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USING COMB FILTER TO ENHANCE SSVEP FOR BCI APPLICATIONS

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Abstract

It is postulated that comb filtering of EEG signal prior to FFT analysis helps enhance the steady state visual evoked potentials, e.g. for brain-computer interface applications. Experimental results are presented to confirm the comb filter usefulness.

1 Introduction

Steady-state visual evoked potentials (SSVEP) are involuntary electrical brain responses to periodic visual stimulus [4]. Besides their application to scientific research and medical diagnosis, they are especially useful for the design of brain-computer interfaces (BCI) – the alternative means of men communication with machines, with no or very limited involvement of peripheral muscles or nerves [13]. They offer great flexibility in optimizing the BCI performance, in terms of speed and accuracy [2, 6, 11, 12]. As other EEG signals, SSVEP are measured with electrodes placed on the skin of human scalp [10]. They are rather week and buried in noise, e.g. caused by muscle activity. Thus, there is a need for EEG preprocessing to increase the evoked signal to noise ratio (SNR).

Fortunately, the stimulus and consequently the brain response in the SSVEP are periodic signals of known periods which can be selected in the stimulus design. This property is utilized in our work. We investigated the benefits of using the idea of comb filtering to suppress noise and artefacts whose spectral components do not coincide with the stimulus fundamental frequency and its harmonics [1, 8, 9]. Comb filtering is a well known technique for luminance and chrominance components separation in colour TV decoders. Adaptive comb filtering was used for electrocardiogram (ECG) signal enhancement in [3]. To the Authors knowledge, no attempt has been reported to apply comb filters to SSVEP enhancement.

2 Steady-state visual evoked potentials analysis

In a brain-computer interface system, the user looks at a display with clearly separated fields, each flickering with a specific frequency. The fields are either uniform [6, 2] or split into 2 halves to implement a half-field stimulation of the human visual system [7]. There is a number of fields in a BCI display, e.g. 12 fields of different flicker frequencies were used in [2] to constitute a virtual telephone keypad, representing numbers 0-9, Backspace and Enter keys. If the user puts his/her spatial attention to a specific display field, the amplitude of corresponding flicker frequency component of the EEG spectrum will increase. Thus the relative amplitude of the EEG frequency spectrum at stimuli frequencies is the indicator of the attentional target among the group of display fields.

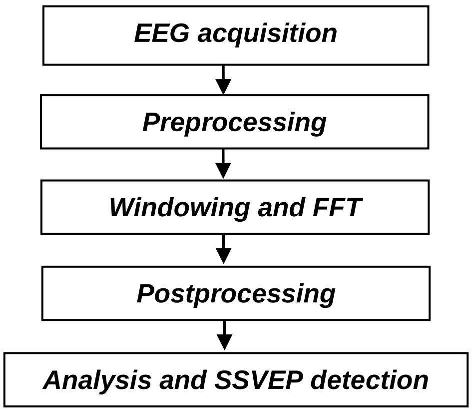


Figure 1: EEG signal acquisition and processing in an SSVEP based BCI system

In general, the EEG contains a continuous distribution of noise power (e.g. related to scalp muscle and spontaneous electrical brain activity) in addition to steady-state VEP. For a given target, the unwanted EEG components include also components of other stimuli frequencies, not intended by the user. The SSVEP frequency values are known, as their fundamental components are equal to the flicker stimuli frequencies. For BCI applications, the presence of the selected component should be detected fast and reliably – its SNR should be made as large as possible. In an attempt to maximize SNR, the SSVEP are measured at places on the scalp that correspond to their largest magnitude [12] or alternate flicker, half-field stimulation with differential measurement is used [7], to name some examples. Given measured EEG, digital signal analysis is used to further improve the SNR related to SSVEP. A large variety of techniques for SSVEP analysis is discussed in [10]. Most often, FFT-derived averaged amplitude spectra (periodograms) are used with partial overlap of FFT windows [6, 2]. Typical steps of EEG signal acquisition and processing performed in a BCI system are illustrated in Figure 1.

The preprocessing covers e.g. banpass filtering, noise and mains frequency components reduction. A widely used technique of windowing assumes 50% overlap in time. The FFT is performed for each window location and a few consecutive amplitude spectra are averaged in the postprocessing step to produce an estimate of power spectrum density (PSD) of the EEG signal in the form of periodogram [9].

The analysis consists in searching for the periodogram frequency component of largest magnitude, above certain threshold. To minimize spectral leakage, the flicker frequencies should be selected such that an integral number of the stimuli cycles is contained in the time interval covered by the window [5]. If this condition is satisfied, the fundamental frequencies of corresponding SSVEP components will coincide with the DFT sample points. This is one of the assumptions for BCI design, see e.g. [6].

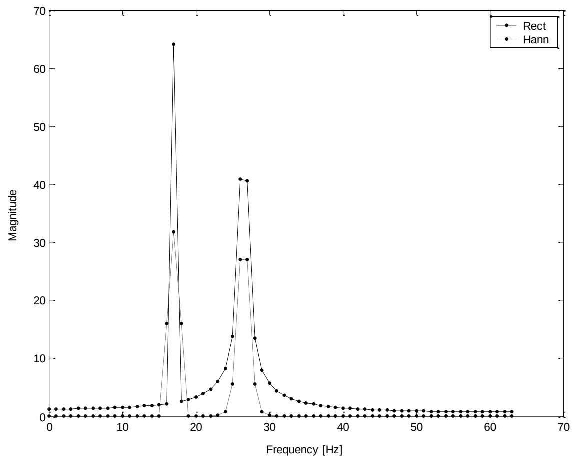


Figure 2: 128-sample FFT-derived amplitude spectra of a sum of 2 sine waves at 17Hz and 26.5Hz, sampled at 128 Hz

Still, there is a need to reduce the spectral leakage of background noise components that have frequencies from the range between DFT sample points. This effect is illustrated by a solid line in Figure 2 where FFT-computed amplitude spectra are plotted for a 128 sample window taken of a sum of two sine waves at frequencies 17 Hz and 26.5 Hz, respectively. Apparently, the power of the second component, whose frequency does not coincide with DFT sample points, leaks into neighbouring DFT samples (solid line). This effect can be reduced by multiplying the signal samples by a properly chosen window function, prior to Fourier transform computation [5]. Indeed, one can see in Figure 2 that von Hann function does the job well (dashed line). However, it simultaneously reduces the spectrum amplitude at the frequency of 16 Hz, thus decreases the SNR. In general, using window functions is not a right preprocessing method for SSVEP enhancement. This example also confirms that the flicker stimuli frequencies should coincide with DFT samples, otherwise the leakage effect will contribute to an increase of the spurious background components.

The proposed preprocessing technique which can help reduce the effect of noise uses a sum comb filter

$$y_k = x_k + x_{k-N} \tag{1}$$

where x_k is the *k-th* signal sample, y_k is the output of the filter at discrete moment k, and N is the number of samples in the window.

The filter (1) is a notch filter with N notch frequencies in the range $0 \le \omega < 2\pi$, where ω is the angular frequency [8]. The magnitude response has then N minima at

$$\omega_k = \frac{(2k+1)\pi}{N} \tag{2}$$

and N peaks at

$$\omega_k = \frac{2k\pi}{N} \tag{3}$$

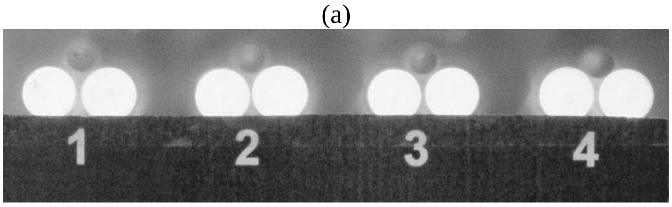
$k=0,1,\ldots,N-1$. The peaks of the comb filter magnitude response coincide with the flicker stimuli frequencies, so it passes the corresponding SSVEP components basically undistorted. On the other hand, notches at frequencies (2) fall between the stimuli frequencies and contribute significantly to attenuation of unwanted EEG background noise. This has been confirmed by experiments described in the following Section.

3 Results and discussion

An experiment was carried out using a half-field alternate stimulation SSVEP technique [7]. The EEG signal was measured differentially using two electrodes located on the left and right side of the occipital part of the scalp (Figure 3a) with a reference electrode placed between them for active compensation of the common-mode signal. The battery-operated differential amplifier and 10-bit A/D converter were placed close to the electrodes (contained in a box shown above the ear of the user in Figure 3a). This module was radio-coupled to the computer via a Bluetooth® interface. The sampling frequency was 200Hz, and the measurement range ±256μV. Four groups of different flicker frequency light emitting diode (LED) pairs are shown in Figure 3b and the upper left corner of Figure 3a, in front of the user eyes. The flicker frequencies were selected in the range above the spontaneous brain signals, equal to 25.0 Hz, 26.5625 Hz, 28.125 Hz, and 29.6875 Hz, respectively for the LED light sources (1 to 4 in Figure 3b). An extra LED was mounted between each two LEDs in a pair, whose light intensity was driven by a current inversely proportional to a feedback signal, defined as the signal/background ratio (S/B).

The feedback signal was computed as the ratio of the amplitude of EEG spectral component at the corresponding frequency to the sum of other amplitudes in the range 23.43-31.25 Hz. This sum represents the strength of background noise of any origin. Thus, for the purpose of this paper the S/B ratio is the estimate of the SSVEP signal to noise ratio. When the user switches his/her attention to a given LED pair, the feedback diode (in the middle of and slightly above the LEDs Figure 3b) reduces its brightness as the amplitude of SSVEP at the corresponding frequency increases. This feedback mechanism is helpful in the process of user training to use our BCI. At the same time, the largest S/B among the 4 frequency components in our experiment indicates the dual-LED light source the user most likely selected by looking at the display.

(a)



(b)

Figure 3: Photographs of 4-frequency alternate half-field stimulation SSVEP experimental setup (a) and of its display with 4 dual-LED targets (b)

To investigate the problem addressed, a male subject was asked to look at the display and switch his attention from one dual LED target to the other, every few seconds, from #1 through #2 and #3 to #4 and back to #1. The subject EEG was measured and its periodogram computed based on 3 consecutive 256-sample windows with 50% overlap (Figure 4). Figure 4 shows the pattern of SSVEP at 4 frequencies and indicates substantial power of spurious background signals.

Applying the von Hann windowing to EEG samples prior to FFT computation results in the spectrogram shown in Figure 5. Windowing apparently reduces the noise power; however, the SSVEP components are reduced in amplitude and “blurred” in frequency, in agreement with the general windowing effects discussed in [5].

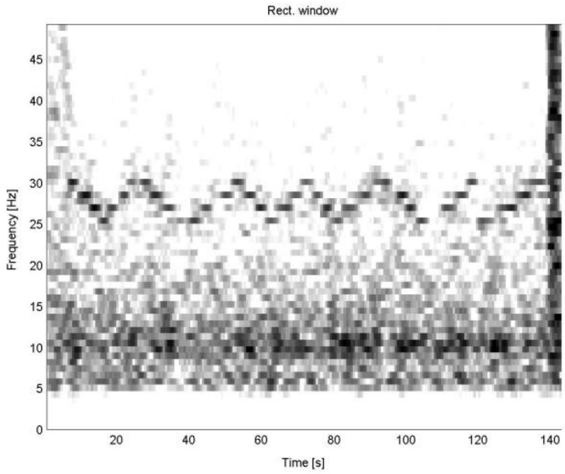


Figure 4: EEG spectrogram (rectangular window)

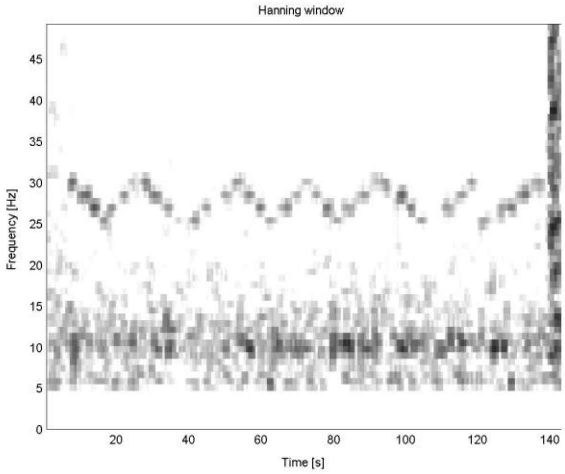


Figure 5: EEG spectrogram (von Hann window)

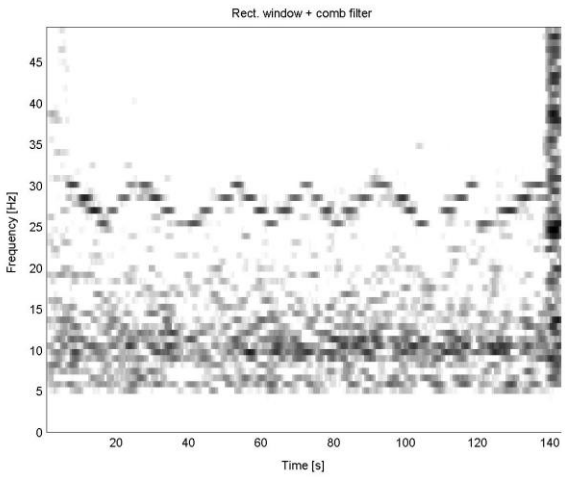


Figure 6: EEG spectrogram (rectangular window, comb filter preprocessing)

Comb filtering the EEG signal instead of windowing gives the spectrum shown in Figure 6. The amplitude of SSVEP components is not reduced as in Figure 5, whereas the background noise is decreased compared to Figure 4. This effect is even better illustrated in Figures 7 and 8 where the S/B ratio is plotted as function of time, at two selected SSVEP frequencies. In most cases, application of the comb filter causes a substantial SSVEP amplitude increase with respect to spurious background signals. No case of S/B decrease was noticed.

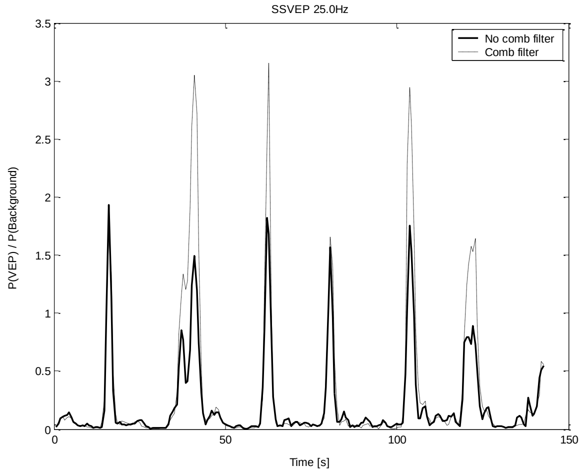


Figure 7: The signal to background ratio at stimulus frequency of 25.0Hz with rectangular window (solid line) and comb filtering (dashed line)

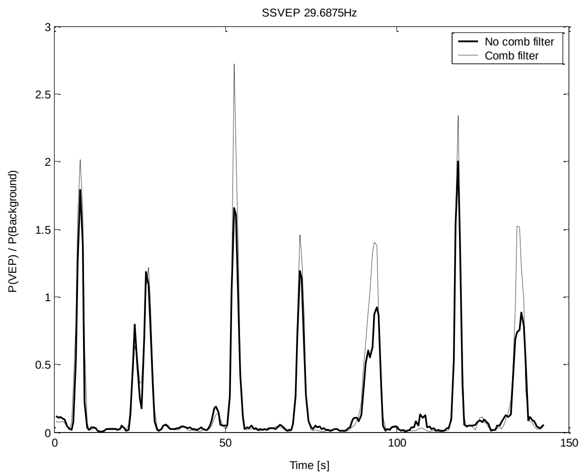


Figure 8: The signal to background ratio at stimulus frequency of 29.6875Hz with rectangular window (solid line) and comb filtering (dashed line)

4 Conclusion

It has been demonstrated that by proper selection of the stimulus frequency in SSVEP BCI systems (such that they coincide with DFT frequency samples) and comb filtering of the EEG signal prior to performing the DFT, substantial enhancement of the SSVEP can be achieved. Experiments show that signal to background ratio is doubled in most cases. This enhancement may contribute to the accuracy increase of brain-computer interfaces. This is the topic of the present research in our laboratory.

Acknowledgements

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