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Frequency Recognition of AM-SSVEP Using Modified CCA and PSDA

M. H. Chang[1], H. J. Baek[1], H. S. Kim[1], K. S. Park[1]
[1]*Seoul National University, Seoul, Republic of Korea*

Correspondence: K. S. Park, Seoul National University, Seoul, Republic of Korea. E-mail: pks@bmsil.snu.ac.kr

Abstract. Steady-state visual evoked potential (SSVEP) response to amplitude modulated stimulus (AM-SSVEP) has been suggested to ease eye fatigue for SSVEP-based BCIs. AM-SSVEP has at least two non-multiple harmonic frequencies, which can be good 'features' to classify AM-SSVEPs. However the frequency recognition method was scarcely investigated for multi-harmonic frequencies. In this study, the modified canonical correlation analysis (CCA) and power spectral density analysis (PSDA) were applied to recognize multi-frequency components of AM-SSVEP. From spectral analysis, seven different harmonic frequency components were identified. Combinations of the harmonic frequencies were employed to estimate the canonical correlation and the sum of SNR from CCA and PSDA, respectively. As a result, the modified CCA outperformed the modified PSDA, and the use of the combination improved recognition accuracy. In particular, the modified CCA with the combination of AM-harmonics using 4 s EEG data seemed to be suitable for a reliable SSVEP-based BCIs.
Keywords: SSVEP, Amplitude modulated stimulus, frequency recognition, multi-harmonic frequency, CCA, PSDA

1. Introduction

Low-frequency steady-state visual evoked potential (SSVEP) has been utilized in brain-computer interface (BCI) because of its high amplitude. But a visual stimulus flickering at low-frequency can cause eye fatigue and even epileptic seizure. Recently a high-frequency stimulus, flickering at higher than 30 Hz, was suggested as a new modality for SSVEP-based BCI with low eye fatigue [Diez et al., 2011]. But high-frequency SSVEP-BCIs made lower performance than low-frequency SSVEP-BCIs [Volosyak et al., 2011]. In our previous study, amplitude-modulated (AM-) stimulus was suggested to encompass advantages of both low- and high-frequency SSVEPs [Chang et al., 2012]. While the AM-stimulus flickers at high carrier frequency, it carries low frequency message in the carrier. Thus, low-frequency SSVEPs under 30 Hz can also be exploited to recognize AM-SSVEP. In this study, we investigated frequency recognition methods for AM-SSVEP that has multi-harmonic frequencies including both low- and high- frequency bands. Modified power spectral density analysis (PSDA) and canonical correlation analysis (CCA) methods were compared in terms of classification performance.

2. Material and Methods

2.1. AM-stimuli

The AM-visual stimulus was fabricated using an LED array flickering as an amplitude-modulated sine wave. The AM-sine wave was generated as the product of a message sine wave $m(t)$ at f_m and a carrier sine wave $c(t)$ at f_c. Using trigonometric functions, AM-sine wave $S(t)$ was expressed as

$$S(\mathrm{t}) = c(t)m(t) = -\frac{1}{2}[\cos(2\pi(f_c + f_m)t) - \cos(2\pi(f_c - f_m)t)]. \qquad (1)$$

Eq. 1 shows AM-stimulus consists of $f_c + f_m$ and $f_c - f_m$ (f_funds) components. f_cs were in high-frequency range (higher than 40 Hz) and f_ms were in low-frequency range (average 11 Hz). Four pairs of f_m and f_c were used in the study: (12, 40), (11, 41), (11, 40), and (10, 40); corresponding f_funds were (52, 28), (52, 30), (51, 29), and (50, 30).

2.2. Experimental settings

Ten subjects participated in the experiment, having consented to the participation. The four AM-stimuli were attached at the cardinal points of a monitor that represented a target. When a target was indicated, subjects had to focus on the relevant LED array for ten seconds without eye or chin movement. Last 9.5 s-length electroencephalogram (EEG) signal was further analyzed to exclude movement noise generated while subjects located a target. EEG data was measured using g.USBamp (g.tec, Austria; f_s = 512 Hz) at O1, Oz, O2, PO3, POz, PO4, P1, Pz, P2, P3, P4, P5, P6, PO7, PO8 referenced and grounded at A1 and Fpz, respectively.

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2.3. EEG analysis

Harmonic frequencies of AM-SSVEP (f_{AMH}s) were reported as $2f_c$, $2f_m$, $f_c \pm f_m$, $f_c \pm 3f_m$ [Chang et al., 2012]. We performed spectral analysis on the 9.5 s data using g.BSanalyze (g.tec, Austria) to confirm the previous report, where the average power over all trials was estimated in terms of the target. Spectral peak frequencies, where SNR was larger than 3, were compared between targets; the frequency commonly appeared in the spectra of more than two targets was defined as f_{AMH}. Modified CCA and PSDA were implemented using the harmonic frequencies for frequency recognition of AM-SSVEP [Bin et al., 2009]. Modified CCA method used a canonical variable (Y) as *sine* and *cosine* of combination of f_{AMH}s and its second harmonics. A class with the highest maximum correlation between EEG signal and Y was assumed as the target where a subject attended. On the other hand, modified PSDA method estimated the sum of SNR at the combination of f_{AMH}s; a class with the highest sum was assumed as the target. EEG signal was a segment of 15-channel data, whose window length varied from 1 s to 9s. For both CCA and PSDA, every combination of f_{AMH}s included f_{fund}s because it was the fundamental stimulus frequencies. Only the highest accuracy among those of the combinations of f_{AMH}s was further considered. Statistical analysis was performed using two-way ANOVA ($\alpha = 0.05$).

3. Results

3.1. AM harmonic frequencies

The reported six AM harmonic frequencies were entirely found in this study. Besides, compared to our previous study, one more f_{AMH} was identified at $2f_c - 4f_m$. Thus 32 combinations of five AM harmonic frequencies ($= 2^5$) including $f_c \pm f_m$ were employed to generate a canonical variable and to estimate SNRs.

3.2. Performance

The estimated accuracy was $85.7 \pm 17.3\%$ for CCA and $62.0 \pm 19.6\%$ for PSDA, which was significantly different by $23.7 \pm 1.9\%$ ($p < 0.001$). Average accuracy of every combination of f_{AMH}s was significantly higher than that of f_{fund}s ($79.6 \pm 20.9\%$ for the combination and $68.0 \pm 21.5\%$ for f_{fund}s; $p < 0.001$). Window length was another factor that affected accuracy ($p < 0.001$). The best combination of f_{AMH}s was proved to be better than f_{fund}s for both modified CCA and PSDA by $11.6 \pm 2.2\%$. Interestingly, there was an interaction between frequency recognition method and window length ($p < 0.01$).

4. Discussion

We found a new harmonic frequency in the spectra of AM-SSVEPs. The new AM harmonic frequency was lower 40 Hz, whereas the estimated frequency range under the previous experimental condition was higher than 44 Hz. This might hinder the identification of the component in the previous study. AM-stimulus is described as the sum of two frequency components as Eq. (1), so that we utilized the sum of SNR rather than a combination of SNR at f_{AMH}s as a feature. In the results, accuracy increased as window length increased, resulting in average accuracy of 85.5 ± 15.9 % with 9 s EEG data. And the modified CCA with combination of f_{AMH} was the best to recognize AM-SSVEP. Finally, the modified CCA with the combination using 4 s-EEG data was assumed to be suitable for reliable SSVEP-BCI with accuracy of higher than 95% ($97.0 \pm 4.5\%$).

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