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Modeling and prediction of daily gas concentration variation at a mining face based on the elliptic orbit model: A case study

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ABSTRACT

Monitoring and analysis of daily gas concentrations at a mining face is a vital task on safety production and security management in the coal-mining industry. This study addresses modeling and prediction of daily gas concentration variations based on the elliptic orbit model. The model describes the hourly variation in daily gas concentration by mapping its time-series into the polar coordinates to create its elliptic orbit trace for further analysis. Experiments show workability of the proposed method that daily gas concentration variation at a mining face of one coal mine in China is well described by the elliptic orbit model. Result analysis and performance comparison of the proposed elliptic orbit model with the classical AR model on the same prediction tasks indicate potentiality of the proposed elliptic orbit model, which presents a vivid approach for modeling and forecasting daily gas concentration variations in an intuitive and concise way.

1. Introduction

Rapid economic development is usually accompanied by a rise in energy demand and consumption, which yields a negative effect on work safety in the coal-mining industry. Thus, daily gas concentration monitoring and analysis has become an increasingly important task in the coal-mining industry due to its significant effect on safety production and security management. Addressing current work safety status in China and analysis of its principal features from a socio-economic viewpoint has been presented [1]. To improve gas extraction efficiency in a single seam with high gas content and low air permeability, a method based on the "fracturing–sealing" integration technology was introduced [2]. Gas diffusion in a cylindrical coal sample can be described by a general solution based on Fick's second law of diffusion and has been widely studied [3]. Based on a coupled coal–gas interaction model, numerical simulation of de-stress blasting in a coal seam for enhancing gas drainage has been presented [4]. By employing geostatistical co-simulation techniques, geostatistical simulation results for rate decline parameters of longwall GGVs (gob gas ventholes) were presented in the study area in the Northern Appalachian basin [5]. On the basis of analysis of anomalous accumulation characteristics of gas compositions in China, the main factors contributing to abnormality of deleterious gas compositions were investigated [6]. As tracer-gases have been important techniques in ventilation analysis, a study of their applications and future role in coal and non-coal mines has been presented [7]. Based on permeability theory and dynamic dispersion by porous media, 3-D numerical modeling simulation for gas transfer in the coal mine goaf was studied [8]. Addressing the gas-dynamic phenomena in underground coal mining, a detailed analysis at pits in the central coal basin of Asturias (Spain) were presented [9]. For predicting coal mine gas emissions, a short-term forecasting model based on chaos theory, three mathematical models including gray prediction, new information and metabolism, and the classical time-series analysis approach were studied [10–12]. To forecast gas and coal outbursts, an application employing a coupled FTA (fault tree analysis) and ANN (artificial neural network) model was introduced [13]. To improve high time-consumption of the traditional LS-SVR (least-squares support vector regression) model in predicting time-series of gas variation, a Bayesian LS-SVR model was introduced [14]. To evaluate the general risk in the four main energy chains (coal, nuclear, gas and hydro), two multi-criteria decision models including the AHP (analytic hierarchy process) method and the PROMETHEE software were presented [15]. Addressing the formation process of outburst shock waves and gas flow during coal and gas outburst, numerical models for simulating the real-time propagation of outburst gas flow and the gas transport process were proposed [16]. Based on historical data in the city of Amsterdam, a probability model for evaluating a gas explosion with respect to a leakage from gray cast iron pipes was presented [17].

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Actually, daily gas concentration variation is also a time-series. Mathematical methods employed for time-series analysis mainly include the classical time-series analysis and computational intelligence [18–20]. Classical time-series analysis is a commonly used technique in statistics, which includes three classical statistical models called the autoregressive (AR), the moving average (MA) and the combination of both (ARMA). This technique analyzes time-series under the most important assumption that the underlying stochastic process is stationary and then the process may be adequately characterized by the lower moments of its probability distribution. The subject in artificial computational intelligence spans a wide horizon. The ANN (Artificial neural networks) is one of the most popular and promising areas in artificial intelligence research, which has reported fairly good performance in many scientific and engineering fields for its nonlinear mapping and learning ability. However, because it is time consuming and the rule-of-thumb choices in establishing its network structure, two major risks with respect to less or excessive training data approximation called under-fitting and over-fitting still exist in ANN models, which will increase the prediction errors of out-of-sample. Thus, to appropriately select one model is one decision depending on the problem and its situation.

This study is from the perspective of time-series analysis. As the variation in daily gas concentration is a time-series, all the factors influencing the variation are implicitly enclosed in its time-sequence. Hence, there exist two basic goals included in the time-series analysis [18]: (a) try to recognize the nature of the phenomenon depicted by the observed sequence, and (b) try to fit a model for forecasting, i.e., to predict its future variation based on the time-series variable. In this study, the "elliptic orbit algorithmic model" [21–24] is proposed for modeling and forecasting daily gas concentration variation by mapping its time-series into polar coordinates.

2. Elliptic orbit model for describing daily gas concentration movement

Variations in daily gas concentration can also be expressed as a time-series. Table 1 lists daily 2-hour-interval gas concentration values (%) at a mining face of one coal mine in China from 2008-07-25 to 2008-07-29 [12].

To further describe its variation from the viewpoint of time-series analysis, we may extend hourly variation in daily gas concentration to be a quasi-periodic time-sequence, as there are 24 h in every day. Then, based on the quasi-periodic extension for daily gas concentration variation, we try to employ the "elliptic orbit model" [21–24] to further depict its variation by mapping its time-series into polar coordinates. That is, let the angular co-ordinate θ represent time points (hour-by-hour) and the radial co-ordinate r represent the corresponding gas concentration values at different points in time. In this way, Fig. 1 illustrates the daily 2-hour-interval gas concentration (%) variation (00:00–22:00) at a mining face of the coal mine in China on 2008-07-25 (Table 1).

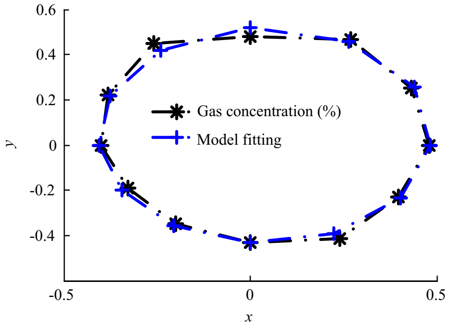

Fig. 1. Gas concentration values (at 2-hour-intervals) at a mining face of a coal mine in China on 2008-07-25 (00:00–22:00), mapped into polar coordinates.

In Fig. 1, it is shown that the daily gas concentration variation (of 2-hour-interval) appears as an elliptic-similar trace, which indicates that its variation may be adequately described by one elliptic orbit. Accordingly, the elliptic orbit model [21–24] for describing the daily gas concentration variation with its modeling parameters is presented below:

$$\boldsymbol{\theta} = \{\theta_1, \theta_2, \ldots, \theta_N\} \sim \text{time(hourly)} \quad (N = 12 \text{ or } 24, \text{etc.}) \tag{1}$$

where putting $N = 12$ for daily 2-hour-interval gas concentration values:

$$r \sim \boldsymbol{L} = \{L_1, L_2, \ldots, L_N\} \tag{2}$$

where $L = \{L_i\}$ denotes the gas concentration observed values at corresponding different points in time. Normally, θ is started at zero and the circle is divided into N equal parts [21–24], such that: $\theta = \left\{0^\circ, \frac{360^\circ}{12}, 2\frac{360^\circ}{12}, \ldots, 11\frac{360^\circ}{12}, 360^\circ(0^\circ)\right\}$ with $N = 12$. In a similar way to mathematical derivation, the elliptic orbit model for describing the daily gas concentration variation is proposed as follows [21–24]:

Define an ellipse in terms of Cartesian coordinates for depicting the daily gas concentration variation by [21–24]:

$$\frac{(x - x_0)^2}{a^2} + \frac{(y - y_0)^2}{b^2} = 1, (ab \neq 0) \tag{3}$$

Rewrite Eq. (3) as:

$$y^2 = \frac{-b^2}{a^2}x^2 + \frac{2b^2}{a^2}x_0 x + 2y_0 y + \left(b^2 - \frac{b^2}{a^2}x_0^2 - y_0^2\right) \tag{4}$$

By setting $c_1 = \frac{-b^2}{a^2}$, $c_2 = \frac{2b^2}{a^2}x_0$, $c_3 = 2y_0$, $c_4 = b^2 - \frac{b^2}{a^2}x_0^2 - y_0^2$, we have:

$$y^2 = c_1 x^2 + c_2 x + c_3 y + c_4 \tag{5}$$

Then, the relationship between Eqs. (4) and (5) is as follows:

$$\begin{cases} a^2 = -\left(c_4 + c_3^2/4 - c_2^2/(4c_1)\right)/c_1, \quad b^2 = \left(c_4 + c_3^2/4 - c_2^2/(4c_1)\right) \\ x_0 = -c_2/(2c_1), \quad y_0 = c_3/2 \end{cases} \tag{6}$$

where $C = (c_1, c_2, c_3, c_4)$ are the orbital parameters for building the elliptic orbit.

Table 1
Gas concentration values at a mining face of the coal mine in China (%).

Daily	0:00	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
2008-7-25	0.48	0.50	0.54	0.48	0.52	0.44	0.40	0.38	0.40	0.43	0.48	0.46
2008-7-26	0.40	0.42	0.44	0.46	0.47	0.41	0.38	0.38	0.40	0.52	0.66	0.70
2008-7-27	0.62	0.60	0.60	0.60	0.58	0.55	0.50	0.48	0.45	0.42	0.41	0.42
2008-7-28	0.54	0.55	0.60	0.55	0.53	0.50	0.52	0.50	0.50	0.50	0.56	0.60
2008-7-29	0.52	0.54	0.56	0.57	0.60	0.52	0.50	0.56	0.48	0.50	0.50	0.54