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LABORATORY NOTE

TRACKING THE DOMINANT FREQUENCY OF THE EEG BY PHASE-LOCKED LOOP DEMODULATION

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Changes in the frequency and amplitude of the EEG are often related to changes in other physiological and behavioural variables. Although there are several methods available at present for tracking these changes in the EEG over prolonged periods (Adey *et al.* 1967; Walter 1968) there remains a need for simpler and less expensive methods.

Hileman and Dick (1971) have used a phase-locked loop (implemented on a hybrid computer) in a method of complex demodulation of the EEG.

The recent availability of phase-locked loops as monolithic integrated circuits has enabled us to develop a new method which is both simple and inexpensive for continuously tracking: (a) variations of frequency within limited bandwidths of the EEG; or (b) the dominant frequency of the raw EEG, that is the frequency of those waves having the maximum amplitude at the time, wherever that frequency may lie between about 1 and 30 c/sec. Development of this method was motivated by the knowledge that a phase-locked loop is the optimum as a frequency demodulator of some noisy signals and near optimum for others (Viterbi 1966).

FREQUENCY DEMODULATION USING A PHASE-LOCKED LOOP

A phase-locked loop consists of a phase-angle detector, a low-pass filter and a voltage controlled oscillator, as in Fig. 1. Assume that the EEG can be represented in the form

$$E_i(t) = V_i(t) \sin[w_c t + \varphi_i(t)]$$

where $V_i(t)$, the amplitude at time t, is a positive variable; w_c is the centre frequency of the process; and $\varphi_i(t)$ is the phase angle at time t.

$V_i(t)$ and $\varphi_i(t)$ are functions which are known to vary with time and it is $\varphi_i(t)$ which we desire to track as a measure of frequency variations in the signal. Assume, for the time being, that the output from a voltage-controlled oscillator (VCO) has the form

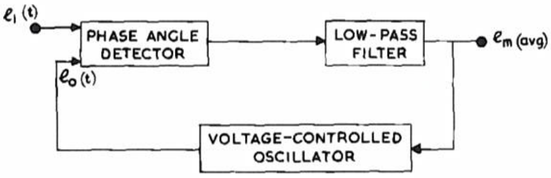

Fig. 1. Block diagram of a phase-locked loop.

$$E_0(t) = V_0(t) \cos[w_c t + \varphi_0(t)]$$

where $V_0(t)$, w_c and $\varphi_0(t)$ are variables analogous to $V_i(t)$, w_c and $\varphi_i(t)$, defined above.

A multiplier is used as a phase detector in the phase-locked loop (Fig. 1). When E_i (t) is multiplied by $E_0(t)$ and the product is low-pass filtered to remove double-frequency terms, the output from the low-pass filter, E_m(avg), is effectively proportional to $V_i(t)\ V_0(t) \sin[\varphi_i(t) - \varphi_0(t)]$, under reasonable assumptions on the bandwidth of the signal $\varphi_i(t)$. If this voltage is used to control the frequency of the VCO, this frequency will be varied so as to reduce the phase difference $[\varphi_i(t) - \varphi_0(t)]$. The output from the VCO will be 90° out of phase with the original signal and will track its frequency variations. The effect of any concomitant changes in the amplitude of the input can be eliminated by passing the signal through a high-gain amplifier-clipper so that the input to the phase-locked loop becomes a square-wave signal of constant amplitude but varying frequency. The output from the phase-angle detector then has a DC component which is proportional to the frequency of the input, with an unwanted double-frequency square-wave which must be removed by low-pass filtering.

IMPLEMENTATION OF THE FREQUENCY DEMODULATION SYSTEM

Implementation of the demodulation system proved to be simple and inexpensive: the total cost of components

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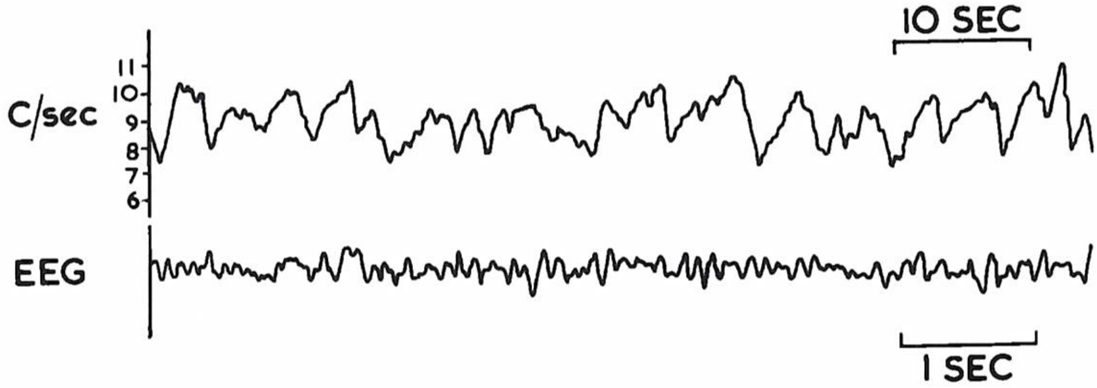

Fig. 2. Output from the demodulator (above) recorded for 70 sec when the input was an EEG (below). Note the different time scales. The time constant of the final low-pass filter was 0.5 sec.

(excluding power supply) was approximately ten dollars. The phase-locked loop was monolithic integrated circuit (RCA, CD4046) which consumed only about 100 microwatt from a 6 V power supply (Morgan and Steudel 1973). This circuit uses an exclusive-OR network to detect the sine of the phase error $[\varphi_i(t)-\varphi_0(t)]$. One external capacitor (0.1 mf) and a resistor (750 kΩ) were selected to make the centre frequency of the VCO approximately 15 c/sec. The low-pass filter within the loop was a single-pole RC circuit, with $R=270$ kΩ and $C=0.1$ mf, so that the "capture" range of the loop was almost as wide as the range of frequencies within which the loop remained locked (1–30 c/sec).

The demodulator output was derived from the low-pass filter via a source follower which was already incorporated into the integrated circuit. The output required further filtering by means of an active, double-pole, low-pass filter constructed around an integrated-circuit (741) operational amplifier. The time constant of this filter was selected to be either 0.5 or 5 sec depending on whether rapid changes in frequency of the input signal or its average frequency were to be tracked. The high-gain amplifier-clipper at the input was a pair of operational amplifiers in series whose output was a square-wave of ± 6 V determined by the power-supply voltages. The input was AC-coupled via a 0.68 mf capacitor, the input resistance of the first operational amplifier being 10 kΩ. An EEG signal of 10 μV was sufficient input for demodulation although, if required, this could be reduced by further amplification at the input.

RESULTS

The demodulator system was calibrated by using an input of sine-waves of known frequency. The DC output was essentially linearly related to input frequency between 1 and 30 c/sec. Using a sine-wave signal to modulate the output from a separate VCO, it was demonstrated that the phase-locked loop was able to track the frequency of the modulated signal, for example, when it varied from 25 to 5 c/šec in 0.5 sec. When the input was the sum of three sine-waves, one of 1.9 V amplitude at 7 c/sec, another of 1.0 V at 8 c/sec and a third of 0.9 V at 4 c/sec, the output was a constant voltage proportional to 7 c/sec. Were the amplitude of one of these sine-waves not to exceed the next largest by about 40%, the demodulator output fluctuated between the frequencies of these two waves.

When an EEG derived from parieto-occipital electrodes was passed first through a 8–12 c/sec and-pass filter and then through the demodulator, the output showed almost continuous fluctuations within that band-width (Fig. 2). Hileman and Dick (1971) described very similar fluctuations using a method of complex demodulation. Comparable results were obtained also from the present system when the band-pass filter at the input was omitted, thereby permitting the dominant frequency of the EEG to be tracked outside the alpha range, into the theta and delta range. Isolated slow waves were registered (although their dominant frequency component was not accurately measured) when the time-constant of the final-sow-pass filter was 0.5 sec.

DISCUSSION

The simplicity and low cost of this method for measuring continuously (and on-line) the frequency of the EEG should facilitate its application in several areas of clinical and laboratory investigation. This method does not replace spectral analysis and related techniques of frequency analysis when information is required about the whole range of frequencies in the EEG. However, the present demodulation system is very useful for tracking either the dominant frequency of the raw EEG or of some particular band-width of it which has been selected by passage through a band-pass filter. The low power consumption and small size of the demodulator should enable it to be incorporated into portable monitoring equipment.

SUMMARY

A method is described for tracking changes in the dominant frequency of the EEG on-line. It is based on the principle of phase-locked loop demodulation and uses a monolithic integrated circuit. The low cost (a few dollars), the small size and low power consumption of this device make it useful for long-term monitoring of the EEG.

RESUME

RECHERCHE DE LA FREQUENCE DOMINANTE DE L'EEG BOUCLE DE DEMODULATION VERROUILLEE EN PHASE

Les auteurs décrivent une méthode de mise en évidence des on-line des modifications de la fréquence dominante de l'EEG. Cette méthode est basée sur le principe de la boucle de démodulation verrouillée en phase et utilise un circuit intégré monolitique. Le prix peu élevé (quelques dollars), la petite taille et la faible consommation d'énergie de ce système le rend utile pour l'enregistrement à long terme de l'EEG.

REFERENCES

ADEY, W. R., KADO, R. T. and WALTER, D. O. Computer analysis of EEG data from Gemini flight GT-7. *Aerospace Med.*, **1967,** *38*: 345–359.

HILEMAN, R. E. and DICK, D. E. Detection of phase characteristics of alpha waves in the electroencephalogram. *IEEE Trans. bio-med. Engng.*, **1971,** *BME-18*: 379–382.

MORGAN, D. K. and STEUDEL, G. The RCA COS/MOS phase-locked-loop: a versatile building block for micropower digital and analog applications. In: *RCA solid state data book series.* RCA Corporation, Somerville, N.J., **1973,** *SSD-203A*: 319–326.

VITERBI, A. J. *Principles of coherent communication.* McGraw-Hill, New York, **1966,** p. 137.

WALTER, D. O. The method of complex demodulation. *Electroenceph. clin. Neurophysiol.*, **1968,** *Suppl. 27*: 54–57.