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An Improved Phase-Tagged Stimuli Generation Method in Steady-State Visual Evoked Potential Based Brain-Computer Interface

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***Abstract*—This paper proposes an improved method for generating different phases of visual stimulus while liquid crystal display (LCD)/cathode ray tube (CRT) is employed as the visual stimulator. Since using the traditional method can only generate the limited frequencies and phases of visual stimulus, increasing the number of different flickering targets becomes very difficult in steady-state visual evoked potential (SSVEP)-based brain-computer interface (BCI). The experimental result shows that the proposed method can generate the visual stimulus with more phase angles than the traditional method. In addition, the proposed LCD visual stimulator can evoke the subject's SSVEP with expected phase.**

Keywords-Brain-computer interface (BCI); Steady-state visual evoked potential (SSVEP); Electroencephalogram (EEG); Liquid crystal display (LCD); Cathode ray tube (CRT)

I. INTRODUCTION

In recent decades, the electroencephalogram (EEG)-based brain-computer interface (BCI) has become more and more attractive in biomedical engineering and has been considered as alternative approach for patients suffering from severe motor disabilities to communicate with the computer or external world without any muscular control [1, 2]. So far, since steady-state visual potential (SSVEP) has high signal-to-noise ratio (SNR) and can be recorded easily from the scalp over the occipital area, many SSVEP-based BCI systems were implemented and achieved the satisfactory performance [3-9].

SSVEP can be considered as a steady periodic response to a repetitive visual stimulus at frequency higher than 6 Hz [3-4]. For this reason, if several flickers are modulated at different frequencies, the user's SSVEP with different frequencies may be evoked by gazing at different flickers. As a result, the user's visual intention can be coded in SSVEP [5-10]. In addition, many studies demonstrated that SSVEP is phase-locked to the visual stimulus [3, 16] so that it can be observed that the frequency and phase information of visual stimulus from SSVEP. Another prototype of SSVEP-based BCI proposed by [3, 11, 12] utilizes the phase-locked characteristic which means that the flickers are modulated at one frequency with distinct phases so that SSVEP with different phases can be elicited by gazing at different flickers. Thus the gazed target can be detected by measuring the phase of SSVEP.

In summary, such SSVEP-based BCIs demand that the visual stimulator can generate the flickering targets with N distinct frequencies or phases. Increasing N may enhance the SSVEP-based BCI's performance in terms of information transfer rate (ITR) [1], so the stimulator design is very critical. In general, there are three types of visual stimulator which are LED (light emitting diode), CRT (cathode ray tube) and LCD (liquid crystal display). In [8], the LED stimulator included of 48 LEDs with distinct frequencies between 6 and 16 Hz while the ITR can be up to 68 bit/min. Unlike the LED visual stimulator, LCD/CRT visual stimulator can be easily implemented and configured in a personal computer. Hence, although the traditional flickers generation method introduced by [3] is restricted due to the limited refresh rate of monitor, many SSVEP-BCI systems still used LCD/CRT stimulator [3, 5, 7, 9, 13]. Accordingly, how to increase the flickers in LCD/CRT is an important issue for SSVEP-based BCI. Using higher refresh rate monitor is a direct way to produce more frequencies and phases but the refresh rate of common LCD is often very low (60 Hz). In [17], H. Cecotti proposed a simple way to produce the stimuli with more frequencies by means of composition of two frequency sequences. In this paper, an improved method based on [3] to produce the visual stimuli with more phases in LCD/CRT monitor was proposed. It takes the influence of flickers' vertical distance into consideration. In addition, the experimental results demonstrated that the proposed method is applicable and the proposed LCD stimulator can be employed in practical SSVEP-based BCI.

II. METHODS

A. Traditional phase-tagged stimuli generation method

Briefly speaking, the principle of flickering target in LCD/CRT monitor is that the target (such as square, rectangle and arrow) is appeared from foreground and disappeared into background at specified rate on screen [4]. In traditional method, the monitor's 60 Hz refreshing signal was considered as a basic clock and the relatively stable 15 Hz phase-tagged flickering signals could be obtained by frequency division as shown in Fig. 1. The high (low) level of flickering signal represented the flicker's color was white (black) at that moment so that the flicker looked like flashing during the processing [3]. Obviously, four phase-tagged flickering signals have four different phases respectively in Fig. 1 since their flashing moments are different. Basically, it can generate 60/n

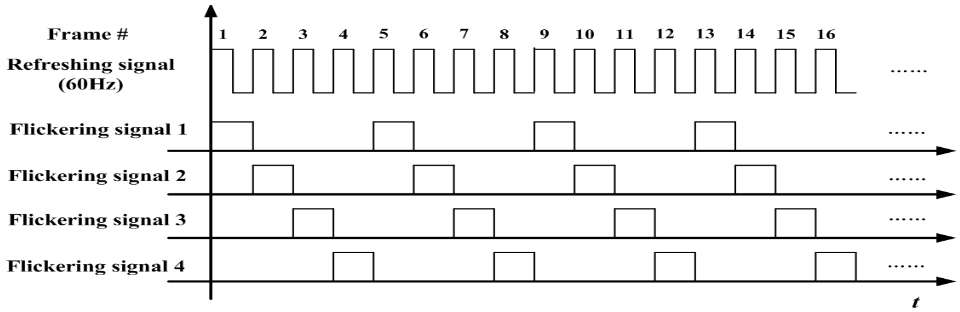

Figure 1. Predefined flickering signals of four flickers.They have same frequency 15Hz and different phases. Two adjacent flickers have a phase difference of 90 deg.

Hz (n is the number of frequency division.) flickering signals which include n different phases and the phase difference is kept at 360/n deg so the available frequency and phase of flickering signal was limited. e.g, the maximum phase number of 20 Hz flickering signal should be 3 and phase difference is 120 deg.

For simplicity, by setting different flashing moments ($m \leq n$, m is an integer), the traditional method can generate the flicker with corresponding phase (ϕ), is given by (1)

$$\phi = -\ (m-1) \times 360/n \text{ (deg)}. \tag{1}$$

B. Improved phase-tagged stimuli generation method

It should be noted that the traditional generation method does not take into account the realistic situation. Based on the operational principle of monitor, the displayed frame is comprised by a matrix of pixels and each row of pixels is displayed sequentially on screen [14]. Namely, the screen does not render the whole frame at the same time. Actually it should be found that the rendering time of two images located at different vertical position have a little time lag. In other words, although the flickers are defined the same frequencies and phases in stimulator program, their practical flickers have phase shift if they are located at different vertical position, which can be used to adjust the phase shift of flickering signal.

Clearly, the key point of phase shift adjustment is to control the rendering time lag. Due to the sequentially rendering in screen, the rendering time lag of flickers is mainly determined by their vertical distance. Thus, varying the flicker's vertical distance leads to the change of phase lag. Moreover, the flickers' phases can be changed by vertical distance rather than predefined in program, so the phases of flickers can be increased significantly. For instance, 60 Hz LCD monitor may merely generate three 20 Hz phase-tagged flickering signals (0, 120 and 240 deg) using the traditional method, whereas actually it may generate 20 Hz phase-tagged flickering signals with more than 3 phases (such as 6 phases are 0, 60, 120, 180, 240 and 300 deg) based on the improved one. The underlying reason is that their predefined phases can be adjusted.

Consequently, the improved method can generate the flicker with different phase (ϕ) when the time lag (t_{lag}) due to sequentially display is considered. It can be described by (2),

$$\phi = -\ (m - 1 + t_{lag} \times f_s) \times 360/n \text{ (deg)}, \tag{2}$$

where t_{lag} and f_s denote the time lag and flickering frequency respectively.

C. Experiments

In this paper, three experiments were carried out. Based on the result, it can be found that the relationship between phase lag and vertical distance of flickers is proportional, using the improved method can increase the number of flicker's phase in LCD stimulator and the proposed visual stimulator can be applied in SSVEP-based BCI system. Our visual stimulator was programmed in Visual C++ 6.0 and DirectX DirectDraw 7.

The relationship between phase lag and vertical distance of flickers was investigated in experiment I. Two 60 Hz LCD monitors were adopted as visual stimulators (ViewSonic 22" and DELL 21", 1024×768 pixel resolution). Nine 1 Hz flickers were generated and distributed uniformly in screen, shown in Fig. 2. All of flickers' phases were predefined 0 deg in the stimulator program. Then we used photoresistor to measure the practical flickering signals. Their time lags were calculated by comparing the predefined flickering signal with measured one. During this experiment, the targets were flickering for 5 sec in each trial while their predefined and practical flickering signals were recorded in the signal oscilloscope (Alligent Technologies, MSO6054A) for offline data analysis. Totally it included of 3 trials and thus 15 sec length data for each target was used for analysis.

Based on the result of experiment I, we used the improved method to design the visual stimulator with six 20 Hz phase-tagged flickers in experiment II. Then the six targets' predefined and practical flickering signal were acquired and their phases could be calculated. Data acquisition procedure was equal to experiment I. Then the proposed stimulator was applied to evoke the subjects' SSVEP in experiment III.

Two male subjects with corrected-to-normal vision participated in experiment III. They were seated in a comfortable chair in front of the visual stimulator about 60 cm.

Their EEG signals were recorded from the scalp via 6 standard EEG electrodes by an amplifier (g.USBamp, Guger Technologies, Graz, Austria). PO_3, PO_4, PO_Z, O_Z were the input electrodes, AF_Z and C_Z were used for the reference and ground respectively. The sampling frequency was 600 Hz. In each trial, subjects were requested to gaze at one of 6 targets for 6 sec in turn and there were 4 sec for preparation between trials. Thus 3 trials EEG data were sampled for each flicker and totally there were 18 trials.

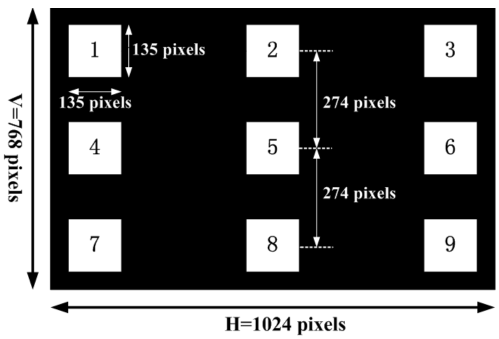

Figure 2. The distribution of nine flickers in the visual stimulator.

III. RESULTS

A. Results of experiment I

Fig. 3 shows the predefined and measured flickering signals of three flickers in experiment I. Note that the high/low level of predefined/practical signal indicates that the target was bright because the resistance of photoresistor was decreasing while the brightness was increasing. It can be observed that the time lag of flicker 1 was around 22.8 ms instead of 0 s. It was probably delayed by the response time of photoresistor and program processing. Three flickers 1, 4 and 7 with the same flickering signals were placed at different rows while they had different time lags that were 22.8 ms, 28.7 ms and 34.4 ms respectively. In addition, the difference of their time lags were around 5.8 ms. For convenience, the phase of flicker 1 was defined as zero deg for phase reference. The others flickers' relative phases can be derived by (3),

$$\theta = -\, t_{lag} \times f_s \times 360/n \ \ (\text{deg}), \tag{3}$$

where t_{lag} and f_s denote the time lag relative to the flicker 1 and flickering frequency respectively. Table I lists all the mean and standard deviation of relative phases. In summary, different vertical position of flicker seems to influence its relative phase. It is consistent with the aforementioned description that flicker located at different vertical position of screen should have phase shift. Meanwhile, using different brands of LCD monitor still can obtain the similar result. Moreover, the analysis of variance (ANOVA) was performed to further evaluate the effects of different positions, row and column, as well as different brands. Results show that flickers placed at different rows will have significant phase shift ($p < 0.0001$). On the contrary, there is no significant influence on the phase shift for different column's flickers ($p > 0.7$) as well as using different brands LCD monitor such as DELL and ViewSonic ($p > 0.6$).

As mentioned above that the flickers are displayed on screen sequentially, the relationship between their phase lag (θ) or time lag (t_{lag}) and vertical distance (d) should be approximately proportional, is given by (4),

$$t_{lag} \,/\, T_r = -\, n \times \theta \,/\, 360 = d \,/\, V, \tag{4}$$

where V is the vertical resolution of screen, T_r is the refresh period of monitor and n is the number of frequency division. Hence, the phase difference θ may be adjusted by varying their vertical distance d. From (4), the range of adjustable phase and time lag is (0, 360/n) deg and (0, T_r) ms respectively. According to the measurement in Table I, 274 pixels vertical distance can cause around 5.8 ms time lag or –2.1 deg phase lag. Based on (4), if the refresh period was 16.67 ms, n=3 and V=768 pixels in experiment, 274 pixels distance should cause around –2.14 deg phase shift theoretically. The theoretical value and experimental value are almost consistent so we can design the flickers with various phase lag by placing the flickers at proper vertical distance.

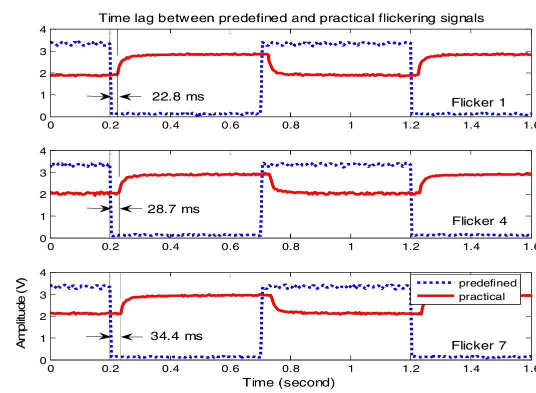

Figure 3. The predefined and measured signals of flickers 1, 4 and 7.

TABLE I. MEAN AND STANDARD DEVIATION OF RELATIVE PHASE FOR NINE FLICKERS IN EXPERIMENT I

Phase (deg)	*LCD monitor brands*			
	ViewSonic		DELL	
Flickers #	***Mean***	***Standard deviation***	***Mean***	***Standard deviation***
1*	0	--	0	--
2	0.12	0.06	0.06	0.06
3	0.06	0.05	-0.06	0.06
4	-2.04	0.06	-1.98	0.07
5	-2.16	0.04	-2.16	0.05
6	-2.04	0.08	-2.22	0.05
7	-4.08	0.04	-4.26	0.04
8	-4.20	0.04	-4.26	0.02
9	-4.14	0.03	-4.20	0.03

*Defined as phase reference

B. Results of experiment II

In this experiment, we designed a LCD visual stimulator (ViewSonic 22", refresh rate 60Hz, 1680×1080 pixel resolution) with six 20 Hz phase-tagged flickers (60 deg phase difference). Apparently, the traditional method is not able to achieve this goal. According to (4), if the vertical distance between two flickers with the same phase is 540 pixels, their phase different should be 60 deg, shown in Fig. 4. Even though two flickers 1 (2 or 3) and 4 (5 or 6) with the same predefined phases recorded in Table II, their vertical distance is 540 pixels, which is capable of causing 60 deg phase shift. Consequently, two vertically adjacent flickers have 60 deg phase lags realistically. The measurements of their practical relative phases are recorded in Table II. The results demonstrate that the proposed visual stimulator produces six phase-tagged stimuli and their phase difference is around 60 deg which is able to fulfill our original goal.

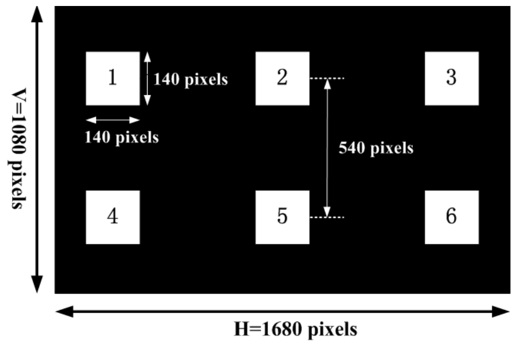

Figure 4. The visual stimulator contained 6 phase-tagged stimuli. Their flickering frequency was 20 Hz. Flickers 1 or 4, 2 or 5 and 3 or 6 were configured as 0, -120 and 120 deg phases, respectively.

TABLE II. COMPARISON OF RELATIVE AND PREDEFINED PHASE FOR SIX FLICKERS IN EXPERIMENT II

Flickers #	***Relative phase (deg)***	***Predefined phase (deg)***
1*	0	0
2	-119.16±0.87	-120
3	-239.61±1.12	120 (-240)
4	-59.04±0.70	0
5	-178.87±1.30	-120
6	-299.11±2.06	120 (-240)

*Defined as phase reference

C. *Results of experiment III*

We applied the proposed visual stimulator designed in experiment II to elicit subjects' SSVEP. In general, the phase angle of SSVEP can be extracted by fast Fourier Transform (FFT) according to (5) and (6) [3]. For instance, x is SSVEP signal evoked by ω_0 (rad/s) stimulus signal so that its phase angle $\theta(x)$ can be calculated by

$$\theta(x) = \tan^{-1} [\mathrm{Image}\{X(\omega_0)\} / \mathrm{Real}\{X(\omega_0)\}], \quad (5)$$

$$X(\omega) = \mathrm{FFT}(x). \quad (6)$$

For each flicker and subject, his SSVEP's FFT coefficients was calculated and plotted on unit circle in Fig. 5 using the function 'circ_plot.m' in CircStat [15]. The small circles denote the FFT coefficients $X(\omega_0)$ projected onto unit circle and the solid line denotes the averaged phase value of each trial for different flickers. Fig. 5 shows that the phases of SSVEP elicited by different flickers have approximately 60 deg difference. However, not all of channels data can provide the satisfactory result so that it should choose one optimal channel for phase information extraction. The proposed selection criterion was considering whether such single channel data has 60 deg phase difference uniformly between six classes, small standard deviation of phase, and good offline classification accuracy together. The offline classification strategy was identifying the flickers by finding the minimum error between $\theta(x)$ and θ_{ref}, where θ_{ref} was a vector of six phase references of flickers [θ_0, θ_0-60, θ_0-120, θ_0-180, θ_0-240, θ_0-300] (deg) and θ_0 represents the averaged phase of SSVEP induced by zero deg stimulus.

All the related phase information of SSVEP is shown in Table III, so the channel selection of S1 and S2 should be PO_4 and PO_Z respectively. Besides, there is a bias between the phase of SSVEPs θ_0 and zero deg flickers. This certain value may be the latency of SSVEP and visual stimulator program processing time.

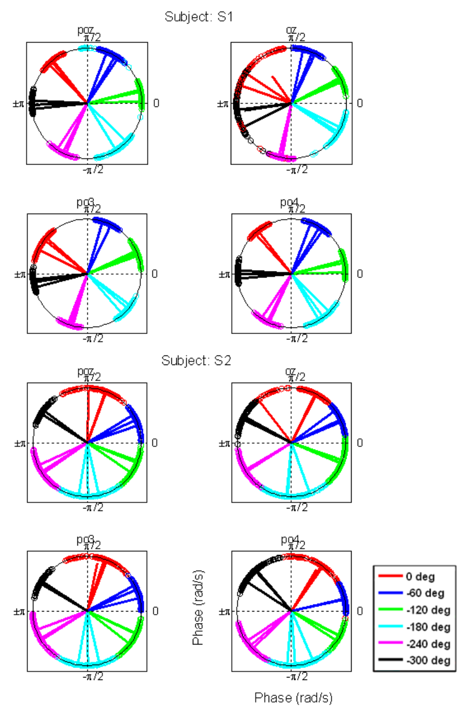

Figure 5. Two subjects' SSVEP phase for each phase-tagged flicker in offline experiments data.

TABLE III. PHASE INFORMATION OF SSVEP CALCULATED IN OFFLINE DATA ANALYSIS

Subject	**Channel**	**S. D.* (deg)**	**Averaged phase lag (deg)**	**θ_0 (deg)**	**Accuracy (%)**
S1	PO_Z	13.85	63.09 ± 13.78	130.91	95.83
	O_Z	13.79	61.04 ± 18.00	147.30	92.41
	PO_3	7.19	59.98 ± 9.92	144.60	99.72
	PO_4	7.09	59.99 ± 9.66	129.77	100.0
S2	PO_Z	11.72	60.01 ± 11.31	75.51	91.76
	O_Z	15.94	59.93 ± 18.87	83.15	88.98
	PO_3	11.83	59.99 ± 11.25	72.15	89.07
	PO_4	12.44	60.01 ± 12.11	56.64	58.70

*Standard deviation

IV. DISCUSSION AND CONCLUSION

In traditional method, the flickers' different phases are produced by only setting different flashing moments, shown in Fig. 1 and (1). Hence, its drawbacks are 1) the available phases are limited; 2) the phases of stimuli probably differ from predefined one. Due to the flickers placing at the same vertical positions but different horizontal positions in many cases, the influence of different vertical positions is usually neglected. We utilized such unobtrusive idea based on vertical distance causing phase lag to improve the traditional visual stimuli generation method.

However, we have to point out that the traditional visual stimuli generation method is still able to generate accurate phase-tagged stimuli only if the flickers are placed at the same vertical position. Otherwise, their vertical distance will influence the flickers' predefined phases. Furthermore, not only the traditional method should take the influence of flicker's vertical position into account, but also the other methods should consider it because sequentially displaying is the inherent characteristic of monitor.

In comparison with the traditional method, the improved method has two main potential applications. 1) It can generate the visual stimuli with more phases than the traditional method. Experiment II demonstrated that six flickers with 3 predefined phases (0, -120 and 120 deg) could be increased to 6 different phases by rearranging their vertical positions. 2) It enables the visual stimuli with distinct frequencies have the same phase difference. For example, the phase difference of 15 Hz and 20 Hz visual stimuli are 90 deg and 120 deg respectively using the traditional method for 60 Hz LCD monitor. However, using the proposed method can make them have the same phase difference. Besides, it can generate the visual stimuli with the same phase but different frequencies. Nevertheless, using the improved method often results in irregular distribution of flickers due to their rearranged vertical positions.

Although CRT monitor had not been tested in our experiments, LCD and CRT have the analogous operational principle, i.e. sequentially display. Thus we also believe that CRT can be employed to generate the visual stimuli using the improved generation method.

In conclusion, although the proposed method has some similarities with the traditional one, the substantial difference is it takes the influence of difference flickers position into account as the vertical distance can cause phase shift. The relationship between phase lag and vertical distance is proportional and it can be described by (4). Theoretically, the proposed method can generate the stimuli with arbitrary phase. In addition, the proposed visual stimulator was designed and applied to SSVEP experiment successfully which demonstrated that it is possible to design the LCD visual stimulator with more phases using the improved method in practical BCI system. Meanwhile, it is meaningful to enhance the BCI performance by means of the proposed visual stimuli generation method to increase the number of flickers. The future work is to apply this proposed stimulator in online SSVEP-BCI system.

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