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Multifractal characteristic analysis of near-fault earthquake ground motions

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ABSTRACT

This study aims to reveal the multi-scaling behavior and quantify the irregularity of near-fault earthquake ground motions from a new perspective of multifractal theory. Based on multifractal detrended fluctuation analysis, the multifractal characteristic parameters of acceleration time series for typical near-fault ground motions are calculated, and their correlations with two period parameters (i.e., mean period T_m and characteristic period T_c) and box-counting fractal dimensions are analyzed. Numerical results of strong nonlinear dependence of generalized Hurst exponents $h(q)$ upon the fluctuation orders q indicate that near-fault ground motions present the multifractal properties and long-range correlation obviously. Furthermore, the scaling exponent $h(2)$ of near-fault records has a strong correlation with their periods T_m and T_c, and strongly negative correlation with their box dimension. Moreover, $h(2)$ can be regarded as a measure of frequency content and irregularity degree of strong earthquake ground motions. Finally, it is pointed out that the long-range correlation of small and large fluctuation is the major source of multifractality of near-fault ground motions.

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1. Introduction

Characteristics of near-fault earthquake ground motions and their damage potential to the civil infrastructures have drawn intensive attention among the academic and engineering community in the recent two decades [1–7]. Especially, the velocity pulses of near-fault ground motions with the rupture forward directivity and fling-step effects usually result in severe damage to medium-long period structures. As is well known, the three main properties of strong ground motions, namely the amplitude, frequency content and duration, are closely related to engineering damage and considered as important factors to structural seismic design. However, the high irregularity and complexity of earthquake ground motions pose a challenge to correctly represent and understand their engineering characteristics.

To investigate the complex phenomena of earthquake process, the theory of nonlinear dynamics is gradually introduced into the field of seismology. Actually, research on earthquake fault dynamics and slip-block dynamical models indicated that the chaotic phenomenon during the earthquake explained the nonlinear stick-slip and friction mechanism of rupturing fault [8–13]. On the other hand, the earthquake ground motions are essentially the site responses of a nonlinearly deterministic geophysical system with multiple variables, and their complicated nonlinear characteristics originate from the different initial conditions of an earthquake dynamic process and the intrinsic nonlinearity involving in the dynamic model, such as the nonlinearity in the faulting movement, media condition and wave motions. As a result, not only the whole earthquake physical process including the gestation, rupture, development and propagation, but also the earthquake ground motions present the chaotic and fractal features of nonlinear dynamics.

A fractal is a natural phenomenon or a mathematical set that exhibits a repeating pattern which displays at every scale, and it is self-similar (or self-affine) and scale-invariant [14–17]. The fractal dimension is not only a quantitative description of the complexity and irregularity but an invariant characteristic quantity for fractal set in nature and engineering field [18–20]. Until now, there are several definitions on fractal dimension, namely, capacity dimension, information dimension, correlation dimension, generalized dimension and so on. These fractal dimensions aim at a global and average description for homogenous fractal objects, but they cannot provide subtle information to represent the extremely complex fractal structure. Therefore, the concept of multifractal analysis based on standard partition function in statistical physics is put forward for understanding the complexity of nature, i.e., fully developed turbulence, diffusion-limited aggregates, and strange sets and so forth [21–23]. Standard partition function

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usually describes the statistical properties of a system in thermodynamic equilibrium which obeys the Boltzmann law. Meanwhile, the multifractality can give a more detailed description for local scaling behavior of inhomogeneous fractal sets, and therefore has been popularly applied to diverse fields, such as the fluctuation analysis of an economic system, physiological signal and medical image analysis, mechanical fault diagnosis and identification, rock fracture characterization, geology hydrological analysis, as well as seismic sequences etc. [24–30].

Generally speaking, the multifractal analysis based on standard partition function is only appropriate to extract the inherent feature of stationary and normalized observational data. For nonstationary time series, Kantelhardt et al. [31] incorporated detrended fluctuation analysis (DFA) into a multifractal system, and then proposed the multifractal detrended fluctuation analysis (MF-DFA). The advantage of a DFA method is that it can systematically filter each order of trend components represented by the fitting polynomial, and detect the long-range correlation of signal with linear and polynomial trend [32]. Hence, DFA is suited to the long-range power-law correlation analysis of nonstationary time series, which can avoid getting erroneous judgment about the correlation. The long-range correlation of time series means that these sample points of the sequence correlate with each other, and the sequence has the property of long memory, self-similarity and scale-invariance. Moreover, Kantelhardt et al. [31] proved that by using the MF-DFA and standard partition function-based multifractal formalism to calculate the scaling exponents of stationary and normalized time series, their results were the same. Numerical simulation and comparison also showed that computational convenience and effectiveness of MF-DFA are superior to those of the wavelet transform modulus maxima method for multifractal analysis of nonstationary time series. Thus, MF-DFA as a preferable method of multifractal analysis has been widely applied to multidisciplinary areas, e.g., air temperature shifts, river runoff records, traffic flow series, crude oil price and financial time series, as well as wind speed records, seismic data etc. [33–37].

Currently, chaos and fractal theory is being extended into the study of earthquake engineering. Using the method of chaotic time series analysis, Yang et al. [38] recently calculated three nonlinear dynamical characteristic indices of acceleration time series of earthquake ground motions, such as the correlation dimension, Kolmogorov entropy and maximal Lyapunov exponent, and exposed the chaotic characteristic of ground motions. Regarding the fractal characterization of near-fault ground motions, the box-counting approach is suggested to quantify the fractal dimensions and frequency contents of earthquake records [39]. Nevertheless, earthquake ground motions are essentially inhomogeneous and typically nonstationary time series in both the aspects of amplitude and frequency, so the monofractal analysis based on the box dimension is not sufficient to reveal their refined and profound properties, as well as to identify their inherent complexity. Instead of investigating the monofractal property by box dimension like in [39], this paper attempts to explore the multifractal behavior of near-fault ground motions under the framework of fractal geometry, and establish the relationship between the associated multifractal index and the irregularity of strong earthquake records.

The main object of this study is to uncover the multifractal properties and irregularity of near-fault strong ground motions by means of multifractal detrended fluctuation analysis. Firstly, the procedure of MF-DFA is introduced in Section 2, and it is pointed out that the extended applications of multifractal spectrum $f(\alpha)$ to some practical nonstationary time series may lead to considerable computational errors. In Section 3, the MF-DFA is suggested to calculate the generalized Hurst exponent $h(q)$ with respect to the fluctuation order q of acceleration time series for several typical near-fault ground motions, and their multifractal scaling behaviors are investigated. Then, the multifractal characteristic parameters of near-fault records from the Chi-Chi, Taiwan earthquake (1999, moment magnitude M_W=7.6) and Northridge, California earthquake (1994, M_W=6.7) are computed, and their correlations with two period parameters (i.e., mean period T_c and characteristic period T_m) and the box-counting fractal dimensions are analyzed in Section 4. The multifractal feature and long-range correlation of near-fault records are further unveiled. Moreover, the multifractal analyses of randomly shuffled ground motions and original records are performed, indicating that the long-range correlation of small and large fluctuation is the major source of multifractality of near-fault ground motions. This work makes an attempt to better understand the strong earthquake ground motions from a new viewpoint of multifractal theory.

2. Procedure of multifractal detrended fluctuation analysis

Due to the nonstationary properties of earthquake ground motions in the aspects of amplitude and frequency content, it is necessary to consider the influence of trend fluctuation when analyzing the multifractal characteristic of time series of earthquake motions. Usually, there are varying trend components in nonstationary time series. The trend represented by the linear, quadratic, cubic, or higher order polynomial means the slow-changing components of signal, and includes the extrinsic and intrinsic trend indicating the predetermined trend and adaptive trend, respectively [40]. For earthquake ground motion, its trend refers to the fluctuation of amplitude with the time. In fact, the trend has a considerable effect on the scaling behavior of nonstationary signal [41]. Consequently, to extract the trend component is helpful for further study on the scaling nature of earthquake ground motion. Notably, the detrended fluctuation analysis was proposed as a popular alternative to remove the trend fluctuation of nonstationary time series and investigate its scaling behavior [32]. Nevertheless, DFA can acquire only a single scaling exponent from a time series. For representing the multifractal object, multiple and even many scaling exponents are required to capture its complex dynamics, so that multifractal detrended fluctuation analysis was developed to satisfy this need of multifractal characterization [31].

2.1. Numerical procedure of multifractal detrended fluctuation analysis

MF-DFA provides a systematic tool to identify and more importantly quantify multiple scaling exponents of nonstationary time series. Numerical procedure of this algorithm [31,33,35] is outlined as follows, for completeness.

(1) For a time series x_k with given length N (k=1, 2,…, N), its "profile" $Y(i)$ namely the cumulative deviation series with respect to the mean value [31] is computed as

$$Y(i)=\sum_{k=1}^{i}(x_k-x_{\mathrm{avg}}),\ i=1,2,\ldots,N \tag{1}$$

where

$$x_{\mathrm{avg}}=\frac{1}{N}\sum_{j=1}^{N}x_j.$$

(2) The profile $Y(i)$ is divided into N_s non-overlapping segments of equal length s where N_s=int(N/s). The same procedure is repeated starting from the opposite end of time series so as

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