A Derivative Method to Calculate Resistance Sensitivity for Mine Ventilation Networks

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Abstract

A reliable and stable ventilation system is essential to the safe operation of underground mines. The stability of a mine ventilation system becomes extremely critical while responding to a fire incident since an unstable ventilation system will pose a risk of airflow reversal. The reversed airflow could bring the fire contaminants such as toxic gases and smoke unexpectedly to working areas. In the past few years, there has been a growing interest in the study of ventilation network stability using the concept of resistance sensitivity, which is described as an indicator of how the airflow in an airway is reacting to a resistance change of other airways. Several methods of calculating the resistance sensitivity in a mine ventilation network have been carried out by researchers and scholars around the world. However, the proposed methods heavily rely on a vast amount of mine ventilation simulations, which are very time consuming and computer-power intensive, especially for a large-scale mine ventilation network. In this paper, a derivative method calculating the resistance sensitivities with a single mine ventilation simulation has been developed and implemented into a mine fire simulation software, MFIRE. The results from the derivative method were verified against the results from a traditional method. The derivative method has been proven to be reliable and accurate.

Keywords Mine ventilation · Ventilation network · Ventilation stability · Resistance sensitivity

1 Introduction

Ventilation is the lifeblood of an underground mine for providing fresh air for miners to breathe and carrying away unwanted contaminants such as respirable dust, explosive gas mixtures, and other harmful airborne particles. A well-designed ventilation system is essential to ensuring safe and efficient underground mining operations. However, a mine ventilation system could be disturbed adversely under fire influence. The rapid change in heat, natural ventilation, and air volume expansion can adversely affect the stability of a ventilation network by reversing airflows and unexpectedly carrying contaminants to working sections or primary escape ways. Therefore, the stability of a ventilation system under fire influence is of utmost importance to the safety of the mine.

The stability of a ventilation network has been recognized as a key factor in determining how the ventilation network responds to anomalous changes, such as those arising from a fire emergency. In recent years, there has been a growing interest in the study of the stability assessment of mine ventilation networks through the concept of sensitivity [2, 3, 5, 7]. The sensitivity in a ventilation network refers to the degree of dependency of airflows in an airway to the resistance change of another airway, heat change, or other conditions. The sensitivity to resistance change has been considered more important than the other conditions. This paper will focus on resistance sensitivity, which reflects how sensitive the airflow in an airway is in responding to the resistance changes of other airways. Besides the application in the ventilation network stability study, the resistance sensitivity has been also used as an assistant tool to predict the airflow distributions in a ventilation network when underground conditions and ventilation controls are changed for the ventilation-on-demand system [6] and to identify the causes of abnormal airflows in a mine ventilation system [8]. In this paper, the resistance sensitivity is referred to simply as "the sensitivity" for ease of use.

Several methods and algorithms have been proposed for calculating the sensitivity in the past. Dziurzyński et al. [2]

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proposed an algorithm to produce the sensitivity matrix by solving the approximation expression of the derivative of the airflow to the resistance. Jia et al. [5] developed a so-called Cross iterative method, which combines the Hardy Cross method for network solution and the iterative method for sensitivity calculation to determine the sensitivity. The calculation of sensitivity in Li et al.'s [6] paper is fairly straightforward with the direct resistance change to a certain airway and then solving the ventilation network for airflow changes. Griffith and Stewart [3] proposed a method to determine the sensitivity by running multiple samples of airflow simulation with randomly perturbed variations for each resistance. Despite the various methods for calculating resistance sensitivity, one thing these methods have in common is that they all require a large number of mine ventilation simulations, which is time consuming and computationally expensive for a large and complicated mine ventilation network. In this paper, the authors are proposing a derivative method to calculate the resistance sensitivity with a single mine ventilation simulation.

2 Derivative Method

2.1 Definition of Resistance Sensitivity

The resistance sensitivity of an airway is an indicator of how the airflow in the airway is affected by the change of resistance in a certain airway. It is mathematically defined as [5, 8]

$$S_{ij} = \lim_{|\Delta R_j \to 0|} \frac{\Delta Q_i}{\Delta R_j} = \frac{\partial Q_i}{\partial R_j} \tag{1}$$

where S_{ij} is the sensitivity of airway i to the change of resistance in airway j; R_j is the resistance in airway j, and Q_i is the volumetric airflow rate in airway i. Li et al. [6] and Dziurzynski et al. [2] also have very similar definitions of resistance sensitivity but with slightly different expressions than Eq. (1).

Given a ventilation network with N airways, each airway can have a number of N sensitivities to the rest of the airways and itself. Therefore, an $N \times N$ sensitivity matrix S can be formed for the ventilation network:

$$S = \begin{bmatrix} S_{11} & S_{12} & \cdots & S_{1N} \\ S_{21} & S_{22} & \cdots & S_{2N} \\ & \vdots & \vdots & \vdots & \vdots \\ S_{N1} & S_{N2} & \cdots & S_{NN} \end{bmatrix} \tag{2}$$

In the above N by N sensitivity matrix, each row represents that the airflow change of each airway is responding to the resistance change of all the airways. For instance, the second row is the sensitivity of airway #2 to all the airways,

and element S_{23} indicates the airflow change of airway #2 to the resistance change in airway #3.

2.2 Useful Terms of the Ventilation Network

Prior to explaining how to obtain the sensitivity matrix through a directive method for a ventilation network, it is often necessary to address several commonly used terms in ventilation network analysis, such as basic mesh, spanning tree, and chord [4]. Figure 1 displays an example of a simple network with six airways and four nodes, where an airway, often referred to as a branch, is a connecting line between two nodes. A mesh is a closed loop of airways in the ventilation network. A suitable number of meshes can be formed in the ventilation network as shown in Fig. 1, but there are only three basic meshes. The basic mesh refers to the mesh containing one airway, which is not included in any other meshes. For a ventilation network with N airways and J nodes, $N - J + 1$ basic meshes will be formed. Hence, the ventilation network shown in Fig. 1 has three basic meshes. In a ventilation network, the spanning tree is a connected graph containing airways that connect all the nodes but creates no meshes. For example, airways 1, 2, and 5 (drawn in blue) are one set of spanning trees for the example network since they connect all four nodes without forming any meshes. A chord is an airway contained in the network but not in a given spanning tree. A ventilation network could have multiple sets of spanning trees and will generate a unique set of chords for a particular spanning tree. In the example network, airways 3, 4, and 6 are the chords corresponding to the spanning tree of airways 1, 2, and 5. For this particular set of spanning trees, the three basic meshes can be formed as 6–2-5, 1–2-3, and 1–2-5–4. Each basic mesh only contains one chord, which is airways 6, 3, and 4, respectively. In this paper, the airways other than
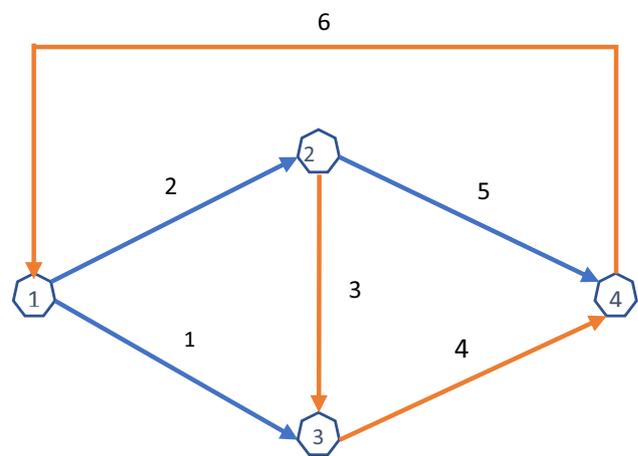

Fig. 1 An example of a simple network

the chord in a basic mesh are referred to as spanning tree airways. In short, a basic mesh is made out of one chord and a few spanning tree airways.

2.3 Mathematical Representation of Resistance Sensitivity Based on Ventilation Network Analysis Theory

Kirchhoff's first and second laws are extensively applied in ventilation network analysis, though they were initially developed as two fundamental laws governing the behavior of electrical circuits. For a ventilation network with the assumption of incompressible air, Kirchhoff's first law states that the quantity of air leaving a node must equal the quantity of air entering a node. As an example, for a ventilation network with N airways and J nodes, the following equation (Eq. (3)) can be used for expressing Kirchhoff's first law:

$$\sum_{j=1}^{N} a_{ij}Q_j = 0 \ (i = 1, 2, \ldots, J) \tag{3}$$

where a_{ij} is a constant defined as follows:

$a_{ij} = 1$, if the end node of airway j is equal to node i (airflow entering node i).

$a_{ij} = -1$, if the starting node of airway j is equal to node i (airflow leaving node i).

$a_{ij} = 0$, if neither of the nodes of airway j is equal to node i.

Kirchhoff's second law applies to the meshes in the ventilation network with a statement that the algebraic sum of all pressure drops around a mesh in the network must be zero. For a ventilation network with N airways and M basic meshes, Kirchhoff's second law can be expressed as

$$\sum_{j=1}^{N} b_{ij}R_jQ_j^2 - H_{Fi} - H_{Ni} = 0 \ (i = 1, 2, \ldots., M) \tag{4}$$

where H_{Fi} is the fan pressure if there is one in mesh i, and H_{Ni} is the natural ventilation pressure in mesh i. b_{ij} is a constant defined as follows:

$b_{ij} = 1$, if branch j is in mesh i and has the same direction with the chord of mesh i.

$b_{ij} = -1$, if branch j is in mesh i and has the opposite direction with the chord of mesh i.

$b_{ij} = 0$, if branch j is not in mesh i.

In a ventilation network, if the airflows of all the chords are known, the airflow of each spanning tree airway can be obtained with known chord airflows by applying the concept of basic meshes and chords to Kirchhoff's first law. Given a ventilation network with N airways and J nodes, it will form $M = N + J - 1$ basic meshes with M chords and $N - M$ (N minus M) spanning tree airways. If the airflows of the M chords are known, the airflows of the N-M tree branches can be expressed using the chord airflows:

$$Q_j \sum_{i=1}^{M} c_{ij}Q_i \ (j = 1, 2, \ldots, N - M) \tag{5}$$

where Q_j is the airflow of spanning tree airway j; Q_i is the airflow of the chord in mesh i; c_{ij} is a constant defined as follows:

$c_{ij} = 1$, if branch j is contained in mesh i and has the same direction with the chord of mesh i.

$c_{ij} = -1$, if branch j is contained in mesh i and has the opposite direction with chord of mesh i.

$c_{ij} = 0$, if branch j is not contained in mesh i.

To substitute Eq. (5) into Eq. (4), we can obtain the following equation (Eq. (6)):

$$\sum_{j=1}^{N} b_{ij}R_j \left(\sum_{i=1}^{M} c_{ij}Q_i \right)^2 - H_{Fi} - H_{Ni} = 0 \ (i = 1, 2, \ldots, M) \tag{6}$$

As it has been defined in Eq. (1), for a given airway k with resistance R_k, the sensitivity of any airway i to the resistance change in airway k is denoted as $\partial Q_i / \partial R_k$. Differentiating Eq. (6) on both sides with respect to R_k leads to the following set of equations:

$$\sum_{j=1}^{N} 2b_{ij}R_jQ_j \left(\sum_{i=1}^{M} c_{ij}\frac{\partial Q_i}{\partial R_k} \right) - \frac{\partial H_{Fi}}{\partial R_k}$$
$$- \frac{\partial H_{Ni}}{\partial R_k} = 0 \sum_{j=1}^{N} 2b_{ij}R_jQ_j \left(\sum_{i=1}^{M} c_{ij}\frac{\partial Q_i}{\partial R_k} \right)$$
$$+ \sum_{j=1}^{N} b_{ij}Q_j^2 - \frac{\partial H_{Fi}}{\partial R_k} - \frac{\partial H_{Ni}}{\partial R_k} = 0 \tag{7}$$
$$(i = 1, 2, \ldots, M)(k \neq j)(i = 1, 2, \ldots, M)(k = j)$$

For a given ventilation network, a system of linear equations with M (number of basic meshes as well as chords) unknowns ($\partial Q_i / \partial R_k$) will be obtained since one basic mesh will yield one linear equation. Therefore, the system of M linear equations with M unknowns is solvable. Neither the fan pressure nor the natural pressure in a mesh is affected significantly by resistance changes; therefore, those two related terms in the equation can be ignored. Write the above system of linear equations into the matrix equation (as shown in Eq. (8)):

$$DX_k = e_k \tag{8}$$

where D is a $M \times M$ matrix with the element $d_{ij} = \sum_{n=1}^{N} 2b_{in}R_nQ_n$; X_k is a column vector with the partial derivatives of the volume flowrate of the chord in each basic mesh to the resistance R_k: $X_k = (\frac{\partial Q_1}{\partial R_k}, \frac{\partial Q_2}{\partial R_k}, \ldots, \frac{\partial Q_M}{\partial R_k})$; e_k is a column vector with M entries, where $e_{ki} = -\sum_{j=1}^{N} b_{ij}Q_j^2$ if branch k is in the mesh i and $e_{ki} = 0$ if branch k is not in the mesh i. Solving the system of linear equations, M partial derivatives of the chords to the resistance R_k will be obtained. The remaining derivatives of N-M tree airways to the resistance R_k can be determined by differentiating both sides of Eq. (5). As of now, the sensitivity $s_{k1}, s_{k2}, \ldots, s_{kN}$, which is the row k in the sensitivity matrix S, is obtained. Following the same procedure, the

derivatives of all the branches to each resistance in the ventilation network can be calculated. Therefore, the sensitivity matrix *S* of a given ventilation network is completed.

3 Implementation in MFIRE

To realize the mathematical model of the sensitivity, the above mathematical model is implemented into the open-source mine fire simulation software, MFIRE, using the programming language Visual C#. Figure 3 is a screenshot of sensitivity tab from MFIRE, which displays the sensitivity matrix using an example of a 49-airway ventilation network (Fig. 2). The left frame in Fig. 3 displays the 49 by 49 resistance sensitivity matrix. A *Save to Excel* feature was created to export the matrix data to an Excel file for data saving and further data analysis utilizing Excel functions. The right frame of the Sensitivity tab was designed for users to check the airways affecting or affected by the airway of interest.

As stated before, the sensitivity indicates the airflow change in an airway because of the resistance change in any airway, including itself, in a ventilation network. In the displayed sensitivity matrix, the K row represents the sensitivity of each airway corresponding to the resistance change

in the K airway, while the K column displays the airflow changes in the K airway in response to the resistance change in each airway. For example, the value of the cell at the cross line of row branch 4 and column branch 5 is 1482. This indicates that the change rate of airflow in airway 5 is 1482 ft^3/min (0.70 m^3/s) responding to the unit change of resistance of airway 4. The positive sign of the sensitivity means the airflow change is in the same direction as the resistance change. In other words, the airflow increases with the resistance increase, and vice versa. Likewise, the negative sign of the sensitivity indicates that the airflow of an airway changes in the opposite direction of the resistance change in the other branch. As a fact, the sensitivity of an airway is always positive to its paralleled connecting airway and negative to its series connecting airway. It is easy to understand that the resistance increase (decrease) of an airway will lead to the airflow decrease (increase) of the other branches in a series circuit and the other way around in a parallel circuit.

The right frame of the sensitivity tag page shown in Fig. 3 is a sorted sensitivity list of the affecting and affected airways to an airway of interest. When an airway of interest is selected, the first two columns will list the airway numbers and their sensitivities which the resistance change of the selected airway affects from the most to the least, while
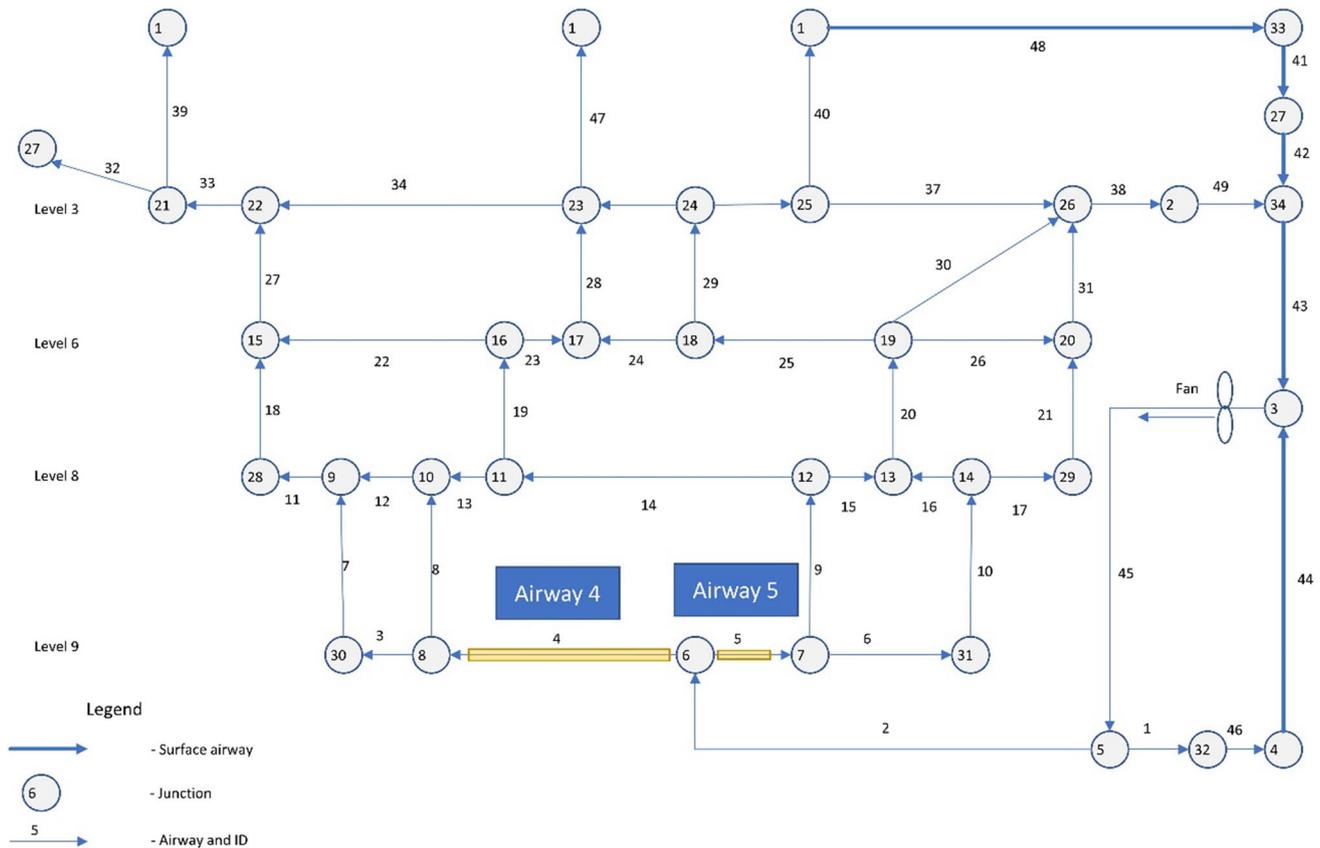

Fig. 2 The schematic layout of the 49-airway network (source: [1])

Log Verbose Data Monitor Sensitivity

Save to Excel

Branch16 ⌄

	Branch1	Branch2	Branch3	Branch4	Branch5	Branch6	Branch7	Branch8	Branch9	Branch
Branch 1	-5	1	0	0	1	0	0	0	0	0
Branch 2	81	-3391	-722	-1092	-2299	-1405	-722	-370	-894	-1405
Branch 3	1	-35	-457	-306	271	164	-457	151	107	164
▶ Branch 4	3	-120	-694	-1602	1482	888	-694	-908	594	888
Branch 5	25	-1029	2517	6066	-7095	-4263	2517	3549	-2833	-4263
Branch 6	6	-247	598	1426	-1673	-4927	598	828	3254	-4927
Branch 7	1	-35	-457	-306	271	164	-457	151	107	164
Branch 8	0	-5	38	-102	98	58	38	-141	40	58
Branch 9	1	-56	139	339	-395	1157	139	201	-1552	1157
Branch 10	6	-247	598	1426	-1673	-4927	598	828	3254	-4927
Branch 11	4	-164	-585	-505	341	222	-585	80	118	222
Branch 12	0	-11	108	55	-65	-37	108	-54	-28	-37
Branch 13	0	0	2	13	-13	-8	2	11	-6	-8
Branch 14	0	-20	96	360	-380	-221	96	264	-159	-221
Branch 15	0	-1	-4	-29	28	129	-4	-26	-101	129
Branch 16	5	-204	502	1215	-1419	-4224	502	714	2805	-4224
Branch 17	0	0	0	0	0	-1	0	0	0	-1
Branch 18	4	-164	-585	-505	341	222	-585	80	118	222
Branch 19	0	-10	21	8	-18	-9	21	-13	-9	-9
Branch 20	8	-342	531	438	-781	-402	531	-92	-379	-402
Branch 21	0	0	0	0	0	-1	0	0	0	-1
Branch 22	0	0	3	2	-3	-2	3	-1	-1	-2
Branch 23	0	-5	-32	-31	26	18	-32	1	8	18
Branch 24	0	0	3	3	-3	-2	3	0	-1	-2
Branch 25	0	-19	43	39	-58	-38	43	-4	-20	-38
Branch 26	0	0	0	0	0	1	0	0	-1	1
Branch 27	5	-207	-145	-159	-48	-23	-145	-15	-25	-23
Branch 28	0	-13	-15	-16	3	3	-15	-1	0	3

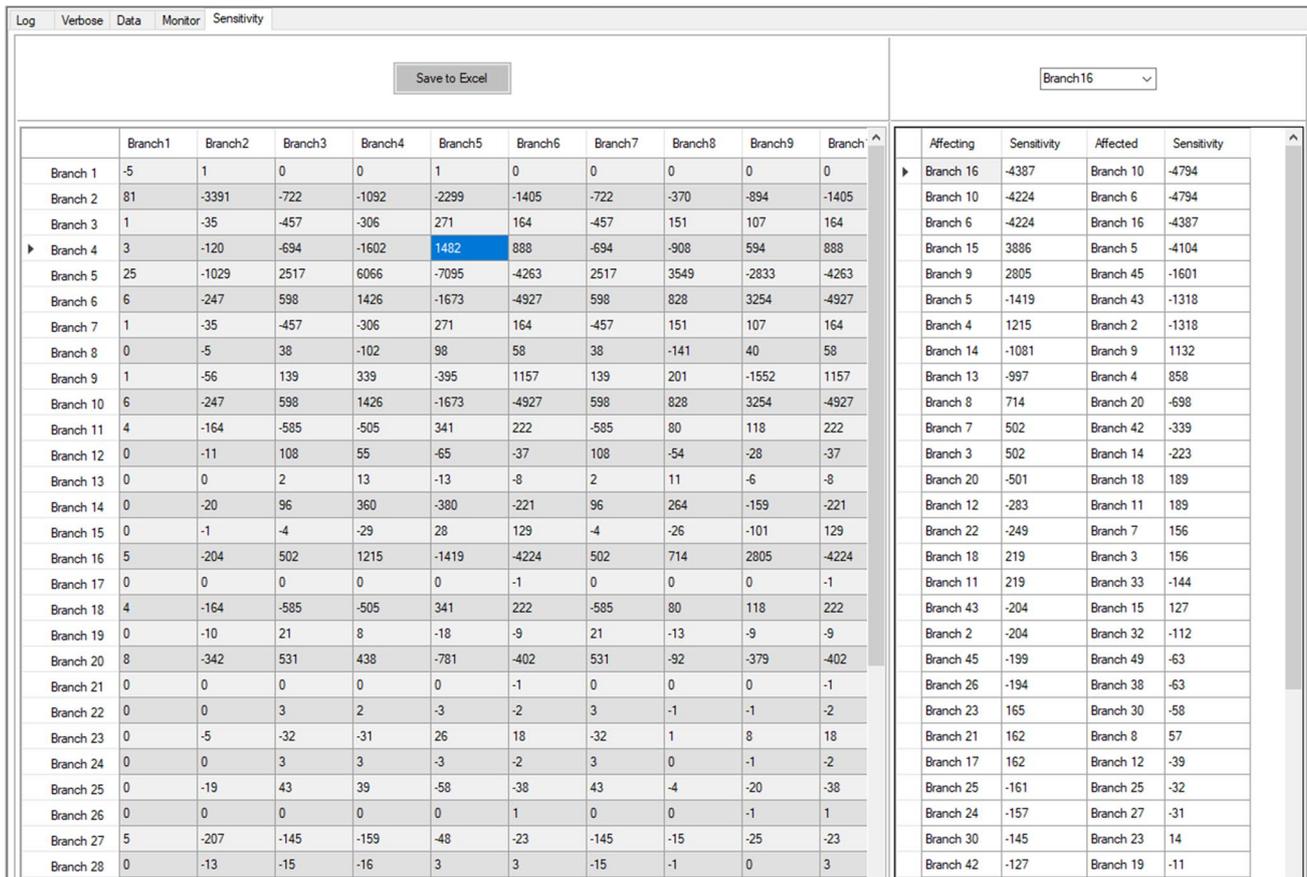| Affecting	Sensitivity	Affected	Sensitivity
Branch 16	-4387	Branch 10	-4794
Branch 10	-4224	Branch 6	-4794
Branch 6	-4224	Branch 16	-4387
Branch 15	3886	Branch 5	-4104
Branch 9	2805	Branch 45	-1601
Branch 5	-1419	Branch 43	-1318
Branch 4	1215	Branch 2	-1318
Branch 14	-1081	Branch 9	1132
Branch 13	-997	Branch 4	858
Branch 8	714	Branch 20	-698
Branch 7	502	Branch 42	-339
Branch 3	502	Branch 14	-223
Branch 20	-501	Branch 18	189
Branch 12	-283	Branch 11	189
Branch 22	-249	Branch 7	156
Branch 18	219	Branch 3	156
Branch 11	219	Branch 33	-144
Branch 2	-204	Branch 15	127
Branch 43	-204	Branch 32	-112
Branch 45	-199	Branch 49	-63
Branch 26	-194	Branch 38	-63
Branch 23	165	Branch 30	-58
Branch 21	162	Branch 8	57
Branch 17	162	Branch 12	-39
Branch 25	-161	Branch 25	-32
Branch 24	-157	Branch 27	-31
Branch 30	-145	Branch 23	14
Branch 42	-127	Branch 19	-11

Fig. 3 Sensitivity matrix and affected and affecting branch list to a selected branch in MFIRE

the second two columns will display the affected branches of which the selected branch is affected by the resistance changes in these branches in descending order. Taking the example shown in Fig. 3, the resistance increase (decrease) in the selected branch 16 will affect itself the most by a 4386 ft^3/min (2.07 m^3/s) decrease (increase) in airflow, and then branch 10, branch 6, and the rest of airways. Similarly, the airflow of branch 16 will be affected most by the resistance changes in branches 10 and 6, and then itself as shown in the second two columns. Using this feature, it will be easy to find out how sensitive a certain branch is to other branches in a ventilation network. This could allow users to have an insight into the mutual dependence of airways. Users can utilize this feature to potentially diagnose the cause of abnormal airflow, develop a ventilation regulating plan, evaluate the ventilation stability, etc.

The sensitivity displayed in Fig. 3 is the value of airflow change in response to a resistance change, which can be called absolute sensitivity. It is useful to display the relative sensitivity, which expresses how large the airflow rate change in an airway is compared to its original airflow rate. The relative sensitivity is the sensitivity divided by the original airflow rate and displayed in the form of a percent (Fig. 4).

4 Verification of the derivative method

As the sensitivity reflects the airflow change in an airway in response to the resistance change in another branch, the sensitivity matrix can be directly obtained by changing the resistance of each branch one at a time and running the ventilation simulation for each, which is the approach Li et al. [6] employed in their work. This approach requires one ventilation simulation for each resistance change. The sensitivity results from this approach can be used to compare them with the outcome from the derivative method proposed in this study. Taking an example of branch 19, we calculated the airflow changes in each branch, while the resistance of branch 19 changes by 0.1, 0.2, and 0.8 (10^{-10} * in.w.g./cfm^2), respectively. To better understand the correlation of the results, the normalized scatterplot is used to display the relationship between the sensitivity from the derivative method and the results from the three fixed-resistance changes. It can be seen from Fig. 5 that the sensitivity calculated from the derivative method is linearly related to the results obtained from the various resistance change. The Pearson coefficients calculated for the three cases are 0.999, indicating that they are positively linear related, and
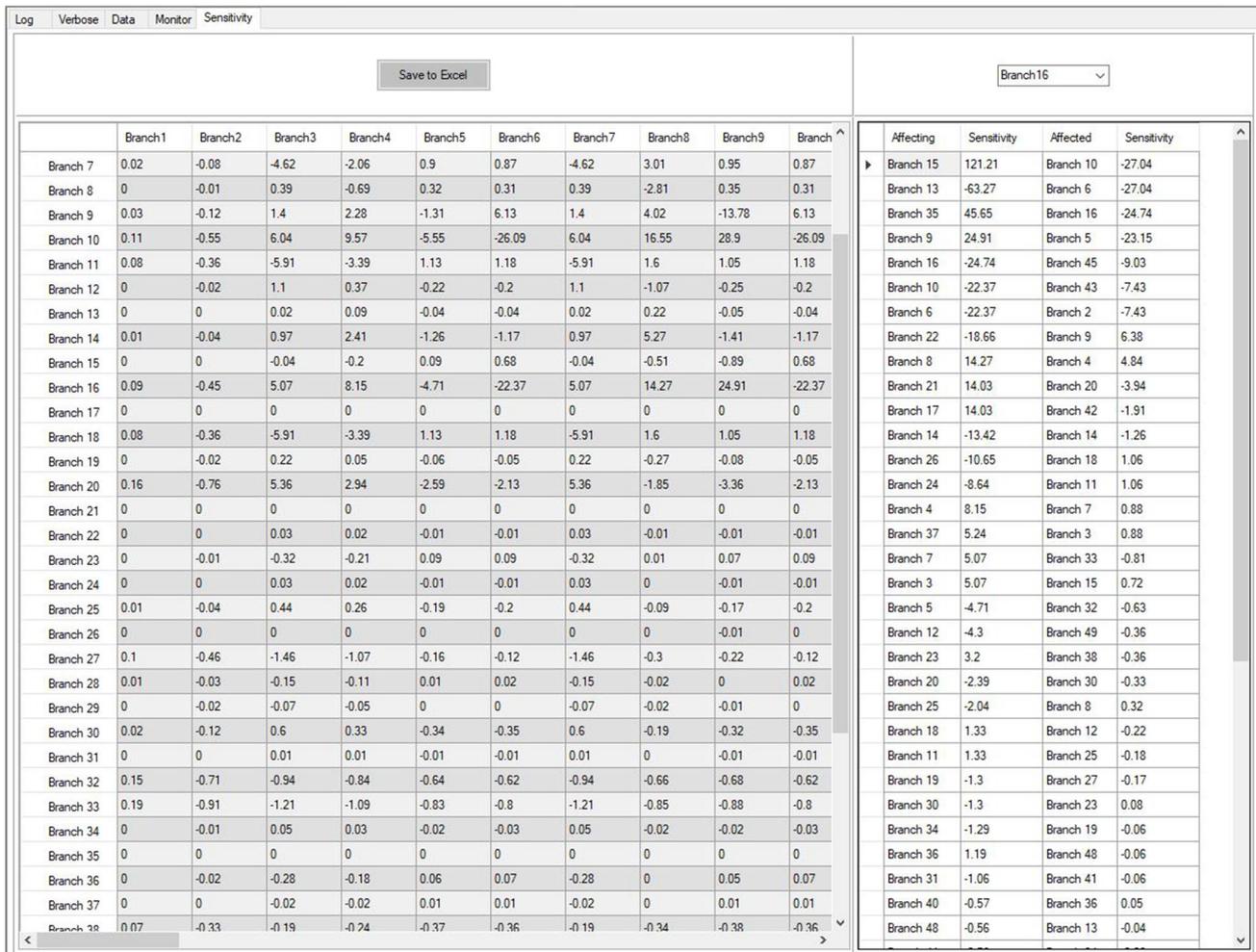
Log   Verbose   Data   Monitor   **Sensitivity**

Save to Excel   Branch16 ▾

	Branch1	Branch2	Branch3	Branch4	Branch5	Branch6	Branch7	Branch8	Branch9	Branch
Branch 7	0.02	-0.08	-4.62	-2.06	0.9	0.87	-4.62	3.01	0.95	0.87
Branch 8	0	-0.01	0.39	-0.69	0.32	0.31	0.39	-2.81	0.35	0.31
Branch 9	0.03	-0.12	1.4	2.28	-1.31	6.13	1.4	4.02	-13.78	6.13
Branch 10	0.11	-0.55	6.04	9.57	-5.55	-26.09	6.04	16.55	28.9	-26.09
Branch 11	0.08	-0.36	-5.91	-3.39	1.13	1.18	-5.91	1.6	1.05	1.18
Branch 12	0	-0.02	1.1	0.37	-0.22	-0.2	1.1	-1.07	-0.25	-0.2
Branch 13	0	0	0.02	0.09	-0.04	-0.04	0.02	0.22	-0.05	-0.04
Branch 14	0.01	-0.04	0.97	2.41	-1.26	-1.17	0.97	5.27	-1.41	-1.17
Branch 15	0	0	-0.04	-0.2	0.09	0.68	-0.04	-0.51	-0.89	0.68
Branch 16	0.09	-0.45	5.07	8.15	-4.71	-22.37	5.07	14.27	24.91	-22.37
Branch 17	0	0	0	0	0	0	0	0	0	0
Branch 18	0.08	-0.36	-5.91	-3.39	1.13	1.18	-5.91	1.6	1.05	1.18
Branch 19	0	-0.02	0.22	0.05	-0.06	-0.05	0.22	-0.27	-0.08	-0.05
Branch 20	0.16	-0.76	5.36	2.94	-2.59	-2.13	5.36	-1.85	-3.36	-2.13
Branch 21	0	0	0	0	0	0	0	0	0	0
Branch 22	0	0	0.03	0.02	-0.01	-0.01	0.03	-0.01	-0.01	-0.01
Branch 23	0	-0.01	-0.32	-0.21	0.09	0.09	-0.32	0.01	0.07	0.09
Branch 24	0	0	0.03	0.02	-0.01	-0.01	0.03	0	-0.01	-0.01
Branch 25	0.01	-0.04	0.44	0.26	-0.19	-0.2	0.44	-0.09	-0.17	-0.2
Branch 26	0	0	0	0	0	0	0	0	-0.01	0
Branch 27	0.1	-0.46	-1.46	-1.07	-0.16	-0.12	-1.46	-0.3	-0.22	-0.12
Branch 28	0.01	-0.03	-0.15	-0.11	0.01	0.02	-0.15	-0.02	0	0.02
Branch 29	0	-0.02	-0.07	-0.05	0	0	-0.07	-0.02	-0.01	0
Branch 30	0.02	-0.12	0.6	0.33	-0.34	-0.35	0.6	-0.19	-0.32	-0.35
Branch 31	0	0	0.01	0.01	-0.01	-0.01	0.01	0	-0.01	-0.01
Branch 32	0.15	-0.71	-0.94	-0.84	-0.64	-0.62	-0.94	-0.66	-0.68	-0.62
Branch 33	0.19	-0.91	-1.21	-1.09	-0.83	-0.8	-1.21	-0.85	-0.88	-0.8
Branch 34	0	-0.01	0.05	0.03	-0.02	-0.03	0.05	-0.02	-0.02	-0.03
Branch 35	0	0	0	0	0	0	0	0	0	0
Branch 36	0	-0.02	-0.28	-0.18	0.06	0.07	-0.28	0	0.05	0.07
Branch 37	0	0	-0.02	-0.02	0.01	0.01	-0.02	0	0.01	0.01
Branch 38	0.07	-0.33	-0.19	-0.24	-0.37	-0.36	-0.19	-0.34	-0.38	-0.36

Affecting	Sensitivity	Affected	Sensitivity
Branch 15	121.21	Branch 10	-27.04
Branch 13	-63.27	Branch 6	-27.04
Branch 35	45.65	Branch 16	-24.74
Branch 9	24.91	Branch 5	-23.15
Branch 16	-24.74	Branch 45	-9.03
Branch 10	-22.37	Branch 43	-7.43
Branch 6	-22.37	Branch 2	-7.43
Branch 22	-18.66	Branch 9	6.38
Branch 8	14.27	Branch 4	4.84
Branch 21	14.03	Branch 20	-3.94
Branch 17	14.03	Branch 42	-1.91
Branch 14	-13.42	Branch 14	-1.26
Branch 26	-10.65	Branch 18	1.06
Branch 24	-8.64	Branch 11	1.06
Branch 4	8.15	Branch 7	0.88
Branch 37	5.24	Branch 3	0.88
Branch 7	5.07	Branch 33	-0.81
Branch 3	5.07	Branch 15	0.72
Branch 5	-4.71	Branch 32	-0.63
Branch 12	-4.3	Branch 49	-0.36
Branch 23	3.2	Branch 38	-0.36
Branch 20	-2.39	Branch 30	-0.33
Branch 25	-2.04	Branch 8	0.32
Branch 18	1.33	Branch 12	-0.22
Branch 11	1.33	Branch 25	-0.18
Branch 19	-1.3	Branch 27	-0.17
Branch 30	-1.3	Branch 23	0.08
Branch 34	-1.29	Branch 19	-0.06
Branch 36	1.19	Branch 48	-0.06
Branch 31	-1.06	Branch 41	-0.06
Branch 40	-0.57	Branch 36	0.05
Branch 48	-0.56	Branch 13	-0.04

Fig. 4 Sensitivity matrix affected and affecting branch list for relative sensitivity (%)

everything the resistance sensitivity calculated from the proposed derivative method is correct. It also needs to be noted that the derivative method may yield different magnitudes of the sensitivity compared to other methods [2, 3, 5, 7], but it will not change the fact that the sensitivity is an indicator of how a resistance change in one branch could affect the airflow of each branch in a mine ventilation network.

5 Conclusions

Resistance sensitivity of a ventilation network is a valuable tool to understand the degree of the interdependency of each branch and the overall stability of the network. This paper presents a derivative method to calculate the sensitivity without the need for numerous simulations of ventilation networks as used in other methods. As compared to other methods, the advantage of the derivative method is the time saving and computer resource saving since it only requires running the ventilation network solution one time. The proposed method

has been implemented into NIOSH's mine fire simulation program, MFIRE, and has proven to provide a useful addition to
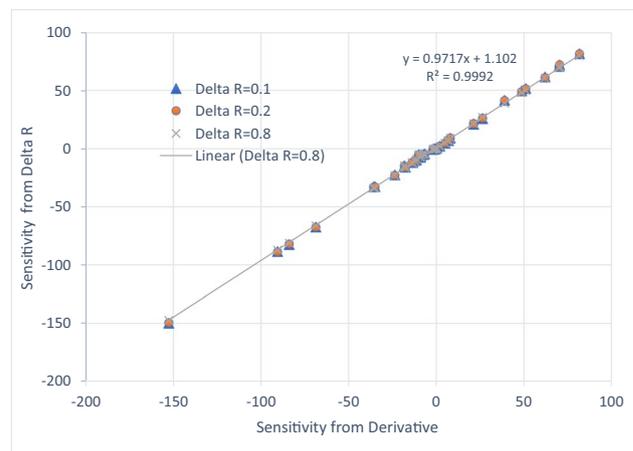
y = 0.9717x + 1.102
R² = 0.9992

▲ Delta R=0.1
● Delta R=0.2
× Delta R=0.8
— Linear (Delta R=0.8)

Sensitivity from Delta R

Sensitivity from Derivative

Fig. 5 The correlation between the sensitivity from the derivative method and normalized resistance changes

the software features. The verification study of the derivative method has shown that the calculated sensitivity results are in excellent agreement with the airflow rate changes from the example cases with a manual resistance change. The sensitivity matrix of a ventilation network provides a good picture of how the airways correlate with each other. It can help mine operators to perform ventilation control and diagnose ventilation problems such as abnormal airflow.

6 Disclaimer

The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company or product does not constitute an endorsement by the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention.

Declarations

Conflict of Interest The authors declare no competing interests.

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