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Analog Matched Filtering Technique for SSVEP Detection

Hardware Overview

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Abstract

Steady-state visual evoked potential (SSVEP) is an electroencephalogram (EEG) activity elicited by continuous flickering of visual stimulus. These are oscillatory electrical potential that are evoked in the brain when the person is visually focusing his/her attention on a visual stimulus that is flickering at frequency 10 Hz and above. SSVEP has been intensively adopted in brain-computer interfaces to map the human brain activity with computers or external devices. These signals are strong in occipital region (visual cortex) of the brain and are nearly sinusoidal waveform having the same fundamental frequency as the visual stimulus. The detection of this frequency can be achieved by a method of matched filtering, in which the matching/correlation of extracted evoked SSVEP signal frequency from the brain with the corresponding stimulated one. The approach presented in this document, to detect the frequency information of the visual stimulus from the evoked noisy EEG signal is using based on quadrature analog matched filtering technique. The hardware details of the matched filtering and it's test results are presented in this report.

1. Introduction

The condition, where the person is cognitively intact but the body is paralyzed, which means the voluntary control of muscles is lost and people cannot move their arms, legs, or faces, and completely depend on wheelchair controlled by his/her brain waves. The only effective way for the paralyzed person to communicate with the environment is with a device that can read brain signals and convert them into control and communication signals. Such a device is called a brain–computer interface (BCI). BCIs rely on electrical measures of brain activity, and rely on sensors placed over the head to measure this activity. Measuring brain activity effectively is a critical first step for brain–computer communication. There are many methods of measuring brain activity through noninvasive means. Noninvasive techniques reduce risk for users/paralyzed persons since they do not require surgery or permanent attachment to the device. EEG (electroencephalography), however, is the most prevalent method of measuring brain activity non-invasively. Many EEG-based BCI systems use an electrode placement strategy suggested by the International 10/20 system. One of the extraction methods of EEG signals from the brain are based on event related or evoked potentials.

Evoked potentials are time-locked responses by the brain that occur at a fixed time after a particular external event. These potentials usually occur when subjected to sensory or aural stimulus, mental event, or a constantly occurring visual stimulus. In fact, visual attention can be implemented with two different BCI approaches, which rely on different stimuli, mental strategies. These approaches are named after the brain patterns they produce, which are called P300 potentials and steady-state visual evoked potentials (SSVEP). SSVEP based BCI requires a number of visual stimuli. Each stimulus is associated with a specific command, which is associated with an output the BCI can produce.

These stimuli flicker continuously with different frequencies in the range of about 6–30 Hz. Paying attention to one of the flickering stimuli elicits an SSVEP in the visual cortex that has the same frequency as the target flicker. That is, if the targeted stimulus flickers at 16 Hz, the resulting SSVEP will also flicker at 16 Hz. Therefore, an SSVEP BCI can determine which stimulus occupies the user’s attention by looking for SSVEP activity in the visual cortex at a specific frequency. The BCI knows the flickering frequencies of all light sources, and when an SSVEP is detected, it can determine the corresponding light source and its associated command.

2. Analog Matched filtering Scheme

A matched filter is the optimal linear filter for maximizing the signal to noise ratio (SNR) for a known signal in the presence of additive noise. Matched filters are often used in signal detection to correlate a known signal, or template, with an unknown signal to detect the presence of the template in the unknown signal.

In RRI-BCI project, we have developed an analog matched filter scheme to detect a definite Steady state voltage evoked potential (SSVEP) existing in the noisy EEG signal, which are emerged from the human brain.

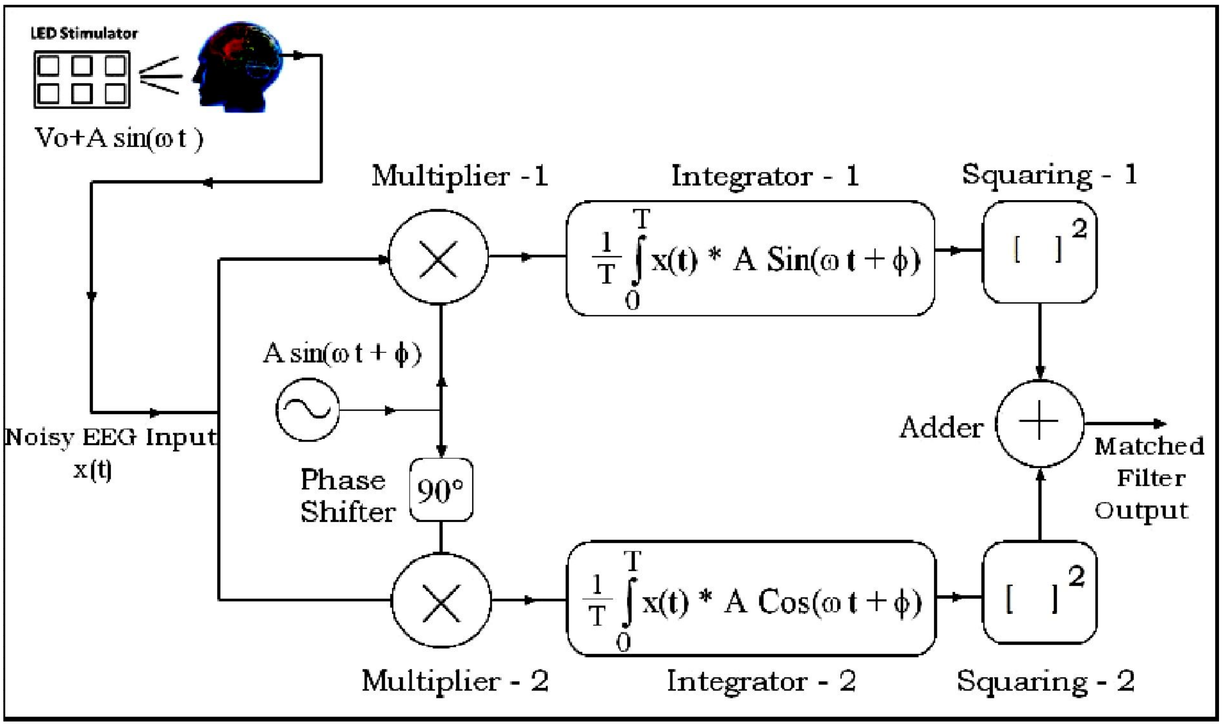


Figure 1 Block Diagram of the Analog Matched Filtering Technique

The analog matched filtering scheme consists of two sections. The first section is the visual stimuli frequency generation and the other is the matched filtering processing part.

2.1 The visual Stimuli generation

Each frequency is associated with a certain event to occur once it’s detected form the brain in SSVEP based BCI. The visual stimuli requires a sine-wave frequency generation of period ‘T’ with amplitude of ‘A’ Vp-p, which enables a LED to flicker for SSVEP signal stimulation from the brain. The sine-wave is generated with non-zero mean value with a positive offset ‘V0’, so that it’s complete full sine-wave (both positive and negative peaks) above zero biases the LED, to avoid the clipping. This ensures the non-generation of harmonics in the flicker frequency, so that the subject should strongly respond to only pure sine-wave variations as shown in the figure 2. The brightness of the visual stimulus can be adjusted according to the subject’s requirement using a current controlled potentiometer.

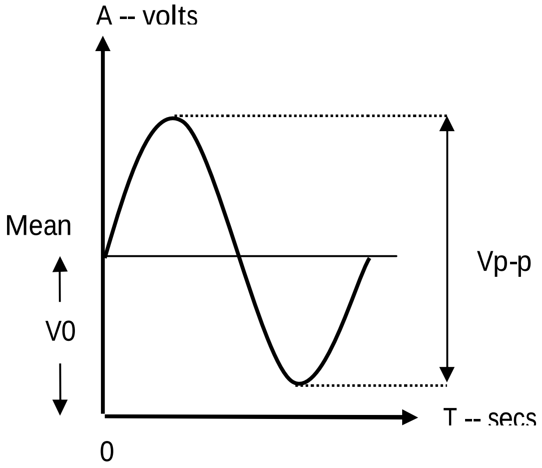


Figure 2 Sine-wave generation with off-set V0

A copy of the generated sine-wave of frequency with mean zero is connected to the processing board through a buffer for matched filtering process.

2.1.1 Stimuli Sine-wave Frequency generation hardware

The visual stimuli sine-wave is generated using ICL8038 waveform generator chip. It is a monolithic integrated circuit capable of producing high accuracy sine, square, triangular, saw-tooth and pulse waveforms with a minimum of external components. The frequency (or repetition rate) can be selected externally from 0.001Hz to more than 300 kHz using resistors and capacitors as shown in the figure 3.

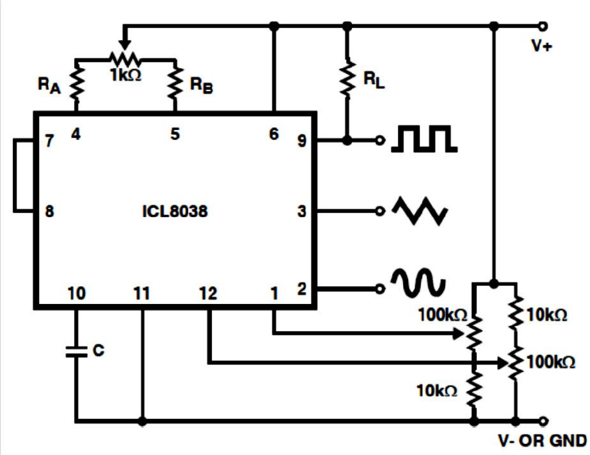


Figure 3 Sine-wave generation circuit

The frequency of the sine-wave is set by choosing the R_A, R_B and C values, using the following relationship

$$\textbf{frequency} = \frac{0.33}{R*C}\ \textbf{Hz}$$

By choosing $R_A = R_B$, the 50% duty cycle is achieved. Further adjustment of the duty cycle is done using the 1KΩ potentiometer connected between the pins 4 & 5.

For BCI- SSVEP experiments, the beta waves frequencies from 12Hz to 18Hz are generated. The capacitor 'C' value is fixed to 1μF for generation of all the frequencies. The fixed values of R_A, and R_B are trimmed to an approximate nearby values. The complete frequency generation circuit can be referred using schematic page attached in the Annexure 1.

2.1.2 Sine-wave Mean offset adjustment

The sine-wave mean offset voltage V0 is adjusted using the op-amp offset control circuit as shown in the figure 4. The amplification gain is set using 'Rf' and 'Rin' resistors. The figure 4 shows the circuitry for mean offset adjustment.

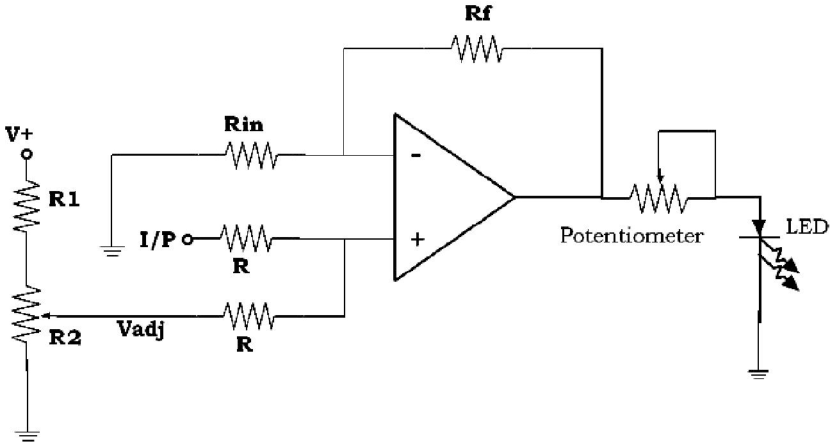


Figure 4 Sinewave mean offset voltage circuit with LED brightness control

By adjusting the resistance value of the 'Vadj' potentiometer, the mean off-set voltage of the sine-wave is adjusted and is to around 3.5 to 4V, such that the LED is made to flicker at the peaks of complete one cycle of sine-wave as shown in the figure 2.

2.2 Analog Matched filter processing

Analog matched filtering process used for SSVEP detection is based on the analogy of quadrature detection. The incoming visual stimulated SSVEP EEG signal from the visual cortex region of the brain is basically modulated by noise in nature. To extract the stimulated frequency information from the noisy signal, the SNR of the corresponding signal needs to be maximized. An analog matched filtering technique is used for this purpose to detect the known template frequency information from the EEG signal.

In this scheme, the noisy EEG signal x(t) is multiplied by both Cos(ωt) and Sin(ωt), where the 'ω' is the generated stimuli of known frequency. Then these quadrature products are integrated over the one period 'T = 1 / 2πf' of the generated template signal individually, squared and added as shown in the figure 1. The mathematical equations illustrates the quadrature matched filtering technique as described below.

<u>Equations :</u>

<u>1st Multiplier product</u>

$P_1 = (V0 + A \sin\omega t) * [A \sin(\omega t+\phi)]$

$= V0 * A \sin(\omega t+\phi) + A^2 \sin^2\omega t * \cos\phi + A^2 \sin\omega t * \cos\omega t * \sin\phi$

Integrating over a period 'T', we get

$$= (V0 * A) \int_0^T \sin(\omega t + \phi) dt + \int_0^T A^2 sin^2 \omega t * \cos\phi\, dt + \int_0^T A^2 \sin\omega t * \cos\omega t * \sin\phi\, dt$$

The 1st term and 3rd term becomes zero and Since sin ϕ and cos ϕ are constants, the P_1 reduces to

$$= A^2 \int_0^T \left[\frac{1-cos2\omega t}{2}\right] * cos\phi\, dt$$

$$= \frac{A^2}{2}\cos\phi \int_0^T dt - \frac{A^2}{2}\cos\phi \int_0^T \cos 2\omega t\, dt$$

$$P_1 = \frac{A^2 T}{2}\cos\phi$$

Squaring P_1, we get

$$P_1^2 = \frac{A^4\, T^2}{4}\, cos^2\phi$$

similarly

2nd Multiplier product

$$P_2 = (V0 + A \sin\omega t) * [A \cos(\omega t+\phi)]$$

$$= V0 * A \cos(\omega t+\phi) - A^2 \sin^2 \omega t * \sin \phi + A^2 \sin \omega t * \cos \omega t * \cos \phi$$

Integrating over a period ‘T’, we get

$$= (V0 * A) \int_0^T \cos(\omega t + \phi) dt - \int_0^T A^2 sin^2 \omega t * \sin\phi \, dt + \int_0^T A^2 \sin\omega t * \cos \omega t * \cos\phi \, dt$$

The 1st term and 3rd term becomes zero and Since sin ϕ and cos ϕ are constants, the P_1 reduces to

$$= - A^2 \int_0^T \left[\frac{1-cos 2\omega t}{2} \right] * sin\phi \, dt$$

$$= - \frac{A^2}{2} \sin\phi \int_0^T dt + \frac{A^2}{2} \sin\phi \int_0^T \cos 2\omega t \, dt$$

$$P_2 = -\frac{A^2 T}{2} \sin\phi$$

Squaring P_2, we get

$$P_2^2 = \frac{A^4 T^2}{4} sin^2 \phi$$

Now adding P_1^2 and P_2^2, the final matched filter output equation leads to

$$\text{MF output} = \frac{A^4 T^2}{4} sin^2\phi + \frac{A^4 T^2}{4} cos^2\phi$$

$$= \frac{A^4 T^2}{4} [sin^2\phi + cos^2\phi]$$

$$= \frac{A^4 T^2}{4} * 1$$

$$\text{MF output} = \boldsymbol{\frac{A^4 T^2}{4}}$$

At any given time, matching of the frequency either with ‘cos’ or ‘sin’ would work, but it ensures that the result will not be 0 at the same time. This technique is used to recover the signal reliably always. By adjusting the amplitude of the incoming EEG signal from the bio-amplifier and the integration time, the matched filter amplitude output can be maximized.

2.2.1 Matched filtering process hardware

The matched filtering process hardware consists of buffers, analog multipliers, 90° phase shifter, the integrators, squarer and an adder. The op-amp buffer stage is used to impedance match between the bio-amplifier and the analog multiplier input section. A phase shifter is used to generate the quadrature 90° phase shift version(Cosine wave) of the stimuli sine-wave. A multiplier is used to multiply the incoming buffered EEG signal with the Sin and Cos waves. The integrators are used to integrate and average the multiplier outputs. The analog multipliers are used as squarers to square the integrated products. An op-amp summer configuration is used as an adder.

a. Analog Multiplier

Multiplier is implemented using Analog devices IC AD633. It is functionally a four-quadrant, analog multiplier. It includes high impedance, differential X and Y inputs, and a high impedance summing input (Z). The low impedance output voltage is a nominal 10 V full scale provided. The Z input provides access to the output buffer amplifier, enabling the user to sum the outputs of two or more multipliers, increase the multiplier gain, convert the output voltage to a current, and configure a variety of applications.

The basic configuration of the analog multiplier is shown in the figure.

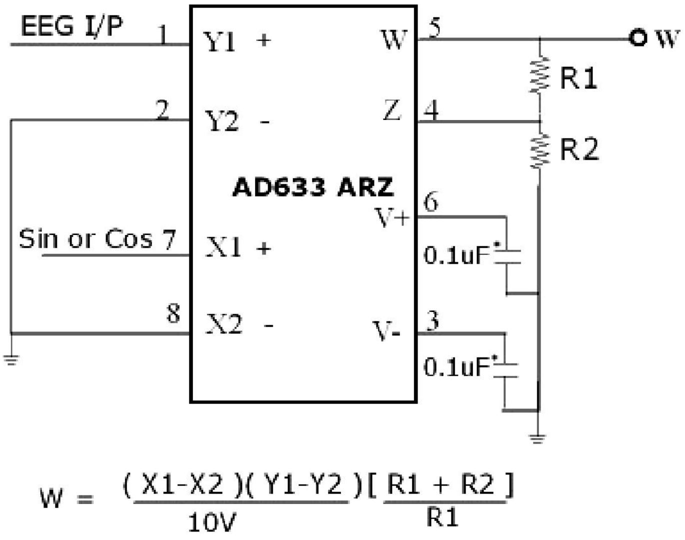


Figure 5 Analog Multiplier Using AD633

The X and Y inputs normally have their negative nodes grounded. The multiplier voltage output ‘W’ can be scaled by setting the R1 and R2 values using the gain equation shown in the figure.

$$W = = \frac{[X1-X2]*[Y1-Y2]}{10V} * \left[\frac{R1+R2}{R1}\right] \quad \text{where } 1K\Omega \leq R1, R2 \leq 100K\Omega \text{ and}$$

this ratio is limited to 100 in practical applications.

In matched filtering section, the multiplier voltage gain in multiplier section is set to ‘5’, with R1 and R2 being 10K and 40K respectively.

b. Phase Shifter

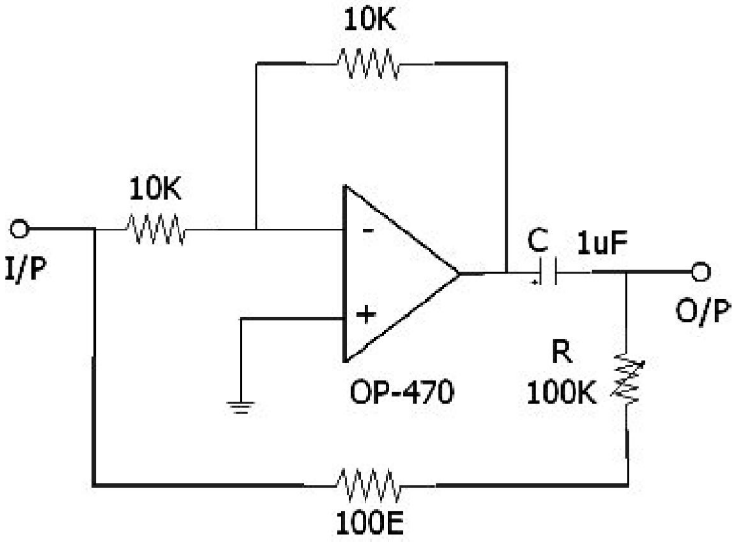


Figure 6 Quadrature Phase shifter Circuit

To generate the quadrature co-sine wave corresponding to the stimuli sine-wave, a OP-470 op-amp based phase shifter has been implemented. The circuit diagram is as shown in figure 6. Basically it’s a frequency independent phase shifter, where in R and C forms the phase lag network with a feedback which produces the 90° phase shift with respect to the sine-wave input as shown in figure 7. The inverting amplifier configuration is set to unity gain. For the flexibility of adjusting the 90° phase, R is chosen as variable, where as rest of all the components are fixed.

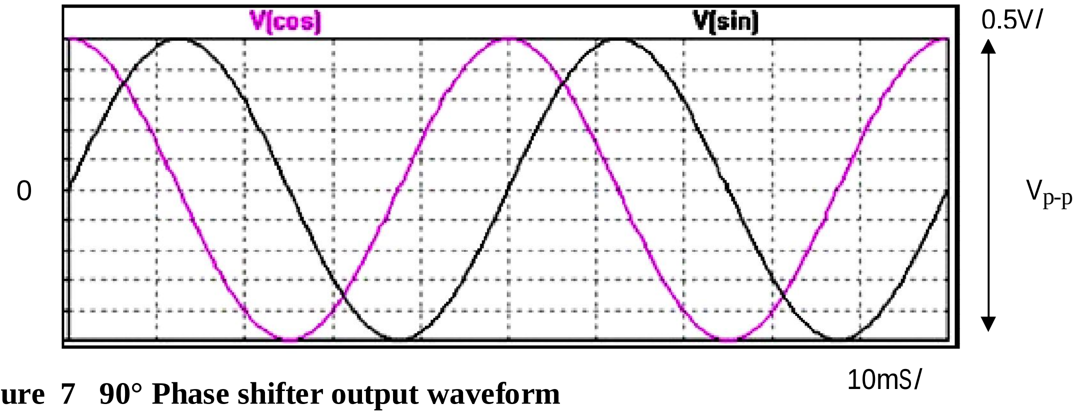


Figure 7 90° Phase shifter output waveform

c. Integrator

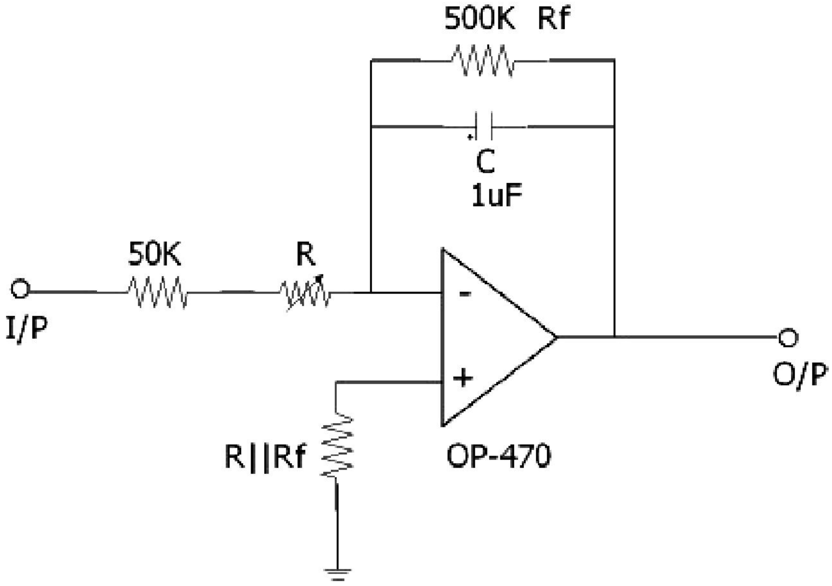


Figure 8 Op-amp Integrator Circuit

The Op-amp Integrator is an operational amplifier circuit that performs the mathematical operation of Integration. The output of the circuit respond to changes in the input voltage over time as the op-amp integrator produces an *output voltage which is proportional to the integral of the input voltage*. The input being the product of EEG and either Sin or Cos waves. As the feedback capacitor, C begins to charge up due to the influence of the modulated input voltage (resultant product from the multiplier), its impedance Xc slowly increase in proportion to its rate of charge, hence the inverting amplifier output voltage amplitude peaks depending on the integration time.

The integration time is determined by the RC time constant, (τ) of the series RC network. The rate at which the output voltage produces (the rate of change) is set by the value of the resistor and the capacitor. The gain of inverting amplifier can be adjusted by the R_f and R values as shown in figure 8. The magnitude of the integrated output voltage is given by

$$\mathbf{Vout} = -\frac{A^2}{\boldsymbol{RC}}\int_0^T x(t) \ast [A \sin(\omega t + \phi)]$$

Where τ = RC is the time constant of integration

$$T = \frac{1}{f} \text{ secs}$$

‘f’ is the stimuli frequency in Hz.

d. Squaring section

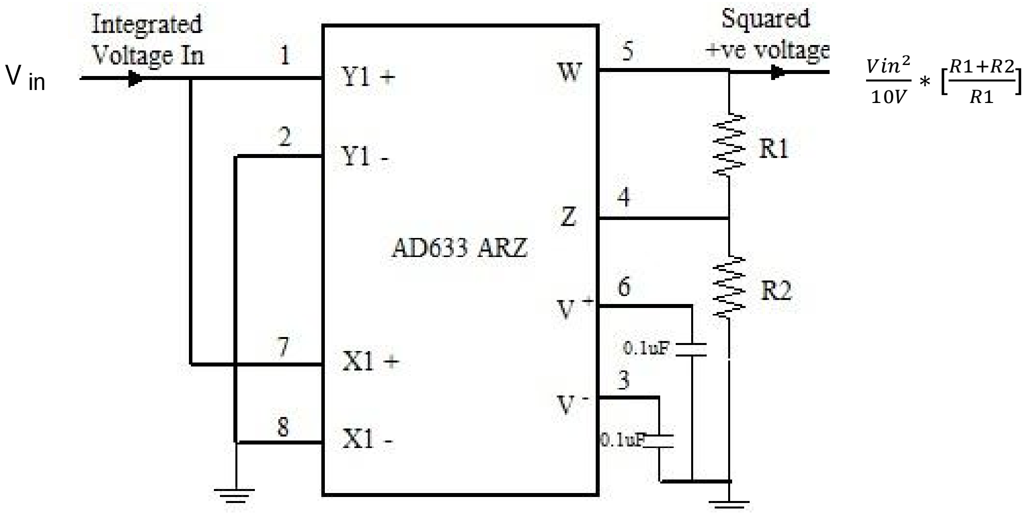


Figure 9 Squarer circuit

The output voltage from the integrator which is integrated and averaged over one/more period ’T’ is squared using a squarer circuit. It is implemented using the chip AD633 multiplier, in which the two non-inverted inputs are tied together, so that the input voltage is self multiplied and resultant output is the mathematical square of the input integrated voltage. The two channel squaring sections (Sin and Co-sine channels) ensures that matched filtering detection is always non-zero output. Here, again the scaling of output voltage is controlled by the gain setting using R1 and R2 values as shown in the figure 9.

e. Adder

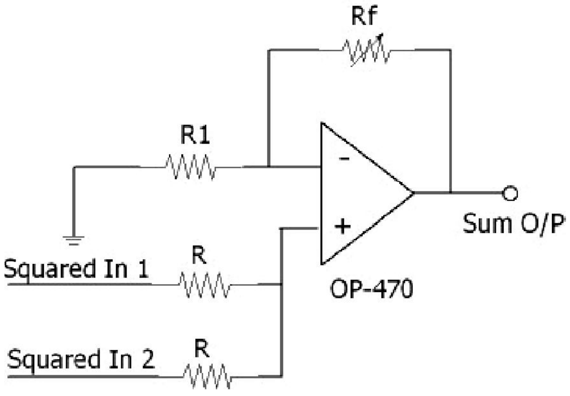


Figure 10 Non-inverting summer circuit

The squared positive voltages from individual Sine and co-sine channels are added to obtain the maximum amplitude which is the detected information corresponding to the mapped visual stimuli frequency of ‘f’ Hz. At any given time of instant, either of the quadrature channels contribute to the detected output voltage. The Op-Amp OP470 is configured as non-inverting summer as shown in figure 10. The D.C gain of the non-inverting configuration can be adjusted using the feedback variable resistor R_f for obtaining the appropriate output voltage level.

Matched Filter output = $E_1^2 + E_2^2$

Where

‘E_1’ is the corresponding detected amplitude of the stimuli frequency from ‘Sin’ channel and

‘E_2’ is the corresponding detected amplitude of the stimuli frequency from ‘Cos’ channel

3. Implementation

A one channel analog matched filter stream comprises of the combination of visual stimuli frequency generation section and the matched filter process section. Four channels of stimuli frequency generation hardware are implemented on one single PCB board and the corresponding four channels of matched filtering process hardware are implemented another single PCB board. Using two such combinations of boards, 8-channel analog matched filter system has been implemented.

Each visual stimuli frequency generation channel has one sine-wave output with mean zero and other output of mean with offset, to which an LED with brightness adjustment is connected for visual stimulation as shown below in the figure 11a.

In the similar manner, every matched filtering processing channel has an EEG input and the corresponding off-set mean sine-wave input. The EEG input is nothing but the noisy amplified signal output from the bio-amplifier and matched filtered detected output is shown by an LED indication D1 D2 D3 and D4 on the board as well as it is terminated on the connector for further interface as shown in the figure 11b.

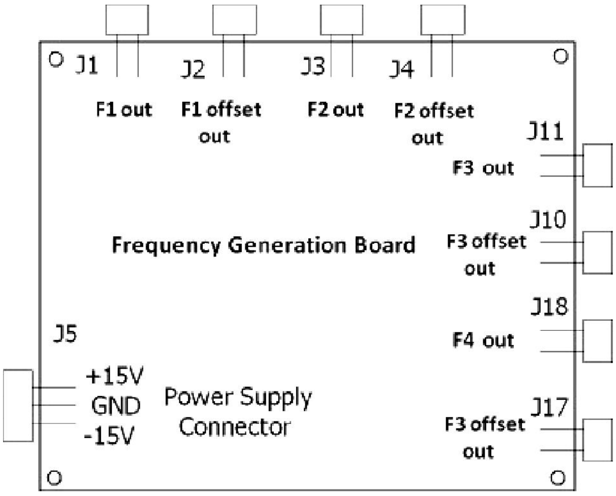


Figure 11a. Frequency Generation board PCB connectivity Layout

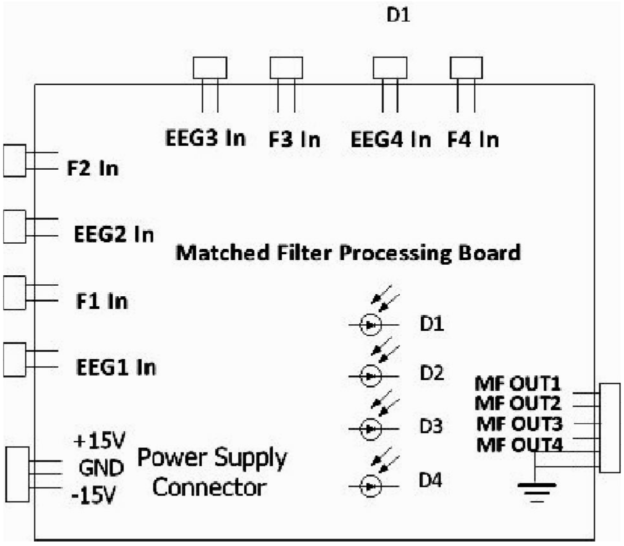


Figure 11b. Matched Filter process PCB board connectivity Layout

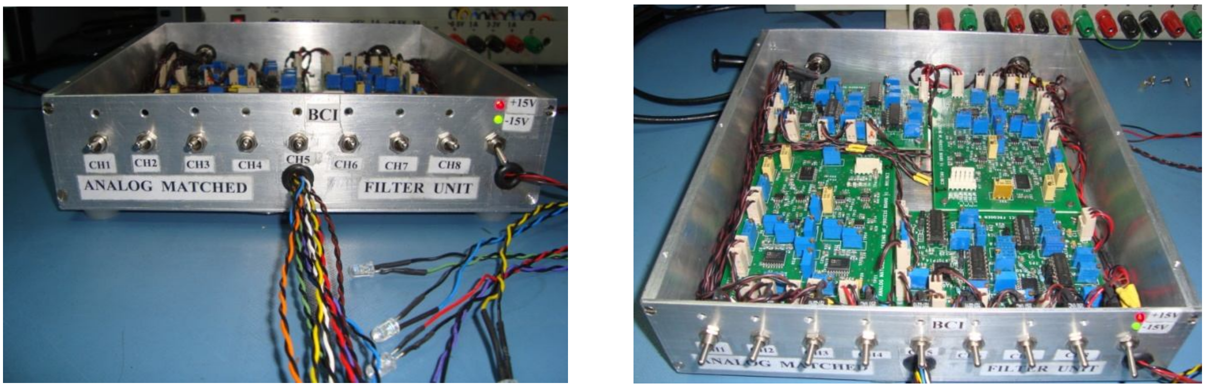


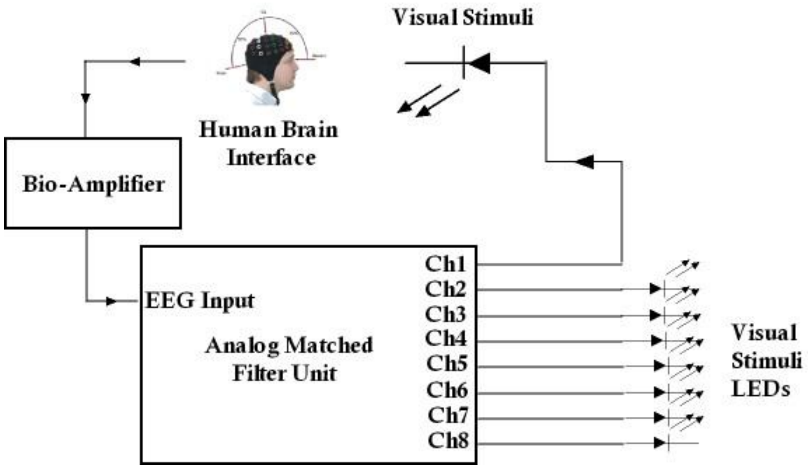
Figure 12 Photograph of Analog Matched Filter Unit

4. Testing and Results

4.1 Testing with Photo-Detector

Initially the analog matched filter unit was tested with photo detector interface. Each of the generated template visual stimulation sine-wave of certain frequency was exposed to the photo detector aperture eye area. The photo detected output voltage was amplified through the bio-amplifier. The amplified signal was fed to analog matched filter EEG input. The integration time of the corresponding integrator in the process board was adjusted to it’s template generated sine-wave period ’T’ secs. Then the corresponding matched filter LED indication output was observed for ON state. At the same time, when other frequency visual stimuli is exposed to the same channel, the matched fitler output observed was OFF state.

4.2 Testing with Human Brain



The analog matched filter unit was tested with human brain by tapping the EEG signal through a sensor which is attached to the person’s scalp. The EEG SSVEP signal was amplified by a bio-amplifier having a gain of about 10000. Adjusted the off-set voltage of the amplified signal, and the integration time of the integrator to the period of ‘T’ secs corresponding to the frequency under detection and observed the matched filter output LED indication of that channel goes high. The detection time observed was about 1-2 secs of duraion of time for all the sine-wave frequencies. Some times the detection is intermittently happening, which is due to EEG signal strength dependency, the concentration of observing the visual stimulation by the person, artifacts and the surface contact status of the sensor attached to the scalp.

5. Conclusions

The EEG – SSVEP signal detection is proved based on the quadrature analog matched filtering techniques. The template visual stimuli frequency generation is achieved using the simplest function generation circuit based on the values of external R and C components. The 8 channel frequencies matched filtering processing has been implemented. The detection time achieved was around 1-2 secs as observed visually. The frequency detection was intermittent some times based on the EEG signal strength. Detection of all the 8 frequencies from 10Hz to 24Hz were possible.

ANNEXURE I

Schematics of Frequency generation and the MF process boards.