SERVOANALYTIC STUDY OF EYE TRACKING MOVEMENT RECORDED BY ELECTRO-OCULOGRAPHY

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When man tries to catch something on a table in his hand, he has to measure error between the material and hand to perform his final purpose. By this is meant that human manual control system includes a feedback of visual system, and is regulated by it. Of course, although the manual control system is complicated and has multiple loop, servoanalytic study of this system has been carried out in a sense of cybernetics, since Wiener pointed out in 1948.[10] As mentioned above, the visual system is one of feedback for human performance, while the visual system consists of eye ball, eye muscles, visual cortex and connection between peripheral and central apparatus. Being controlled by these apparatus, eye movement can be done smoothly so as to satisfy his will. Namely, the visual system, one feedback of the human manual control system, has so-called multiple loop and information from the visual system probably propagates to motor cortex and regulates the human performance. In order to clarify the manual control system in terms of servomechanisms, it may be considered that eye tracking control system is a servomechanism and be reasonable that the system is studied and analysed by a method of frequency response as well as Stark, Iida and Willis's work[7] or other works[4] on the manual control system in man.

MATERIAL AND METHOD

The experiment of the servoanalytic study on the eye tracking movement was performed on four young emmetropic subjects. The subject sat with his jaw on a fixed pad in front of a cathode ray oscilloscope whose diameter was 12 centimeter, and whose distance to the subject was 15 centimeter. Accordingly, the movement of the target was ± 15 degrees on the surface of the cathode ray oscilloscope. Light spot of the target, whose diameter was 2 millimeter, moves horizontally and sinusoidally in range of 0 to 2.0 cps on the surface of the oscilloscope as the spot was driven by a low frequency

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oscillator (Fig. 1). The subject was ordered to carefully follow the spot of light by binocular movement. The eye movement was recorded through a.c. amplifier on a ink writing recorder, for which two silver electrodes with square form of 1 square centimeter were pasted on the lateral side of both eyes by jelly paste for electrocardiogram. The recording is termed electro-oculography whose principle is to be charged positive on the cornea and negative on the retina and to change the charge with rotation of the eye ball. The change of the charge, amplitude on the recording paper, is propotional to sine function of a half rotatory angle of the eye ball according to Fenn and Hersh's work[3] in 1937. As a result of such frequency response, two values of gain and phase difference were calculated by comparison between horizontally and sinusoidally moving target and the movement of eye ball. However, the response to the sinusoid was not linear in this experimental range of the frequency response, so other technique was applied for analysis of data which will be mentioned in the following chapter.

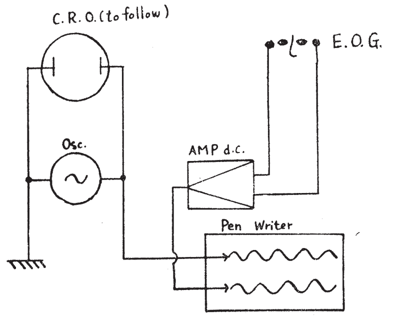


FIG. 1. Diagram of experimental apparatus.

EXPERIMENTAL RESULT

1. Sample record of a frequency response

Since in 1907 Dodge[1] reported two kinds of eye movements, saccadic and smooth movements, the fact has been long and exactly confirmed. However, nobody could explain the exact nature or relation of two movements. As seen in Fig. 2, the record of the eye position shows no trace of smooth tracking. In this Figure there are two types of the records, response to the target position with 0.6 and 1.5 cps. In upper trace of the Figure the response to the target movement of 0.6 cps is shown, in which the eye movement reveals mostly smooth movement superimposed with small degree of saccadic movement. On the contrary, the record in lower trace of 1.5 cps experiment is one of fairly rapid eye movement, and shows steep tracking between peaks and saccadic movement at each peak which may occur in the procedure of eye fixation or in quick turning of eye ball. When these two types of eye tracking movements are considered carefully, the following fact will be observed; the eye tracking movement does not respond to the target movement of high frequency with linear relation but includes the response with non-linear relation. This fact is interesting as compared with the response in the manual control system in man. Man can follow beautifully his hand to target of a single sinusoid in the range of 0 to 8 or 10 cps.[7] Although this paper mentions only the response to single sinusoid in the eye tracking movement, the more detailed can not be stated here. However, the eye tracking movement

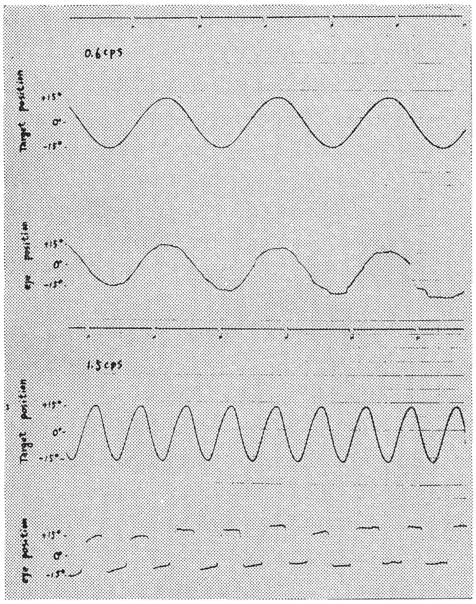


FIG. 2. A typical record of single sinusoid experiment.

changes to the movement of square wave form at frequency between 0.8 and 1.0 cps below that the eye tracking movement shows smooth sinusoid as the response to the target on the cathode ray oscilloscope. That is, in terms of electronics, it may be said that in the eye movement the linear relation is broken and the non-linear relation appears at high frequency of the target. Beyond 2.0 cps of the target movement, the eye ball shows no clear response to the target, as periodic function. This phenomenon may be called saturation which is one of situation in the non-linear behaviour of the system.

Also, in the experiment of 0.6 cps, phase difference between the target position and eye position was probably not noticed and somehow difficult to accurately measure. This becomes more obvious in 1.5 cps experiment of Fig. 2.

2. Servoanalysis of eye tracking movement

In servomechanisms, a technique of the frequency response is used to measure stability of the system and to design more stable system. In the analysis of the eye tracking movement the same technique was utilized in the range of adequate frequencies. As available frequency were 12 frequencies chosen between zero and 2 cps. Beyond 2 cps the response with the periodic pattern (sinusoid) could not be obtained, having great difficulty to analyse the record. It was impossible to identify a peak of the target movement with a peak of the eye tracking movement. Even if more effort to analyse the frequency response in the eye tracking movement is done there, it will be nonsense and invalid. When it will be done at frequency above 2 cps, the analysis has to be carried out in a standpoint of noise-analysis. In the view of this point, this experiment did not be continued at higher frequency than 2 cps. This fact did not follow us to apply the same method as motor coordination experiment by Stark *et al.*[7] to this eye tracking experiment. The method seems to be satisfactory at lower frequency than 2 cps, maximum frequency of the eye tracking experiment, and not to seize valuable data for a great effort. Although single sinusoid experiment has been carried out, the data for discussion was picked up from steady response apparent after several cycles from switch on of the low frequency oscillator. This situation has been called so-called open loop in terms of psychology because of having established "prediction" in man which diminishes his attention to carefully follow the target on the cathode ray oscilloscope.[4)]

At 0.8-1.0 cps the response changes the sinusoidal pattern to the square form, so it is impossible that the usual technique to calculate the gain and phase difference is used. For this situation a method of analysing non-linear system was employed, which is Fourier analysis. In the Fourier analysis each cycle of the response was divided to eight portions whose amplitude was measured respectively. This procedure was done in three cycles of each frequency response. Then, having used a digital computer the values of the amplitude of each frequency and phase difference were calculated through the foundamental harmonics of the Fourier analysis. Thus, a value of gain or phase difference is a mean of the values on three cycles.

Fig. 3 shows Bode diagram of single sinusoid experiment in the eye tracking system. The gain response in the range of this experiment indicated fairly stable and constant value around 1.0 in cases of K. N. and M. I.. However, in both cases the response showed slight decay at frequency adove 0.8 cps

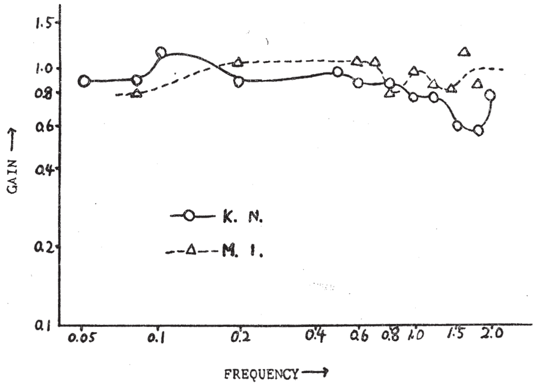


FIG. 3. Frequency response gain data (Bode diagram).

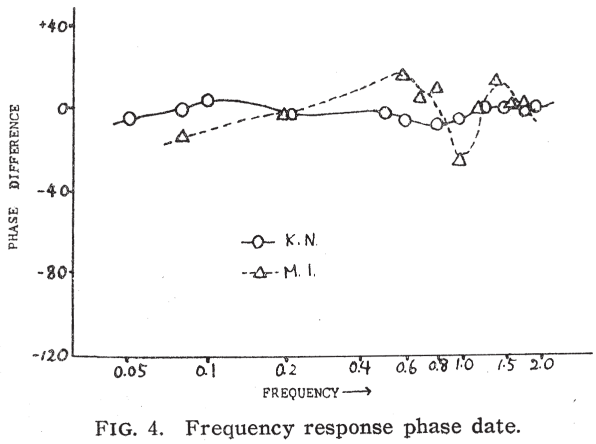
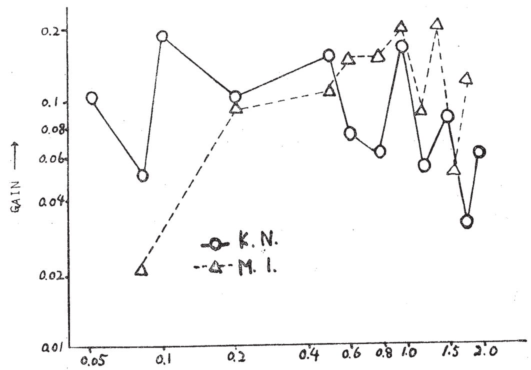


FIG. 4. Frequency response phase date.

with similarity of the response pattern. In Fig. 4 there is shown phase difference data with correspondence of gain curve at each frequency in Fig. 3. The phase difference data showed no lead or lag, suggesting sufficient and accurate following. Only in the case of M. I. the curve revealed slight deviation from zero degree of phase difference, involving small lead or lag in the neighborhood of 1.0 cps. Thinking the phase difference in the case of M. I. of fluctuation, the phase data in both cases have no discrepansy. This means that the stability of the eye tracking system may be quite sufficient in the experimental range with 1.0 of gain and no phase shift.

In the range of this experiment, as mentioned above, the response pattern changes from the linear relation to the non-linear relation at 0.8–1.0 cps. This phenomenon will be clarified in Fig. 5 which was obtained from the second harmonics from Fourier Analysis of gain data in the experiment. Fig. 5 shows a peak at 1.0 cps, as compared with the response at 0.8 cps, while the curve declines beyond 1.0 cps in both cases. These peak and slope suggest that the response pattern in the eye tracking system changes at such frequencies.

The analytic method taken in this experiment is one for non-linear system, so Nyquist diagram, one technique of reviewing stability in linear system, can not be applied in this stage. However, the stability of the system in finite range can be understood by simple inspection of the Bode diagram and phase curve in this experiment. Although the servoanalytic study is applied to analyse such feedback system as heart pumping system, motor coordination system in man and so forth, one of purpose is to describe a transfer function of the system which expresses mathematically a behaviour of the system. In this experiment the gain data shows no noticeable fluctuation, indicating the gain value between 1.0 and 0.8. Accordingly, in this experiment the transfer function of the eye tracking control system may be described as $F(s)=1$ which is the function of the open loop because of being picked up from steady response of the eye tracking experiment.



FREQUENCY⟶

FIG. 5. Frequency response gain data due to second harmonics of Fourier analysis.

DISCUSSION

In order to record the eye movement are several methods involving direct and indirect technique. Among the indirect methods there are cornea-reflex-method with photoelectric apparatus, reflex method of infrared ray, direct photography, and electro-oculography. Usually the investigations of the eye movement have been carried out by the cornea-reflex-method. The electro-oculography (EOG) has not been used for the analysis of the eye movement, but for the recording of nystagmus (electronystagmogram) in general. Recently Shackle *et al.*[6] applied EOG to record the eye movement in cerebral palsied children and exphasized employment of EOG to the analytical study in the eye movement. The EOG, recording of potential between the cornea and retina, will be used to more analytical study in future than previous one.

Since Dodge[1] investigated the eye movement, it has been recognized that the eye movement is not simple but consists of saccadic and smooth movements. The saccadic movement appears in response to sinusoidal input of frequency below 0.8 cps superimposed in the smooth movement. In the peak of the input of frequency above 0.8 cps the response shows no sinusoidal pattern but square-wave form in which there is apparent saccadic movement as the work of Fender *et al.*[2] and Stark *et al.*[8], although the record by Sünderhauf[9] was a little different. Rashbass[5] reported both movements showed different reaction to barbiturates, interfering the smooth movement with it.

The sinusoidal pattern of the response changes to the squarewave pattern at 0.8–1.0 cps. The phenomenon including two types of movements in the eye movement leads us to some difficulty of analysing the frequency response in the eye tracking movement. Accordingly, in this experiment the application of Fourier analysis was considered to solve the difficulty and a programming for use of digital computer was done. This is very interesting in the standpoint of the servoanalysis and the method applied here is fundamental in servoanalysis of non-linear system. The manual control system in man is different in the frequency response and behaves sufficiently and sinusoidally in the range between 0 and 10 cps. Also, in such frequencies the response to the sinusoid did not change the behaviour. Why the eye tracking movement differs from the response in the motor coordination system? This will be interpreted by many and different parameters in both systems. For example, characteristics of the eye muscle and eye ball have to be considered as difference between both control systems. In this experiment the experimental range was taken between zero and 2.0 cps, in agreement with Fender's work[2] and Stark's one.[8] Fender studied the eye tracking movement up to 2.5 cps and mentioned the small amplitude sinusoidal eye movement appeared even at such high frequency. In Stark's work, although not dealing with the response at higher frequency in detail, it had been clarified that at such high frequency the response becomes so erratic that it is difficult to identify the sinusoidal response. And Stark investigated the eye tracking movement in response to single sinusoid and numeral sinusoids. The former was called predicatable input experiment and the latter unpredictable input experiment in his work as well as an experiment of motor coordination system in man by Stark *et al.*[7], for when man responds to a monotonous stimulation, man can predict the stimulation after several seconds, or several cycles if sinusoidal stimuli. Recent work of eye tracking movement by Stark *et al.*[8] used not only single sinusoid of predictable input but four or more sinusoids to which man can not respond with sufficient prediction. In this sense, the complicated stimuli will be necessary to carry on the experiment of measurement in man or man-machine systems.

In his experiment the data of frequency response were calculated immediately by on-line digital computer. However, his method using digital computer is essentially the same as the method in this experiment. Because the Fourier analysis was applied to calculate the rotatory angle of eye movement and phase difference. It was, of course, tiresome to measure many points on the record as Fig. 2, as compared with Stark's computer system. In the unpredictable experiment of the eye tracking movement the computer technique must be applied for analysis, because the response to sinusoidal stimuli behaves non-linearily at frequency above 0.8 cps. When used a band pass filter a frequency as a component of the response to the mixed sinusoids is distorded in shape the analysis of which becomes meaningless in terms of servomechanisms. The Bode diagram plotted from the analytic method, as mentioned above, in this experiment showed the same tendency as Stark's work, while the phase curve revealed mostly no deviation from zero degree in the response between zero and 2.0 cps, differing from the previous works by Fender *et al.*[2] and Stark *et al.*[8]

In determination of stability, which is the most important in servomechanisms, of the linear system Nyquist's criterion lends a problem of the stability more easily to a physical interpretation. However, this is discussed only in the data of the linear system but not in the eye movement of changing from linear behaviour to non-linear one. The frequency response between zero and 2.0 cps in this experiment showed mostly 1.0 in gain and slight deviation from zero degree in phase difference, and this will give us the following suggestion that the system of the eye tracking control is stable in such range.

And, although one of aims to use the frequency response for analysing the system in man is to describe a transfer function which indicates the behaviour of the system, the response data in this experiment do not lead us to describe the transfer function of the eye tracking control system. If not accurate but trying very tentatively, the transfer function may be expressed only $F(s)=1$. Accordingly, when it needs to make more accurate transfer function of the system, other method than the frequency response must be applied to.

In this experiment, in spite of being multiple loop in the eye tracking control system, the system was thought a servomechanism and tested. The changing of the response behaviour at 0.8–1.0 cps may be due to characteristics of the eye tracking control system or might be mainly characteristic of eye muscles or eye ball operated by the eye muscles, which are peripheral organ in the eye tracking control system.

SUMMARY

Eye tracking control system was tested by frequency response using single sinusoid. Eye movement was recorded by electro-oculography with two silver electrodes pasted on lateral sides of both eyes by jelly for electrocardiogram.

1. At low frequency below 0.8 cps the response appeared with smooth movement superimposed with saccadic movement and at high frequency above 0.8 cps there was apparent saccadic movement in the response.

2. The response to single sinusoid changes to non-linear behaviour at 0.8–1.0 cps. For this, Fourier analysis was applied to calculate both gain and phase difference.

3. The Bode diagram showed slight decay at the frequency below 0.8 cps, while the phase curve indicated mostly no deviation in range of frequency between zero and 2.0 cps.

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