Method for determining and refining the interval of data collection of gas-dynamic processes by safety criterion

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Abstract. To solve the problems of controlling the gas-dynamic processes of production areas and air distribution in the ventilation network, their mathematical description is required, which can be obtained only on the basis of a detailed study and determination of the parameters and characteristics of gas-dynamic processes and regularities of air distribution. The mathematical description of the production ventilation system is complicated by the fact that the variables that determine the state of the control system are random functions of time. Therefore, the main attention should be paid to determining the probabilities of the characteristics of aerogasdynamic processes. The mathematical description of the ventilation of the production area into static and dynamic characteristics was the basis for the development of an optimal control algorithm for the production area. The control algorithm for the ventilation of the mining area consists of subalgorithms for controlling the parameters of the mine atmosphere, primary processing of the received information, and generating control actions. Their development is possible on the basis of research and mathematical description of gas-dynamic processes and methods for controlling the parameters of the mine atmosphere. Effective control of gas-dynamic processes in production areas is possible only when considering the entire ventilation system, due to the interconnectedness of aerodynamic parameters. The task of optimal air distribution control in the network is to ensure the required airflow rates for ventilation, determined as a result of solving the first problem with minimal energy costs for ventilation.

1. Introduction

In accordance with the requirements of safety rules, deviations of the methane concentration from the limits of the norm, even of a single, short-term nature, are completely unacceptable, since they can lead to an emergency mode [23]. When monitoring such an object, it is important not to miss any, even rather rare, excess of the maximum permissible level [1–4, 24]. Therefore, the problem of determining the measurement interval \( \Delta t \) by the safety criterion will be solved in the following setting. Let in the process of normal operation of the object on the observation interval \((0, T)\) a non-stationary discrete sequence of methane concentration values is obtained \( C(t_k), t_k = t_{k-1} + \Delta t, \Delta t = \text{const} (K = 1, 2, 3, \ldots) \) [17-20].
It is required to find such a functional $I_C$, which for the time interval between two adjacent measurements of methane concentration should not exceed the value of the safety criterion $\beta$.

When conducting research, as functional $I$, it is proposed to choose the absolute difference in the values of the controlled process $X(t)$ in neighboring points $t_k$ and $t_{k+1}$:

$$I = \left| X(t_{k+1}) - X(t_k) \right|$$

or $rms$ measurement function:

$$I = \left( \frac{1}{\Delta t} \int_{t_k}^{t_{k+1}} \left[ X(t + \tau) - X(t_k) \right]^2 d\tau \right)^{\frac{1}{2}}$$

In the general case [5-7], the functional $I$ depends on the values of the controlled process $X(t_k)$, time $t$, and measuring interval $\Delta t$.

$$I = I[X(t_k), t, \Delta t]$$

2. Materials and methods

During the experiments, it was shown that with a limited input action on an inertial object, $0 < U(t) \leq M$, $M > 0$ the functional (1) and (2) constructed from the realizations of the output signal significantly depend on both the $M$ number and the dynamic characteristics of the object. This influence is reflected, for example, in the fact that the slew rate of the output signal is always limited for any law of variation of $U(t)$, including a stepwise one. Therefore, with a limited effect on an inertial object, the output signal increment will always be a finite value for a fixed measurement interval $\Delta t$.

Since the mining area is an inertial object with a limited input impact, a slightly modified functional can be used to solve the problem posed (1). The required $I_C$ functional must correspond in its structure and be always positive, i.e. $I_C > 0$. Taking this requirement into account, we choose as the functional $I_C$ the positive difference between the methane concentration values at adjacent measurement points and $t_k$ and $t_{k+1}$:

$$I_C = C(t_{k+1}) - C(t_k)$$

where:

$$C(t_{k+1}) \geq C(t_k)$$

For the selected functional, the dependence $I_C = f(\Delta t)$ can be plotted according to the discrete sequence of the methane concentration process as follows.

Let us choose the discreteness interval equal to $t_n = \Delta t$ and determine the values of a function (4) for $K = 1, 2$. Let the values of $I_C$ obtained in this case $I_C(t_1) \leq 0$, $I_C(t_2) \leq 0$ satisfy the inequalities. We discard $I_C(t_2) \leq 0$ as not satisfying condition (5) and determine the next value of the function $I_C(t_3)$ for $K = 3$. If, then from $I_C(t_2) \geq 0$ the found positive values we will choose the largest one. Let, then, having fixed the largest value, we take the next step $I_C(t_4)$ and $I_C(t_1)$ to determine the value for $K = 4$. If, fixing $I_C(t_4) \geq I_C(t_3)$ the largest value, we take the next step, determine the value of the function $I_C(t_5)$ for $K = 5$, compare it with, etc [5-8].

Having thus passed the entire discrete sequence $C(t_k)$ for the values $K = 1, 2, 3, ...$, we find for the selected discreteness interval $\Delta t$ the maximum value of the function For the next discreteness interval $\Delta t_2 = 2\Delta t$, perform the above actions and find the maximum value $I'_C(\Delta t_2)$, etc.

As a result, we obtain a discrete sequence of maximum values of the function $I'_C(\Delta t)$ for different
discreteness intervals:

\[ I_C^*(\Delta t_1), I_C^*(\Delta t_2), I_C^*(\Delta t_3), \ldots, I_C^*(\Delta t_m) \]  

(6)

Discrete sequence (6) represents the values of the upper bounds of the function:

\[ I_C^*(\Delta t) = \max[C(t_{k+1}) - C(t_k)] \]  

(7)

\[ C(t_{k+1}) \geq C(t_k) \]  

(8)

Using the obtained sequence (8), we construct a graph \( I_C^*(\Delta t) \) (Figure 1), which is a monotonically increasing function with a maximum equal to the maximum value of the amplitude of fluctuations in the concentration of methane \( C(t) \) in the observation interval \( /0, T/ \).

![Graph of limiting functions of methane concentration according to the safety criterion.](image)

Figure 1. Graphs of the limiting functions of methane concentration according to the safety criterion.

The measurement interval according to the safety criterion \( \Delta t \) is determined by solving the equation:

\[ I_C^*(\Delta t) = \beta_{\text{estab}} \]  

(9)

Let us consider what the duration of the observation interval should be to ensure the specified accuracy of determining the values of the function \( I_C^*(\Delta t) \) from the realizations of non-stationary gas-dynamic processes.

As you know, in the case of non-stationary processes, their characteristics are determined by several independent implementations by finding the arithmetic mean of the results obtained for different implementations [8–13]. The length of the used realization in this case, the valley, significantly exceeds the value of the interval at which the characteristics of the process are determined [9–12, 25-27].

Using the experimental results, for the process of methane concentration, it is possible to choose the implementation length equal to 1 day, since during this time at least one full production cycle has time to be completed in the longwall. The duration of this cycle significantly exceeds the value of the maximum measurement interval \( \Delta t_{\beta} = 30 \) minutes, for which it is still advisable to determine the value of the function \( I_C^*(\Delta t) \) in practice.

Since the production processes at the site, carried out within one day, practically do not affect the nature of the aerogasdynamic process during the next day, the daily realizations of the methane concentration process can be considered independent [13-15]. The equivalent of several independent daily sales in this case is a multi-day implementation obtained in the normal operation of the site.
The values of the function $I^*_C(\Delta t)$ determined for each implementation will change in a certain range over a long observation interval:

$$I^*_C(\Delta t) = \frac{I^*_{\text{max}}(\Delta t)}{I^*_{\text{min}}(\Delta t)}$$

We divide $I^*_C(\Delta t)$ the entire range into a number of quanta in accordance with a given error in measuring the true function $I^*_C(\Delta t)$.

For gas-dynamic processes, the probabilities of the values of the function $I^*_C(\Delta t)$ falling into the extreme quanta of the range are small. In this case, you can use the Poisson formula. The probability $P_k$ that the value of the function $I^*_C(\Delta t)$ will appear $k$ times in the extreme quantum, i.e. will with a certain accuracy be a scene of the maximum value of the function $I^*_C(\Delta t)$, is determined by the expression:

$$P_k = \frac{\lambda^k}{k!} e^{-\lambda}$$

The parameter $\lambda$ is expressed as: $\lambda = a T$ and $a$ – the average number of hits in the extreme quantum per unit time; $T$– observation time.

Thus, the parameter $\lambda$ characterizes the average number of hits of the function $I^*_C(\Delta t)$ estimate in the extreme quantum of the range for the entire duration of the experiment.

If the probability distribution within the range is symmetric, the probability of the function $I^*_C(\Delta t)$ falling into both the upper and lower quanta of the range at least once is determined by the formula:

$$P_0 = (1 - e^{-\lambda})^2$$

From the last expression, given the value of $P_0$, we can find $\lambda$. To determine the observation interval, we use formula (11), transformed as follows:

$$T = \frac{\lambda}{P_0} T_0,$$

where $P$ – the probability of falling into the extreme quantum of the range $I^*_C(\Delta t)$, $T_0$ – observation interval equal to 1 day.

Suppose that the values of the function $I^*_C(\Delta t)$ within the range are distributed according to the normal law. Then, to determine the probability $P$, one can use the formula for finding the probability of hitting a random variable on a section from $I_k$ before $I_n$:

$$P(I_k \leq I^*_C(\Delta t) \leq I_n) = \frac{1}{2} \left[ \Phi \left( \frac{I_n - m}{\sigma \sqrt{2}} \right) - \Phi \left( \frac{I_k - m}{\sigma \sqrt{2}} \right) \right]$$

where:
- $\Phi$ – Laplace function;
- $m$ – mathematical expectation of function values $I^*_C(\Delta t)$;
- $\sigma$ – root-mean-square deviation of the values of the function $I^*_C(\Delta t)$ from the mathematical expectation.

Let us assume that the maximum value of the function $I^*_C(\Delta t)$ is equal to $I_n = m + 2\sigma$. Then, setting
different accuracy, obtaining an estimate for the maximum value of the function $I'_C(\Delta t)$, using formula (14), we find the values of the probability of falling into the extreme quantum of the range $P$.

The results of the calculation according to the formulas (12–14) of the observation intervals (Table 1) indicate that to increase the accuracy of determining the estimates of the values of the function $I'_C(\Delta t)$, it is inappropriate to increase the observation interval, for example, to obtain 20–30% of the accuracy of the estimate, the required observation interval should be equal to 2–4 months [16] (Table 2).

In the conditions of changing the parameters of the site over time, a simpler way to increase the accuracy of estimates of the measurement interval is the method of their refinement in the process of dispatch control and management.

| No | Relative error in determining the function $I'_C(\Delta t)$ | Coefficient $I_k$ | Probability $P$ | $\Phi(\frac{I_k - m}{\sigma\sqrt{2}})$ | Observation time, $t$ day |
|----|----------------------------------------------------------|-------------------|-----------------|---------------------------------|------------------------|
| 1  | $5$                                                      | $m + 1.9 \sigma$  | $0.11500$       | $0.9439$                        | $320$                  |
| 2  | $10$                                                     | $m + 1.8 \sigma$  | $0.01345$       | $0.9284$                        | $274$                  |
| 3  | $15$                                                     | $m + 1.7 \sigma$  | $0.0221$        | $0.9110$                        | $166$                  |
| 4  | $20$                                                     | $m + 1.6 \sigma$  | $0.0320$        | $0.8913$                        | $115$                  |
| 5  | $30$                                                     | $m + 1.4 \sigma$  | $0.0563$        | $0.8427$                        | $65$                   |
| 6  | $40$                                                     | $m + 1.2 \sigma$  | $0.0923$        | $0.7707$                        | $40$                   |
| 7  | $50$                                                     | $m + \sigma$      | $0.1354$        | $0.6845$                        | $27$                   |
| 8  | $60$                                                     | $m + 0.8 \sigma$  | $0.1920$        | $0.5713$                        | $19$                   |
| 9  | $70$                                                     | $m + 0.6 \sigma$  | $0.2517$        | $0.4519$                        | $15$                   |
| 10 | $80$                                                     | $m + 0.4 \sigma$  | $0.3238$        | $0.3076$                        | $12$                   |
| 11 | $90$                                                     | $m + 0.2 \sigma$  | $0.3986$        | $0.1580$                        | $10$                   |

It is proposed to refine the measurement interval in the process of supervisory control and management according to the following method.

At a pace with the arrival of discrete control data, the values of the function $I'_C(\Delta t)$ are calculated by formula (3) and compared with the specified value of the safety criterion $\beta_{estab}$. If values appear that satisfy the inequality $I''_C(\Delta t) \geq \beta_{estab}$, a new value of the measurement interval $\Delta t'$ is determined.

To derive the formula by which it is possible to determine the new value of the measurement interval $\Delta t'$, we use Figure 1, the curve $I''_C(\Delta t)$ in the figure corresponds to function (5) obtained before the change in the gas regime of the section. From the curve $I''_C(\Delta t)$, we find the measurement interval $\Delta t'$, which provides the given value of the safety criterion $\beta_{estab}$ (segment ML in Figure 1).

The curve $I''_C(\Delta t)$ was obtained after changing the gas situation at the site. Using it, we find that under new conditions with the measurement interval $\Delta t'$, the maximum error exceeds, the value of the safety criterion $\beta_{estab}$ is equal to $I''_C(\Delta t)$ (segment PL in Figure 2).
Figure 2. Graphs of the limiting functions of methane concentration by the criterion of accuracy.

The value of the measurement interval $\Delta t_\beta$, which is required to ensure the specified value of the safety criterion $\beta_{estab}$, in a new situation, is found by drawing a straight line from point $M$ parallel to the abscissa axis until it intersects the curve at point $N$. The perpendicular dropped from point $N$ cuts off on the abscissa axis a segment equal to the new value of the measurement interval $\Delta t_\beta$.

As you can see from the Figure 2, measurement interval $\Delta t_\beta$ can be found from equality:

$$\Delta t_\beta = \Delta t - \Delta t_2$$

The value $\Delta t_2$ define from a right-angled triangle:

$$\Delta t_2 = \frac{PM}{\tan \alpha} = \frac{I_c'(\Delta t_\beta) - \beta_{estab}}{\tan \alpha}$$

Approximate formula for determining the measurement interval $\Delta t_\beta$, when $I_c'(\Delta t_\beta) \geq \beta_{estab}$, we get by substituting the value $\Delta t_2$ from (16) into expression (15):

$$\Delta t_\beta = \Delta t_\beta - \frac{I_c'(\Delta t_\beta) - \beta_{estab}}{\beta_{estab}} = \Delta t_\beta - \frac{I_c'(\Delta t_\beta) - \beta_{estab}}{\beta_{estab}} \cdot \Delta t_\beta$$

Thus, we finally have:

$$\Delta t_\beta = [2 - \frac{I_c'(\Delta t_\beta)}{\beta_{estab}}] \cdot \Delta t_\beta$$

An experimental check carried out below has shown that the use of formula (17) to refine the measurement interval at the rate of the process gives a satisfactory accuracy for monitoring and control purposes.

Formula (17) is quite simple and can be easily implemented in the supervisory control system as a separate device or in the form of application software included in the object control loop.

3. Conclusion

1. The optimal measurement interval was determined according to the experimental data.
2. A certain interval for measuring the concentration of methane, which is called the optimal interval.
3. The information retrieval interval, determined by the measurement accuracy criterion, is limited by the lower and upper limits.
4. The sequence of measuring the concentration of methane in the optimal range has been determined.
5. A method has been developed for determining and refining the interval for collecting information from gas-dynamic processes according to the safety criterion.

6. The interval of information retrieval was determined according to the data of an active experiment.

7. The technique was used to determine the estimate of the time interval between adjacent measurements using the root-mean-square error.

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