Detection of Linear Frequency Modulated Flash Visual Evoked Potential by Fractional Fourier Transform

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***Abstract*—Linear frequency modulated visual evoked potential was explored in this paper, the stimulator, experimental paradigm, detection and analysis methods of visual evoked potential are generalized. The steady-state visual evoked potential can be seen as an specialization of linear frequency modulated visual evoked potential, which contains a set of linear frequency modulated signals corresponding to the stimulator, as well as steady-state visual evoked potential containing the fundamental and higher sine harmonics consistent with stimulus signal. In this work, time-frequency analysis methods, especially Fractional Fourier Transform which has a good focusing property for linear frequency modulated signals were used to detect the parameters of VEP evoked by LFM flash signal. The effectiveness of Fractional Fourier Transform for linear frequency modulated visual evoked potential shows feasibility and possibility for applications in brain-computer interface.**

Keyword-Visual Evoked Potential (VEP); Linear Frequency Modulated signal (LFM); Fractional Fourier Transform (FRFT); wigner distribution

I. INTRODUCTION

Visual Evoked Potential is a kind of physiological electrical activity, which is transferred to the occipital visual cortex of the brain through visual pathway when visual organs are stimulated by flash or patterns. Depending on the variety of the flash stimulation frequencies, flash visual evoked potentials can be divided into transient visual evoked potential (TVEP) and steady-state visual evoked potential (SSVEP). The spectral components of SSVEP include the stimulation frequency and its harmonic frequencies. So the detection of SSVEP may have a very high signal to noise ratio (SNR) [1], and is generally used in brain-machine interface (BCI) system in recent years [2]. Also because of the reaction of the state from the retina to the visual cortex neural pathways [3], SSVEP is an important type of observation signal to study brain activities.

So far, whether it is transient or steady-state, visual evoked potential study and application are mostly concentrated on the relationship between the frequency of stimulator and response signals, rather than the change rate of stimulation frequency and evoked EEG signals. At present, there are researches starting to focus on brain's response with visual evoked potential when the stimulus frequency changes, like Jordi Bieger [4], who adopted three different ways of stimulus frequency variation to observe if human brain can follow the stimulus frequency change timely and make a reasonable response even if the frequency change is accelerating. One of his purpose is to reduce the number of stimulus frequencies in BCI by changing the stimulus frequency in a certain way. Experiments confirmed that when the stimulus frequency changes from one to another, the steady-state VEP response can follow this change accurately and quickly. However, when the stimulus frequency grows linearly, how to detect and evaluate the corresponding change of VEP response (so called LFM-VEP) has become a problem which needs for prompt solving.

The spectrum of SSVEP has notable peaks on the stimulus frequencies, which are often described as the weight sum of sinusoidal fundamental signal and a set of harmonic signals [5]. And as we know, the linear FM signal is the generalization of a single frequency signal, steady-state signal is a special case of LFM signal when the chirp rate of the LFM signal is zero. While the previous study shows that LFM-VEP also contains a set of corresponding chirp component and harmonic signals, the relationship between VEP and the LFM stimulus signal has been preliminarily obtained by detecting and estimating the linear frequency modulation components in EEG utilizing Fractional Fourier Transform (FRFT), which has good focusing properties of LFM signals. The existing time-varying signal processing conclusions provide important inspiration and reference for this issue [6]. Based on the above motivation, this work designed a series of experiments in order to explore and verify the detection method of the LFM-VEP through time-frequency analysis, especially via FRFT.

II. PRINCIPLE OF LFM SIGNAL DETECTION USING FRFT

A. LFM Signal Detection based on FRFT

Fourier Transform (FT) is a classic tool to analysis and process stationary signal, but it appears incapable for non-stationary or time varying signals. FRFT, as a generalized form of the traditional Fourier Transform, can effectively estimate the frequency modulation rate, center frequency, amplitude and phase of LFM signal stimulation. Compared with the Wigner-Ville distribution, FRFT avoids the problems of cross-term in the analysis of multi-component LFM signals [7]. If parameter information of LFM-VEP can be detected accurately, the corresponding stimulus source can be effectively identified since LFM-VEP contains the LFM component of stimulus signal with same chirp rate, so it is beneficial to use LFM-VEP in BCI systems in terms of its chirp rate parameter detection.

An important relationship between FRFT and Wigner distribution is that the line integral projection of a signal's Wigner distribution in Fractional Fourier Domain (FRFD) is the square of the mode of the signal in this FRFD [8]. That is:

$$\left|F_p(x)\right|^2 = R_\alpha\left[W(t,v)\right] \quad (1)$$

As shown in Figure 1, the Wigner distribution of a finite length LFM signal in time-frequency plane is rendered as oblique dorsal shape. Therefore, FRFT of a LFM signal in a FRFD which is perpendicular with the oblique line, a distinct peak will occur in the fractional domain, while the projection value will be small in the other domains. However, the energy of white noise evenly distributed over the entire time-frequency plane, and will not have energy accumulation in any FRFD. Using this feature, detection and parameter estimation for LFM signal by FRFT can be available.

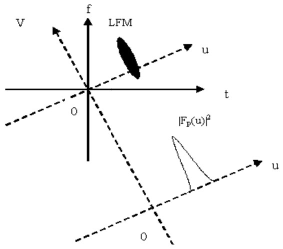


FIGURE I. WIGNER DISTRIBUTION OF THE LFM SIGNAL AND ITS FRFD PROJECTION

Since LFM signal shows different energy accumulation properties in different FRFDs, the basic idea of detecting LFM signals with unknown parameters is scanning with the variable of rotate angle α, demanding FRFT of the observed signals, thus forming two-dimensional (2-D) distribution of signal energy in the plane of parameter (α,u). In this plane, LFM signals can be detected through 2-D peak searching via a certain threshold, and the parameters also can be estimated [9].

Single-component LFM signal with noise can be expressed as:

$$x(t) = s(t) + w(t) = a_0 \exp\left(j\varphi_0 + j2\pi f_0 + \pi\mu_0 t^2\right) + w(t) \quad -\Delta t/2 \le t \le \Delta t/2 \quad (2)$$

ψ_0, f_0, μ_0 are unknown parameters, $w(t)$ is additive white noise, the above detection process can be expressed as:

$$\{\hat{\alpha}_0, \hat{u}_0\} = \arg\max_{\alpha,u} \left|X_\alpha(u)\right|^2 \quad (3)$$

$$\hat{\mu}_0 = -\cot\hat{\alpha}_0 \quad (4)$$

$$\hat{f}_0 = -\hat{\mu}_0 \csc\hat{\alpha}_0 \quad (5)$$

Using the above formulas, the frequency f_0 and chirp rate μ_0 can be estimated by FRFT. Here, α is rotate angle of FRFT in time-frequency plane.

B. Matlab Theoretical Simulation of LFM

On the basis of the above theroy, a detection experiment in Matlab was implemented on a LFM signal:

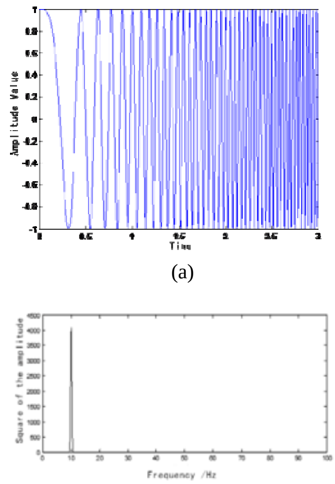
$$s(t) = e^{j2\pi f_0 t + j\pi u_0 t^2} + w(t),\ f_0 = 10, u_0 = 2,$$

whose sampling rate is 512 Hz, recording time $T = 3s$, $w(t)$ is additive white noise.

Without adding white noises that is the case SNR=0, using FRFT to the LFM signal continuously with the variable of order p or rotate angle α, then search the peak point in every (α,u) plane. The FRFT Detection result is shown in Figure 2. The parameters (α,u) of the maximum peak are substituted into equation (4) and (5), and then the estimation of the LFM signal is:

Chirp rate μ_0 =2Hz/s; deviation is 0Hz/s.

Center frequency f_0 =10.0013Hz; Deviation is 0.0013Hz.



(a)

(b)

FIGURE II. (a)TIME-DOMAIN WAVEFORM OF LFM SIGNAL (b) THE FRACTIONAL FOURIER TRANSFORM POWER SPECTRUM

According to the above theoretical simulation results, the error of the detection results is within an acceptable range, so that the parameters of LFM signals can be effectively estimated through FRFT.

III. DETECTION OF LFM-VEP

As it has been proved that the flash visual evoked potential signal stimulated by LFM contains a set of LFM signals with parameters corresponding to the simulator [6]. According to the relationship between FRFT and Wigner-Ville distribution, the stimulator parameters can be obtained by detecting the LFM parameters from VEP signal, which is carried out by peak searching in FRFT domains, then complete the target identification. The detection can be verified by the following two experimental paradigms:

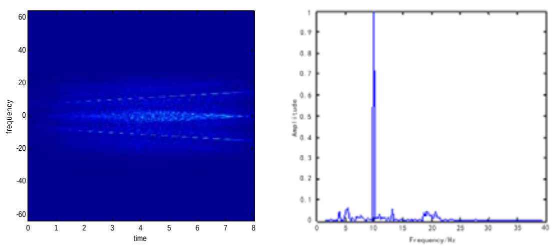
(1) Use different LFM signals to modulate single LED flash to stimulate the user ‘eyes every time, and then search the collected EEG on the FRFT order of 0-2 to find the order corresponding to the maximum peak, and calculate the present chirp rate of VEP to determine whether it is corresponding to the LED flash stimulus.

(2) A stimulus array composed of multiple LEDs with different LFM chirp rates, flash simultaneously to stimulate the user ‘eyes. The user subjectively choose to watch one of the LEDs, then search the collected EEG on every FRFT order corresponding to every chirp rate of the LEDs respectively to find the order that the maximum peak appears, and to achieve recognition of the LED target. In this perspective, LFM-VEP can be applied to BCI system.

IV. EXPERIMENTAL RESULTS AND ANALYSIS

To generate the required LFM flash stimulation signals with different chirp rates and center frequencies, the stimulator we developed includes two parts: LFM signal generator based on FRGA and triode switch LED array driver circuit [10]. Using 32 lead EEG (international 10-20 standard) machine to record the experiment data, and the reference electrode was located in the mastoid position around ear, and storage Oz records of evoked potential data for the following analysis.

According to the experimental paradigm, the collected EEG data were preprocessed firstly to remove power-line interference and baseline wander, also superimposed and averaged to reduce the influence of spontaneous EEG, for the success of detection [6]. Figure 3(a) shows the Wigner distribution of the post-preprocessed signal with rate of 2Hz/s and Center frequency of 13Hz. In Wigner distribution, signal energy is accumulated, and appears linear shaped distribution, that is to say there are a set of LFM signals in the EEG.



(a) (b)

FIGURE III. (a)THE WIGNER DISTRIBUTION OF LFM-VEP (b)LFM-VEP FRACTIONAL FOURIER TRANSFORM POWER SPECTRUM

The VEP signal, which is evoked by the LFM flash stimulator, is transformed to various fractional Fourier domains continuously. The FRFT order p is from 0 to 2, with step length 0.001. Search the energy accumulation peak in the plane (p,u) of every order p . In each order of $p_0 = 1.0154, p_1 = 10.42$, there is a sharp peak respectively, like shown in Figure 3(b). The LFM signal parameters corresponding to p_0 and p_1 are estimated as: $u_0 = 2.046 Hz/s$, $f_0 = 13.0013 Hz$ and $u_1 = 4.048 Hz/s$, $f_1 = 26.003 Hz$. Since in the p_0 and p_1 FRFD, there are two linear frequency modulation signals respectively, and $u_0 = 2.046 Hz/s$ is consistent with the stimulus chirp rate, while $u_1 = 4.048 Hz/s$ is the chirp rate of harmonic VEP signal. The chirp rate of stimulus flash signal at this time is 2 Hz/s, and center frequency is 13 Hz. Both of them are roughly consistent with the estimated parameters. Considering the EEG signal is easy to be interfered, and has low SNR, the deviation is belong to an acceptable range. Therefore the VEP at this time includes a set of LFM signals corresponding to the stimulus signal, and the signal detection algorithm based on FRFT can effectively estimate the parameters of LFM-VEP and consequently the chirp rate parameters can be used to mark different LFM flash simulator, which provides possibility of application in BCI system.

In this experiment, the absolute deviation of chirp rate between stimulator and the detected result is in (0-0.065) Hz/s range, and the relative deviation is less than 6%.

Figure 4 shows the fitting results from the experimental data. Fitting function is a linear function, and fitting line slope is 1.04. Because of the inverse relation of the deviation and sample size in a limit range [11], increasing the number of samples may improve the fitting precision, like increasing stimulus chirp rate samples from 2-3Hz/s, and the slope of fitting line approaching to 1. Whereas the low SNR and existing deviation, the slop can be regarded as 1. Therefore, the LFM-VEP signal contains a set of chirp signals whose chirp rates are same as the stimulus signals.

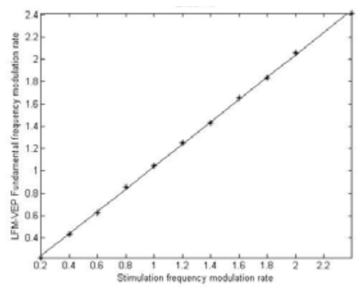


FIGURE IV. LINEAR FIT OF LFM-VEP AND THE STIMULATION SIGNAL CHIRP RATE

In a typical BCI system based on SSVEP, users selectively watch visual stimulus which are arranged in different locations and each flash in different stable frequencies. Because the response of the steady-state visual stimulation will cause the fundamental VEP signal which have same frequency with the stimulator, and harmonic VEP waves, the stimulus which is watched can be indentified through estimate the SSVEP frequency components. The target stands for the corresponding action in BCI system, so as to achieve the brain-machine control [12]. According to the above conclusion, under the condition of LFM signal simulation, the brain will generate evoked potential which has the same chirp rate as the LFM simulation. And the stimulation parameters can be detected through FRFT, from which the stimulus target can be determined, and thus the LFM signal can be used as the stimulation of brain-computer interface.

The existing BCI based on SSVEP is insufficient, the usually used SSVEP evoked by single frequency signal, is easier to be interfered by background EEG [13]. Because of their own properties， LFM-VEP and FRFT weaken the interference of spontaneous EEG to some extent. What’s more, single frequency signal is a special case of LFM signal, while FRFT is a generalization of the traditional FT, so as the generalized form of traditional BCI system based on SSVEP, the research of BCI system based on LFM-VEP is of great potential.

V. CONCLUSION

This article uses LFM flash signal as a new stimulus mode, and uses FRFT which has good focusing property for LFM signals to detect the VEP signal and estimate parameters. Similar to the SSVEP, LFM- VEP can also be described as weighted sum of a set of LFM signal. It may contain more information about brain function and visual pathway, and become a new kind of BCI control signal. Through the improvement of subsequent experiment method and signal processing algorithm, LFM-VEP must promote people's understanding of VEP and its applications in various fields.

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