Epilepsy Recognition by Higher Order Spectra Analysis of EEG Signals

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INTRODUCTION

Epilepsy is a brain disorder that is characterized by sudden and recurrent seizures. Epilepsy can cause abnormal electrical activity in the brain and may alter consciousness, perception, sensation, behavior and body movement. According to reports, "approximately 1% of the world's population suffers from epilepsy" (Collins, 1993) while about 85% of them live in the developing countries (WHO, 2012). According to the International League Against Epilepsy (ILAE), in 1981, epileptic seizures are divided by their clinical manifestation into Partial (Focal) and Generalized seizures. Generalized seizures are divided into several main types, such as Absence, Atypical Absence, Myoclonic, Clonic, Tonic, Tonic-clonic, and Atonic seizures. Partial seizures are divided into three main types such as Simple partial, Complex partial, and Secondarily generalized seizures.

Monitoring electroencephalogram (EEG) signals has become an important tool in the diagnosis of epilepsy. EEG signals are recorded in two essential ways: The first and most common is non-invasive recording known as scalp recording. The second is invasive recording that is often known as inter-cranial EEG. Generally, the recognition of epilepsy can be achieved by visual viewing of EEG recordings for inter-ictal and ictal activities by an experienced neurophysiologist. However, visual review is very time-consuming and inefficient, especially in the case of long-term EEG recordings. Frequency bands of EEG signals are interesting to be interpreted such as delta (1-4 Hz), theta (4-8 Hz), alpha (8-13 Hz), beta (13-30 Hz) and gamma (> 30 Hz). About dynamical states of epileptic EEG signals, there are some main classic states of inter-ictal, pre-ictal, ictal, and post-ictal; but clinical and laboratory experiments leave little doubt that a pre-seizure period exists in temporal lobe and perhaps other forms of epilepsy.

BACKGROUND

A lot of research has been undertaken in assessment of epilepsy over the last few years (Andrzejak, 2001; Andrzejak & Widman, 2001; Tzallas, 2007; Chua, 2007; Hosseini, 2013; Guo, 2010). Gotman (1982) presented a computerized system for recognizing a variety of seizures. Murro et al. (1991) developed a seizure recognition system based on the discriminant analysis of the EEG signal recorded from the intracranial electrodes. They used three features include relative amplitude, dominant frequency and rhythmicity. A recognition sensitivity of 91-100% was achieved, with false positive rates of 1.5-2.5 per hour. Kannathal et al. (2005) have shown the importance of various entropies for recognition of epilepsy. Subasi (2007) used a method for analysis of EEG signals using discrete wavelet transform (DWT) and classification using an adaptive neuro fuzzy inference system (ANFIS). They conclude that, the ANFIS model achieved accuracy rates which were higher than that of the stand-alone artificial neural network model. In most researches, choosing suitable features is important for epilepsy seizure recognition. Higher-order spectral (HOS) or polyspectra analysis is by now a well established signal analysis technique with many applications in science and engineering, especially biomedical signal processing (Shahid, 2005; Hosseini, 2009; Hosseini, 2010; Xiang, 2002; Zhou, 2008; Abootalebi, 2000).

This article studies features related to the third order statistics of the signal, namely the bispectrum and bicoherence with both quantitative and qualitative view. The rest of this article is as follows: the database, brief review of higher-order spectral features, Hinich test, normalization and classifier are explained. Then the results and performance is illustrated. Finally, the discussion is reported.

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DATABASE

Basically, for studying epilepsy the subjects that are used are either human or animal. EEG signals used for this research are obtained from Bonn University, Germany, which is available in public domain (Andrzejak, 2001). The complete datasets consists of five sets of data (denoted *A*–*E*), each containing 100 single-channel EEG segments. Each segment has N=4096 sampling points over 23.6 seconds. All EEG signals were recorded with the same 128-channel amplifier system and 12 bit A/D resolution, with sampling rate of the data at 173.61 Hz and the spectral bandwidth of the acquisition system between 0.5 to 85 Hz. These segments were selected and cut out from continuous multi-channel EEG recordings after visual inspection for artifacts such as muscle activity, eye movements etc. Sets *A* and *B* have been recorded from external surface EEG recordings of five healthy volunteers in the wake and relax state with eyes open and eyes closed, respectively. Sets *C*, *D* and *E* have been recorded from depth electrodes EEG recordings from five patients. Set *C* were recorded from the hippocampal formation of the opposite hemisphere and set *D* is from within the epileptogenic zone of the brain (Inter-ictal period), and Set E were recorded during seizure attack activity (Ictal). For a more detailed description of the data, please refer to the (Andrzejak, 2001; Andrzejak & Widman, 2001).

METHODS AND MATERIALS

Brief Review of Higher Order Spectra

In signal processing first and second order statistics have gained significant importance. One of the most used tools in signal analysis is the power spectrum. If $x(k)$, k=0±1±2,…,±n is a real stationary random process, the power spectrum, is calculated of Wiener Khin-Chin theorem, as follow:

$$P(f) = F\left\{r(u)\right\} = \sum_{u=-\infty}^{+\infty} r(u)e^{-j2\pi fu} = \left|X(f)\right|^2 \tag{1}$$

where F denotes the Fourier transform and r. denotes the auto-correlation function. The auto-correlation function, m_2u, of a stationary random process, $x(k)$ is defined as,

$$r(u) = E\{x(k).x(k+u)\} = m_2(u) \tag{2}$$

where E denotes the expected value operator.

If $r(u,v)$ denotes the third moment sequence (triple auto-correlation) of $x(k)$,

$$r(u,v) = E\{x(k).x(k+u).x(k+v)\} = m_3(u,v) \tag{3}$$

The first moment is the mean μ of the signal, the second, third and fourth central moments are called variance σ2, skewness and kurtosis respectively.

Higher order spectra are the extension to higher orders of the concept of the power spectrum. The power spectrum is a common operation; spectral moments of order >2 are referred to as higher order spectra. HOS is a function of two frequencies unlike the power spectrum which is a function of one frequency variable. HOS contain information not present in the power spectrum. HOS from on a set of functions with name higher order statistic are defined. They are spectral representations of higher order moments and cumulants of a signal, which are generalization of the auto-correlation function.

In practice, due to the finite length signals and high computation bispectrum is used. For a discrete time series, the bispectrum is the Fourier transform of the third order correlation of the signal and is given by

$$Bis(f_1, f_2) = E[X(f_1).X(f_2).X^*(f_1 + f_2)] \tag{4}$$

where asterisk denotes complex conjugate, $X(f)$ is the Fourier transform of the signal $x(nT)$, n is an integer index, T is the sampling interval. The bispectrum is related to the skewness of a signal and the bispectrum is complex-valued, and therefore, it has magnitude and phase. Bispectrum is a function of two independent frequencies, f_1 and f_2, which could take on both positive and negative values. This method is known as direct fast Fourier transform (FFT) based method. There is also another indirect method, which is used in our study. For more details on this method please refer to (Hosseini, 2009; Abootalebi, 2000; Swami, 2000).