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Analysis of crude oil markets with improved multiscale weighted permutation entropy

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HIGHLIGHTS

- Improved multiscale weighted permutation entropy (IMWPE) is proposed and tested superior to MWPE method.
- The complexity property of crude oil market is studied by IMWPE approach.
- The ensemble EMD is applied to decompose the crude oil returns.
- Complexity of EEMD-based IMFs time series is investigated.

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ABSTRACT

Entropy measures are recently extensively used to study the complexity property in nonlinear systems. Weighted permutation entropy (WPE) can overcome the ignorance of the amplitude information of time series compared with PE and shows a distinctive ability to extract complexity information from data having abrupt changes in magnitude. Improved (or sometimes called composite) multi-scale (MS) method possesses the advantage of reducing errors and improving the accuracy when applied to evaluate multiscale entropy values of not enough long time series. In this paper, we combine the merits of WPE and improved MS to propose the improved multiscale weighted permutation entropy (IMWPE) method for complexity investigation of a time series. Then it is validated effective through artificial data: white noise and $1/f$ noise, and real market data of Brent and Daqing crude oil. Meanwhile, the complexity properties of crude oil markets are explored respectively of return series, volatility series with multiple exponents and EEMD-produced intrinsic mode functions (IMFs) which represent different frequency components of return series. Moreover, the instantaneous amplitude and frequency of Brent and Daqing crude oil are analyzed by the Hilbert transform utilized to each IMF.

1. Introduction

It is comprehensively recognized that financial markets are amongst complexity systems that human society has brought up. Empirical studies, in which many methods from complex-system-theory and statistical sciences are more and more applied, has been paid much attention in recent years for discovery of nonlinear features in financial dynamics [1–9]. Due to the high number of interactions between different agents, an almost arbitrary level of complexity of market segments is reached. In the present paper, we perform the complexity characteristics analysis of a certain market segment, namely

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the crude oil market. As one of the fundamental energy source and important chemical raw materials, crude oil is proved to be of great importance both in energy and financial markets. In the past decades, international crude oil prices have experienced drastic fluctuations, especially when it occurs wars in Organization of Petroleum Exporting Countries (OPEC) or appreciation/depreciation in United States dollar (USD). Investigating the dynamics of crude oil market seems to be crucial and necessary. The data adopted in this work comes from daily spot prices of European Brent crude oil which is one of the main global crude oil benchmarks and Chinese Daqing crude oil.

On the most basic grounds, a system is said to be "complex" when it does not match patterns regarded as simple [10]. However, there is neither a unique way of defining the complexity rigorously nor a consistent way in which the complexity is used in the literature. Intuitively, complexity is associated with "meaningful structural richness" [11] incorporating correlations over multiple spatiotemporal scales. Researchers have actually defined several complexity quantifiers that are calculated to unveil the hidden complex temporal structures ruling the system dynamics. Entropy is a very popular and powerful statistical measure of complexity because of its ability in capturing the uncertainty and disorder of the time series without imposing any constraints on the theoretical probability distribution [12]. A family of entropy parameters, such as Shannon entropy [13], Kolmogorov entropy [14], approximate entropy (ApEn) [15], sample entropy (SampEn) [16,17], etc., have witnessed extensively applications in various fields, especially in the financial stock markets. If prices were a pure random walk, the variations would be a completely uncorrelated string of numbers. We would say that such string of data is completely disordered and its entropy is maximized. On the other hand, if the price variations are somewhat correlated, then the entropy does not attain its maximal value [18]. For example, L. Zunino et al. [18] used the complexity-entropy causality plane to distinguish the stage of stock market development and found that, for the stock markets, the temporal correlations are the main factor of inefficiency. Further, a generalization of the complexity-entropy causality plane was proposed to characterize and classify time series [19]. Entropy moreover is the base of other methodologies, like generalized maximum entropy (GME) which has also different applications [20–22]. Amongst them, permutation entropy proposed by Bandt and Pompe [23] shows advantages of simplicity, fast calculation, robustness for analyzing different kinds of time series, including chaotic, random and real-world time series, which has been employed in the context of neural [24], physiological signals [25–28], climate system [29] and financial market time series [30–32]. Although permutation entropy has many advantages in distinguishing dynamical behaviors of nonlinear time series, it ignores the amplitude information of nonlinear time series. Thus, Fadlallah et al. proposed weighted-permutation entropy (WPE) which retains the amplitude information of time series [33]. WPE permutes a vector in a time phase space and calculates the variance of the vector as a weight to compute the Shannon entropy, which can significantly improve the robustness and stability of WPE, especially for the signals containing considerable amplitude information because of its immunity to degradation by noise and (linear) distortion. Then the multiscale weighted permutation entropy [34,35] was introduced as a combination of multiscale method and WPE, and was applied to analyze the signals from vertical upward oil-in-water two-phase flow experiments. But the first step of WMPE, the coarse-graining process, considerably reduces the time series length because, to inspect the deeper temporal scales, MWPE uses a procedure similar to sub-sampling. This may yield an imprecise estimation of entropy when the time series is short. To overcome this problem, in this paper, an improved MWPE (IMWPE) is proposed by incorporating the idea of composite multiscale entropy (CMSE) method [36] where multiple coarse-grained series (the number is equal to the multiscale factor) are obtained for one multiscale factor in the first step. In this following, the IMWPE method is tested in the white and $1/f$ noise compared with MWPE approach. Then it is employed to analyzed the nonlinear complexity of Brent and Daqing crude oil from 3 aspect: first is about the returns, second is about the return volatility series and third is the IMFs (intrinsic mode functions) time series after performing the ensemble empirical mode composition (EEMD) [37] of returns, which represents the different scales (or frequency) of the original time series. The EEMD method is a noise-assisted data analysis method and by adding finite white noise to the investigated data, it can eliminate the mode mixing problem in EMD [38].

The organization of this paper is as follows. Next section briefly introduces the methods of MWPE and the proposed IMWPE. Section 3 describe the employed data of Brent and Daqing crude oil, and shows a preliminary analysis of them. Section 4 is devoted to demonstrate the empirical results of the complexity properties analysis of artificial data and crude oil by nonlinear IMWPE approach, mainly focusing on the return series (including volatility series) and EEMD-based IMFs series. Finally, Section 5 concludes.

2. Methodologies

2.1. MWPE algorithm

Multiscale weighted permutation entropy (MWPE) [34,35] is defined as the weighted PE values over different scales and its estimation can be described as follow:
(i) For a time series $\{x(t), t = 1, 2, \dots, N\}$, construct the consecutive coarse-grained time series $\{y^s(j), j = 1, 2, \dots, \mathrm{int}(N/s)\}$, determined by the factor s,

$$y^s(j) = \frac{1}{s} \sum_{i=(j-1)s+1}^{js} x(i) \tag{1}$$