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DETERMINATION OF A MATRIX COLUMN OF AIR VOLUME OUTPUT SENSITIVITY TO CHANGES IN SIDE BRANCHES RESISTANCE IN A MINE VENTILATION NETWORK

Abstract

Ventilation networks in collieries are exposed to production-induced or accidental changes in air volume distribution evoked by various factors, including planned, accidental or emergency changes in side branches resistance. The distributed air reacts to such changes, which may have a negative impact on the state of hazards eliminated by ventilation methods. The propagation of disturbances in ventilation systems in collieries may be analyzed by simulated computations of air volume distribution in the ventilation network. In the analysis of the disturbance pattern propagation, methods utilizing the theory of sensitivity are useful. The discussed method of determining a matrix column of air output sensitivity to changes in side branches resistance is useful in the solution of many problems occurring in ventilation net-works in collieries.

Abstrakt

Větrací sítě v hlubinných dolech jsou v důsledku těžby nebo náhodně vystaveny změnám v distribuci objemu vzduchu způsobeného četnými faktory včetně plánovaných, náhodných nebo havarijních změn v odporu postranních chodeb. Distribuovaný vzduch na takové změny reaguje, což může mít negativní vliv na stav nebezpečí eliminovaný ventilačními metodami. Šíření poruch ve ventilačních systémech hlubinných dolů je možné analyzovat simulovanými výpočty distribuce objemu vzduchu ve ventilační síti. Při analýze šíření poruchového schématu jsou užitečné metody využívající teorii citlivosti. Diskutovaná metoda stanovení sloupce matice citlivosti dodávaného vzduchu na změny v rezistenci postranních chodeb je užitečná při řešení mnoha problémů vznikajících ve větracích sítích hlubinných dolů.

Key words: mine ventilation network, sensitivity of the air volume of the change of the resistance side-branches

1 INTRODUCTION

The process of ventilation control in a deep colliery requires the knowledge of the reaction of the air distribution pattern to changes in the parameters of the side branches of ventilation networks, including planned changes implemented by constructing or changing control or adjustment of resistance, the set-up of main and auxiliary fans control equipment, as well as changes evoked accidentally by damage to the network components. Prior assessment of possible changes in airflow distribution enables the

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design and selection of optimum procedures in either planned or emergency circumstances. The availability of updated information on the ventilation network makes it possible to simulate airflow distribution by means of computer-aided calculations and appropriate conclusions. In the absence of such information, the decision-making process requires a lot of experience and knowledge on the part of the personnel responsible for colliery aeration.

The airflow in a colliery, as well as air output distribution to particular work-stands depend on the operation of the main fans, resistance of the headings, control and ventilation dams, structure of the ventilation network, and natural factors, which is shown schematically in Figures 1 and 2. In a steady state, for actual input data, it is possible to determine the response of the network, i.e. airflow output $\boldsymbol{V_{ia}}$ in particular side branches, resistance increments $\boldsymbol{W_{ia}}$, and definite values of fan dams $\boldsymbol{H_i}$. Such ordering is self-effective in a colliery, in accordance with regularities of airflow through the network, as well as in the course of calculations, where the mathematical description of the results is possible. The results of measurements taken in a colliery and the calculation results are used for the analysis of the quantitative schemes, potential schemes, and other schemes (see Fig. 2).

The introduction of a change, or an accidental change in the input data evoke a different response of the network. The airflow distribution, resistance increments and fan dams are subject to small or bigger changes. The analyzed schemes, i.e. the quantitative and potential ones, change their forms. The information on the changes may be derived in the course of test trials or by calculating the airflow distribution. Multi-option calculations often enable the selection of the optimal way of the network layout. Sometimes, to secure better certainty, an additional test trial is made in a colliery, to certify the choice of a particular layout option.

In the course of calculations and analyses of ventilation networks, many different coefficients are used to illustrate the actual condition of the network operation, and the combination of its components. Such coefficients may also involve the sensitivity of various variables describing the airflow in the network to the changes in the quantities, which are treated as independent variables. In the mining practice, the most interesting are the airflow output sensitivities to changes of side branches parameters, especially to changes in their resistance, which is the main scope of the paper.

2 MATHEMATICAL AND PHYSICAL INTERPRETATION OF AIRFLOW OUTPUT SENSITIVITY TO CHANGES IN SIDE BRANCHES

The concept of sensitivity is applied in many fields of science and technology, including, i.e. the control theory, tolerance, design of technical systems [1, 2, 5, 11]. Sensitivity connects related variable $\boldsymbol{y(x_1, x_2, ..., x_n)}$, also called the system function with independent variables $\boldsymbol{x_1, x_2, ..., x_n}$, also called system parameters. Change in system function $\boldsymbol{y}$ in the vicinity of the nominal values of system parameters $\boldsymbol{x_1, x_2, ..., x_n}$ may, approximately, be expressed in the following form:

$$\Delta y = \sum_{i=1}^{n} \frac{\partial y(x_{ia})}{\partial x_i} \Delta x_i \tag{2.1}$$

where:

$\Delta y = y - y_0$ - change in the value of the system function,

$\Delta x = x_i - x_{i0}$ - change of the i-th parameter 1, 2, ..., n,

y_0, x_{i0} - initial value of the system function and the i-th parameter,

$\frac{\partial y(x_{i0})}{\partial x_i}$ - value of the partial derivative of the system function in relation to the i–th parameter, calculated at initial operation point x_{i0}, referred to as absolute sensitivity.

Apart from absolute sensitivity, relative sensitivity $\frac{\partial \ln y}{\partial \ln x_i}$ is also used, as well as semi-relative one $\frac{\partial \ln y}{\partial x_i}$ or $\frac{\partial y}{\partial \ln x_i}$.

In a colliery ventilation system, every air volume output V_i may be treated as dependent on the side branch parameters and, in particular, to their resistance R_j (Fig. 1, 2):

$$V_i = V_i(R_1, R_2, ..., R_j, ..., R_m) \qquad i, j = 1,2, ..., m \tag{2.2}$$

For actual side branch parameters R_a the response of the system takes the form of actual air distribution V_a. The change of the selected parameter R_i implies, theoretically, the change of all air outputs V_i, which may be presented in the following way (Fig. 1, 2):

$$V = F(R) \tag{2.3}$$

The actual airflow output is assigned to the actual parameters:

$$R_a \rightarrow V_a \tag{2.4}$$

Change ΔR in the space of parameters R leads to changes ΔV in airflow distribution V:

$$R_a + \Delta R \rightarrow V_a + \Delta V \tag{2.5}$$

Accordingly, the following differential quotient is formed:

$$\frac{V_i - V_{ia}}{R_j - R_{ja}} = \frac{\Delta V_i}{\Delta R_j} \tag{2.6}$$

Some of the analyzed relations $V_i(R_j)$ may be strong, whereas others weak. This information may be derived from sensitivities $\partial V_i/\partial R_j$ calculated for the actual condition of the ventilation system operation. Thus, airflow output sensitivity V_i to resistance change R_j may also be interpreted as the value of the boundary of the differential quotient:

$$\varepsilon_{ij} = \lim_{R_j \to R_{ja}} \frac{V_i - V_{ia}}{R_j - R_{ja}} = \lim_{\Delta R_j \to 0} \frac{\Delta V_i}{\Delta R_j} = \frac{\partial V_i}{\partial R_j}(R_{ja}) = tg\alpha \tag{2.7}$$

The above is also presented in Fig. 3. Directivity index $tg\alpha$ of the line tangential to curve $V_i(R_j)$ is the required sensitivity which determines an increasing or decreasing nature of relation $V_i(R_j)$ around the actual operation point R_{ja}. To simplify the notation, sensitivity shall be denoted as ε_{ij}.

In mining practice, it seems useful to know the value of sensitivity ε_{ij} for selected airflow output V_i, i.e. to assess the impact of all resistances R_j on airflow output V_i and conversely, to determine how the selected i-th resistance R_j influences all airflow outputs V_i. In the generalized case, sensitivity matrix E may be considered:

$$E = [\varepsilon_{ij}] \qquad i, j = 1, 2, ..., m \tag{2.8}$$

3 RECOGNIZED METHODS OF DETERMINING THE AIRFLOW OUTPUT SENSITIVITY TO CHANGES IN THE RESISTANCE OF SIDE-BRANCHES

Publications concerning airflows through mine ventilation systems recognize the relevance of airflow output sensitivity to changes in the resistance of side-branches. Such quantities connected with sensitivity were used by Simode [11] to illustrate and analyze the changes in airflow outputs with changes in the resistance of side-branches, and fan dams. However, Simode does not present effective methods of determining sensitivity coefficients, as in [1, 11 and others] he postulates to designate them by means of the incremental method with two network solutions.

The issue of determining the airflow output sensitivity to the parameters of the side-branches was discussed in [2], where to determine any l-th row of matrix E J. Chojcan applied Tellegen's theorem well recognized in electrical engineering. Specially constructed auxiliary network S^* has a structure identical to basic network S. The components (side-branches) of S^* have resistances R_i^* equal to:

$$R_i^* = \frac{dW_i}{dV_i}(V_{ia}) \tag{3.1}$$

where the value of the differential coefficient is determined at the actual operation point of the i-th side-branch of basic network **S**. Relations $W_i(V_i)$ are the characteristics of the side-branches in basic network S and take the following form:

$$W_i = R_i \cdot V_i \cdot /V_i/ \quad \text{for side-branches with resistance } R_i \tag{3.2}$$

$$W_i = - H_i(V_i) \quad \text{for side-branches with fan of characteristic } H_i(V_i) \tag{3.3}$$

The side-branches which have the assumed constant airflow output $V_i = const$ in the main network are assigned by Chojcan [2] to flow $V_i^* = 0$ in the auxiliary network (which is equivalent to the existence of infinite resistance R_i^* in this side-branch). The constructed auxiliary network S^* is linear. The characteristics of passive components are as follows:

$$W_i^* = R_i^* \cdot V_i^* \qquad (3.4)$$

To determine airflow output sensitivity V_l to changes of side-branches resistances R_i, i.e. the values of differential coefficients $\partial V_l/\partial R_i$ i = 1, ..., m, Chojcan installed source $H_l^* = 1$ in the 1-th side-branch of auxiliary network S^*, forcing the flow therein. In the course of solving network S^*, flows V_i^* are used, in the next step, to calculate sensitivity $V_l/\partial R_i$. Next, the sensitivity of the 1-th airflow output to the change of the i-th resistance is derived from the following dependence [2]:

$$\frac{\partial V_l}{\partial R_i} = -V_l^* \cdot V_l \cdot |V_i| \qquad i = 1, 2, ..., m \qquad (3.5)$$

Further ways of determining the sensitivity of airflows to other parameters of side-branches (fan dams, given airflow output) presented in [2] shall not be discussed here. To designate another row of sensitivity matrix E, the above calculations are repeated. Auxiliary network S^* is then identical, the only difference being that source H^* enforcing the flow is installed in another side-branch.

4 METHOD OF DETERMINING A SELECTED COLUMN OF MATRIX E OF THE AIRFLOW OUTPUT SENSITIVITY TO CHANGES IN THE RESISTANCE OF SIDE-BRANCHES

The values of the terms of any r-th column of matrix E of the airflow output sensitivity to the change in the resistance of the r-th side branch are derived in the course of transforming the equations of network equilibrium [3, 4, 6, 7]. Under normal (steady) operating conditions of the network, the following equations hold:

- Kirchhoff's I law for nodes: $S \cdot V = 0$ (3.6)
- Kirchhoff's II law for meshes: $C \cdot W = 0$ (3.7)
- characteristics of side branches: $W_i = R_i \cdot V_i \cdot |V_i|$ for branches with resistance (3.8)

$H_i = H_i(V_i)$ for branches with a fan (3.9)

where:

V_i - air volume output, m^3/s,

W_i, H_i - energy loss or increment per one volume unit of the airflow J/m^3, Pa,

R_i - aerodynamic resistance of side branch, kg/m^7,

S - node-side branch matrix with dimensions $(n - 1) \cdot m$,

C - mesh-side branch matrix with dimensions $\nu \cdot m$,

n - number of nodes in the network,

$\nu = m - n + 1$ - network cyclic number,

V - single-column m matrix of airflow outputs,

W - single-column m matrix of air energy losses or increments per one volume unit.

The occurrence of change $\boldsymbol{dR_r}$ of one selected resistance leads to the emergence of a new flow state $\boldsymbol{V + dV}$ and $\boldsymbol{W + dW}$, for which the node and mesh equations are satisfied:

$$\boldsymbol{S \cdot (V + dV) = 0} \qquad (3.10)$$

$$\boldsymbol{C \cdot (W + dW) = 0} \qquad (3.11)$$

Accordingly, the differentials of airflow outputs $\boldsymbol{dV}$ satisfy the equations for nodes; whereas differential coefficients $\boldsymbol{dW}$ satisfy those for meshes:

$$\boldsymbol{S \cdot dV = 0} \qquad (3.12)$$

$$\boldsymbol{C \cdot dW = 0} \qquad (3.13)$$

The relation between the differential of the i-th airflow output $\boldsymbol{dV_i}$ and the i-th energy dissipation $\boldsymbol{dW_i}$ may be determined from the characteristics of the i-th side branch. For side branches with resistance $\boldsymbol{R_i}$, this relation, assuming that airflow output $\boldsymbol{V_i}$ under the actual operating conditions of the network is positive, has the following form:

$$dW_i = \begin{cases} 2 \cdot R_i \cdot |V_i| \cdot \dfrac{dV_i}{dR_r} \cdot dR_r & \text{for } i \neq r \qquad (3.14) \\ V_r^2 \cdot dR_r + 2 \cdot R_r \cdot V_r \cdot \dfrac{dV_r}{dR_r} \cdot dR_r & \text{for } i = r \qquad (3.15) \end{cases}$$

For clarification, it should be mentioned that in such view, the only independent variable is resistance $\boldsymbol{R_r}$, which substantiates the application of normal differential coefficients. For fans with characteristics $\boldsymbol{_i(V_i)}$, the following dependence may be assumed:

$$\boldsymbol{H_i(V_i) = - W_i(V_i)} \qquad (3.16)$$

Thus, differential $\boldsymbol{dW_i}$ for these side branches may be expressed as:

$$dW_i = \frac{-dH_i}{dV_i} \cdot \frac{dV_i}{dR_r} \cdot dR_r \qquad (3.17)$$

For fans operating on the descending section of characteristic ***H(V)*** the following relation holds: $-\dfrac{dH_i}{dV_i} \geq 0$.

Equations (3.14, 15, 17) holding for appropriate differentials, also hold for derivatives $\dfrac{dV_i}{dR_r}$, $\dfrac{dW_i}{dR_r}$, and, accordingly, for sensitivity ε_{ir}. Hence, the following system of equations may be obtained:

(3.18)

$$\begin{cases} \sum_{i=1}^{m} s_{ji} \cdot \dfrac{dV_i}{dR_r} = 0 & j = 1, 2, ..., n - 1 \quad (3.2.18a) \\ \sum_{i=1}^{m} c_{ji} \cdot \dfrac{dW_i}{dR_r} = 0 & k = 1, 2, ..., \nu - 1 \quad (3.2.18b) \\ \dfrac{dW_i}{dR_r} = \begin{cases} 2 \cdot R_i \cdot |V_i| \cdot \dfrac{dV_i}{dR_r} & \text{for } i \neq r \quad (3.2.18c) \\ V_r^2 + 2 \cdot R_i \cdot |V_r| \cdot \dfrac{dV_r}{dR_r} & \text{for } i = r \quad (3.2.18d) \\ \dfrac{-dH_i}{dV_i} \cdot \dfrac{dV_i}{dR_r} & \text{for side branches with a fan} \quad (3.2.18e) \end{cases} \end{cases}$$

where: s_{ji} and c_{ki} are elements of matrices ***S*** and ***C*** with the values of 1, -1, 0, following the assignment of the i-th side branch to the j-th node or the k-th mesh.

The system of equations (3.18) may be regarded as an algebraic system of linear equations with unknown values of derivatives $\dfrac{dV_i}{dR_r}$, $\dfrac{dW_i}{dR_r}$ under the actual operating conditions of the network.

All resistances R_i, airflow outputs V_i, and values of derivatives $\dfrac{dH_i}{dV_i}$, may be regarded as known from the actual operating conditions of the network. In equations (3.18) these quantities shall work as coefficients of the unknowns or of free terms. Let us also assume the following auxiliary notation:

$$R_i^* = \begin{cases} 2 \cdot R \cdot |V_i| & \text{for side branches with resistance} \quad (3.19a) \\ -\dfrac{dH_i}{dV_i}(V_{ia}) & \text{for side branches with a fan} \quad (3.19b) \end{cases}$$

The values of derivatives $\dfrac{dW_i}{dR_r}$ may easily be eliminated from (3.18). After such transformation, a new system of equations is derived (3.20):

$$\begin{cases} \sum_{i=1}^{m} s_{ji} \cdot \varepsilon_{ir} = 0 \qquad j = 1,2,...,n-1 & (3.20a) \\ \sum_{i=1}^{m} c_{ki} \cdot R_i^* \cdot \varepsilon_{ir} = \begin{cases} 0 & \text{when the k-th mesh does not include this side branch} \quad (3.20b) \\ -c_{ki} \cdot V_r^2 & \text{when it includes this side branch} \quad (3.20c) \end{cases} \end{cases}$$

The system of equations (3.20) in view of the unknown values of sensitivity i ε_{ir}, is a system of linear equations with m unknowns. The number of equations is:

$n - 1 + \nu = n - 1 + m - n + 1 = m$

and is equal to the number of the unknowns. The matrix of the equation system coefficients consists of numbers s_{ji}, c_{ki}, R_i^*. The three terms column contains zeros for the equations derived from the node equations and mesh equations not containing the r-th side branch; and numbers $-\,c_{kr}\, V_r^2$ for the equations formed from the mesh equations containing the r-th side branch. Such system may easily be solved by commonly recognized methods. However, huge networks require computer-aided calculations.

The scope of the research involved the formulation of an appropriate algorithm and program [3, 4, 7] to prepare the input data for the calculation of sensitivity ε_{ir} from the digital representation of the network model and calculation results of actual state dissipation, solving the emerged system of equations (3.20). While testing the discussed method and program, the obtained values of sensitivity ε_{ir} were compared with J. Chojcan's findings [2] and the results of the incremental method (where sensitivity may be approximated from $\Delta V_i/\Delta R_r$) quotient. Likewise, the test results were also compared with the values of derivative dV_i/dR_r for certain cases, where it is possible to derive relation $V_i(R_r)$, and, accordingly, to determine the value of this derivative. All the above comparisons proved the accuracy of the discussed method and the devised program. Once the values of sensitivity ε_{ir}, are known, i.e. the values of derivatives

$\boldsymbol{dV_i/dR_r}$ from equations (3.14, 15, 17), the next step involves the values of derivatives $\boldsymbol{dW_i/dR_r}$ and $\boldsymbol{dH_i/dR_r}$. Thus, it is possible to check the response of the airflow distribution and the pressure and potential fields, under the actual operating condition of the network, to the introduced elementary change of resistance $\boldsymbol{dR_r}$.

To obtain the values of $\boldsymbol{\varepsilon_{ir}}$ for another column of sensitivity matrix $\boldsymbol{E}$, identical calculations are executed. In extreme cases, when a complete form of matrix is required, the calculations should be made for r = 1, 2, ..., m. The discussed method of determining sensitivity constitutes a supplement to the one previously developed by Chojcan [2].

For simple ventilation network schemes, or normal sub-networks, the signs of sensitivity are obvious for staff responsible for their aeration, as they can draw on their professional experience and the simplicity of the network. In more complex cases, however, difficulties may arise in the assessment of the impacts from the implementation of planned resistance changes on airflow distribution, especially in flat and non-flat networks, where the regularities involved in the structure of the network are of essential importance.

Computer-aided sensitivity signs and values are stored in the memory and may be retrieved to facilitate the solution of successive problems involved in ventilation network airflows in collieries [8, 9, 10].

5 CONCLUSIONS

The discussed method of determining the airflow output sensitivity to changes in the resistance of side branches under actual operating conditions of the network involves differentiating the system of the equations of the network equilibrium, which, subsequently, leads to a system of linear equations with the unknown values of sensitivity.

Airflow output sensitivities to change in the resistance of side-branches are applied for solutions of problems that might occur in mine ventilation networks.

The signs of sensitivity are obvious in networks consisting of only parallel and linear connections of the side-branches or network sections (the so called: normal networks).

In diagonal networks, the signs of sensitivity are not that obvious in the side-branches diagonal to the side where the disturbance occurs.

6 SUMMARY

The paper deals with the structure of mine ventilation networks and the sensitivity of air currents to changes of the resistance of side-branches. Both accidental and intended changes of the resistance lead to changes in the distribution of air. In order to evaluate them it might be useful to gather information resulting from changes in the elementary airflow rate dV_i brought about by elementary changes of the resistance dR_r in the actual operative state of the network, i.e. the sensitivity $\varepsilon_{ir} = dV_i/dR_r$. This sensitivity depends on the parameters of the branches in the operative state of the network and its structure.

In the process of controlling the ventilation of a deep mine, a necessity of possessing information about the changes in the propagation of air arising at intended or accidental changes of side branch parameters is essential. Also of use in this sphere can be the information resulting from the knowledge of air expenditure sensitivity on the changes of side branch resistances. Presented in the paper is a method of determining these sensitivities making use of the so-called associated network. This refers to the determination of rows and columns of the matrix of sensitivity. After differentiating the system of equilibrium of the mine ventilation network, a system of linear equations is obtained, in which for the current state of the network operation unknown are the searched-for sensitivities. The solution of this system is possible by means of commonly used methods. The paper also gives an illustration of the developed method, making use of the associated network. Such an illustration makes it possible to detect the regularities taking place in the network of different structures. An example of a diagonal network has been presented. It has been pointed out that in such networks the signs of sensitivity are not always determined on account of the relative diagonality of the side branches, particularly to the side branch in which the disturbance occurs.

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RESUMÉ

Tato práce se zabývá strukturou důlních větracích sítí a citlivostí větrných proudů na změny rezistence postranních chodeb. Jak náhodné tak zamýšlené změny rezistence vedou ke změnám v distribuci vzduchu. Aby bylo možné je vyhodnotit, mohlo by být užitečné shromáždit informace vyplývající ze změn základní rychlosti průtoku vzduchu dR_r v provozním stavu sítě, tj. citlivosti $\varepsilon_{ir} = dV_i/dR_r$. Tato citlivost závisí na parametrech postranních chodeb v provozním stavu sítě a její struktuře.

V procesu řízení ventilace v hlubinném dole je potřeba získávat informace o změnách v proudění vzduchu vznikajících v důsledku zamýšlených nebo náhodných změn parametrů postranních chodeb zásadní. Užitečnou v této oblasti mohou být rovněž informace vyplývající ze znalosti citlivosti spotřeby vzduchu na změny rezistence postranních chodeb. V této práci je představena metoda určování těchto citlivostí pomocí tzv. přidružené sítě. Ta se vztahuje na stanovení řad s sloupců matice citlivosti. Po rozdělení systému rovnováhy důlní větrací sítě je získán systém lineárních rovnic, ve kterém neznámou stavu provozu sítě jsou hledané hodnoty citlivosti. Řešení tohoto systému je možné pomocí běžně používaných metod. Práce rovněž ilustruje vyvinutou metodu za použití přidružené sítě. Tato ilustrace umožňuje zjistit pravidelnosti, ke kterým dochází v síti s různými strukturami. Je uveden příklad diagonální sítě. Bylo zdůrazněno, že v takových sítích známky citlivosti nejsou vždy určovány z důvodu relativní diagonality postranních chodeb, zejména u postranní chodby, ve které k poruše dochází.

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