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A Solution to Harmonic Frequency Problem: Frequency and Phase Coding-Based Brain-Computer Interface

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Abstract—**In this paper, we propose a modified visual stimulus generation method and feature detection algorithm to design a frequency and phase coding steady-state visual evoked potential (SSVEP) based brain-computer interface (BCI). By utilizing both frequency and phase information, we solve the harmonic frequency problem in our proposed SSVEP-BCI system. The offline experimental results show that the proposed feature detection algorithm can enhance the classification rate over 10% (from 69%±12% to 82%±8%) even though only one signal electrode is used and the harmonic frequencies (6.67Hz, 13.33Hz, 8.57Hz and 17.14Hz) are employed.**

I. INTRODUCTION

A brain computer interface (BCI) is an alternative communication channel between human and computer, which is able to translate the brain activities of the patients suffered from some severe disabled diseases into the computer commands to communicate with the external world [1],[2]. Up to now, the BCI system based on steady-state visual evoked potential (SSVEP), a periodic response to a visual stimulus modulated at a frequency higher than 4 or 6 Hz [11],[14] , has received much attention in BCI research due to its three advantages: good system performance, little user training, and easy system configuration [11].

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 [7], the LED stimulator included of 48 LEDs with distinct frequencies between 6 and 16 Hz while the information transfer rate (ITR) can be up to 68 bits/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 is restricted due to the limited refresh rate of monitor, many SSVEP-BCI systems still used LCD/CRT stimulators [8]-[13]. However, one limitation of a LCD/CRT stimulator is that the available stimulus frequencies generated by a monitor are insufficient due to the limited refresh rate [5]. Even though the number of the flickers can be increased by combining phase information [20], the available phases generated by a monitor are also limited by the refresh rate and fixed. More important, the conventional feature detection algorithms cannot identify the SSVEPs evoked by the visual stimuli at stimulus frequencies with harmonic relationship (i.e., harmonic frequency problem). As a result, the number of stimuli in the BCI system with a LCD/CRT monitor is further limited.

To solve the harmonic frequency problem, a modified visual stimulus generation method and a feature detection algorithm based on both frequency and phase information are proposed. In [21], our previous study demonstrates that the modified visual stimulus generation method is able to generate the stimulus phases with a very high resolution of $360/nV$ (deg), which can generate arbitrary phase of a flicker. It can guarantee SSVEPs with different phases such that our proposed feature detection algorithm using both frequency and phase information can overcome the harmonic frequency problem. Furthermore, it may boost the classification rate over 10% against the conventional one.

The remainder of this paper is organized as follows. In Section II we briefly introduce the modified visual stimulus generation method. The harmonic frequency problem and a frequency and phase coding SSVEP-BCI system are addressed in Section III, and the offline experimental results are reported in Section IV. Finally, some discussions and conclusions are provided in Section V.

II. VISUAL STIMULATOR DESIGN FOR SSVEP-BASED BCI

A. *Traditional Visual Stimulus Generation Method*

To evoke a subject's SSVEP, the visual stimulator needs to present a repetitive visual stimulus to the subjects. This repetitive visual stimulus can be generated by a flashing light source or LED, alternating a pattern with foreground/ background color, and rendering different graphics on an LCD/CRT screen [4]. As stated above, even though LED can generate more visual stimuli, many SSVEP-BCI systems still used the LCD/CRT stimulator due to its ease, flexibility, and convenience [5].

In conventional method proposed by [11], 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. Obviously, four phase-tagged flickering signals have four different phases respectively in Fig. 1 since their original phases are different. Basically, it can generate $60/n$ 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 (e.g., maximum phase number of a 20 Hz flickering signal should be 3 and phase

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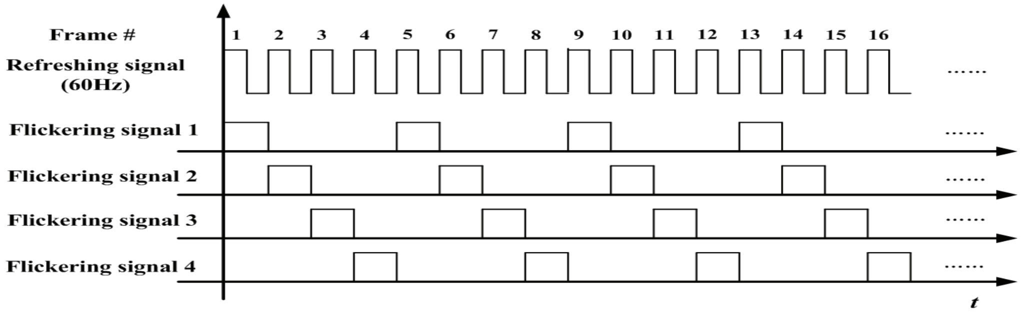
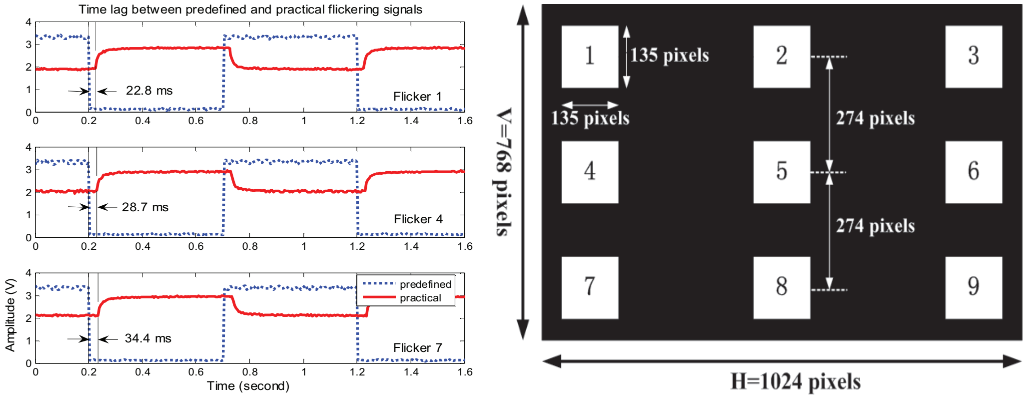


Fig. 1. Predefined flickering signals of four flickers flashing at 15Hz but different phases. Two adjacent flickers have a phase difference of 90 deg.



(a) (b)

Fig. 2. Flickers with the same predefined stimulus frequency (1 Hz) and phase (0 deg) located at different vertical positions (b) have different phases in practical while the traditional visual stimulus generation method is used. The dot line represents the predefined visual stimulus signal generated by (2) and the red solid line represents the practical visual stimulus signal measured by a photoresistor. The high/low level of predefined/practical signal indicates that the flicker is bright (or white) because the resistance of photoresistor is decreasing while the brightness is increasing. For more detailed information, see [21].

difference is 120 deg).

By setting the number of frequency division n_k and original flashing moment m_k ($m_k \le n_k$, m_k is an integer), the conventional method can generate the flicker with corresponding stimulus frequency (f_{sk}) and phase (ϕ_k) while a monitor with R (Hz) refresh rate,

$$f_{sk} = R / n_k . \tag{1}$$

$$\phi_k = -(m_k - 1) \times 360 / n_k \,(\text{deg}). \tag{2}$$

where the subscript k indicates the k-th flicker. Apparently, the number of all available frequencies and phases is proportional to the monitor's refresh rate R. Table I lists the available frequency and phase of a visual stimulus generated by a 60Hz monitor by means of the conventional visual stimulus signal method.

According to [20], Jia *et al*. proposed that embedding the phase information into the frequency coding SSVEP-BCI system can increase the number of flickers, but the phase (ϕ_k) of a flicker is limited by R and fixed, which is inconvenient for practical application.

A. Modified Visual Stimulus Generation Method

In order to generate more phases or generate arbitrary phase of a flicker, a modified visual stimulus generation method is proposed.

It should be noted that the conventional visual stimulus generation method does not consider 'progressive scanning'. 'Progressive scanning' is a monitor's operational principle, which implies that the displayed frame is comprised by a matrix of pixels and each row of pixels is displayed sequentially on screen [6]. Namely, the screen does not render the whole frame at the same time. Actually the rendering time of two images located at different vertical positions have a little time lag. In other words, although the flickers are defined as the same frequencies and phases in stimulator program, their practical flickers have phase shift if they are located at different vertical position. It means that the phase of a flicker (ϕ_k) is not only determined by setting the original flashing moment in (2), but also depended on its rendering time lag/vertical position since the rendering time lag of flickers should be mainly determined by the flicker's vertical position (see Fig. 2)

To sum up, this modified method taking the rendering time into consideration may generate the flicker with more phases (ψ_k) than the traditional one. It can be described by (3). Meanwhile, its stimulus frequency is still given by (1).

$$\begin{aligned} \psi_k &= -(m_k - 1 + \tau_k \times R) \times 360 / n_k \\ &= \phi_k - \tau_k \times R \times 360 / n_k \,(\text{deg}). \end{aligned} \tag{3}$$

where τ_k denotes the time lag. The phase of a flicker (ψ_k) is

TABLE I
THE AVAILABLE FREQUENCY AND PHASE OF A VISUAL STIMULUS GENERATED BY A 60HZ LCD/CRT MONITOR BY MEANS OF THE TRADITIONAL VISUAL STIMULUS GENERATION METHOD

n_k	f_{sk} (Hz)	ϕ_k (deg), m_k=0,1,…,n_k-1
2	30	0,-180
3	20	0,-120,-240
4	15	0,-90,-180,-270
5	12	0,-72,-144,-216,-288
6	10	0,-60,-120,-180,-240,-300
7	8.57	0,-51.42,-102.85,-154.28,-205.71,-257.14,-308.57
8	7.5	0,-45,-90,-135,-180,-225,-270,-315
9	6.67	0,-40,-80,-120,-160,-200,-240,-280,-320
10	6	0,-36,-72,-108,-144,-180,-216,-252,-288,-324

determined by m_k and τ_k while R and n_k are kept constant. We use ψ_k to denote the phase generated by the modified method to distinguish the phase (ϕ_k: predefined phase) generated by the conventional one. Our experimental results in [21] demonstrated that the relationship between their phase lag (θ_j) or time lag (τ_j) and vertical distance (d_j) should be proportional, which is given by (4) and (5),

$$\tau_k / T_R = -n_k \times \theta_k / 360 = d_k / V, \tag{4}$$

$$\theta_k = -(d_k / V) \times 360 / n_k. \tag{5}$$

where V is the vertical resolution of screen and T_R is the refresh period of a monitor. Hence, the phase lag θ_k may be adjusted by varying the vertical distance d_k in (4). In general, the relative phase (ψ_{jk}) is usually adopted during the calculation and presentation in practical. Eventually, the phase difference (ψ_{jk}) between two flickers (the j-th and k-th flicker) modulated at the same stimulus frequency (n_j=n_k=n) should be represented by,

$$\begin{aligned}&\psi_{jk}=\psi_{j1}-\psi_{k1}=\\&(\psi_j-\psi_1)-(\psi_k-\psi_1)=-(m_{jk}+d_{jk}/V)\times 360/n(\text{deg}),\end{aligned} \tag{6}$$

where $m_{jk}=m_j - m_k$ and $d_{jk}=d_j - d_k$. According to (6), assume that ψ_{j1} is the original phase of the j-th flicker so its phase can be adjusted to the other phase (ψ_{k1}) by rearranging m_j and d_j to m_k and d_k respectively, which can be described by

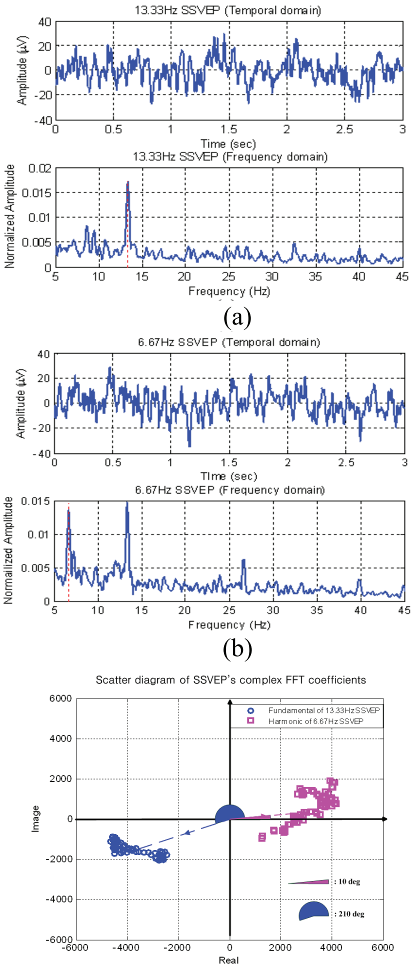
$$\psi_{k1} = \psi_{j1} + (m_{jk} + d_{jk} / V) \times 360 / n(\text{deg}). \tag{7}$$

From this formula, it is easy to find that m_{jk} is used to adjust the phase value with a very low phase resolution of 360/n and d_{jk} is used to adjust the phase with a high phase resolution of ($1/V \times 360/n$) in the range of (0, 360/n) deg.

Consequently, with this modified visual stimulus generation method, the phase of a flicker is no longer limited by R and can be adjusted with a high resolution of $1/360Vn$ (deg). In other words, this method can generate arbitrary phase of a flicker such that the evoked SSVEPs may have significantly different phases.

III. FREQUENCY AND PHASE CODING-BASED BCI SYSTEM

Several papers have developed a new prototype of SSVEP-BCI system: phase coding SSVEP-BCI [11],[15]-[18]. Recently, embedding the phase information into the frequency coding SSVEP-BCI can be utilized to increase the number of flickers [20] so that the system performance can be significantly enhanced. Unlike this idea, our purpose of implementing the frequency and phase coding SSVEP-BCI is to solve the harmonic frequency problem as well as boost the system's classification rate.



(a)

(b)

(c)

Fig. 3. The SSVEPs evoked by two stimulus frequencies 13.33Hz and 6.67Hz. Both prominent peaks locate at 13.33Hz which are (a) stimulus frequency and (b) harmonic frequency respectively. (c) These two SSVEPs have different phases.

A. Harmonic Frequency Problem

The harmonic frequency problem means the conventional approaches are inapplicable for identifying the SSVEPs evoked by the flickers modulated at the harmonic frequencies since the SSVEP potentials elicited by harmonic frequencies usually have the confusing frequency information. In frequency coding SSVEP-BCI, the conventional approaches detect the stimulus frequency from SSVEP by finding at which frequency SSVEP has maximum power (see Fig. 3(a)) [7],[9]-[13]. However, the amplitude of SSVEP (or frequency information) is very unstable and varies with subjects so that occasionally the harmonic component has the most prominent amplitude [11] (see Fig. 3(b)). In this case, the conventional approaches make a wrong detection.

TABLE II

FIVE SUBJECTS' SSVEPS' PHASES (Φ_S) ARE EVOKED BY TEN STIMULI WITH DIFFERENT FREQUENCIES AND THE SAME PHASE (0 DEG) (MEAN±S.D (DEG))

SSVEP^k(f_s)		**Subjects**				
k	**f_s(Hz)**	**S1**	**S2**	**S3**	**S4**	**S5**
1	20.00	***187.2±25.4***	***181.6±24.4***	***143.2±19.0***	***148.1±21.2***	***68.5±27.5***
	17.14	***264.2±13.0***	***23.3±30.4***	***330.2±50.2***	***300.7±17.3***	***252.4±23.4***
	15.00	***348.3±13.9***	***54.7±21.8***	***50.2±42.4***	***355.0±13.1***	***300.8±42.6***
	13.33	***40.9±8.2***	***97.5±21.8***	***115.7±39.1***	***61.8±35.7***	***20.7±28.5***
	12.00	100.2±10.0	173.9±12.4	170.3±36.1	116.0±10.3	89.8±39.7
	10.00	198.5±24.9	249.7±35.6	231.1±43.8	219.9±41.2	182.3±44.6
	8.57	269.1±25.8	335.7±17.2	284.6±40.3	308.9±16.8	259.2±35.0
	7.50	284.5±21.7	336.2±32.0	306.9±39.5	323.1±35.7	274.7±28.5
	8.00	347.4±22.3	20.0±25.8	7.4±43.8	359.6±19.5	337.0±33.1
	6.67	339.3±29.0	353.4±32.6	308.8±62.6	18.6±41.8	-0.4±49.0
2	20.00	317.7±45.7	58.0±47.1	1.0±49.2	6.4±51.9	199.2±36.6
	17.14	327.6±50.6	28.3±50.6	332.4±58.1	164.5±71.1	72.6±54.1
	15.00	239.5±35.2	197.3±37.8	227.1±27.0	149.6±57.4	311.7±60.4
	13.33	165.2±71.8	348.5±36.5	56.6±28.4	344.7±61.1	91.1±45.4
	12.00	108.0±74.9	105.8±18.7	198.1±42.1	124.1±73.5	229.6±21.1
	10.00	***375.4±52.2***	***329.8±45.8***	***73.5±61.9***	***324.2±42.3***	***25.8±37.3***
	8.57	***165.2±17.1***	***162.6±54.2***	***154.4±51.5***	***182.0±28.7***	***193.8±18.5***
	7.50	***223.6±11.6***	***239.3±17.7***	***226.8±39.9***	***232.8±19.5***	***214.9±23.9***
	8.00	278.1±16.0	275.1±30.2	244.0±34.5	277.7±18.8	271.5±29.3
	6.67	***352.0±23.6***	***344.2±13.2***	***310.7±48.4***	***362.9±16.1***	***358.8±16.6***
Average phase difference between SSVEP^2(f_h) and SSVEP^1($2f_h$), f_h=10, 8.57, 7.5, 6.67 (Hz)						
		97.5±21.2	**135.1±30.2**	**144.2±43.4**	**107.6±24.2**	**38.1±28.0**

f_s: stimulus frequency (Hz). S.D.: standard deviation

Actually, applying the additional phase information in conventional approaches can help it solve the harmonic frequency problem since SSVEPs evoked by harmonic frequencies may have different phases. To make sure their significantly different phases, the modified visual stimulus generation method can be used to generate the suitable phases of the corresponding flickers which can evoke SSVEPs with different phases.

We embed the phase information into the feature space. This new feature combining frequency and phase information can be much more separable, which will help us overcome the harmonic frequency problem.

B. Relationship between Latency and Phase of SSVEP

Although SSVEP is phase-locked to the visual stimulus, it does not imply that the phase of SSVEP (Φ_S) is equal to the phase of the flicker (Φ_F) exactly. Since SSVEP does not response to the visual stimulus immediately, it is always elicited after the latency time L [14].

Due to L there should be a phase difference, or labeled as initial phase Φ_I, between the stimulus and SSVEP. The relationship between the phase difference Φ_I and latency L may be described by

$$\Phi_S = \Phi_F + \Phi_I, \tag{8}$$

$$\Phi_I = -(L \times 360 \times f_s - q \times 360), \tag{9}$$

where f_s denotes the stimulus frequency and q denotes the number of cycles. Hence, even if Φ_S and Φ_F are given, L still cannot be obtained due to the unknown q. In general, the latency varies with changes in stimulus frequency, electrode placement, time, and subject. The average value of L at 25~60Hz, 15~25Hz, and 6~15Hz are 30~60ms, 85~120ms, and 135~350ms respectively and it is difficult to be measured exactly [14],[19].

Table II lists the phases of SSVEPs evoked by ten visual stimuli with different frequencies but the same phase (0 deg). Apparently, the phase information varies with the changes in stimulus frequency and subject even though the conditions of the experiments are identical. The small standard deviations of SSVEPs' phases indicate that SSVEPs are phase-locked to the stimulus. Besides, the phase difference between SSVEP^2(f_s) and SSVEP^1(f_s) may be related to the subject because the latency of SSVEP^2(f_s) varies with the subject and frequency (f_s=6.67, 7.5, …, 15, and 20 Hz. Here we use SSVEP^k(f_s) to denote the frequency component of SSVEP evoked by f_s (Hz) stimulus frequency. The superscript k indicates the number of harmonics). So far, we do not yet find the exact relationship between the phase of SSVEP^2(f_s) and SSVEP^1(f_s). In fact, the different phases of SSVEP^2(f_h) and SSVEP^1($2f_h$) can be used to distinguish them (f_h=7.5 or 10Hz), shown with italic types in Table II respectively. Their phase differences are different from each other (e.g, S2 and S3 have large phase difference but S5 has very small phase difference of 38 deg).

In summary, the flicker's phase is usually unequal to SSVEP's phase (or $\Phi_F \neq \Phi_S$). Although SSVEPs evoked by the stimuli with the same phases, the SSVEPs' phase varies with the changes in stimulus frequency and subject such that the phase difference between SSVEP^2(f_h) and SSVEP^1($2f_h$)

are also intersubject variability. As a result, to make sure their large phase difference, the modified visual stimulus generation method should be used to adjust the corresponding flickers' phases.

C. Feature Detection Algorithms

One general algorithm to extract the SSVEP's frequency information is fast Fourier transform (FFT) and to identify the index of N stimulus frequencies by

$$i = \arg\max\{|X(f_1)|, |X(f_2)|, \cdots, |X(f_N)|\}, \tag{10}$$

$$X(f) = FFT(x), \tag{11}$$

where f_j denotes the stimulus frequency of the j-th flicker (j=1,2,…,N). Actually, this algorithm (or the analogous algorithm) was already implemented in many frequency coding SSVEP-BCIs [7]-[13]. Here we aim to embed the phase information of (12) into (10). This idea should improve the classification rate of the original algorithm.

$$\theta(X(f_j)) = \tan^{-1}[\mathrm{Im}\{X(f_j)\} / \mathrm{Re}\{X(f_j)\}], \tag{12}$$

where $\mathrm{Im}\{X(f_j)\}$ and $\mathrm{Re}\{X(f_j)\}$ represent the image and real part of $X(f_j)$ respectively.

For simplicity, the frequency and phase feature in our feature detection algorithm can be denoted as $|X(f_j)|$ and $|\theta(X(f_j)) - \Phi_{Sj}|$ respectively where Φ_{Sj} represents the phase of SSVEP evoked by the j-th flicker with frequency f_j (Hz) and phase Φ_{Fj} (deg). Assume that there is a feature combination function $y_j = F(|X(f_j)|, |\theta(X(f_j)) - \Phi_{Sj}|)$ to combine the frequency with phase feature together and the function value y_j represents that the degree of SSVEP frequency and phase-locking to the stimulus. As a result, the maximum y_j indicates that f_j (Hz) is the stimulus frequency so that the maximum classifier in the conventional feature detection algorithm of (10) still can be used here. Three feature combination functions $F(|X(f_j)|, |\theta(X(f_j)) - \Phi_{Sj}|)$ are proposed here. As we know that the frequency feature $|X(f_j)|$ should be very large but the phase feature $|\theta(X(f_j)) - \Phi_{Sj}|$ should be very small while SSVEP is evoked by the j-th flicker. To let the feature value y_j as obvious as possible, we use the following simple ways: 1) Dividing the frequency feature by phase feature directly, 2) Combining the frequency feature with phase feature based on the proper weight vector W, and 3) Normalizing both frequency and phase features can map them into [0,1] interval, which can avoid their different dimensions while combination. All of them are described by (13)-(15) respectively

$$\begin{aligned} y_j &= F_1(|X(f_j)|, |\theta(X(f_j) - \Phi_{Sj})|) \\ &= |X(f_j)| / |\theta(X(f_j) - \Phi_{Sj})|, \end{aligned} \tag{13}$$

$$\begin{aligned} y_j &= F_2(|X(f_j)|, |\theta(X(f_j) - \Phi_{Sj})|) \\ &= [w_1 \times |X(f_j)| + w_2 \times |\theta(X(f_j) - \Phi_{Sj})|] = WS, \end{aligned} \tag{14}$$

$$\begin{aligned} y_j &= F_3(|X(f_j)|, |\theta(X(f_j) - \Phi_{Sj})|) \\ &= \frac{|X(f_j)|}{\sum_{i=1}^{N} |X(f_i)|} + \frac{\Psi(X(f_j))}{\sum_{i=1}^{N} \Psi(X(f_i))}, \end{aligned} \tag{15}$$

where

$$\Psi(X(f_j)) = \max_{i=1}^{N} (|\theta(X(f_i) - \Phi_{Si})|) - |\theta(X(f_j) - \Phi_{Sj})|, \tag{16}$$

and W=[w_1, w_2], S=[$|X(f_j)|$, $|\theta(X(f_j)) - \Phi_j|$]^T. The index of identified stimulus frequency is based on finding the maximum y_j,

$$i = \arg\max\{y_1, y_2, \cdots, y_N\}, \tag{17}$$

For function $F_1()$, y_j is yield by simply dividing the frequency feature by the phase feature. For function $F_2()$, y_j is the linear combination of the frequency and phase feature, or $y_j=WS$ where W indicates that the importance of these two features and S denotes the feature vector. Basically, the feature vector S can be divided into two classes, $S(f_s)$ and $S(f_{ns})$, which represents that S is extracted from the SSVEP at stimulus frequency (f_s) or non-stimulus frequency (f_{ns}) respectively. Thus W can be trained by LDA to maximize the distance between $WS(f_s)$ and $WS(f_{ns})$. For function $F_3()$, y_j is the summation of the frequency feature and the preprocessed phase feature after normalization. $\psi(X(f_j))$ represents the preprocessed phase feature.

Compared (17) with (10), the difference lies on whether it uses the phase information. Likewise, we also can define another function $F_0()$ where $y_j = F_0(|X(f_j)|, |\theta(X(f_j)) - \Phi_{Sj}|) = |X(f_j)|$ for the conventional feature detection algorithm.

D. Flicker's Phase Adjustment

As mentioned in Section III-A, the prerequisite of solving the harmonic frequency problem by means of embedding the phase information into the feature detection algorithm is the large phase difference between SSVEPs at harmonic frequencies. Otherwise, their analogous phases make no contribution to identify SSVEPs at harmonic frequencies. For example, in Fig. 3 if phase{SSVEP^2(6.67)}=10 (deg) and phase{SSVEP^1(13.33)}=20 (deg), not only the frequency information but also the phase information is confusing in this case. As a result, using both frequency and phase information is still difficult to identify SSVEP^2(6.67) and SSVEP^1(13.33).

However, their phase difference can be enlarged to the maximum phase difference when the phase of 13.33 Hz flicker is adjusted to shift -190 deg by means of the modified visual stimulus signal generation method. It may generate the proper phases of the corresponding flickers which can evoke the SSVEPs with different phases. Based on (7), the phase of 13.33 Hz flicker, 20 deg, can be adjusted into -170 deg while m_{jk} and d_{jk} are set to 5 and -270 respectively. Eventually their phase difference is adjusted to the maximal value 180 deg. With this flicker's phase adjustment, it can avoid the confusing phase information.

In next section, the flicker's phase adjustment is applied to make SSVEPs at harmonic frequencies have different phases if necessary. Then the performance of identifying the stimulus frequency is obviously enhanced.

IV. EXPERIMENTS

A. Experiment Paradigm

Eight subjects (S1~S8) from University of Macau (seven males and one female, ages from 21 to 26 years old) who gave informed consent were seated on a comfortable chair before the visual stimulator in an illuminated room. The subjects' EEG signals were recorded by 6 electrodes (PO_3, PO_z, PO_4, O_1, O_z, and O_2) placed over the occipital area. The ground/reference electrode was placed at FC_z/AF_z. The EEG amplifier settings (g.USBamp, Guger Technologies, Graz, Austria) were set to 0.5 and 60Hz and the notch filter (50Hz) was on. The sampling rate was 600Hz. This dataset was used to evaluate the conventional and proposed feature detection algorithms. In particular, subject S5 carried out this experiment twice. It is because that we found that his SSVEP data have the confusing frequency and phase information from his SSVEP dataset in his first offline experiment. Consequently, his second offline experiment with the flicker's phase adjustment was performed two weeks later (see Fig. 4 and Table III).

An LCD monitor (ViewSonic, 22 inch, 120Hz refresh rate, 1680×1080 screen resolution) was used as the visual stimulator. With the proposed visual stimulus generation method, the visual stimulator displayed 5 flickers flashing at 17.14Hz, 13.33Hz, 12Hz, 8.57Hz, and 6.67Hz respectively and all 0 phases. This experiment consisted of 4 runs containing 15 trials each. Each trial lasted for 10s. Subjects were instructed to focus on one of flickers according to the following paradigm: from 0 to 4s a cue appeared indicating the subjects which flicker was required to focus on while the flickers flashed. From 4s to 10s the subjects gazed at the specified flicker for 6s. Then the next trial started. The order of gazed-flickers was random in each run. Thus this dataset had 12 trials for each flicker. After each runs the subjects had a break. The whole experiment lasted about 40 min.

B. Offline Data Analysis

We collected a total amount of 60 trials (or 4 runs) for each subject, among which the first 15 trials (first run) were for estimating the phase and the remaining 45 trials were used to calculate the classification accuracy. In particular, we adopted the 1st, 2nd, 3rd, and 4th run data to train the weight vector $W=[w_1, w_2]$ for $F_2()$ respectively and the others to calculate the accuracy. Hence, the classification accuracy for $F_2()$ averaged over those 4 calculated results (4-fold cross validation). Six electrodes' signals were analyzed but only one with the best accuracy was reported here.

C. Results of Offline Data Analysis

Table IV lists the average classification rate of 8 subjects across 5 different data segments (1s to 5s). The item (e.g, 0.81/PO$_4$) represents the accuracy is 0.81 which is the best one from analyzing all six electrodes and the corresponding electrode is PO$_4$. Since S5's SSVEPs have the confusing frequency and phase information (Table III), only 2~3% improvement of accuracy benefit from the proposed algorithms (Table IV). For this reason, the second experiment with the flicker's phase adjustment for S5 was carried out. Fig. 4 shows that only first and second flicker's phase should be adjusted. After adjustment of their vertical positions and predefined phases, two phase difference between SSVEPs at harmonic frequencies were enlarged to around 180 (deg) and the improvement of his accuracy was enhanced significantly (see Table IV). It also can be found that the accuracy of each subject is enhanced when using both frequency and phase information in feature detection algorithm, and $F_3()$ provides the best accuracy in Table IV. A t-test indicates that $F_3()$

TABLE III

THE FREQUENCY AND PHASE INFORMATION OF S5'S SSVEP IN THE 1-ST AND 2-ND OFFLINE EXPERIMENT

Experiment	**SSVEP^k(f_s)**		**FREQUENCY INFORMATION (NORMALIZED)**	**PHASE. INFORMATION (DEG)**
(1 or 2)	***k***	***f_s***		
1	1	17.14	0.10±0.05	252.4±23.4
1	1	13.33	0.14±0.08	20.7±28.5
1	2	8.57	0.09±0.03	193.8±18.5
1	2	6.67	0.14±0.04	358.8±16.6
2	1	17.14	0.11±0.04	346.2±21.0
2	1	13.33	0.21±0.05	194.0±36.9
2	2	8.57	0.11±0.03	189.0±16.6
2	2	6.67	0.14±0.03	357.1±13.6

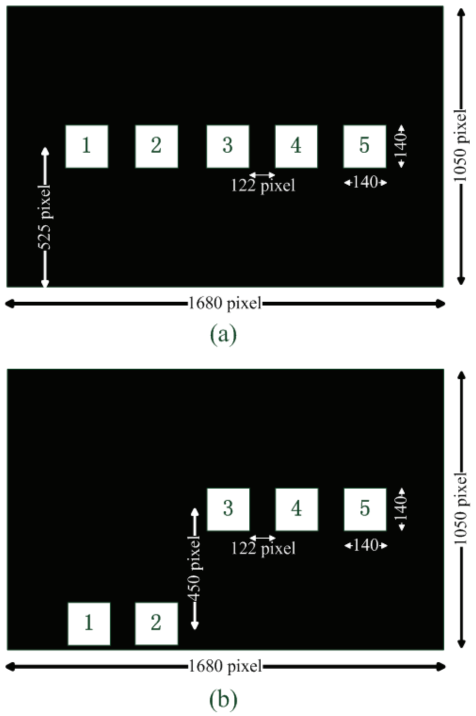


Fig. 4. The distribution of five flickers in the monitor for subject S5. (a) S5 carried out the first offline experiment. All flickers were configured as ϕ_k=0 deg and d_k=525 pixel (k=1,2,…,5). (b) S5 carried out the second offline experiment. The 1-st and 2-nd flickers were configured as ϕ_1=–257.14 deg, ϕ_2=–200 deg and d_1=975 pixel, d_2=975 pixel respectively after flicker's phase adjustment. His SSVEPs frequency and phase information are listed in Table III.

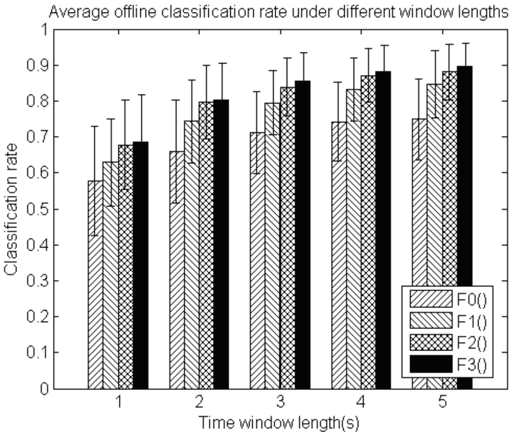


Fig. 5. Average offline classification rate across 8 subjects under different feature detection algorithms and time window lengths.

performs better than the other functions $F_0()$, $F_1()$, and $F_2()$ with a significance of $p<0.01$ so $F_3()$ works best. In addition, its average accuracy rate can be increased from 69±12% to 82±8% (over 10%) when comparing $F_3()$ with $F_0()$. Fig. 5 shows the average accuracy across 8 subjects for different time window lengths and feature detection algorithms.

In summary, all of them can improve the accuracy rate while $F_1()$ provides a little improvement. It is because that $F_1()$ utilizes the least knowledge to combine the frequency and phase feature in comparison with $F_2()$ and $F_3()$. $F_2()$ and $F_3()$ utilize the prior knowledge and all classes' feature to train the weight vector W and normalize the frequency and phase feature so they can combine them reasonably based on W and with consistent dimensions due to normalization respectively. In conclusion, $F_3()$ will be selected as the feature detection algorithm in our coming SSVEP-BCI system since it does not need any training.

Fig. 6 illustrates the comparison between the feature value of $F_0()$ and $F_3()$. The feature value of $F_0()$ and $F_3()$ are

TABLE IV
THE AVERAGE OFFLINE CLASSIFICATION RATE OF 8 SUBJECTS ACROSS 5 DIFFERENT TIME WINDOW LENGTH (1S, 2S,…, AND 5S) FOR DIFFERENT FEATURE DETECTION ALGORITHMS (ACCURACY/ELECTRODE)

Subject	$F_0()$	$F_1()$	$F_2()$	$F_3()$
S1	0.81/PO4	0.90/PO4	0.91/PO4	0.93/PO4
S2	0.76/POz	0.81/Oz	0.88/Oz	0.89/Oz
S3	0.58/O1	0.61/O1	0.67/O1	0.71/O1
S4	0.85/PO3	0.89/PO3	0.88/Oz	0.92/PO3
S5	***0.63***/POz	***0.65***/Oz	***0.64***/PO4	***0.66***/POz
S5*	0.68/Oz	0.80/Oz	0.88/Oz	0.88/Oz
S6	0.73/PO3	0.73/PO3	0.79/PO3	0.80/PO3
S7	0.50/O1	0.68/O1	0.72/O1	0.73/O1
S8	0.59/POz	0.72/POz	0.76/POz	0.76/POz
Mean	**0.69**	**0.77**	**0.81**	**0.82**
S.D.	**0.12**	**0.10**	**0.09**	**0.08**

*The second experiment for S5 with the flicker's phase adjustment

frequency information (i.e., SSVEP's amplitude) of (10) and the combined value y_j of (15) respectively. Different colors represent the feature value at different frequencies. From these five feature value, the index of the largest one can be identified as the index of stimulus frequency. As a result, the targets of 15 trials are '513422514314532' based on the top one. Apparently, the feature value of $F_3()$ can achieve the better performance than $F_0()$ since the proposed algorithm $F_3()$ can identify the harmonic frequencies in the 1-st, 4-th, 7-th, 9-th and 13-th trial.

V. DISCUSSIONS AND CONCLUSIONS

In this paper, we proposed a frequency and phase coding SSVEP-BCI system to solve the harmonic frequency problem by means of a modified visual stimulus generation method and feature detection algorithm based on both frequency and phase information. The offline analysis results show that our proposed feature detection algorithm $F_3()$ can enhance classification rate from 69% to 82% (over 10%) while the

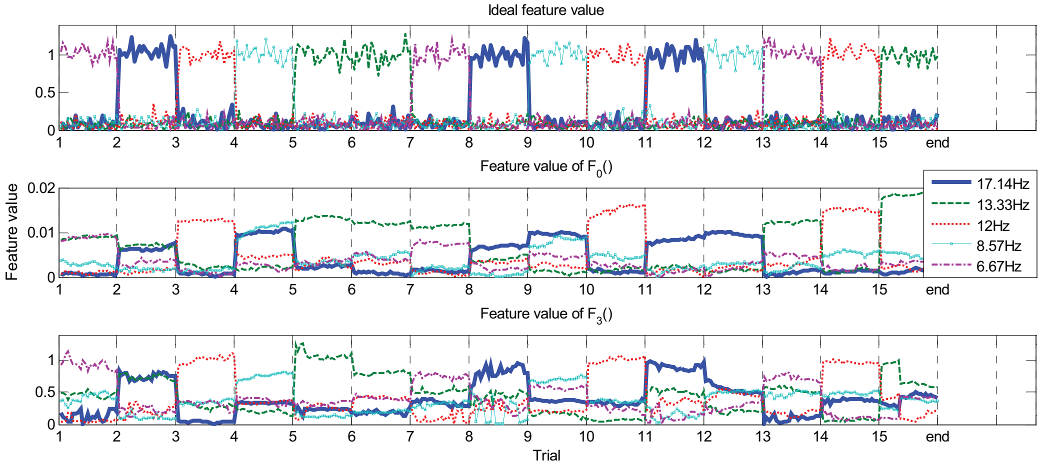


Fig. 6. Feature value of two detection algorithms $F_0()$ and $F_3()$ while analyzing the SSVEP dataset from S5 containing 15 trials. Five flickers flashed at stimulus frequencies with harmonic relationship: 17.14, 13.33, 12, 8.57 and 7.5Hz. More details about this experiment paradigm can be found in Section IV. The top one represents the ideal feature value while S5 gazed at 15 flickers at the order '513422514314532'.

stimulus frequencies with harmonic relationship. Hence, the harmonic frequency problem is overcome by our proposed approach.

In [8], G. Bin is the first one to propose the solution to the harmonic frequency problem. He indicated that the multi-channel detection technology canonical correlation analysis (CCA) can overcome the harmonic frequency problem. Hence, a detailed comparison of the proposed algorithm and CCA is our following work. Actually, the feature combination function $F()$ should be further optimized to combine both frequency and phase feature in a more efficient way. Finally, an online frequency and phase coding SSVEP-BCI system will be designed and implemented in the future.

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