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Multifractal characteristics of gas disaster accident in coal mine

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Abstract. In order to explore the law of development and the characteristics of evolution of death toll caused by gas disasters in coal mine, with the multifractal detrended fluctuation analysis (MF-DFA) method, we analyzed the three time series of death toll caused by gas disaster, coal and gas outburst, and gas explosions in coal mine from 2006-2015 in China. It concluded that all of three time series have multifractal characteristics, the multifractal spectrum width $\Delta\alpha_{tc} > \Delta\alpha_{bz} > \Delta\alpha_{ws}$, and the largest fluctuation and multifractal intensity of death toll time series of coal and gas outburst. The multifractal spectrum function $f(\alpha)$ is right hook-shape, and the $\Delta f < 0$, it forecast that three kinds of time series are likely to rise in the future, which coincided with the upward trend of the number of coal mine gas accidents and deaths toll in 2016. The results shows that MF-DFA theory reflect the complex nonlinear dynamic mechanism of gas disaster system in coal mines, and provides a theoretical basis for the prediction of gas accidents in coal mines. The multifractal theory of detrended fluctuation reflects the complex nonlinear dynamic mechanism of gas disaster system, and provides a theoretical basis for the prediction of gas accidents in coal mines.

1. Introduction

Coal dominated in energy production and consumption structure in China. Coal accounted for 62% of the total energy consumption in 2016[1-2]. For a long time, the dependence of economic development on coal resources, as well as the depletion of shallow coal resources, the increasing of depth and scale of mining, and the increase of gas pressure and content in coal mines have led to the increase of the pr-obability and severity of coal mine gas disaster accidents, seriously affecting the life safety of miners and restricting the safe and efficient production of coal mine [3-5].

As coal mine gas accidents are affected by coupling of various factors [6], the coal mine safety sys tem presents the structural characteristics of the complex nonlinear dynamic system [7]. Fractal is a no nlin-ear theory, which has achieved certain engineering application effect in coal mine disaster prevent ion and control. For example, fractal analysis of coal mass failure and rock burst AE signal [8-10], for ecast of gas emission[11], fractal prediction of coal and gas outburst and gas emission [12-14], fracta l an-alysis of safety situation key indexes of coal mines and gas explosion accidents[7,15], Tectonic an d fr-actal characteristics of coal and gas outburst[16], fractal characteristics of AE Sequence of coal or rock[17] and accident time series[18]. For the single fractal is susceptible to interference of the nonstat ion-ary trend of time series, so it can't accurately revealed the implied multifractal characteristics of no

nst-ationary time series [19-21]. Whereas the multifractal detrended fluctuation analysis (MF-DFA) m ethodfilters out the trend of unknown components in the original sequence and avoided the misjudgem ent ofcorrelation in the analysis of nonstationary time series[21]. Therefore, in this paper, the MF-DF A will be used to analysis the time series of coal mine gas disaster accidents in 2006-2016 in China, an d also study the nonlinear dynamic characteristics of coal mine gas disasters evolution, which is expect ed to provide basis for prevention of coal mine gas disaster, improvement of coal mine safety and guar antee of economic benefits of enterprises.

2. Research method and Data selection

2.1. Multi-fractal detrended fluctuation Analysis (MF-DFA)
Based on the DFA method, Kantelhardt et al[19] proposed Multi-Fractal Detrended Fluctuation Anal ysis (MF-DFA), which filters out the unknown trend in the original data sequence, so that the remaini ng deviation sequences still retains the volatility components of the original data sequence, thus avoidi ng the wrong judgment of correlation in the process of non-stationary time series analysis[19].

For a time series of gas disaster $\{x_i\}$ ($i = 1, 2, \ldots, N$) have N samples, and this series is of compact su pport. The analysis procedure [19] of generalized MF-DFA are as follows:

(1) Calculating the accumulated deviation of $\{x_i\}$ is to eliminate the influence of time fluctuations. The series of accumulated deviation $y(k)$ can be shown that:

$$y(k) = \sum_{i=1}^{k}[x_i - \bar{x}], i = 1, 2, \ldots, N \tag{1}$$

Where, $\bar{x}$ is the average of $\{x_i\}$.

(2) Divided $y(k)$ into $N_s = int(N/s)$ non-overlapping segments $v_j (j = 1, 2 \ldots, N_s)$ of equal length s. Since the length N of the series is often not exactly divided by s, the same procedure should be done from the tail of the sequence to ensure data integrity. Thereby, $2N_s$ intervals of equal length can be obtained.

(3) In each segment v, $y(k)$ is fitted by least-square method, thus $y(k)$ can be transformed to polyno-mial function $p_v^m(k)$ that represents local trend. then the detrended time series is calculated as Eq. (2).

$$y_v(k) = y(k) - p_v^m(k) \tag{2}$$

(4) The variance for $2N_s$ detrended segment is calculated,

$$F^2(s, v) = \frac{1}{s}\sum_{i=1}^{s} y_v^2(k) \quad v = 1, 2, \ldots, 2N_s \tag{3}$$

where, $v = 1, 2, \ldots, 2N_s$

(5) Then, introduce a parameter q, the qth order fluctuation function $F_q(s)$ can be obtained,

$$F_q(s) = \{\frac{1}{2N_s}\sum_{v=1}^{2N_s}[F^2(s, v)]^{q/2}\}^{1/q}, \ q \neq 0 \tag{4}$$

$$F_q(s) = exp\{\frac{1}{4N_s}\sum_{v=1}^{2N_s}[F^2(s, v)]\}, \ q = 0 \tag{5}$$

(5) In order to know how fluctuation function $F_q(s)$ depend on the time scale s for different q, we shoul d repeat step 2 to 4 for different segment lengths s, and analysis doubly logarithmic plots $F_q(s)$ verus s for each q, can determined the scaling behavior of the fluctuation functions.

$$\log F_q(s) = log C + h(q)log(s) \tag{6}$$

If the series are longrange power law correlated, $F_q(s)$ will increase as a power law for the large values of s,

$$F_q(s) \propto s^{h(q)} \tag{7}$$

Where, $h(q)$ is called generalized Hurst exponent. For q=2, it will retrieved to DFA [19]. When the se ries has a single fractal feature, the scale behavior of the deviation in all intervals is consistent, $h(q)$=c onst. When the series has multi-fractal feature, $h(q)$ varies with q.

(6) The q-order Hurst exponents h(q) is only one of the scaling exponent. Another one scaling exponent τ(q) can be calculated from the $h(q)$ obtained from MF-DFA by,

$$\tau(q) = qh(q) - 1 \tag{8}$$

The singularity spectrum f(α) is another way to characterize the multifractality of the series.

(7) Another way to characterize the multifractal series is singularity spectrum *f(α)*, which is related to τ(q) via Legendre transform [19],

$$\alpha = \tau'(q) \tag{9}$$
$$f(\alpha) = q\alpha - \tau(q) \tag{10}$$

Where α is the Hölder exponent or singularity strength. Width spectrum $\Delta\alpha = \alpha_{max} - \alpha_{min}$ indicates the difference between maximum and minimum probability. The larger the value of $\Delta\alpha$ is, the more in homogeneous and stronger multi-fractal strength of the time series distribution is. *f(α)* is singularity sp ectrum, which represents fractal dimensions of △α. The maximum value of *f(α)* indicates the continuit y of fluctuations.

2.2. Data selection

Statistics from the accident inquiry system [22] of the Ministry of Emergency Management of the peo-ple's Republic of China shows that 4346 people died in 546 coal mine gas disaster accidents in China between 2006 and 2016. The time series of gas disaster accident, coal and gas outburst accident and ga s explosion accident is shown in Table 1 and figure 1 to figure 3.

From table 1 and figure 1 to figure 3, the number of accidents and deaths of coal mine gas disasters showed a trend of fluctuating decline from 2006 to 2016. The number of accidents dropped from 107 in 2006 to 8 in 2015, a drop of 92.52%; the death toll from 738 in 2006 to 56 in 2015, a drop of 92.41%. This indicated that the control effect of coal mine gas disaster had achieved remarkable results, gas ac-cidents have been curbed to a certain extent, and the overall safety status was improvi-ng. However, In2016, there were 8 gas disasters and 145 deaths, respectively 3.2 times and 1.5 times as many as in 2015, indicating that the safety situation were becoming serious challenges.
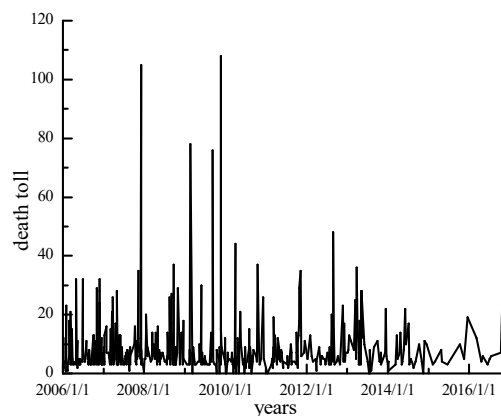

Figure 1. The death toll sequence diagram of coal mine gas accidents from 2006 to 2016

Table 1. Classification statistics of coal mine gas disaster and death toll from 2006 to 2016

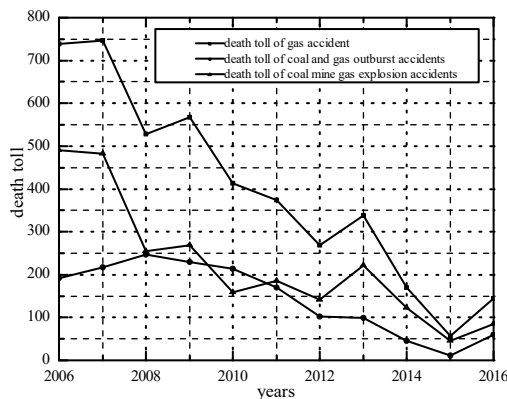| Classification		2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
gas accident	death toll	738	747	528	567	414	374	269	338	170	56	145
	number	107	89	66	58	64	49	34	34	25	8	12
outburst accident	death toll	192	217	247	230	214	169	102	99	46	11	60
	number	33	30	32	19	26	21	15	12	7	2	4
explosion accident	death toll	491	483	255	268	159	185	142	221	122	45	85
	number	58	47	28	25	29	25	14	19	17	6	8

Figure 2. Death toll statistics of coal
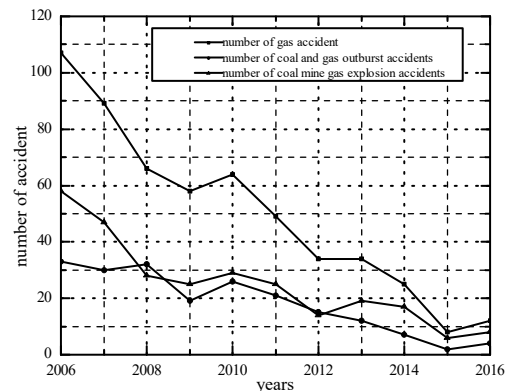Mine gas accidents from 2006-2016

Figure 3. Occurrence number statistics
of gas accidents from 2006-2016

As is shown in Figure1, there were Numbers of major accidents of coal mine gas disaster occurred in China from 2006 to 2016, which resulted in a large numbers of death and inestimable property losses, has brought enormous adverse social impact. the time series characteristics of coal mine gas accidents shown nonstability and nonlinearity of fluctuation. Therefore, MF-DFA were used to analyze the internal law of human casualties caused by gas accidents.

3. Results and Discussion

Time series of death toll caused by coal mine gas accidents, coal and gas outburst accidents and gas ex plosion accidents in China from 2006-2015 were analyzed by using MF-DFA method. Here defines q $\in$[-10,+10] with increments of 0.2. m =2 as the order of fit polynomial of detrended procedure.
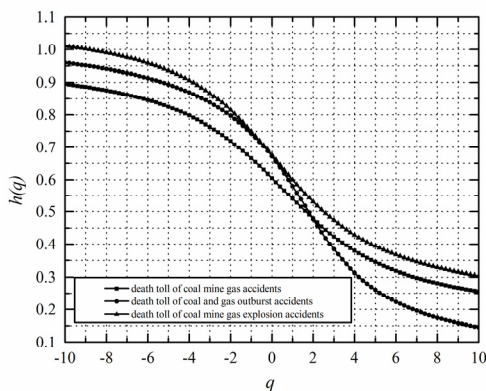

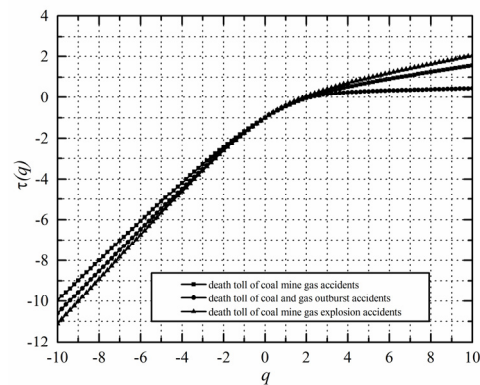Figure 4. Relationship between $h(q)$ and q

Figure 5. Relationship between $\tau(q)$ and q

(1) Shown in Figure 4: when q varied from -10 to10, the $h(q)$ of death toll series of coal mine gas acci-dents, coal and gas outburst accidents and coal mine gas explosion accidents descends from 0.8951 to 0.2562, 1.0106 to 0.3036, 0.9598 to 0.1453 respectively, which indicated the generalized Hurst exponents $h(q)$ of three series depends on q, the three series had different intrinsic dynamics mechanism, and there were obvious multifractal character. so it were appropriate to analysis the series by using monof-ractal. The varied range of $h(q)$ of three series is 0.6839, 0.7070,0.8145 respectively, which said that the death toll series of coal and gas outburst accidents has stronger multifractality.

(2) In Figure 5, the relationship between τ(q) and q is an obvious nonlinearity. It confirmed the three series has mutlfractal characters. The stronger the nonlinearity is, the stronger the multifractal is. It also illustrates that the death toll series of coal and gas outburst accidents has stronger multifractality.

(3) The multiplefractal spectrum are all a convex bell curve, indicating that the multiple fractal characteristics exist in all series features. Table 2 and Figure 6 shown that the width of the multifractal

spectrum $\Delta\alpha_{tc} > \Delta\alpha_{bz} > \Delta\alpha_{ws}$, which shows that the death toll series of coal and gas outburst accident has the largest fractal intensity, followed by gas explosion series and gas disaster accident series. This reflect the situation in Fig.5 and Fig.2.
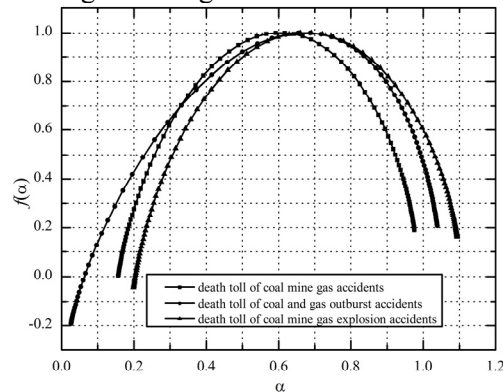

Figure 6. Multifractal spectrum

Table 2. Multi-fractal spectrum parameter

Accidents type	α_{min}	α_{max}	$\Delta\alpha$	α_0	$f(\alpha_{min})$	$f(\alpha_{max})$	Δf
gas accident	0.1566	0.9761	0.8195	0.6174	0.0041	0.1901	-0.1860
outburst accident	0.0261	1.0391	1.0130	0.6876	-0.1916	0.2075	-0.3991
explosion accident	0.1992	1.0943	0.8951	0.6908	-0.0438	0.1630	-0.2068

(4) Multifractal spectrum presents the right hooked and the left side significantly below the right side. It shows that high amplitude events of the death toll plays a leading role, which indicate that the death toll caused by accidents has a rising trend in the future, it is consistent with the actual situations of the trend as shown in Figure 1. It is further explained that the distribution differences of time series can be described by using multiple fractal spectra, which can better reflect the nonlinear dynamic characteristics hidden in time series compared with the single fractal characteristics of coal mine gas disasters .

Multifractal spectrum $f(\alpha)\sim\alpha$ shows a right hook-shaped, the left side is significantly lower than right side, indicating that the higher amplitude of the death toll events take dominant position, and the future number of deaths toll caused by accidents has an upward trend, which is consistent with the actual situation in 2016 (compared with 2015) in Figure 1.

4. Conclusions

MF-DFA, which is more appropriate to study nonstationary time series, were used to study the death toll series caused by coal mine gas disaster accidents in China from 2006 to 2015. The conclusions are as follows:

(1) The time series of death toll caused by coal mine gas accidents, coal and gas outburst accidents and coal mine gas explosion accidents have multifractal characteristics.

(2) The shape, location and distribution range of multifractal spectrum reflect the intrinsic dynamic pr-operties of different types of accidents. Therefore, comparing with the monofractal, MF-DFA method can better reveal the multifractal characteristics hidden in non-stationary time series, and the multifractal parameters can be used to characterize the internal dynamic mechanism.

(3)There is a certain correlation between the deaths toll caused by coal mine gas disaster accidents and the parameters of multifractal spectrum, which can be used to predict the future trend.

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