Amplitude and Phase Analysis of EEG Signal by Complex Demodulation

Sun K. Yoo, Hee Cheol Kang

***Abstract*—**Analysis of amplitude and phase characteristics for delta, theta, and alpha bands at localized time instant from EEG signals is important for the characterizing information processing in the brain. In this paper, complex demodulation method was used to analyze EEG (Electroencephalographic) signal, particularly for auditory evoked potential response signal, with sufficient time resolution and designated frequency bandwidth resolution required. The complex demodulation decomposes raw EEG signal into 3 designated delta, theta, and alpha bands with complex EEG signal representation at sampled time instant, which can enable the extraction of amplitude envelope and phase information. Throughout simulated test data, and real EEG signal acquired during auditory attention task, it can extract the phase offset, phase and frequency changing instant and decomposed amplitude envelope for delta, theta, and alpha bands. The complex demodulation technique can be efficiently used in brain signal analysis in case of phase, and amplitude information required.

***Keywords*—**EEG, Complex Demodulation, Amplitude, Phase.

I. Introduction

THE analysis of amplitude and phase characteristics for delta, theta, and alpha bands at localized time instant from EEG signals is important for the characterizing information processing in the brain. The alpha and theta rhythms of EEGs respond in different and opposite ways. Studies have found that, with increasing task demands, theta synchronizes, whereas alpha desynchronizes [1]-[4]. Theta change associated with an external stimulus have been attributed to Hippocampus function, as activation of this brain region is correlated with increased theta rhythms on EEG [5]. More widely, many research trails have been conducted to reveal the relationship between different brain sites and between different oscillating brain signal patterns [6]-[8], typically the delta, theta, and alpha bands patterns. The brain connectivity, in other words, brain network, can be sometimes well described by amplitude and phase information. If the group of neurons harmonizes well, the energy will be efficiently utilized in the brain, enabling the complicated operation for the human. Those harmonized group operation can be monitored by the amplitude and phase at the scalp EEG electrodes.

Fourier transform is generally used to extract the phase and amplitude information from the time series data, but the unit of time resolution will be bounded by the data sample size (epoch size), which cannot be avoided because of the block based Fourier transform property. Thus, relationship between time and frequency resolution is reciprocal. However, the brain operation can be dynamically reconfigured depending on the task fulfilled. The fine time resolution is indispensible to detect the time instant event where the dynamic reconfiguration or changing status occurs. In this paper, complex demodulation method [9], [10] was used to analyze EEG (Electroencephalographic) signal, particularly auditory evoked potential response signal.

Sun K. Yoo is with the department of Medical Engineering, Yonsei University College of Medicine (corresponding author; phone: 82-10-3458-2435, fax 82-2-363-9923, e-mail: sunkyoo@yuhs.ac).

Hee Cheol Kang is with the department of Family medicine, Yonsei University College of Medicine (phone: 82-2-2228-2332, fax: 82-2-362-2473, e-mail: kanghc@yuhs.ac).

II. Material and Method

A. Complex Demodulation

Real EEG signal, acquired from the scalp electrode can be transformed into complex numbered representation of EEG signal. The amplitude and phase information can be extracted from the complex signal, corresponding to the analytic signal representation. Let $x(t)$ be the original real EEG signal. The complex demodulation of real EEG signal, is defined as analytic transform, which applies the multiplication of the ($\sin wt$) and ($-j\cos wt$) to $x(t)$, t=1, ..., n [9], [10].

$$y(w,t) = x(t)\cos(wt) - j\sin(wt) \quad (1)$$

w=2, 6, and 10 Hz

where n is the number of EEG samples, $y(w, t)$ is the complex demodulated EEG signal at w frequency bands (2 Hz, 6 Hz, and 10 Hz are assigned as w for delta, theta, and alpha bands, respectively). According to the frequency shift property in the frequency domain, the multiplication procedure shifts the center frequency of the raw EEG signal into the zero frequency (DC). That is, 2, 6, and 10 Hz for w moves the original EEG signals composed of delta, theta, and alpha bands components into the zero baseband components (zero frequency centered shifted EEG signals), respectively. Then, application of the low pass filter (F) to each zero frequency centered EEG signals for delta, theta, and alpha, three bandwidth decomposed complex signals can be obtained.

$$c(w,t) = F\{y(w,t)\} \quad (2)$$

In order to obtain the decomposed delta, theta, and alpha band limited signals, the pass band ripple and phase distortion for the low pass filter should be minimal. For sharp transition at cutoff frequency, plat pass band ripple, and small delayed response time, 7th order Butterworth IIR (Infinite Impulse

Response) filter with 4 Hz cutoff frequency (matching to the EEG delta, theta, alpha bandwidth of 4 Hz) is adopted. Successive application of forward and backward processing of Butterworth filter to the band decomposed complex signal enables the zero-phase filter implementation. Then, amplitude and phase response can be obtained with sampled time resolution for each delta, theta, and alpha band, respectively.

$$A(w,t)=\sqrt{real\{c(w,t)^2\}+imaginary\{c(w,t)^2\}} \quad (3)$$

$$\phi(w,t)=\tan^{-1}\frac{real\{c(w,t)\}}{imaginary\{c(w,t)\}} \quad (4)$$

From the phase response, the instantaneous phase difference (IPD) [9] is obtained by time differentiation of the phase response signal. It reflects the changes in the signal frequency, and phase offset at transition time instant as peak and valley shapes.

$$I(w,t)=\Delta\phi(w,t)/\Delta t \quad (5)$$

B. Experimental Design

The biological signals were recorded on two-channel amplifiers (Biopac MP150™) with one-channel electroencephalography capabilities (EEG; central Cz using a GRASS electrode with conductive gel).

The signals were then digitized at a sampling rate of 1000 Hz. The EEG electrodes were positioned at Cz in the midline, right earlobe (reference), and forehead (ground).

The high pass filter of the EEG signal was set to 0.5 Hz, and the low pass filter was 100 Hz. The 60 Hz notch filter was on at all times. The high pass filter of the PPG signal was set to 0.5 Hz and the low pass filter was 10 Hz.

The event-related attention was performed as follows: The numbers from 1 to 9 were recited randomly through the headset for 9 minutes, and the subjects pressed the spacebar on the keyboard when the designated number was spoken.

III. Result

Figs. 1 ~ 3 show the delta, theta, and alpha band signals decomposed by complex demodulation with simulation data. The *sin (2πft)*, corresponding to delta band signal, is synthesized (Fig. 1). The peak of the power spectral density (b) at 2 Hz is shifted to the peak at zero frequency (green color). The amplitude of the delta band signal (c) is apparent comparing with other band signals (d, e), but shows the oscillating pattern, because delta band is too adjacent to zero baseline frequency with leaked overlapped bandwidth over 4 Hz.

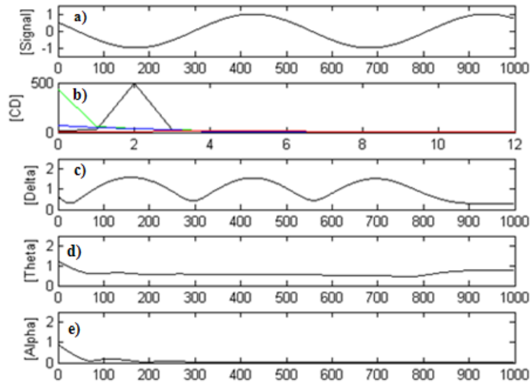

Fig. 1 Complex demodulation of synthetic data of 2 Hz center frequency. (a) synthetic signal, (b) power spectral density (black for original data, green for shifted delta, blue for shifted theta, and red for shifted alpha), (c) delta amplitude, (d) theta amplitude, and (e) alpha amplitude

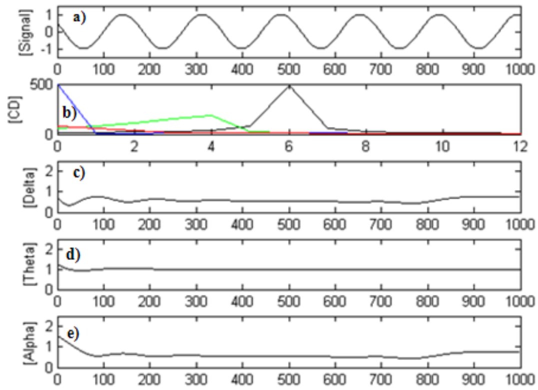

Fig. 2 Complex demodulation of synthetic data of 6 Hz center frequency. (a) ~ (e) are the same as Fig. 1

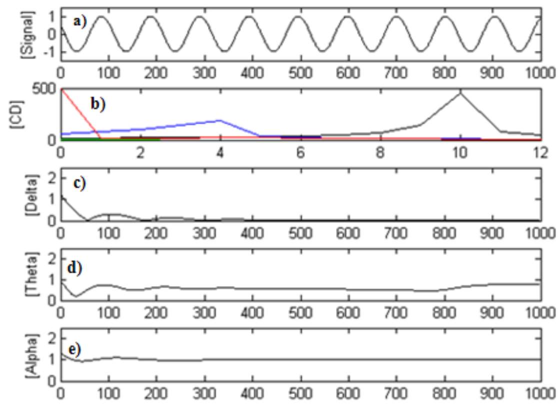

Fig. 3 Complex demodulation of synthetic data of 10 Hz center frequency. (a) ~ (e) are the same as Fig. 1

Figs. 2 and 3 show the complex demodulation of the synthetic theta band, and alpha band signals, respectively. The peak of the power spectral density (b) at 6 Hz, and 10 Hz is shifted to the peak at zero frequency (green color). The amplitude of the theta band, and alpha band signals (c) is apparent (near amplitude of 1) comparing with other band signals (d, e), respectively.

Figs. 4 and 5 show composition of synthesized two band signals. The delta signal (center frequency of 2Hz with zero phase offset) and alpha signal (center frequency of 10Hz with $\pi/3$ phase offset) were mixed at 500 m sec (Fig. 4). The theta signal (center frequency of 6Hz with zero phase offset) and alpha signal (center frequency of 10Hz with $\pi/3$ phase offset) were mixed at 500 m sec (Fig. 5).

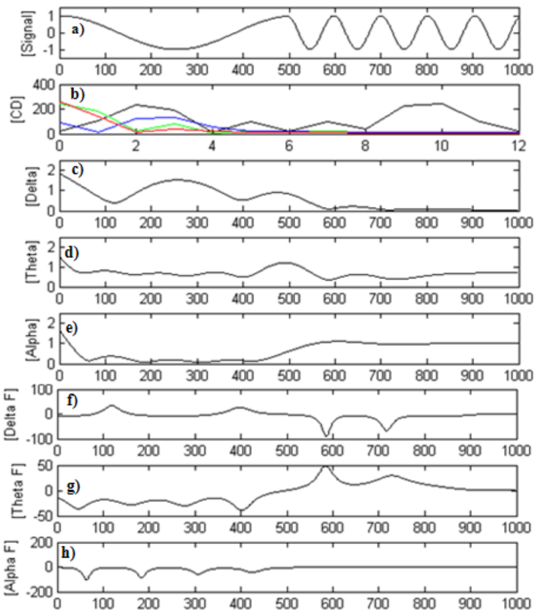

Fig. 4 Complex demodulation of synthetic data of 2 Hz and 10Hz center frequencies. (a) synthetic signal, (b) power spectral density (black for original data, green for shifted delta, blue for shifted theta, and red for shifted alpha), (c) delta amplitude, (d) theta amplitude, (e) alpha amplitude, (f) delta IPD, (g) theta IPD, and (h) alpha IPD

As shown in Fig. 4, the amplitude signal for delta (c), and alpha (e) depict the pattern of synthetic signals with 500 m sec transition. Similarly changes in slope and peak and valley pattern are observed at phase response pattern (IPD: Instant Phase Difference). But, large inter-band cross talk of magnitude (d) and phase (g) is observed at intermediate band of theta. Regarding to theta and alpha composition (Fig. 5) similar patterns are observed with replacement of inter-band cross talk of theta (Fig. 4) to alpha (Fig. 5).

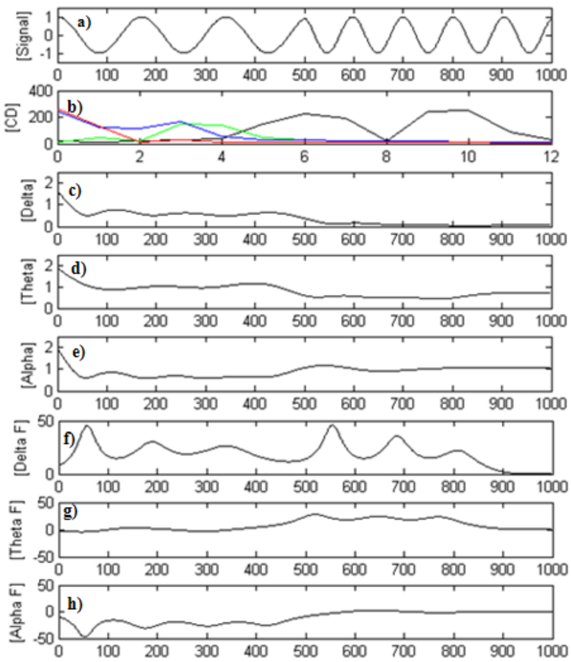

Fig. 5 Complex demodulation of synthetic data of 6 Hz and 10Hz center frequencies. (a) ~ (e) are the same as Fig. 4

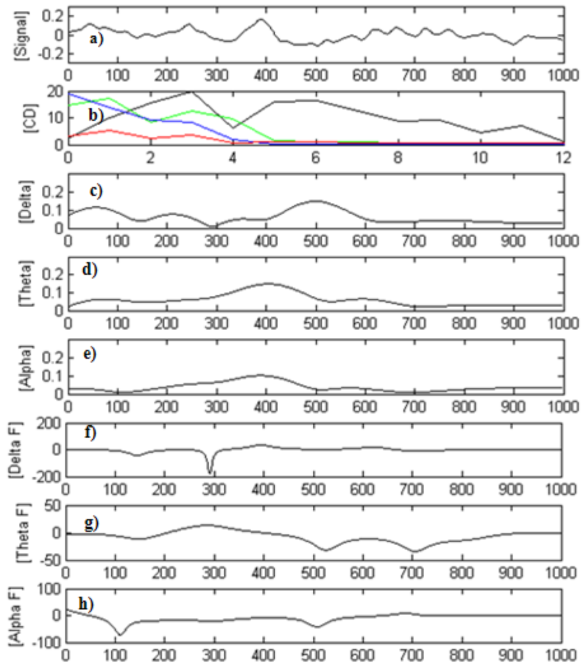

Fig. 6 Complex demodulation of real EEG data. (a) ~ (e) are the same as Fig. 4

Fig. 6 shows the complex demodulation of the real EEG data. As indicated in [5]-[11] that the evoked response pattern can be generated by the combination of delta, theta, and alpha band signals), the evoked EEG signal is composed by three band signals (b is for the spectral domain indication, and c, d and e are for delta, theta, and alpha signals, respectively). The changing instant at around 300 m sec (f for delta PID), 520 m sec and 700 m sec (g for theta PID), and 120 m sec (h for alpha PID) match the raw EEG signal pattern (a) well.

IV. Conclusion

In this paper, complex demodulation method was used to analyze EEG (Electroencephalographic) signal, particularly auditory evoked potential response signal, continuously with sufficient time resolution and designated frequency bandwidth resolution required. The complex demodulation decomposes raw EEG signal into 3 designated delta, theta, and alpha bands with complex EEG signal representation at sampled time instant, which enables the extraction of amplitude envelope and phase information. Throughout simulated test data, and real EEG signal acquired during auditory attention task, it can extract the phase offset, phase and frequency changing instant and decomposed amplitude envelope for delta, theta, and alpha bands. The complex demodulation technique can be efficiently used in brain signal analysis in case of phase, and amplitude information required.

Acknowledgment

This work was supported by a National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIP; No. 2010-0026833).

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