XVII. NEUROLOGY*

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A. BLACK-BOX DESCRIPTION AND PHYSICAL ELEMENT IDENTIFICATION IN THE PUPIL SYSTEM

Black-box input-output analysis of nonlinear systems is, at present, a control-systems

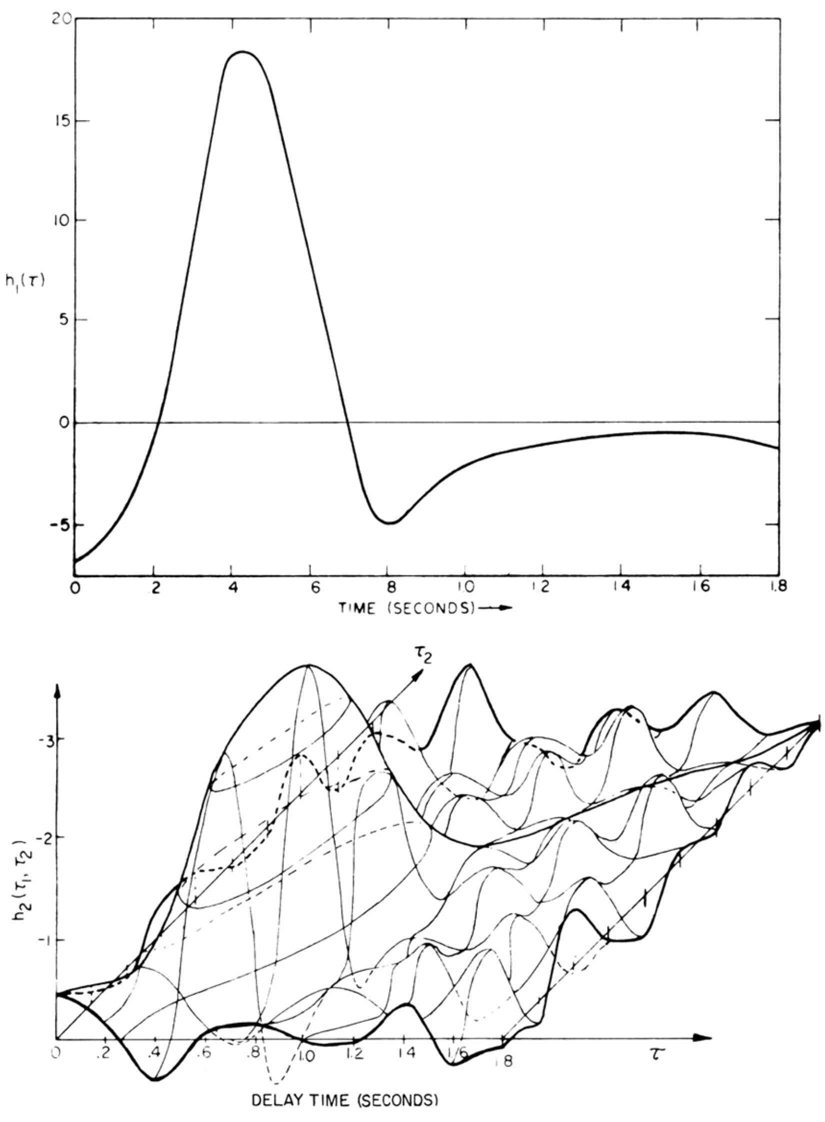

Fig. XVII-1. First- and second-order kernels of open-loop pupil light servomechanism.

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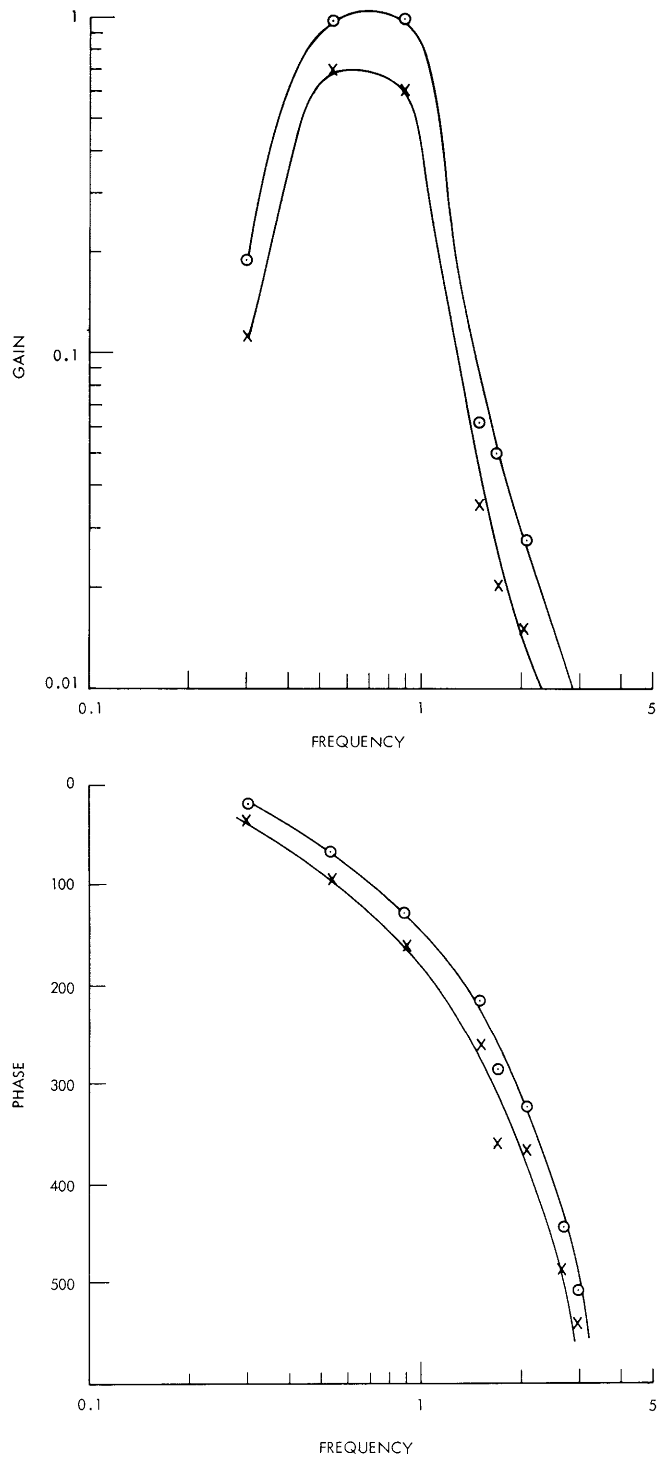

Fig. XVII-2. Bode plot of drugged (X) and undrugged (⊙) pupil.

area of much activity. Functional analysis[1-4] has a mathematical elegance that is attractive, and we have applied this method[5] to the pupil light reflex. Figure XVII-1 shows $h_1(T)$, the first-order kernel, and $h_2(T_1, T_2)$, the second-order kernel, as two-dimensional and three-dimensional functions, respectively. Work is now under way to refine the experimental method to obtain more consistent and reliable data.

However, since our goal is identification of the physical laws of the anatomical-physiological elements that together make up the pupillary system, we have attempted to dissect into the black box. The high-frequency cutoff is probably due to the output mechanical elements, the iris muscles, as the experiment illustrated in Fig. XVII-2 demonstrates.[6] Here, locally applied drugs that partly overstimulate both the sphincter and dilator muscles reduce the bandpass of the system and the gain. This confirms a previous experiment[7] in which gain measurements were not obtained.

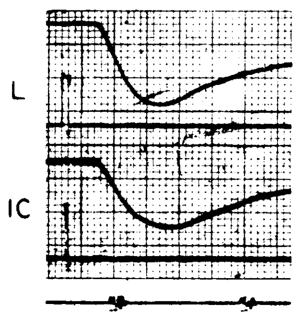

Fig. XVII-3. Impulse response of pupil to light (L) and electrical intracranial (IC) stimulation.

Frank H. Baker[8] has shown that in anesthetized cats direct intracranial stimulation by electrodes stereotactically placed near the motor fibers of the oculomotor nerve produces pupillary contraction with approximately the same transport delay and third-order response as does light stimulation of retina, as shown in Fig. XVII-3. Estimates of nerve conduction times and synaptic delays for the pupillary system range from 10 msec to 20 msec, in agreement with the assigning of 90 per cent of the transport delay and all of the high-frequency attenuation to the output neuromuscular elements.[9]

These experiments indicate the range of approaches utilizing system theory, and neurophysiological and neuropharmacological dissection techniques, both of which are necessary to make a quantitative and into-the-black-box analysis of a neurological control system.

L. Stark

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B. PUPIL VARIATION AND DISJUNCTIVE EYE MOVEMENTS AS A RESULT OF PHOTIC AND ACCOMMODATIVE STIMULATION

There are several methods of stimulating the iris muscles which result in a variation of the pupil diameter (Fig. XVII-4). First, the eye can be stimulated with light. A signal goes from the retina to the central nervous system (CNS), and then back to the iris muscles.[1] This photic response is involuntary, and thus prediction does not occur. Second, a target can be moved on the optical axis of one eye, while a cooperative subject tries to keep it in focus. It is evident that this method of providing a stimulus necessitates a voluntary contrubution by the subject and thus prediction may occur. In this situation, an error signal goes to the CNS, indicating how far the image is out of focus. This is an even-error signal, but in our present experimental arrangement, since there are additional clues such as the size and brightness of the target, we actually work with an odd-error signal.[2] From the CNS there is a signal path to the ciliary muscle and the dioptric strength of the lens varies in such a way as to obtain clear vision. Also, an additional signal goes from the CNS to iris muscles, and pupil diameter varies to control depth of focus of the eye.

Third, the accommodation input by way of the CNS results in a disjunctive eye movement of the other eye, although this eye cannot see the target. Figure XVII-4 is a simplified block diagram of these various inputs, outputs, and interactions. The experimental arrangement is shown in Fig. XVII-5; it is possible to stimulate one eye with either a light or an accommodation input and to measure the pupil size. The associated disjunctive movements of the other eye which resulted from the

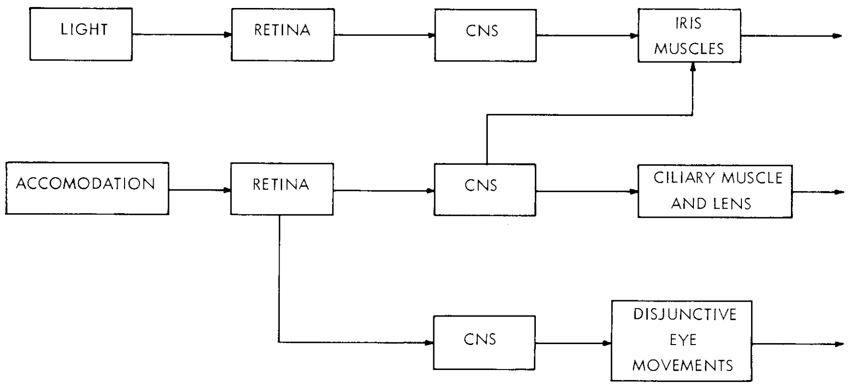

Fig. XVII-4. Block diagram of the interacting iris-lens-convergence system.

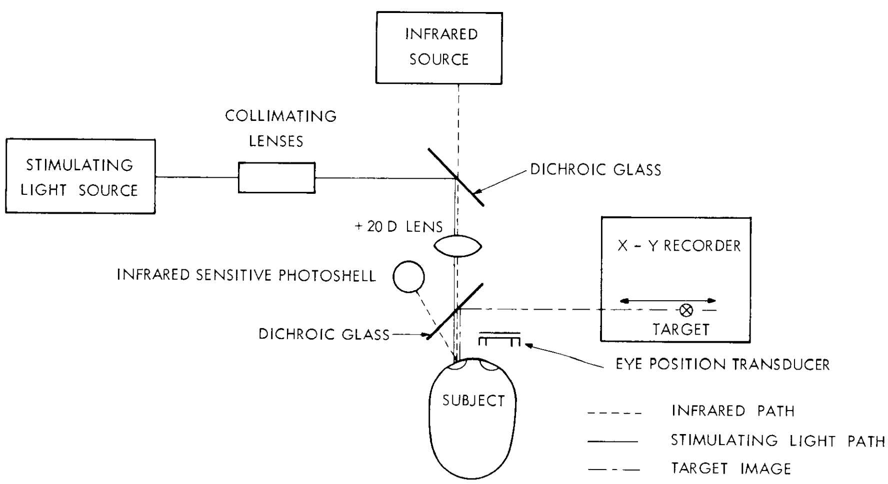

Fig. XVII-5. Experimental arrangement.

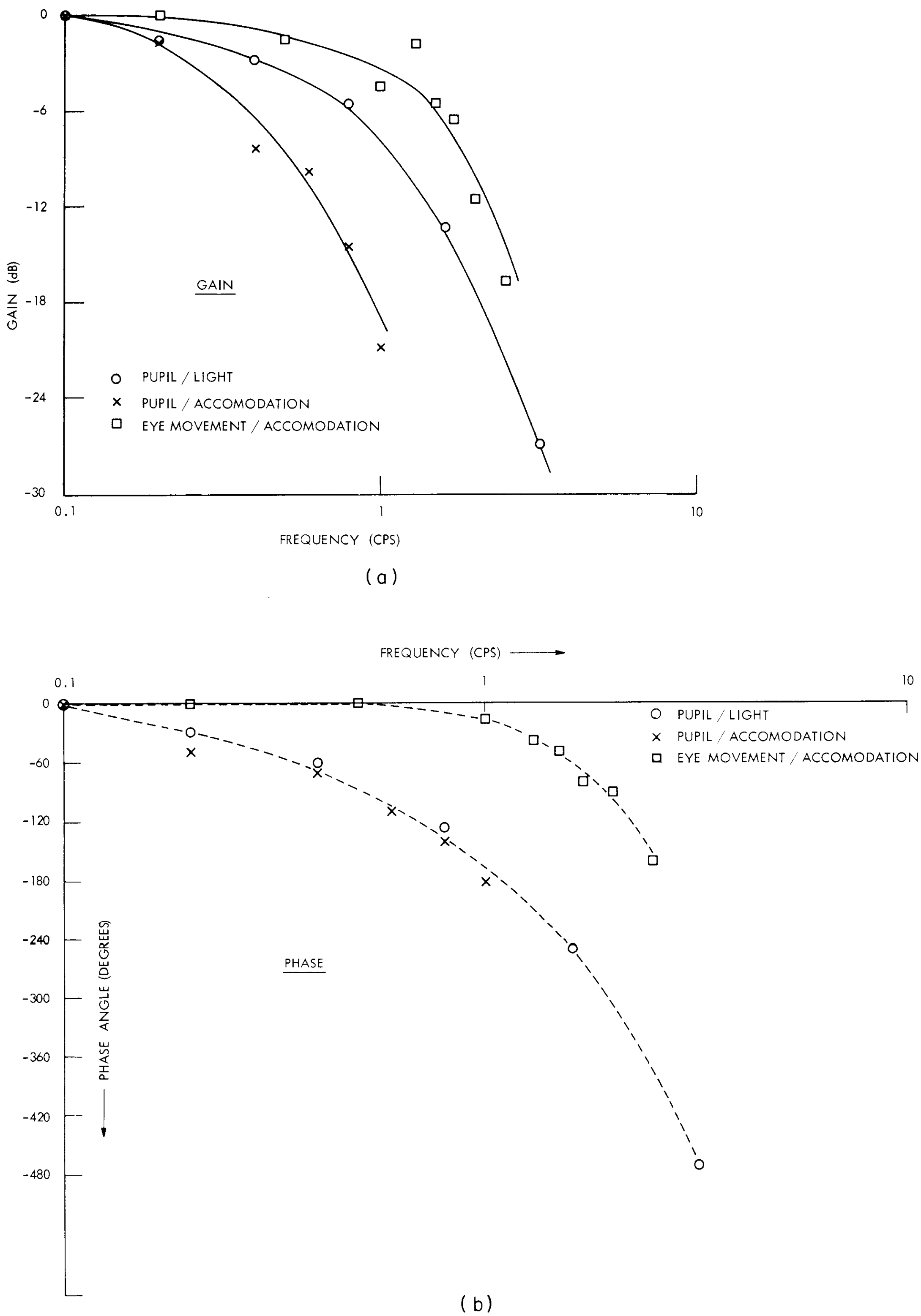

Fig. XVII-6. Frequency-response plots of various input-output relationships.

accommodation input were measured separately with equipment previously described.[3]

To obtain an idea of the dynamics of the various systems, the eye was stimulated with a sinusoidal light input or with a sinusoidal target-position input in the optical axis of one eye. The variations in pupil diameter of the same or the disjunctive movements of the other eye are measured. Bode plots are shown in Fig. XVII-6.

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C. REMOTE PATIENT-TESTING INSTALLATION

We have set up a communication link between the Howe Laboratories of the

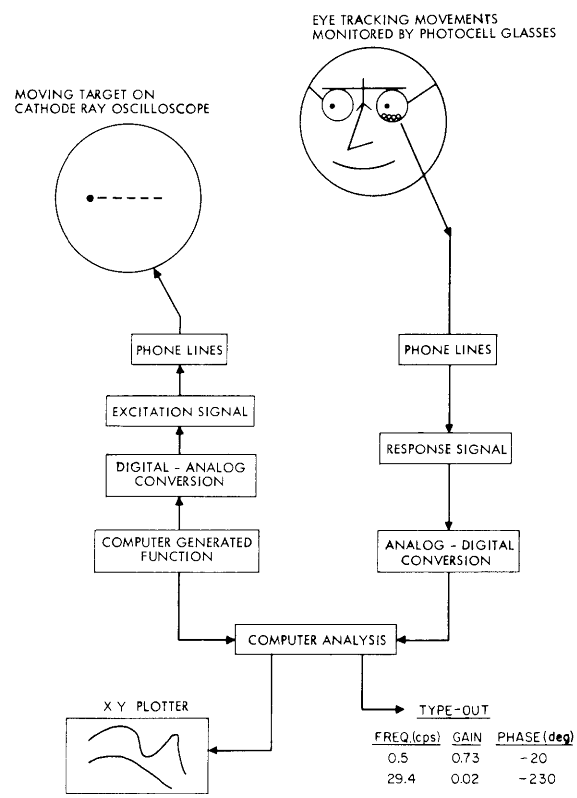

Fig. XVII-7. Block diagram of remote patient-testing installation using on-line computer.

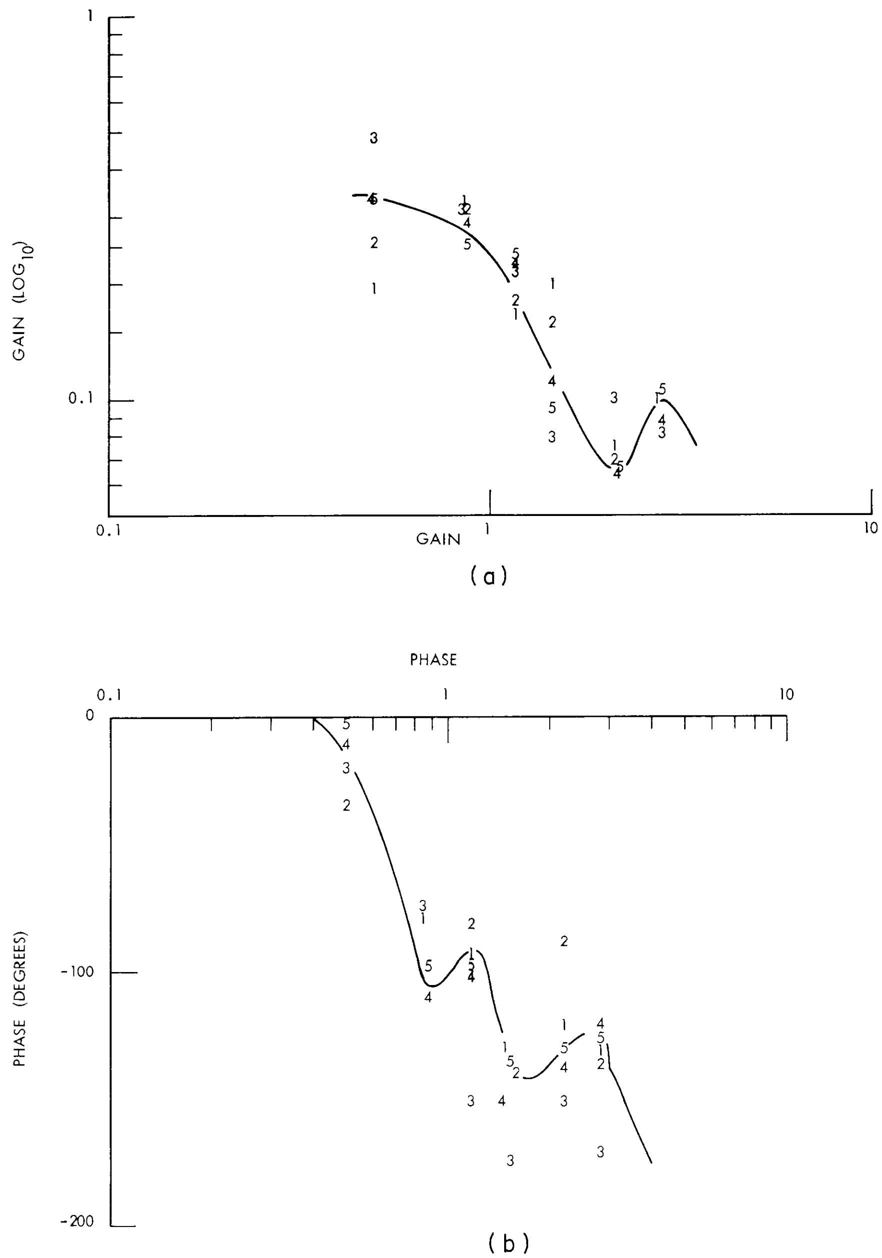

Fig. XVII-8. Bode plot of eye-tracking movement control system.

Table XVII-1. Gain and phase as a function of frequency typed out by on-line computer.

```
        ANNE TROELSTRA TRACKNNG   1 18 62   PAW LS GS

Run No.                                               AVERAGE      000110
     FREQUENCY   GAIN        PHASE

        00.496   00.197 - 34.507
        00.859   00.328 - 74.035
1       01.160   00.169 - 91.111
        01.455   00.203 -124.507
        02.162   00.078 -122.619
        02.757   00.103 -137.103
     END


        AVERAGE     000119
     FREQUENCY   GAIN        PHASE

        00.496   00.261 - 36.869
        00.859   00.312 -111.339
2       01.160   00.183 - 83.970
        01.455   00.160 -138.365
        02.162   00.072 - 88.613
        02.757   00.101 -139.574


        ANE TROELSTRA  1 18 62 EOM AT COGAN LABAVERAGE      000130
     FREQUENCY   GAIN        TPHASE

        00.496   00.486   03.580
        00.859   00.310 -128.197
3       01.160   00.218 -129.181
        01.455   00.080 -156.037
        02.162   00.101 -128.660
        02.757   00.083 -154.824
     END


        AVERAGE     000109
     FREQUENCY   GAIN        TPHASE

        00.496   00.337 - 10.619
        00.859   00.287 -115.173
4       01.160   00.222 - 99.144
        01.455   00.115 -150.253
        02.162   00.064 -138.814
        02.757   00.089 -123.566
     ENDAVERAGE     000105
     FREQUENCY   GAIN        TPHASE

        00.496   00.324 - 03.578
        00.859   00.255 - 99.093
5       01.160   00.238 - 95.431
        01.455   00.095 -131.185
        02.162   00.068 -131.632
        02.757   00.101 -131.888
     END
```

Massachusetts Eye and Ear Infirmary[1] and an on-line computer (GE 225) in the Electronic Systems Laboratory, M.I.T., for studying neurological eye-movement defects. The communication links are four pairs of standard low-fidelity "direct" telephone lines, traveling approximately 3 miles in roundabout fashion from Cambridge to Boston.

The experimental arrangement, as shown in Fig. XVII-7, consists of a pseudo-random excitation signal that is generated by the computer, converted by the computer DIOB (data input-output buffer) to an analog voltage, and transmitted over one pair of lines (0-2000 cps bandwidth) to drive a horizontally moving spot on an oscilloscope face. The patient is instructed to follow the spot; the angular direction of his eyes is measured by a pair of photocell goggles,[2] and this response signal is sent back over another pair of lines, and is digitalized by the DIOB. The GE 225 computer then analyzes the gain and phase lag at each frequency of interest and types out the information. A typical typeout is shown in Table XVII-1. Figure XVII-8 is a plot of five successive runs on A. Troelstra.

The peak in the frequency response has been predicted by a sampled-data model of the eye-movement control system.[3] An X-Y plotter will be installed in the hospital laboratory and the plotted frequency response will be available a few minutes after the experiment.

L. Stark, P. A. Willis, Gabriella W. Smith

References

1. Dr. David Cogan, Dr. Carl Kupfer, and Dr. Ernst Meyer of Howe Laboratories, Massachusetts Eye and Ear Infirmary, are opthalmologists associated with us in this project.

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D. EXPERIMENTS ON DISCRETE CONTROL OF HAND MOVEMENT

Previous reports assembled evidence regarding sampled-data control phenomena in hand motor coordination[1] and also presented a rather complete sampled-data model for eye-movement tracking.[2] Recently, a thesis[3] has been completed which further explores experimental phenomena, which are interpretable in terms of a discrete model.

Unpredictable ramps are used as an input signal, and the rotational load is made low enough so that the mechanical output elements (muscles, load, apparatus) do not smooth the output signal too drastically. The response of the hand is then a series of steps, as shown in Fig. XVII-9; the hand control system is evidently a discrete position control system. When step amplitudes and times between steps are plotted as a function of ramp velocity as in Fig. XVII-10, it is clear, since only the amplitude and not the sampling period is velocity-dependent, that the nature of the discontinuity is

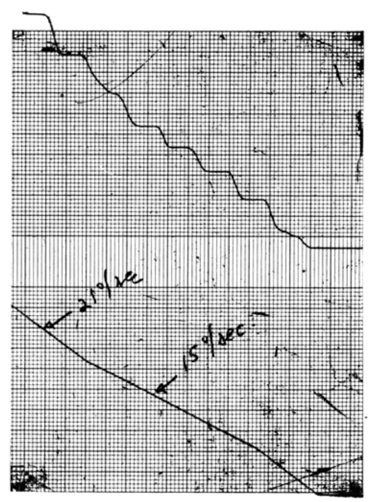


Fig. XVII-9. Random ramp response.

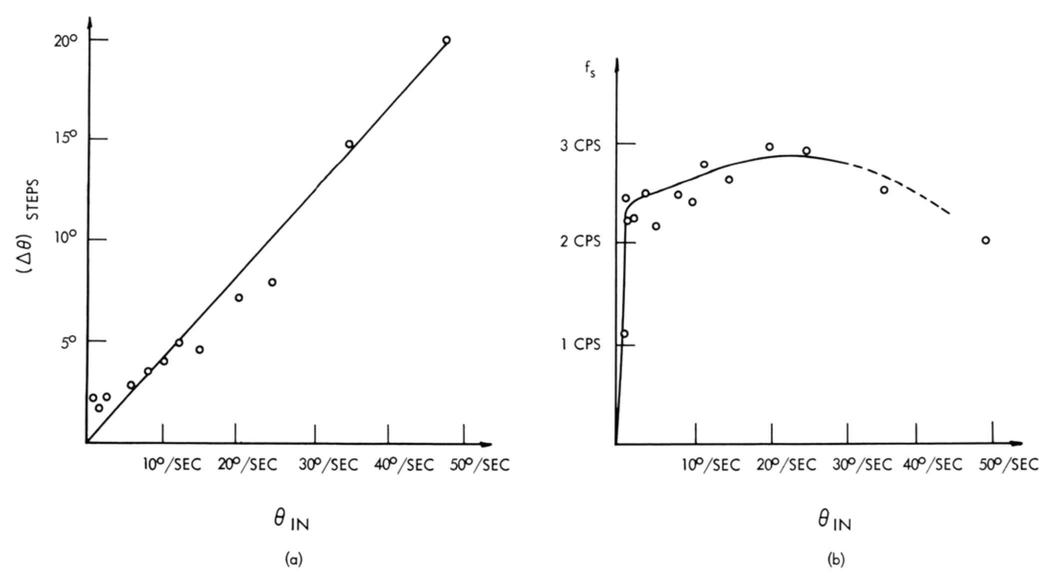
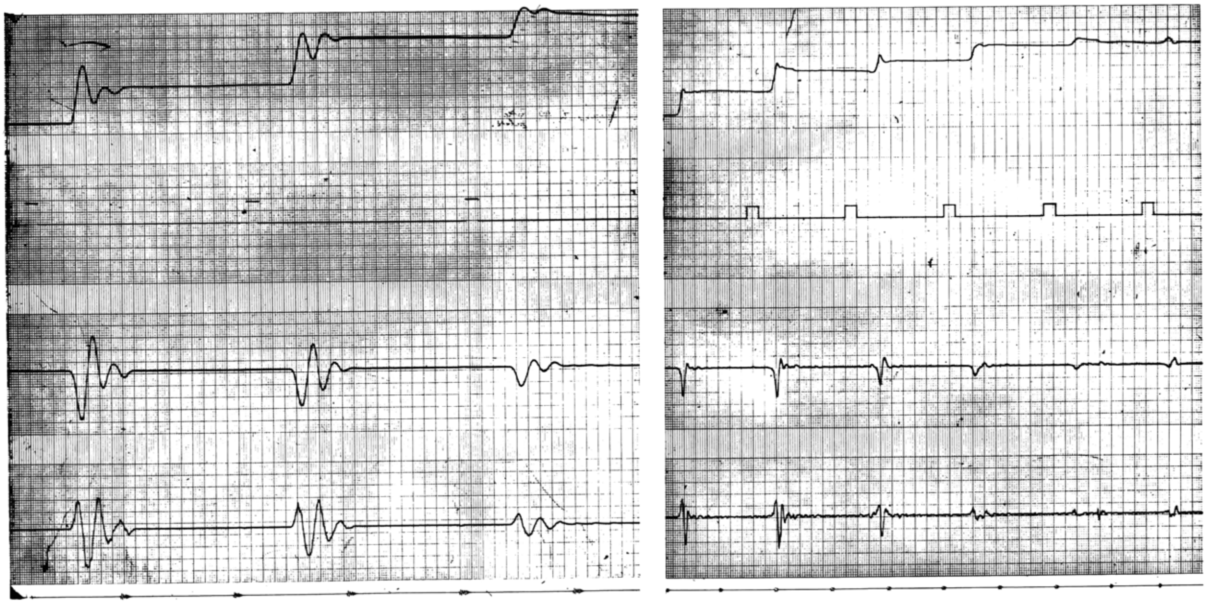


Fig. XVII-10. Dependence of (a) step amplitude, and (b) step frequency as a function of ramp velocity.

not quantization, but rather like a sampled-data system.

Experimentally, varying feedback by means of an environmental clamp is often useful in dissecting a system,[4,5] especially when one can open the loop. When the loop is



(a) (b)

Fig. XVII-11. Pulse response under open-loop conditions.

opened, an unpredictable pulse input should produce a step response. The responses to the initial pulses in experiments such as those displayed in Fig. XVII-11 do indeed approximate steps. Since the inputs are repetitive, and thus eventually predictable, the subject adapts and finally compensates for the change in feedback. The last response to each series of input pulses in Fig. XVII-11 is more nearly a (dynamically limited) pulse. Thus, the position control loop and the adaptive nature of the hand system are both demonstrated in these open-loop experiments.

F. Naves, L. Stark

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