrated in redundant correction column of mass flow.

Using the adjustment analysis of ventilation network (formula (6)), the correlation matrix \( A = \begin{bmatrix} -0.08, 1.24, -0.02, -0.09, -0.95, 0.09, 0, 0.09, 0.11, -0.02, -0.17, 0.08, -0.28 \end{bmatrix}^T \), then the mass flow of each branches is calculated. It illustrates in the adjustment analysis column of mass flow in Table 4.

**Table 4. Air quantity correction of branches.**

| Branch | Calculated by circuit | Calculated by redundant correction | Calculated by adjustment analysis | Corrected air quantity /m³·s⁻¹ |
|--------|-----------------------|----------------------------------|----------------------------------|-----------------------------|
| 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                      |

As the air quantity is product of mass flow and air density, the air quantity is calculated and shown in column of corrected air quantity in Table 4. The real-time air quantity of each branch can be obtained by only 10 wind speed sensors (7 must install points and 3 redundant install points) in whole ventilation system. It only accounts for 52.6% of the total number of branches.

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

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

The dynamic monitoring system of air quantity is established. The application in a complex ventilation network shows that it only needs 10 wind speed sensors (7 must install points and 3 redundant install points) to calculate the air quantity of 19 branches. And this method has a good popularization and application value in the future.

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