

APPLICATION OF FREQUENCY DISCRIMINATION TECHNIQUE TO THE

ANALYSIS OF ELECTROENCEPHALOGRAPHIC SIGNALS*

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I. INTRODUCTION

The experimental analysis of EEG waveforms has been dominated by spectral decomposition and amplitude analysis, mainly autocorrelogram techniques though crosscorrelation technique has been used for phase measurements. These techniques as applied to the analysis of EEG signals are abundant in literature. To cite a few of them, we note that the earliest ones were done by Brazier and Barlow [1], [2], [3], [4], and notable simplifications done by Kamp, et al. [5], DeBoer and Kuyper [6], and Vo-Ngo et al [7]. The fact that the phases of EEG signals as compared to a reference clock signal contain information about the mental alertness has been pointed out to us by Anliker [8] who has used phase-vector and contour-graphic techniques to study the phase entrainment phenomenon. Adey and Walter [9] have used a phase detection technique in the analysis of EEG records in the cat. The EEG α -rhythm has been treated as the result of mutual synchronization of a population of spontaneously oscillatory processes by Wiener [10]. The potential usefulness of the phase entrainment in either recognizing the pathological states of the brain or classifying mental states might be widely explored if investigators had a reliably simple direct measurement technique. In this paper we describe a frequency discrimination technique as realized by an inexpensive frequency discriminator for direct on-line measurement of the entrainment phenomenon in EEG as entrained by the frequency of a sensory stimulus. We demonstrate the use of this device for detecting the presence or absence of the stimulus effect and the measurement of the time delays in the entrainment.

In our study, the EEG signal is first filtered by a narrow-band filter with center frequency about the α -rhythm of the individual. We shall denote this filtered EEG signal as alpha signal $\alpha(t)$. It is then reasonable to consider the alpha signal as narrow-band random process with the alpha frequency f_{α} as the mean frequency of the spectral band. Then a sample function of this random process is expressed as [11]

$$\alpha(t) = a(t) \cos [2\pi f_{\alpha} t + \phi(t)] \quad (1)$$

If the bandwidth of its power density spectrum is much smaller than its mean frequency f_{α} , then the processes $a(t)$ and $\phi(t)$ in Equation (1) will be slowly varying functions of time as compared to $\cos 2\pi f_{\alpha} t$ so that the interpretation of $a(t)$ and $\phi(t)$ as envelope and phase has meaning. The alpha signal process $\alpha(t)$ can thus be interpreted as amplitude and phase modulated signal process with

carrier frequency f_{α} . The process $\phi(t)$ can also be interpreted as a relative phase angle, in the sense that the alpha signal process $\alpha(t)$ differs in phase from the signal $(\cos 2\pi f_{\alpha} t)$ by $\phi(t)$. It is only in this manner that we are able to ascribe meaning to the phase of EEG as a time-varying quantity. The fact that the angular velocity or frequency in radians per second is the time derivative of the angular position leads us to define the instantaneous frequency $f_i(t)$ in cycles per second or Hertz by

$$f_i(t) = f_{\alpha} + \frac{1}{2\pi} \frac{d\phi}{dt} \quad (2)$$

The second term in Equation (2) which is proportional to the rate of change of the time-varying phase $\phi(t)$ can be interpreted as the instantaneous frequency deviation relative to the α frequency f_{α} provided it is stable. Our technique to be described in detail provides a direct measurement of $(d\phi)/(dt)$. The study on the statistical properties of the random processes $a(t)$ and $\phi(t)$ will be reported in another article.

When the brain is excited by an outside stimulus frequency f_s and the EEG is entrained by the stimulus, then we should have

$$f_i(t) = f_{\alpha} = f_s, \quad t_n + \tau_n \leq t \leq t_f + \tau_f \quad (3)$$

where t_n and t_f signify respectively the time instants at which the stimulus is on and the stimulus is off, and τ_n denotes the time delay between t_n and the time instant at which the entrainment occurs and τ_f , the time delay between t_f and the time instant at which the entrainment disappears. Equation (3) implies that

$$\frac{d\phi}{dt} = 0, \quad t_n + \tau_n \leq t \leq t_f + \tau_f \quad (4)$$

Since our technique measures $(d\phi)/(dt)$ directly, the measurement of EEG signals which were recorded while the human subjects with eyes closed were stimulated by stroboscopic flashes at the rate of 10 flashes per second for one minute, then no stimulation for one minute, then another minute of stimulation, etc., does show that $(d\phi)/(dt) = 0$ for alternate one minute intervals.

The schemes used for the measurement of $(d\phi)/(dt)$, τ_n , and τ_f , and for the automatic detection of the states of stimulus-on and stimulus-off in the EEG are to be described next.

II. METHOD

An ideal frequency discriminator should produce an output voltage linearly dependent on input

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frequency. There are many ways for the realization of frequency discrimination. The most commonly used one is the so-called balanced demodulator with the well-known S curve. The scheme which we have used here is the zero-crossing detector type as described in [12]. In order to eliminate the influence of the amplitude variation $a(t)$, we use an amplifier followed by a hard limiter in front of the detector. The output of the frequency discriminator is proportional to the instantaneous frequency $f_1(t)$ as expressed in Equation (2), and does not depend on the amplitude of the signal. We are, however, interested in the rate of change of $\phi(t)$. The value f_0 in Equation (2) is subtracted. In our device f_0 can be preset at any value in the range of 5-15 Hz. The device thus yields $(K/2\pi)(d\phi/dt)$ on-line. The characteristic curve of the device is given in Fig. 1. In Fig. 2, we show the functional block diagram of the analysis scheme. Detailed circuitry of the device is given in Fig. 3.

The response time or delay τ_n (or τ_f) is defined as the length of time elapsed since the onset (or end) of stimulus to the time instant at which the brain wave is entrained (or desynchronized). This delay τ_n (or τ_f) is, in a sense, the time which the brain takes to synchronize (or desynchronize). There is a noticeable delay between the onset of stimulus-on (or stimulus-off) and the time at which the entrainment is measurable. This fact is shown in Fig. 4 where the $(d\phi)/(dt)$ as the output of the frequency discriminator does not reach a flat plateau (or start to wander) immediately after the onset of stimulus-on (or stimulus-off). The fluctuation of the $x(t) \triangleq (d\phi)/(dt)$ curve is measured by the quantity

$$\rho \triangleq \sum_{i=1}^N |x(t_i) - m_N| \quad (5)$$

within a specified window width N , where m_N is the mean value of $(d\phi)/(dt)$ or $x(t)$ in the window; i.e.,

$$m_N = \frac{1}{N} \sum_{i=1}^N x(t_i) \quad (6)$$

New values of ρ are calculated by sliding the window. The onset of the flatness (or the wandering) is determined by the time instant at which ρ is below (or above) a preset threshold that is determined experimentally. The response time or delay τ_n (or τ_f) is measured as the time lapse between the onset of stimulus-on (or stimulus-off) and the onset of the flatness (or the wandering) of $(d\phi)/(dt)$ as measured by ρ . Owing to the delay introduced by the window width, a correction constant is subtracted from the above obtained time intervals.

The detection scheme utilizes the same program as that used in measuring the response time or delay, but without the prior knowledge of the onset of stimulus-on and stimulus-off. In other words, the influence of stimulus (entrainment) is said to be detected whenever the quantity ρ reaches a value below a preset threshold.

These schemes are realized by digital computer programs in PAL III language used on a PDP-8 computer. Both of these measurements can be performed on-line. Figure 5 depicts the flow chart of the computer program for the response-time measurement.

III. RESULTS

Although the measurements were performed on EEG signals recorded on magnetic tape, they can be per-

formed on-line. As mentioned before, these EEG signals were recorded while the subjects with eyes closed were stimulated by stroboscopic flashes for one minute at the rate of 10 flashes per second, then no stimulation for one minute, then another minute of stimulation, etc. The flashes were generated by Grass photo stimulator model PS-2E on its intensity scale No. 2. The EEG signals are the differential potentials between the electrodes placed at left parietal and left occipital. The EEG signals are referred to as either stimulus-entrained or non-entrained. In order that the EEG signal be more appropriately described by the narrow-band-process model, the EEG signal was passed through a narrow-band filter with a band-width of 1.5 Hz centered at 10 Hz to obtain the alpha signal $\alpha(t)$ as described previously.

A section of the output of the frequency discriminator along with the same section of EEG signals of subject B being analyzed and a square wave indicating when the stimulus was turned on or off are shown in Figs. 6 and 7. The display of apparent high frequency components in the raw EEG of Figs. 6 and 7 are due to the slower writing speed (30 cm per minute) of our strip chart recorder as compared to the conventional writing speed. It is clearly seen that there is a delay following the onset of the stimulus before entrainment is detected; the EEG remains synchronized for a short period of time also after the stimulus was turned off. In Figs. 8, 9, and 10, we show the output of the frequency discriminator with the early, middle, and late sections of EEG signals of subject H as the input along with a square wave indicating the events of stimulus-on and stimulus-off. The offset of time coordinates in the above figures is due to the positions of pens of the strip chart recorder. From these figures, we observe that subject H synchronized with the stimulus very well at the beginning section (13th min. to 19th min.) of the experiment as shown by the measurement of $(d\phi)/(dt)$ depicted in Fig. 8. As shown in Fig. 9, however, the subject's EEG signal did not entrain to the stimulus frequency as well during the middle (105th min. to 111th min.) of an experimental session which lasted about three hours. There is no sign of entrainment of the EEG signal in the end section (176th min. to 182nd min.) of the experiment as shown in Fig. 10. The capability to synchronize with the stimulus may be a measure of certain brain states such as alertness. Further study is needed for this measurement by this technique. The frequency discrimination technique as realized by an inexpensive device is effective in measuring the entrainment phenomenon of EEG signals.

It is possible that variations in the delays τ_n and τ_f in synchronization and desynchronization, respectively, might give some indication of change of levels of alertness, although our data does not include alertness estimates. Results of the measurement of delays for both subjects are shown in Figs. 11 and 12, respectively. The abscissas in the figures denote the time since the beginning of the experiments and the ordinates are the measured delays. Any $\tau_n > 25$ seconds is considered as not synchronized. Subject B seems to have longer response time to stimulus-on in the first hour of experiment than those in the second hour. Subject H did not entrain so well after the first hour of experiment. In general, we see that it takes longer for the subjects to synchronize with the stimuli than it takes to return to the natural states after the stimuli were shut off. The statistics of τ_n and τ_f and their correlation with the mental

states of subjects need further study. However, the technique for measuring these delays is satisfactory.

In Figure 13, we show a typical section of the conditions or states of the stimulus-on and stimulus-off of EEG as results of computer analysis of the output of the frequency discriminator in comparison with the timing track for the on and off of the stimulus. This was generated by a double-threshold detector. The thresholds were determined experimentally. We analyzed the records of both subject B and subject H. The ratio of the sum of the differences between the time of the on and off conditions of EEG as determined by the detector and on-off timing track for the stimulus to the total time of on and off as measured by the timing track was calculated. This ratio is 28.6 per cent for subject B and 35.8 per cent for subject H. We did not take into account the time delays introduced by the smoothing window and the frequency discriminator in the evaluation of these ratios. The values of these ratios may be reduced. The use of the above-mentioned ratio as a performance measure of the detector is appropriate if we do not have the knowledge of the length of time and the manner in which the stimulus is turned on or off. With the knowledge that the stimulus was turned on for one minute, then shut off for one minute, then was on for another minute, etc., and counting only the number of the on-off cycles as determined by the detector, we obtain the following result:

- (1) For subject B, there are 57 on-off cycles detected by the detector as compared to 57 on-off cycles on the timing track (a 100 per cent detection).
- (2) For subject H, there are 56 on-off cycles detected by the detector as compared to 59 on-off cycles on the timing track (a 94.7 per cent detection).

IV. CONCLUSIONS

The frequency discrimination technique described here has been effective in measuring the entrainment phenomenon in EEG signals. We have shown that the narrow-band-process model used here for characterizing signals is valid. The technique as realized by an inexpensive device described previously provides an effective way for further study on the synchronization phenomenon as related to alertness. Statistical properties of the phase $\phi(t)$ must be gathered for further interpretation of mental states.

V. ACKNOWLEDGEMENT

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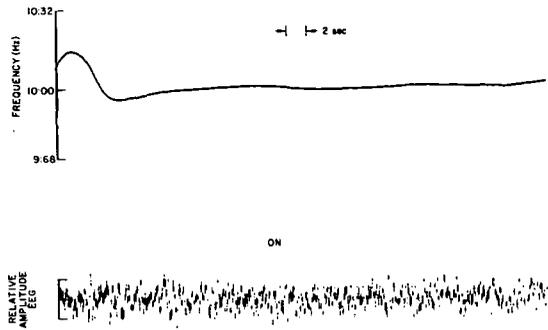


FIG. 6 MEASUREMENT OF $\frac{d\phi}{dt}$ AND THE DISPLAY OF RAW EEG INPUT TO THE SCHEMATIC DIAGRAM SHOWN IN FIG. 2 WHEN STIMULUS IS ON. STRIP-CHART RECORDER WRITING SPEED IS 30 CM PER MINUTE.

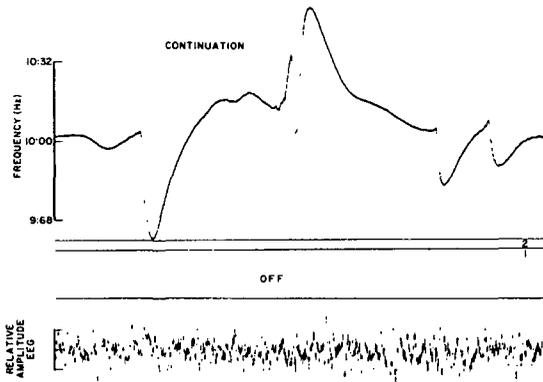


FIG. 7 MEASUREMENT OF $\frac{d\phi}{dt}$ AND THE DISPLAY OF RAW EEG INPUT TO THE SCHEMATIC DIAGRAM SHOWN IN FIG. 2 WHEN STIMULUS IS OFF. STRIP-CHART RECORDER WRITING SPEED IS 30 CM PER MINUTE.

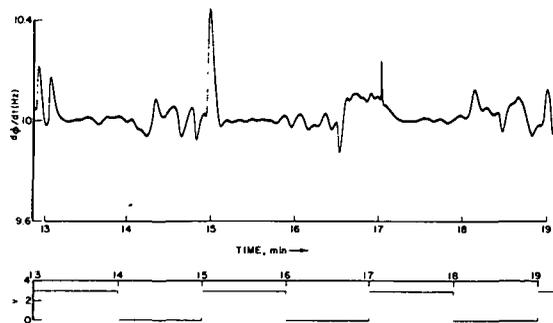


FIG. 8 MEASUREMENT OF $\frac{d\phi}{dt}$ OF THE ALPHA SIGNAL OF THE EARLY PART OF EEG RECORD OF SUBJECT H.

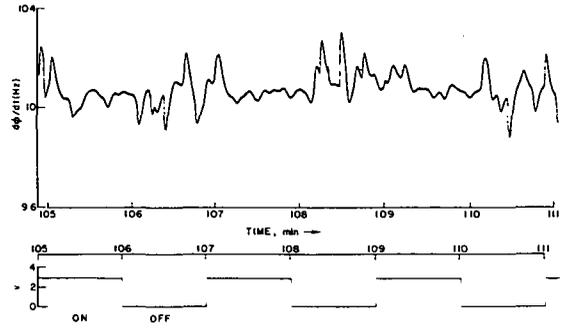


FIG. 9 MEASUREMENT OF $\frac{d\phi}{dt}$ OF THE ALPHA SIGNAL OF THE MIDDLE PART OF EEG RECORD OF SUBJECT H.

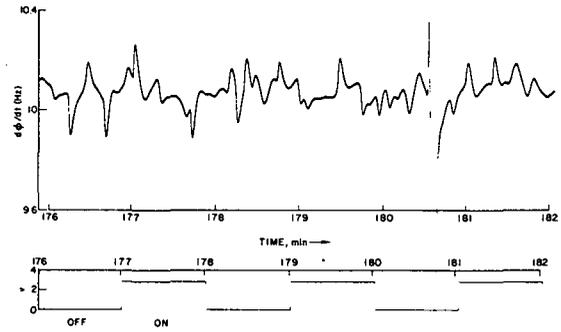


FIG. 10 MEASUREMENT OF $\frac{d\phi}{dt}$ OF THE ALPHA SIGNAL OF THE LATE PART OF EEG RECORD OF SUBJECT H.

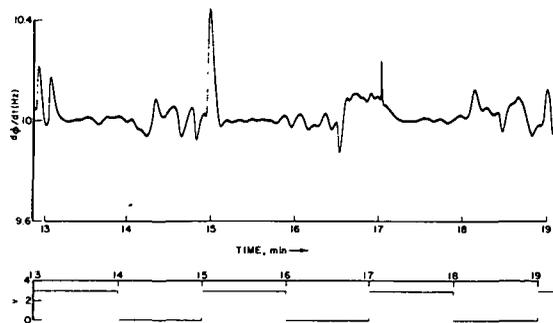


FIG. 13 THE STATES OF STIMULUS-ON AND STIMULUS-OFF OF EEG AS RESULTS OF THE ANALYSIS IN COMPARISON WITH THE ACTUAL ON AND OFF OF THE STIMULUS.

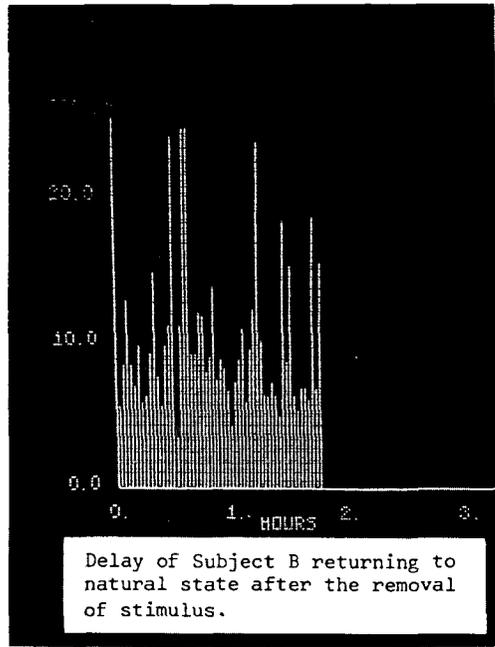
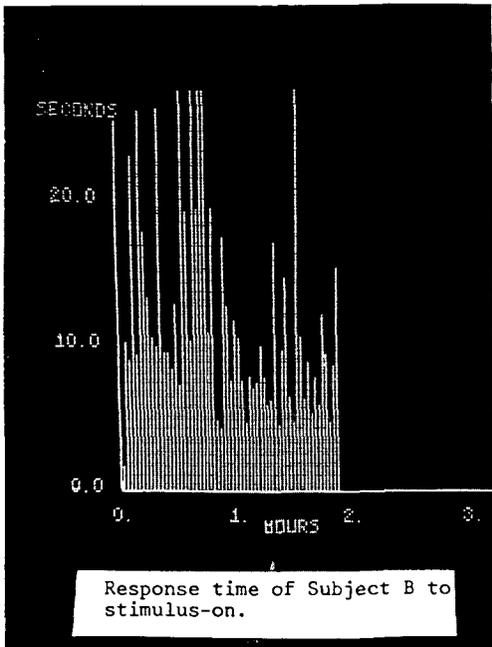


Fig. 11. RESPONSE TIME STUDY OF SUBJECT B.

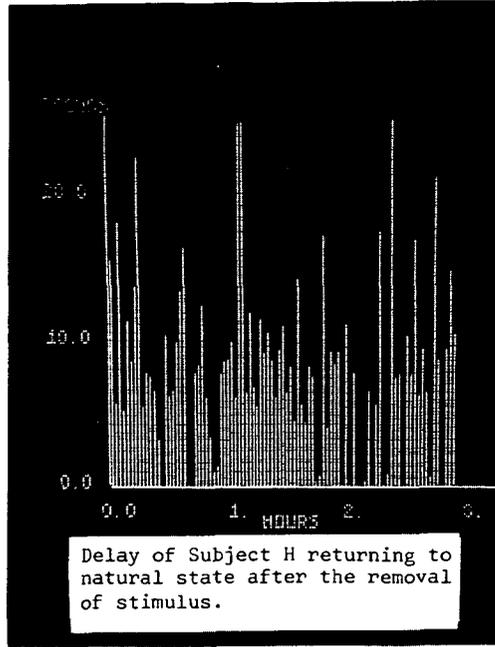
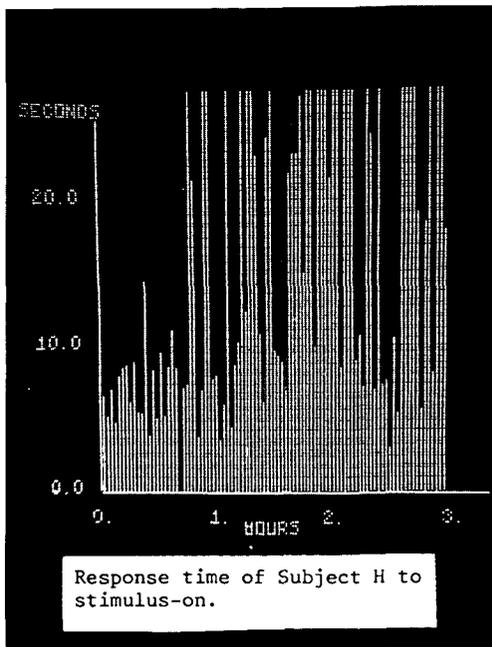


Fig. 12. RESPONSE TIME STUDY OF SUBJECT H.