# AN INVESTIGATION OF THE EFFECT OF PREVIEW ON HUMAN TRACKING BEHAVIOR

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SUMMARY

This research has been aimed at determining the effect of "preview," or anticipation, on human control behavior in a pursuit tracking task. The methodology used was that of man-machine control systems and basic statistical regression theory.

First, the characteristics of the human controller in pursuit tracking have been formulated using control systems theory. Then, the human controller element has been identified in the time domain based partly on linear statistical regression theory.

The data base for the study was developed from laboratory experiments utilizing an analog computer and various pieces of peripheral equipment. Two students served as subjects.

Based on the experimental results obtained from the investigation, it was first demonstrated that preview in tracking tasks has a significant effect on the mean square error for different experimental conditions. Second, the least squares estimates were obtained for the impulse response sequences of the human controller. The power spectrum for the residual errors in the linear regression models has been calculated and Bode diagrams were obtained. Such frequency response data for the human controller element did not indicate any clear specific pattern for estimating the transfer function of the human controller.

The remnant power spectral density has been estimated and a linearity coefficient has been defined and calculated for different

frequencies. It seemed from these results that time variant and nonlinear characteristics of the human controller are quite significant for both subjects used in this study.

# CHAPTER I

## INTRODUCTION

Manual control systems are an important and interesting class of control systems--important because they are in such common use and interesting because they have properties that are highly desirable. Of particular interest is the human controller's ability to modify his activities to respond appropriately to numerous different possible control situations, an ability the effect of which is to make the human a distinct and true component of the overall system.

Most of the research that has been conducted to study the behavior of the human controller has taken the form of tracking study, a technique which essentially attempts to describe the relations which exist between measures of tracking behavior and task variables, and to assess the effect of task variables on performance. Adams [1] defines a one-dimensional tracking task as follows:

> An externally driven input signal defines an index of desired performance and the operator actuates the control system to maintain alignment of the output signal of the control system with the input signal. The discrepancy between the two systems is the error and the operator responds to null the error (p. 168).

There are two types of tracking tasks: pursuit tracking and compensatory tracking. The two types are differentiated principally by the way in which the tracking information is presented. In pursuit tracking, the input signal and the output signal of the control system are displayed to the operator separately, and the operator is required to try to match the two signals in order to reduce the error between them. In compensatory tracking, however, the error between the input and the output of the control system is displayed to the operator; the operator does not see the input or the output separately and his task is to minimize this error. Figures 1 and 2 show the difference between pursuit and compensatory control systems.

"Preview span" is defined as the distance ahead of time that the human controller is able to "see" and respond to the input. Thus, at some time t the controller is provided with the input for all points in the interval $[t, t + T_p]$ where $T_p$ denotes the preview span. Immediate examples are vehicular control and pilot studies, such as studies on spacecraft altitude control, atmosphere reentry, aircraft takeoff, aircraft landing, and submarine depth control, to name just a few. Further elaboration of the use of preview in manual control systems can be found in Kelley [12] and Warner [36].

This research presents the results of experimental studies of the effect of preview or anticipation on human performance in a pursuit control system. The human controller's task was to follow a certain random path both with and without preview, and to try (by matching input and output signals) to reduce the error between the two signals. The experimental data therefore provided a basic description of human controller behavior for these special tasks and gave an indication of performance for different values of preview. The statistical characteristics of input signal or forcing function, output signal of the controlled element, and the output of controller,

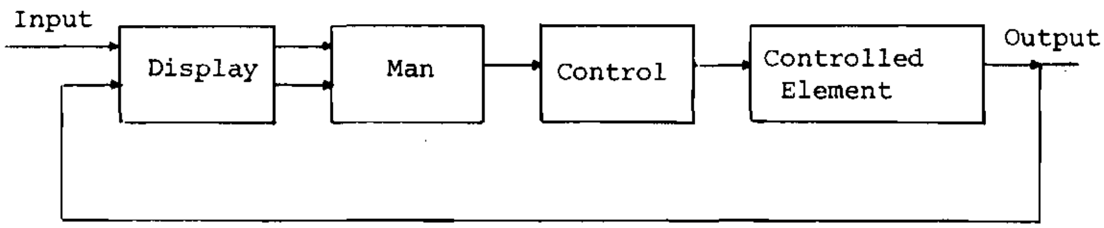


Figure 1. Pursuit Manual Tracking System

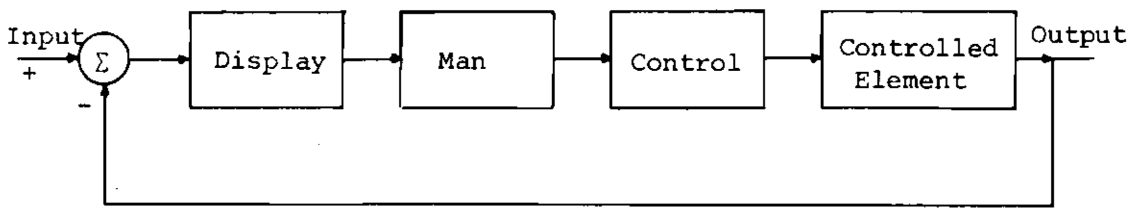


Figure 2. Compensatory Manual Tracking System

with regard to autocorrelation and crosscorrelation were the principal variables studied experimentally.

# CHAPTER II

## LITERATURE REVIEW

The literature associated with the effect of preview or anticipation on human controller performance is extensive.

Poulton [20] studied the effect of anticipation span reaction time. Two different types of experiments were carried out: in the first, a skilled response had occasionally to be altered at a given point after a variable warning period; in the second, the subject had to react to two auditory signals separated by a short time interval which was systematically changed (the second signal being, variously, expected or unexpected). It was found that a subject's unreadiness to respond to a signal, as observed by lengthened reaction time, may be due either to the subject's not having prepared himself because he was not expecting the signal, or because he was just not able to prepare himself quickly enough. Preparation for reacting to the second signal, when both were expected and had to be reacted to, was between 0.2 and 0.4 seconds. In most cases the reaction time appeared to be 0.2 seconds. These times were shorter than the usual reaction time because delay due to incorrect anticipation was excluded. Poulton concluded that unreadiness appeared to be due to the fact that the subject was simply not expecting the signal, and that preparation for a signal took longer when a skilled response had to be extended than when it had to be stopped. He suggested that so-called "psychological refractoriness" is due to a lack of foreperiod in which the subject is able to prepare for the next response while making the current one.

In another set of experiments with two-pointer (pursuit) and one-pointer (compensatory) tracking tasks, Poulton [21] showed that tracking was more accurate with a two-pointer display than with a one-pointer display, and that increased accuracy was associated with increased anticipation. Poulton [22] also described the use of remembered information in tracking as anticipation. The immediate received information concerning the course, speed, and acceleration was defined as "speed anticipation." Remembered information concerning the course and its characteristics was defined as "course anticipation." In a two-pointer display, course anticipation was regarded not by viewing the response point motion, but by recognizing the sensory cues provided by his control movements. As a result, one had the notion of anticipation where the course was going and the recognition of structure as consideration in a model of the controller.

In yet another experimental study on a type of pursuit tracking, Poulton [23] determined the subject's ability to learn and use his knowledge of the statistical properties of the input and compared the effectiveness of visual information about a course acquired <u>before</u> tracking with that of visual-kinesthetic information obtained <u>while</u> tracking. The subject was asked to use a pencil to trace courses that consisted of constant slopes separated by sudden discontinuities in direction, and was required to meet a time criterion.

Half of the courses were patterned, in the sense that they contained systematic trends which could be used in prediction; the other courses were random. In three conditions vision was restricted (by a mask attached to the pencil) to that part of the course near the tip of the pencil. In one of the conditions the part of the course which had already been traced could also be seen, and in this and another condition the course could be studied visually before tracking. In the fourth condition there was no restriction on the subject's vision. Overshooting of a corner dropped when the portion of the corner could be predicted either from the sequential structure of the previous part of a pattern course or from a knowledge of the common statistical properties of the course. Visual information acquired before tracking was found to be <u>less</u> effective than visual-kinesthetic information acquired while tracking.

In another pursuit tracking experiment, Crossman [4] studied the effect of preview on continuous tasks involving pursuit tracking, and used information theory to measure human performance. Without preview of the course the channel capacity was found to be about 4 bits per second, whereas with preview the channel capacity improved up to at least 8 bits per second. Based on this study Crossman suggested that a human controller system consisted of parts arranged serially: a decision mechanism which receives its input from display and uses its output to influence an effector mechanism, which in turn controls the muscular activity needed to carry out the instruction. (In effect, then, the decision mechanism is translating the incoming signals into instructions for the effector system.)

Citing studies of other investigators, Crossman suggested that the decision mechanism has a channel capacity of up to 20 bits per second for "compatible" tasks such as tracking with preview, and for hand movements he suggested that the channel capacity of the effector mechanism will reach 10 bits per second. However, since the two mechanisms are in series, the lower capacity of 10 bits per second for the whole system is expected. Yet even this lower capacity rate was never achieved in the experimental study, and the explanation Crossman proposed for this fact was that the subject was sampling between the course ahead and the tracking error and then transmitting the wrong sampling he was using. Crossman thus suggested that the effector mechanism is actually sampling his error at a rate that, when multiplied by the bits per sample for hand movements, will produce up to 10 bits per second.

Poulton [23] also discussed human performance in making skilled movements and considered the results of several compensatory and pursuit tracking tasks. Some of these results were related to preview tracking tasks. First, it was concluded that a rapid aiming movement which was completed in about 0.5 sec cannot contain a voluntary correction, since a voluntary movement has a reaction time. Furthermore, a rapid aiming movement should not be affected by visual monitoring, since there is no time to use this visual information. Referring to the work of Gottsdanker [10], Poulton pointed out that subjects match the rates at which tracking objects are moving and then referred to some work of Elkind [8] to show that this rate-matching appears at the higher frequencies in the closed-loop transfer function. Based on results of Senders [27], he claimed that the display which provides the greatest amount of information about target rates will give the best tracking scores. Finally, he recalled from his own work into eye-hand span in simple serial tasks that zero-lag tracking occurs when the future track of the target is visible for 0.4 seconds ahead. A view of 0.3 seconds results in increased lag.

Subsequently, Poulton [24] studied the effects of postview and preview on tracking performance. In this experimental study, inputs consisting of both simple and complex sine waves were tracked by subjects, and the subjects' view behind and ahead was varied systematically in different trials. The results of the experiment showed that postview of the course and of the response improved performance because it made the subjects realize the present rates and reversals of the course, so that they could learn its structure and be able to respond faster and more accurately. Poulton stated that although 0.5 seconds of postview was sufficient for information on present course velocity and acceleration, a 7-second postview gave better results. In a preview condition, 0.5 seconds was sufficient to remove the need to predict, but preview seemed especially effective when the subject saw the next reversal before he reached the previous one. The reason for this, Poulton explained, is that the subject tends to aim in the course without having to use intermediate targets.

Kelley [13] has used a fast time model in developing a somewhat complicated "predictor display" for a human controller which presents a prediction of future response based upon present controller position and state variable of the position. A fast analog model of the controlled process is repetitively clamped with "present" state variables of the controlled process as initial conditions to the integrators of the fast model (Figure 3). The model is then unclamped and, as it quickly runs its course, the response is a prediction of the future course of the actual process. This is repeated several times within each second. The model's response is displayed on an oscilloscope so that the human controller can observe the predictive response as the model is repetitively recycled starting from an updated "now" state and running a certain time into the future. Kelley's studies revealed that such predictive displays resulted in significant improvement of human tracking performance.

Sheridan [29] first introduced the notion of an extended convolution integral to a human controller in the case of input anticipation or preview. In this formulation, the controller's unit impulse response function consists of a nonzero preview component that starts prior to the occurrence of the unit impulse as well as a memory component that extends throughout the controller's finite memory span. The effective convolution limits thus extends from the beginning of the preview span to the end of the memory span. This extended convolution idea is basic to the model formulation in this investigation and will be further elaborated on in the next chapter.

In an experimental investigation into preview tracking Sheridan et al. [28] considered tracking under three conditions--first, without preview; then with preview, but with the stylus constrained

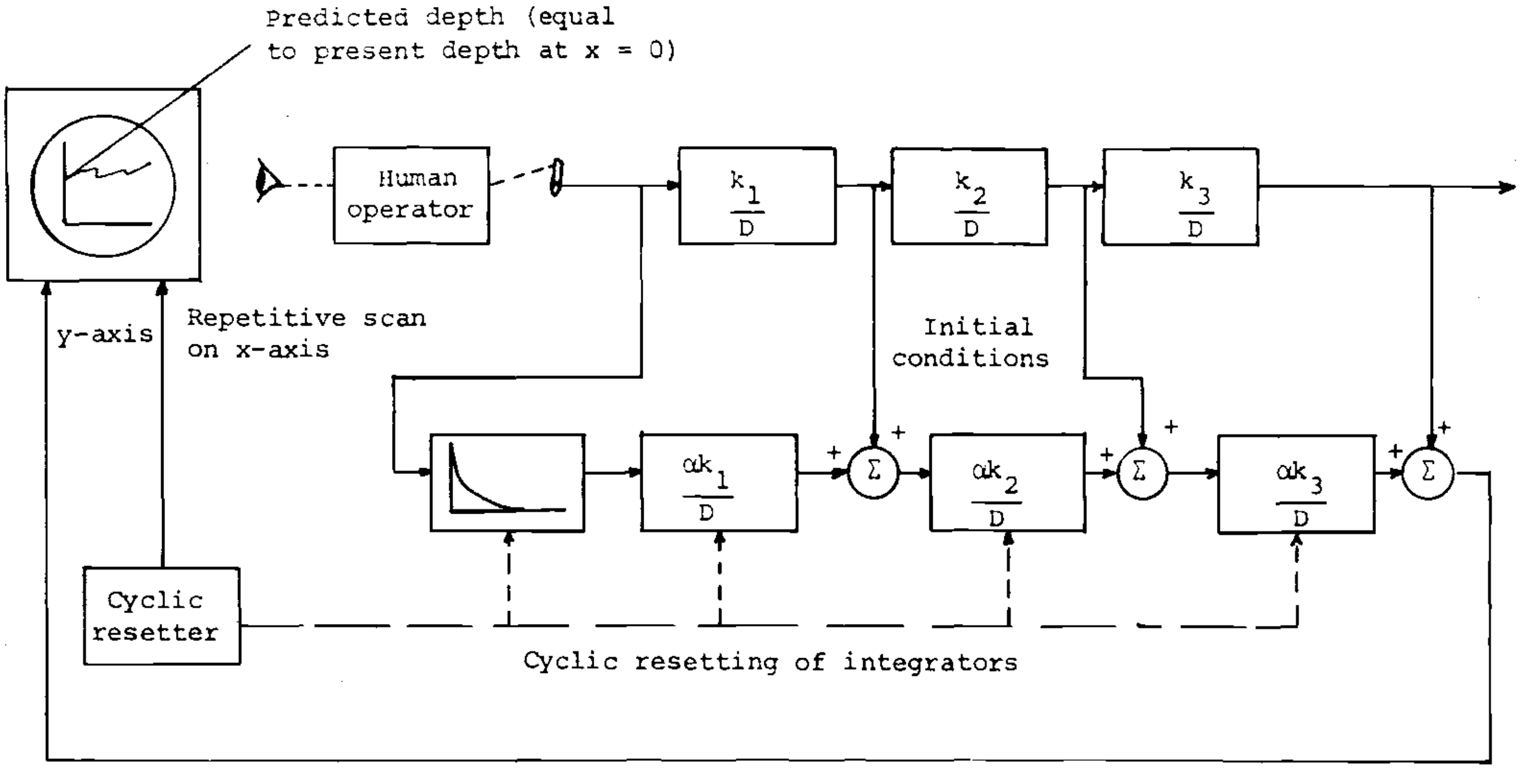


Figure 3. Kelley's Prediction Model

(placed against the edge of the viewing window); and, lastly, under a "self-paced" condition, in which no constraint was set on the location of the stylus within the window. Performance indicated, as expected, that the controller performed better with preview than with no preview. Using the self-pacing preview window, the subject either moved the window upstream along the course or kept the pen at about the same position, but in any event the result was that the subject's performance improved, even in comparison to the preview condition. Sheridan therefore suggested that self-pacing with preview facilitates planning ahead.

A second set of experiments was conducted in which subjects performed along successive semicircular arcs of different radii and at their own speed. The radius of curvature was a strong determinant of course-following speed. Subjects performed more slowly for smaller radii and faster for larger radii. Sheridan and his colleagues concluded that the experiment indicated that there is a slowing-up at high frequencies and a speeding-up at lower frequencies as a means of compressing the bandwidth and permitting generally high gain and better closed-loop performance.

In another set of experiments in which a pursuit tracking display was used, Sheridan [28] presented a target t seconds in advance. It was found that this form of preview was of little use beyond t = 1/2 sec, regardless of any controlled precess lag. This was explained as an apparent inability to remember the previewed function in a continuous "conveyor belt" fashion.

Stark, Vossius, and Young [32], using a simple instrument for measurement of eye movements, demonstrated that changes in the characteristics of the target-position signal will have important effects on the nature of the biological servomechanism controlling the movements. In particular, they suggested that an adaptive predictor can allow the system to overcome its innate delays upon exposure to a regular input pattern. The experimental data which these researchers presented illustrated the striking difference between predictable and unpredictable input signals.

Recently, Kvålseth [16] developed an experimental model that incorporated preview constraints for serial motor movements involving arm rotation. Without preview constraint, the rotary arm movement task produced a maximum movement information of 4.7 bit/sec, but when preview constraints were imposed the movement information was reduced to 3.9 bits/sec (as compared to a marginal preview information rate of 12.5). The movement variable was found to account for about 70 percent of the total contribution to movement time. The error rates were determined to be highest in the no-preview-constraint case, and were affected by both movement and preview information.

The developments reviewed above can be summarized in two brief statements:

First, most investigators considered a single one-dimensional input rather than a complex visual field and an associated visual response. As a result, most of the behavioral characteristics described are very specialized models of human controller behavior.

Second, the results obtained from most of the investigators indicate that, for reasonably accurate tracking, only a short preview is required. The usefulness of preview is associated with the identification of course properties (such as reversals) and with the estimation of bandwidth.

As has been shown, most of the work previously conducted in the area of tracking with preview has focused on the psychological aspects of the human controller's behavior. In contrast, the research reported in this thesis has employed mathematical modeling (along with appropriate experimental procedures) to measure the effect of different values of preview on human controller performance. Derivation of analytic models of the human controller which can relate the parameters of his characteristics to different values of preview of the input signal has also been attempted, and a measure of the degree of linearity for the human controller at different frequencies has been obtained. Although transfer functions for the human controller have been formulated in a number of compensatory tracking studies, a measure for the open loop describing function in pursuit tracking was not previously obtained, whereas, in this report, the derivation of impulse response functions and frequency response functions corresponding to different preview conditions for the human controller in pursuit tracking is presented. That result shows that the research described herein has made a distinct and new contribution to the area of investigation.

# CHAPTER III

# MATHEMATICAL BACKGROUND*

## Model Formulation

The purpose of this chapter is to develop a mathematical model of human controller dynamics. Once such a model has been formulated, a method for estimating the model parameters will be proposed. Subsequent discussions will attempt to analyze experimental findings concerning ways in which these model parameters were influenced by changes in the preview or anticipation span of the controller input or forcing function.

The basic man-machine control system in the pursuit case, together with an identification of the various system variables and elements is given in Figure 4. This diagram shows the human controller as an element of a closed-loop system. If the characteristics of the human controller for a given task are assumed to be capable of quasi-linear description, the mathematical model of the human controller will consist of two linear transfer functions plus an additional quantity inserted as an input into the system by the human controller (see Figure 5). The "remnant" term $r(t)$, which was first used by Tustin [34] in the study of the nature of the operator's response in manual control, accounts for the nonlinear

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*The mathematical formulations in this chapter were developed by Dr. T. Kvålseth, School of Industrial and Systems Engineering, Georgia Institute of Technology.

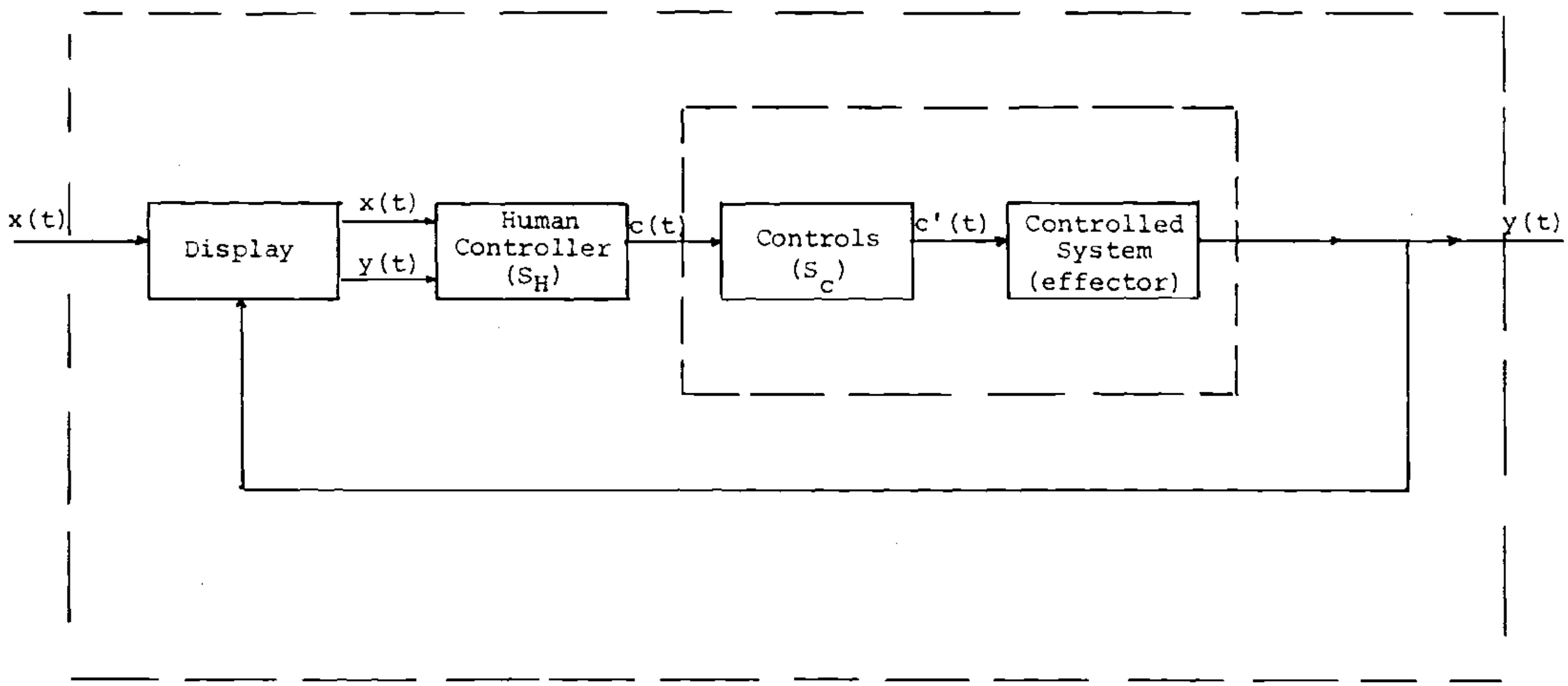


Figure 4. Basic Man-Machine Control System

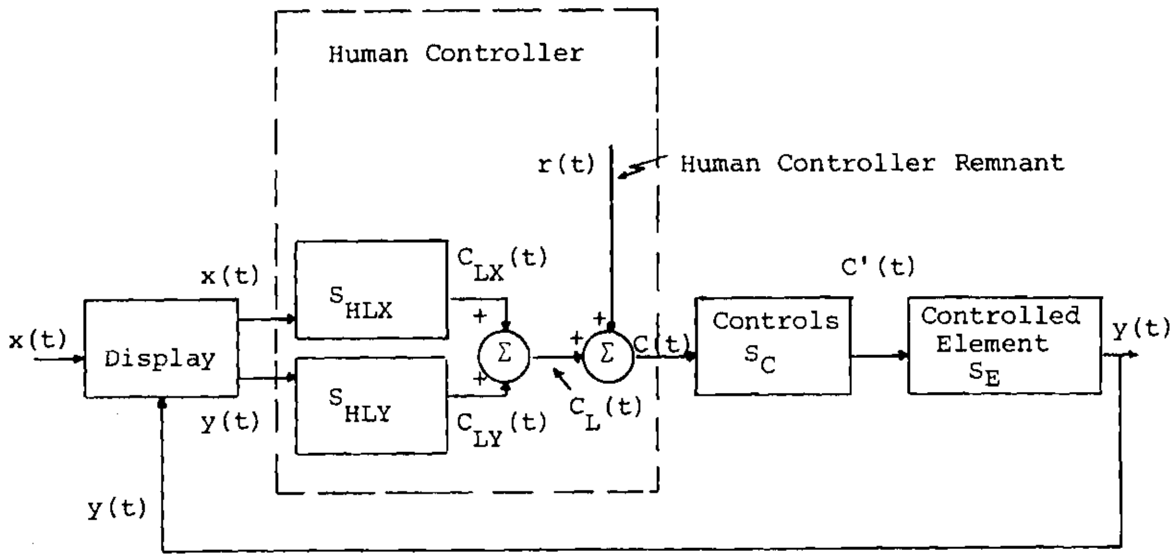


Figure 5. Equivalent Block Diagram of Pursuit System with Linearized Controller

and time-variant portion of the human controller ($S_H$), whereas $S_{HLX}$ and $S_{HLY}$ account for the linear and time-invariant characteristics of the human controller.

In the fundamental control situation considered in Figure 5, the linear and time-invariant human controller elements $S_{HLX}$ and $S_{HLY}$ operate on the input x(t) and output y(t), respectively, whereas the remnant terms r(t) adds to the human controller output before it reaches the controls. In the problem at hand, the task is to find the characteristics of the human controller--that is to say, $S_{HL} = \{S_{HLX}, S_{HLY}\}$ and r(t) and some closely related quantities from measurements made on observable signals in the loop.

In trying to formulate relationships involving the system elements $S_{HLX}$ and $S_{HLY}$ and the signals x(t), y(t), and c(t), the general assumption needs to be made that the cross-correlation function between the forcing function x(t) and the remnant r(t) is zero. An examination of Figure 5 will reveal immediate problems encountered due to the fact that r(t) is not orthogonal to y(t); that is to say, due to the fact that the cross-spectral density of y(t) and r(t) is not equal to zero. The solution to this problem is to move the human controller component terms outside and into the feedback loop, so that the configuration shown as Figure 6 results.

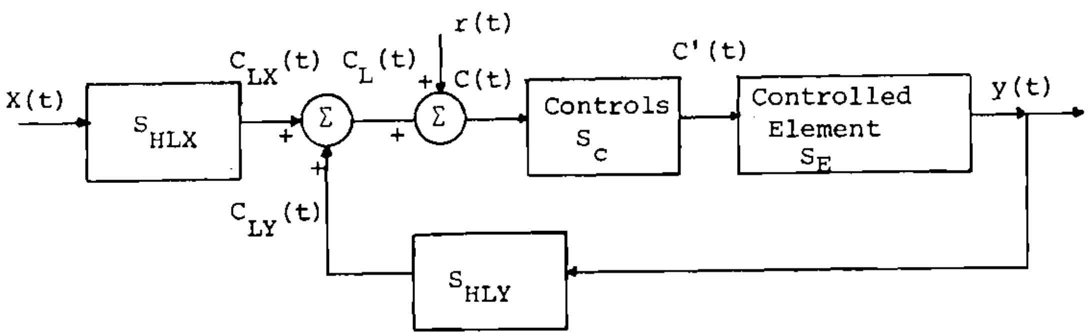


Figure 6. Alternative Block Diagram of Pursuit System

Furthermore, if $H_{HY}(f)$, $H_{HX}(f)$, and $H_{CE}(f)$ denote the frequency response functions corresponding to the unit impulse response functions $h_{HY}(t)$, $h_{HX}(t)$, and $h_{CE}(t)$, and if $H_{CE}(f)$ is the joint frequency response function of the controls and controlled element, then Figure 6 reduces to the diagram shown as Figure 7.

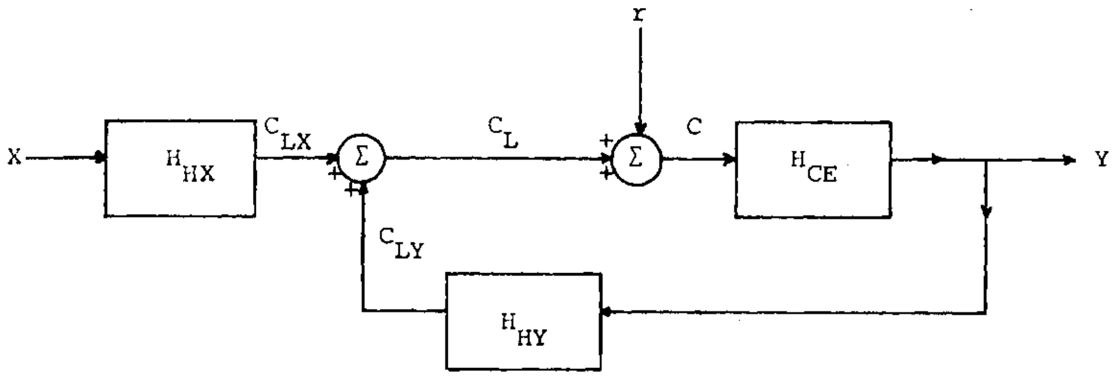


Figure 7. Block Diagram of Pursuit System in Frequency Response Form

The following correlation relationships may now be formulated.

$$R_{XC}(\tau) \triangleq \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} X(t)C(t+\tau)dt$$

$$= \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} X(t)[C_L(t+\tau) + r(t+\tau)]dt$$

$$= \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} X(t)[C_{LX}(t+\tau) + C_{LY}(t+\tau) + r(t+\tau)]dt$$

$$= R_{XC_{LX}}(\tau) + R_{XC_{LY}}(\tau) + R_{Xr}(\tau) \qquad (3.1)$$

where $R_{Xr}(\tau) = 0$ for all $\tau$ by assumption. Furthermore, we have that

$$R_{XC}(\tau) = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{+T} X(t) \int_{-\infty}^{+\infty} h_{HX}(t')X(t+\tau-t')dt'dt$$

$$+ \lim_{T} \frac{1}{2T} \int_{-T}^{+T} X(t) \int_{-\infty}^{+\infty} h_{HY}(t')Y(t+\tau-t')dt'dt$$

$$= \int_{-\infty}^{+\infty} h_{HX}(t')dt' \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} X(t)\ X(t+\tau-t')dt$$

$$+ \int_{-\infty}^{+\infty} h_{HY}(t')dt' \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} X(t)\ Y(t+\tau-t')dt$$

$$= \int_{-\infty}^{+\infty} h_{HX}(t')\ R_{XX}(\tau-t')dt' + \int_{-\infty}^{+\infty} h_{HY}(t')\ R_{XY}(\tau-t')dt'$$

or,

$$R_{XC}(\tau) = h_{HX}(\tau)^{*}\ R_{XX}(\tau) + h_{HY}(\tau)^{*}\ R_{XY}(\tau) \tag{3.2}$$

Taking Fourier transforms on both sides of equation (3.2) yields

$$S_{XC}(f) = H_{HX}(f)S_{XX}(f) + H_{HY}(f)S_{XY}(f) \tag{3.3}$$

## System Identification in the Time Domain

Let $T_p$ denote the preview span or anticipation span and $T_m$ the memory span of the human controller $S_H$. For the time being, consider that $T_m$ is finite and fixed. With these effective convolution integral limits, equation (3.2) becomes

$$R_{XC}(\tau) = \int_{-T_p+T_r}^{T_{mx}} h_{HX}(t)R_{XX}(\tau-t)dt + \int_{0+T_r}^{T_{my}} h_{HY}(t)R_{XY}(\tau-t)dt \tag{3.4}$$

where $T_{mx}$ and $T_{my}$ denote the memory spans relevant to the system $S_{HLX}$ and $S_{HLY}$ (see Figure 5); $T_r$ denotes the reaction time delay of $S_H$ ($T_r \approx 0.20$ sec). The values of $T_{mx}$ and $T_{my}$ need to be determined through some trial-and-error calculations, as will be explained later on. The next equation, (3.5) may be approximated as

$$R_{XC}(\tau) \approx \sum_{p=-1}^{-N_1} h_{HX}(pH) R_{XX}(\tau-ph)h + \sum_{p=1}^{N_2} h_{HX}(ph) R_{XX}(\tau-ph)h$$

$$+ \sum_{p=1}^{N_3} h_{HY}(T_r+ph) R_{XY}(\tau-ph)h \qquad (3.5)$$

where, clearly

$$N_1 h = T_p - T_r \quad , \quad N_2 h = T_{mx} \quad , \quad N_3 h = T_{my} - T_r$$

Now, for different values $qh$ ($q = 0, 1, 2, \ldots, M$) of $\tau$, equation (3.5) produces the following set of equations.

$$R_{XC}(qh) = \sum_{p=-1}^{-N_1} h_{HX}(ph) R_{XX}[(q-p)h]h + \sum_{p=1}^{N_2} h_{HX}(ph) R_{XX}[(q-p)h]h$$

$$+ \sum_{p=1}^{N_3} h_{HY}(T_r+ph) R_{XY}[(q-p)h]h + \varepsilon_q$$

$$q = 0, 1, 2, \ldots, M \qquad (3.6)$$

If $R_{XC}(\tau)$, $R_{XX}(\tau)$, and $R_{XY}(\tau)$ are replaced by their estimates $\hat{R}_{XC}(\tau)$, $\hat{R}_{XX}(\tau)$, and $\hat{R}_{XY}(\tau)$, then, for different values of $\tau$, the following linear statistical model results.

$$\begin{pmatrix} \hat{R}_{XC}(0) \\ \hat{R}_{XC}(h) \\ \vdots \\ \hat{R}_{XC}(Mh) \end{pmatrix} = h \begin{pmatrix} \hat{R}_{XX}[(0+1)h] & \hat{R}_{XX}[(0+2)h] & \ldots & \hat{R}_{XX}[(0+N_1)h] \\ \hat{R}_{XX}[(1+1)h] & \hat{R}_{XX}[(1+2)h] & \ldots & \hat{R}_{XX}[(1+N_1)h] \\ \vdots & \vdots & & \vdots \\ \hat{R}_{XX}[(M+1)h] & \hat{R}_{XX}[(M+2)h] & \ldots & \hat{R}_{XX}[(M+N_1)h] \end{pmatrix} \begin{pmatrix} h_{HX}(-h) \\ h_{HX}(-2h) \\ \vdots \\ h(-N_1h) \end{pmatrix}$$

$$+h \begin{pmatrix} \hat{R}_{XX}[(0-1)h] & \hat{R}_{XX}[(0-2)h] & \ldots & \hat{R}_{XX}[(0-N_2)h] \\ \hat{R}_{XX}[(1-1)h] & \hat{R}_{XX}[(1-2)h] & \ldots & \hat{R}_{XX}[(1-N_2)h] \\ \vdots & \vdots & & \vdots \\ \hat{R}_{XX}[(M-1)h] & \hat{R}_{XX}[(M-2)h] & \ldots & \hat{R}_{XX}[M-N_2)h] \end{pmatrix} \begin{pmatrix} h_{HX}(h) \\ h_{HX}(2h) \\ \vdots \\ h_{HX}(N_2h) \end{pmatrix}$$

$$+h \begin{pmatrix} \hat{R}_{XY}[(0-1)h] & \hat{R}_{XY}[(0-2)h] & \ldots & \hat{R}_{XY}[(0-N_3)h] \\ \hat{R}_{XY}[(1-1)h] & \hat{R}_{XY}[(1-2)h] & \ldots & \hat{R}_{XY}[(1-N_3)h] \\ \vdots & \vdots & & \\ \hat{R}_{XY}[(M-1)h] & \hat{R}_{XY}[(M-2)h] & \ldots & \hat{R}_{XY}[(M-N_3)h] \end{pmatrix} \begin{pmatrix} h_{HY}(0.2+h) \\ h_{HY}(0.2+2h) \\ \vdots \\ h_{HY}(0.2+N_3h) \end{pmatrix}$$

$$+ \begin{pmatrix} \varepsilon_0 \\ \varepsilon_1 \\ \vdots \\ \varepsilon_M \end{pmatrix} \tag{3.7}$$

for which the least square estimators $\hat{h}_{HX}$ and $\hat{h}_{HY}$ can be obtained.

Once the estimates of the impulse-response functions $h_{HX}(t)$ and $h_{HY}(t)$ have been obtained as outlined above, the frequency response functions $H_{HX}(f)$ and $H_{HY}(f)$ may be obtained by the method described by Davies [5] on page 184 of System Identification for Self-Adaptive Control.

Accordingly,

$$H_{HX}(jf) = h \sum_{p=-N_1}^{N_2} h_{HX}(ph) \cos(phf) - jh \sum_{p=-N_1}^{N_2} h_{HX}(ph) \sin(phf) \qquad (3.8)$$

and

$$H_{HY}(jf) = h \sum_{p=1}^{N_3} h_{HY}(ph) \cos(pfh) - jh \sum_{p=1}^{N_3} h_{HY}(ph) \sin(pfh) \qquad (3.9)$$

As indicated, the reaction-time delay $T_r$ has been left out of equation (3.9; for the sake of simplicity $T_r$ may be excluded from equations (3.5), (3.6), and (3.7). Having obtained the frequency response functions $H_{HX}(f)$ and $H_{HY}(f)$, it is then possible to obtain the transfer functions $H_{HX}(S)$ and $H_{HY}(S)$ (cf. Davies [5], pp. 198-206).

## Remnant Considerations

It is possible to shift to the left the remnant team of the quasi-linear model of the human operator shown in Figure 7. The result of such a shift is the configuration shown as Figure 8.

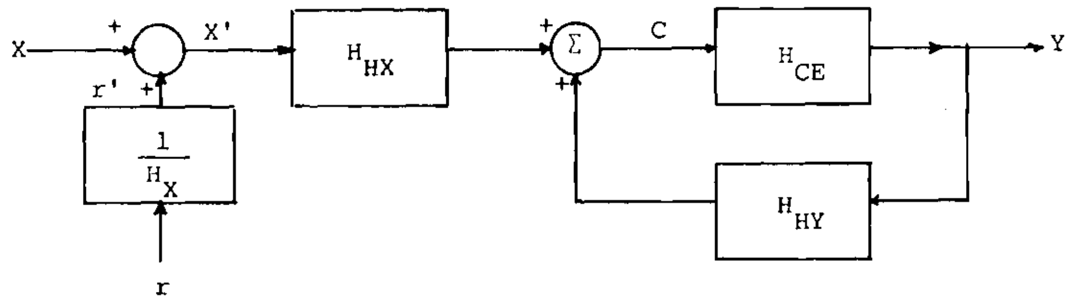


Figure 8. Quasi-Linear Model of Human Operator with Shifted Remnant

It is then possible to reduce Figure 8 to the form shown in Figure 9.

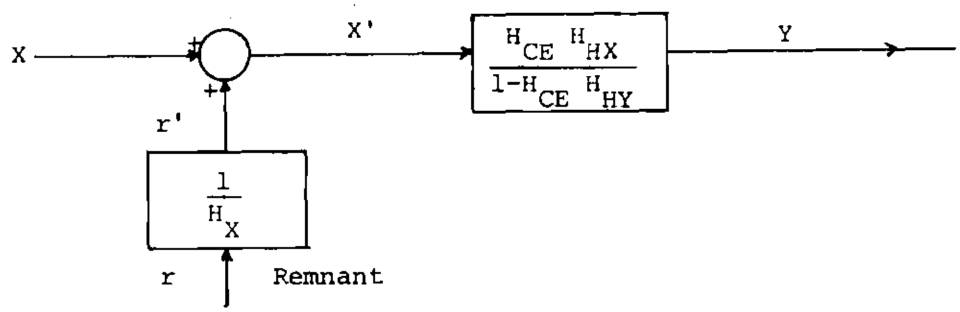


Figure 9. Simplified Quasi-Linear Model of Human Operator with Shifted Remnant

Let $S_{X'X'}(f)$ and $S_{YY}(f)$ denote the power spectral density functions of X'(t) and y(t), respectively. Then, for the block with input X'(t) and output y(t) in Figure 9, the following fundamental spectral relationship applies (see Ref. [3], p. 137):

$$S_{YY} = \left| \frac{H_{CE}(f)H_{HX}(f)}{1 - H_{CE}(f)H_{HY}(f)} \right|^2 S_{X'X'} \tag{3.10}$$

where $S_{X'X'}(f)$ is given by the following:

$$R_{X'X'}(\tau) = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} [X(t) + r'(t)][X(t+\tau) + r'(t+\tau)]dt$$

$$R_{X'X'}(\tau) = R_{XX}(\tau) + R_{Xr'}(\tau) + R_{r'X}(\tau) + R_{r'r'}(\tau) \tag{3.11}$$

But $R_{Xr'}(\tau) = 0$ for all $\tau$ since $R_{Xr}(\tau) = 0$ for all $\tau$ by assumption. It is also well known that

$$S_{r'r'}(f) = \left|\frac{1}{H_{HX}(f)}\right|^2 S_{rr}(f) \tag{3.12}$$

Then, from equations (3.10, 3.11, and 3.12), it is found that

$$S_{YY}(f) = \left|\frac{H_{CE}(f)H_{HY}(f)}{1 - H_{CE}(f)H_{HY}(f)}\right|^2 \left\{S_{XX} + \left|\frac{1}{H_{HX}}\right|^2 S_{rr}\right\} \tag{3.13}$$

From equation (3.13) it follows that

$$S_{rr}(f) = \left|\frac{1 - H_{CE}(f)H_{HY}(f)}{H_{CE}(f)}\right|^2 S_{YY}(f) - \left|H_{XX}(f)\right|^2 S_{XX}(f) \tag{3.14}$$

From Figure 9 it is clear that

$$S_{CC}(f) = \frac{1}{\left|H_{CE}(f)\right|^2} S_{YY}(f) \tag{3.15}$$

From equations (3.13), (3.14), and (3.15) it follows that "the linearity coefficient" $\rho$, which provides some measure of the degree of linearity for the human controller, may be expressed as follows:

$$\rho(f) \triangleq 1 - \frac{S_{rr}(f)}{S_{CC}(f)}$$

$$= 1 - \left|1 - H_{CE}(f)H_{HY}(f)\right|^2 + \left|H_{HX}(f)H_{CE}(f)\right|^2 \frac{S_{XX}(f)}{S_{YY}(f)} \quad (3.16)$$

# CHAPTER IV

# METHOD

## Experimental Apparatus

The controller input or forcing function for this experiment was generated by Hewlett-Packard model 3722A low-frequency broadband noise generator which provides two types of random noise output--a two-level (binary) output and a continuous analog waveform of approximately Gaussian amplitude distribution. The latter random function was used in this experiment. The spectrum of the Gaussian output of the random noise generator is approximately rectangular. The bandwidth (at 3db point) of the Gaussian noise is selectable from 0.00015 Hz to 50 K Hz. In the random mode, the output of this noise generator has continuous spectra extending down to d.c. line. The output of the generator is at 3.16v rms for Gaussian distribution, but a precision RMS amplitude control provides a variable output ranging from 0.1v up to the level of the fixed output [26]. Since the output of the random noise generator is greater than the voltage desired for the recorder, a voltage divider network was used in the experiment to obtain the desired voltage (see Figure 10). The voltage divider network consisted of two resistors connected in series. In Figure 10 the voltage $V_1$ across the total impedances is divided by the resistors so that only part of voltage $V_1$ appears across $R_2$. By selecting the resistors at specified values, it was possible to obtain the desired voltage $V_2$ for the recorder.

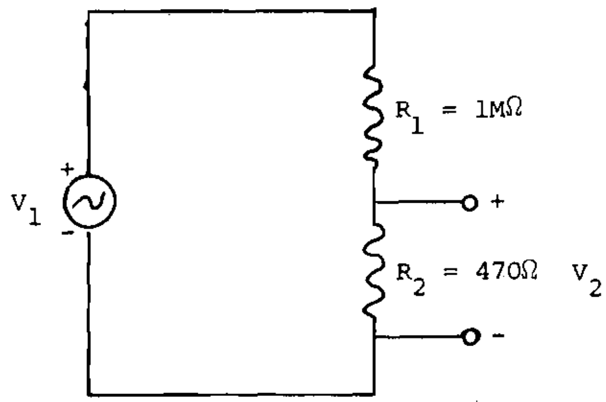


Figure 10. The Voltage Divider Network

In this experiment the values of $R_1$ and $R_2$ were chosen as 1 M$\Omega$ and 470 $\Omega$, respectively.

The recorder used in the experiment was a Speedomax XL recorder, which is a potentiometric-type, null-balance, variable-response-time instrument, which can be used as either a one-pen or a two-pen recorder. As a two-pen recorder, it can simultaneously measure and record two functions on a moving chart 10 inches (250 mm) wide. The two pens on the recorder are approximately 0.1-inch (3.0 mm) apart on the time axis. The recorder has five different chart speeds.

In order to generate a random course for tracking purposes in the first part of the experiment, only one pen recorder was used to record the random signal. The chart speed was set at the maximum of 1200 cm/hr.

The "plant" or controlled element was a simple integrator simulated on an analog computer. The input to this element was provided by a joystick which was operated by the subject and which was housed in a wooden box equipped with two connector jacks. These jacks were of the three-conductor type, providing connection for power supply, output, and ground. The jacks were labeled either as the y axis (front-back) or as the x axis (right-left) connectors. The cords that connected these jacks had clearly marked plugs; however, only one cord had a ground connection, since the ground was common for both the x and y axes. The input plug was connected to the 100-volt receptacle on the analog computer patchboard. The output plug was inserted into the input of the integrator on the computer patchboard. The maximum angle of deviation of the joystick from the vertical position was 60° in any direction.

The analog computer used in this experiment for the plant dynamics was a System Donner model 10/20 which is an all-solid-state analog computer [2] that has an operating range of $\pm 100$ v and 20 operational amplifiers with a removable patchboard which mates directly with computing modules to eliminate all problems of board cabling. All computing components in the SD 10/20 are modular plug-in units which allow for a wide choice of computing capabilities.

Since the plant was represented by a first-order exponential lag of the from $\frac{1}{1+S}$ a patchboard with integrators such as the model 3320 dual integrator was an appropriate tool for this experiment. As shown in Figure 11, the 3320 is divided into three sections: the top and bottom integrators and a logic section common to both. The top integrator was used in this experiment. Basic patching of the integrator was as shown in Figure 11.

Preview constraints were incorporated into the experiment by

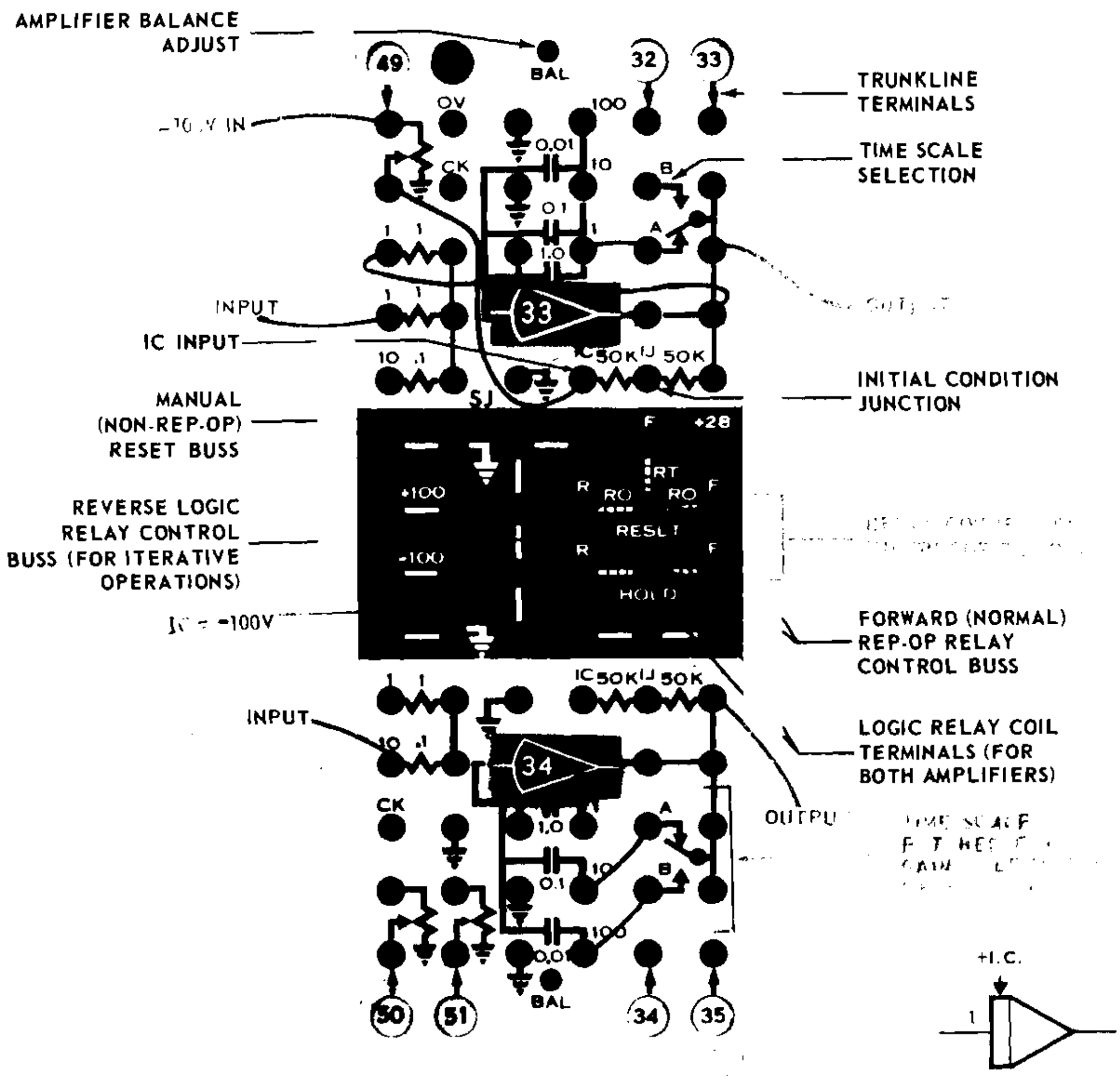


Figure 11. Simple First-Order Exponential Lag System

Source: Analog Computer Instruction Manual, p. 18.

attaching a rectangular cardboard plate to the hinged cover of the recorder. The position of the rectangular cardboard was changed for different preview conditions. The cardboard plates were attached in such a way that the controller could only see the input or forcing function for the interval $T_p$. For the maximum preview case, the hinged cover of the recorder was removed providing a preview distance of 1 cm or 3 sec.

## Experimental Task

The pieces of equipment used were placed on the top of a table in front of which the subject was seated. The joystick was placed in the right corner of the table next to the recorder. The movements of the pen on the strip chart recorder corresponded to the movements of the joystick. The experimental task required each subject to move the joystick to the right and to the left, causing the pen on the strip chart recorder to move correspondingly. With the joystick exactly at the center, the strip-chart pen would travel in a straight line at the center of each path. Because of the preview constraint the subject could, in some cases, see only a small portion of the path that he had to follow; in other cases, nothing could be seen beforehand. The subjects were told to control the system so that it would follow the already-drawn random curve as accurately as possible, using the recorder pen which corresponded to the output of the plant.

The random curves mentioned above were generated by the Gaussian noise generator and recorded on the strip chart before the actual tracking started (Figures 12 and 13). The bandwidth was set at 0.5 cps and 0.15 cps; the RMS amplitude was set at 3.16, and the sequence length at infinity.

## Subjects

Two unpaid subjects were used in the experiment; both were right-handed male graduate students. The subjects were free to assume any position while performing the task, and both chose the ordinary sitting position. It did not prove necessary to make provision for differences in sitting height for the two subjects. In preliminary experiments, not reported here, the subjects showed marked visual fatigue with lacrimation, a condition discovered to have resulted from insufficient rest periods and very long experimental sessions. With extra rest periods, the subjects rarely if ever complained of visual fatigue, and tracking performance improved considerably. Each of the two subjects performed the experiment both with and without preview. It took one hour and fifteen minutes, including the rest period, to perform the experiment.

## Experimental Condition

The six experimental conditions used consisted of two different forcing function bandwidth frequencies of 0.15 cps and 0.5 cps and three different preview conditions, i.e., maximum preview of 3 sec or 1 cm, 1.5 sec, and no preview. The order of these conditions were randomized and different for each subject. Prior to each run, the joystick was set at the vertical position, so that the pen on the strip chart was on the center line. Then, with the recorder set at

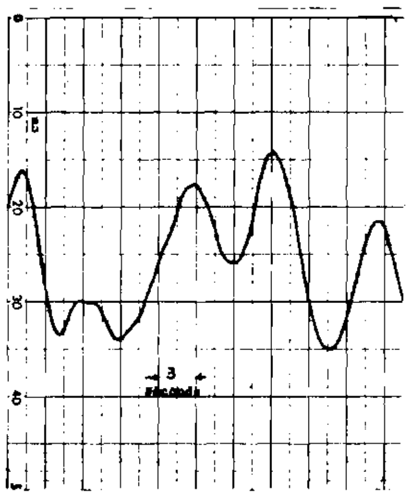

Figure 12. Random Input Signal x(t) at $f_c = 0.15$ Hz

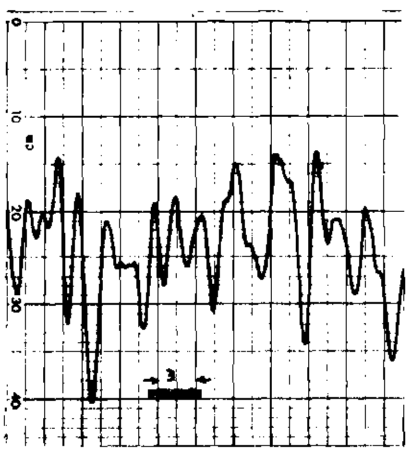

Figure 13. Random Input Signal x(t) at $f_c = 0.5$ Hz

the maximum speed of 1200 cm/hr, the subjects were initially given a practice period of three minutes. A one-minute practice session was allowed before each new experimental condition. Following each practice session, the recorder was turned off and the subjects were given sufficient time to observe the initial random curve and place the joystick as desired for their initial control input. The subjects were notified to start as the recorder was turned on. Then the task was to follow the random signal (marked in red) with the plant output (marked in blue) as accurately as possible. The subjects performed the experiment for five minutes. Then they were told to stop, and were given a four-minute rest period. This procedure was repeated for each of the six different experimental conditions. The movement of the joystick with time was also recorded simultaneously in a separate curve. Figure 14 is a typical result obtained from the experiment.

## Data Preparation

Subject data were taken in analog form from the strip-chart recorder discussed previously. These time-continuous data, which consisted of the original random input, the controller output (i.e., the output of the joystick), and the output of the controlled element, were converted manually into digital form. Only the two conditions of no-preview and maximum-preview for both subjects at 0.5 Hz forcing function bandwidth will be analyzed in the following discussion. The continuous random records were sampled at $h = 0.3$-second intervals, which corresponded to 0.1 cm on the strip chart. From these charts, the experimenter was able to obtain the sampled-

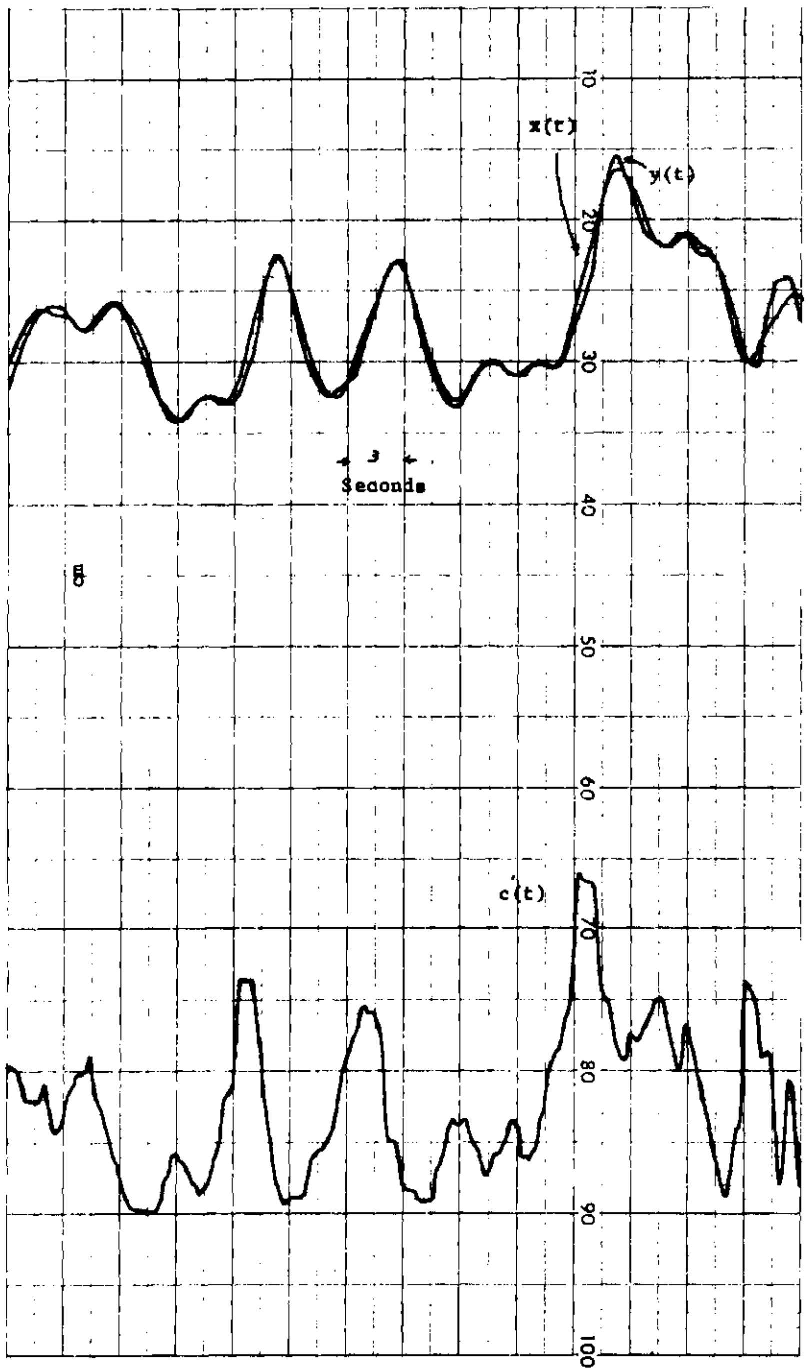


Figure 14. Typical Subject Performance ($f_c$ = 0.15 Hz for 3.0 second Preview)

data quantities required for determining the transfer characteristics of the human controller under alternative preview conditions, as outlined before. The particular data acquisition procedure used will be discussed subsequently.

# CHAPTER V

## DATA ANALYSIS PROCEDURES

This choice of the sampling interval h = 0.3 sec met the requirement that $h \leq \frac{1}{2_{fc}}$ for fc = 0.15 Hz and fc = 0.5 Hz, as suggested by Bendat and Piersal [3, p. 320] for digital computation of autocorrelation and cross-correlation estimates of time-continuous signals. Note that fc is the cutoff frequency in hertz of the signal x(t); that is, the cutoff frequency chosen for the gaussian noise generator. It appeared reasonable to assume that y(t) had approximately the same cutoff frequency. Another requirement was that the maximum number of lags used for the correlation functions should be about one-tenth of the number of samples used. For the cross-correlation function estimate

$$R_{xy}(rh) = \frac{1}{N-r} \sum_{n=1}^{N-r} x_n \, y_{n+r} \quad ; \quad r = 0, 1, 2, \ldots, m \tag{5.1}$$

where N is sample size, r is number of correlation lag values, m is maximum number of correlation lag values, and h is the sample interval. It is suggested (cf. [3], p. 320) that

$$N = \frac{m}{\varepsilon_r^{\,2}} \text{ with } N > 10 \text{ m} \tag{5.2}$$

where $\varepsilon_r$ is the normalized standard error desired for spectral calculations. Note that the maximum lag number is related to maximum time displacement of the estimate by

$$\tau_{max} = \tau_m = mh \tag{5.3}$$

and the value of sample size and record length $T_S$ is related by

$$T_S = Nh \tag{5.4}$$

The next problem was to determine the appropriate values of $N_1$, $N_2$, $N_3$, M in equation (3.6). The value of M, which needed to be considerably larger than the total number of other parameters in the regression model, was estimated from the inequality

$$M > 2(N_1 + N_2 + N_3) \tag{5.5}$$

since the value of h was previously chosen, $N_1$ follows from:

$$N_1h = T_p - T_r \tag{5.6}$$

where, as before, $T_p$ denotes the preview span and $T_r$ denotes the reaction time delay of $S_H$ ($T_r \simeq 0.20$ sec). It was furthermore assumed that

$$T_{mx} = T_{my} \tag{5.7}$$

so that

$$N_2h = N_3h + T_r \tag{5.8}$$

and hence

$$N_3 = N_2 - \frac{T_r}{h} \tag{5.9}$$

In the no-preview condition, the value of $N_1$ was equal to zero, and values of $N_2$, $N_3$ were set equal to .20. For the 3-seconds-preview condition $N_2$ and $N_3$ were set equal to 15 and from equation (5.6) $N_1$ was chosen equal to 10.

The value of M which satisfied equation (5.5) was chosen as $M = 90$ for the first subject and $M = 125$ for the second subject. This inconsistency in choosing M values was due to the fact that only 500 data points ($N = 500$) was used for analysis of the second subject's performance compared to 1000 points ($N = 1000$) for the first subject.

The values of $\hat{R}_{XC}(rh)$, $\hat{R}_{XX}(rh)$, and $\hat{R}_{XY}(rh)$ were obtained from the Bio-Med Autocovariance and power spectral analysis program BMD02T (see Ref. [6], p. 459). These values obtained were used as dependent and independent variables, respectively, for the linear statistical model given in equation (3.7). The autocovariance and power spectral analysis program computed the autocovariance, power spectrum, cross-covariance, cross-spectrum of the data. The values of the autocovariance and cross-covariance functions obtained from this program were equal to autocorrelation and cross-correlations desired because the time series used were automatically centered by the computer program.

# CHAPTER VI

# RESULTS AND DISCUSSION

## Impulse Response Function Estimates

Once the values of $N_1$, $N_2$, $N_3$, M, h had been chosen, it was possible to use the Biomed program BMD02D (see Ref. [6], p. 233) for stepwise regression. This program computes a sequence of multiple linear regression equations in a stepwise manner. At each step, one variable is added to the regression equation--the variable which would make the greatest reduction in the error sum of squares, (or, equivalently, the variable which has the highest partial correlation with the dependent variable partialed on the variables which had already been added, thus having the highest F value). In addition, variables can be forced into the regression equation (nonforced variables are automatically removed when their F values are too low).

A regression equation was chosen with zero intercept as dictated by equation (3.6). The F levels for inclusion and deletion were equated to zero in all cases in order to bring all the variables into the regression, except for the case of no preview for both subjects, in which the values 0.01 and 0.005 for inclusion and deletion, respectively, were sufficient.

On the basis of such multiple linear regressions, the least squares estimates obtained for the impulse response sequences $\{h_{HX}(ph)\}$ and $\{h_{HY}(ph)\}$ are given in Tables 1 and 2. These data

Table 1. Values of Frequency Responses $h_{HX}$, $h_{HY}$ for 0.3 sec Preview Case (Note that only $h_{HX}$ values exist for t < 0).

| P | Subject I | | | | Subject II | | | |
|---|---|---|---|---|---|---|---|---|
| | $h_{HX}$(ph) | t | $h_{HY}$(ph) | t | $h_{HX}$(ph) | t | $h_{HY}$(ph) | t |
| -10 | 0.12 | 0.09 | | | -5.46 | -2.41 | | |
| - 9 | -0.92 | -0.38 | | | 8.95 | 1.59 | | |
| - 8 | - | - | | | -3.10 | -0.43 | | |
| - 7 | 2.93 | 0.67 | | | -3.62 | -0.58 | | |
| - 6 | -1.79 | -0.35 | | | 5.03 | 0.86 | | |
| - 5 | - | - | | | 0.12 | 0.02 | | |
| - 4 | 1.64 | 0.25 | | | -1.60 | -0.24 | | |
| - 3 | 4.21 | 0.42 | | | 5.84 | 0.90 | | |
| - 2 | -3.00 | -0.31 | | | -2.57 | -0.44 | | |
| - 1 | -0.20 | -0.03 | | | -1.17 | -0.43 | | |
| 1 | 1.84 | 0.82 | -8.89 | 2.96 | - | - | -3.65 | -1.53 |
| 2 | - | - | 10.48 | 1.78 | -0.63 | -0.57 | 4.08 | 1.36 |
| 3 | -3.68 | -1.31 | -1.59 | 0.31 | -0.28 | -0.46 | - | - |
| 4 | 1.52 | 0.43 | - | - | -0.47 | -0.86 | -0.50 | -0.21 |
| 5 | 3.84 | 1.17 | -7.21 | 1.43 | -0.41 | -0.61 | - | - |
| 6 | -3.92 | -1.80 | 7.44 | 1.63 | -0.34 | -0.17 | 3.67 | 0.96 |
| 7 | - | - | - | - | -0.29 | -0.11 | -2.78 | -0.54 |
| 8 | 0.84 | 0.79 | -2.42 | 1.15 | 2.04 | 0.90 | -2.24 | -0.59 |
| 9 | 0.19 | 0.19 | - | - | 0.03 | 0.02 | - | - |
| 10 | -1.12 | -1.01 | - | - | 1.03 | 0.44 | -0.63 | -0.28 |
| 11 | -0.25 | -0.26 | 2.11 | 0.66 | 0.67 | 0.28 | 0.25 | 0.47 |
| 12 | -0.27 | -0.26 | -0.03 | 0.01 | -0.01 | -0.01 | -1.27 | -0.41 |
| 13 | 0.64 | 0.68 | - | - | -0.23 | -0.18 | -0.62 | -0.15 |
| 14 | 0.98 | 1.02 | -2.95 | 1.20 | 0.40 | 0.35 | 1.43 | 0.46 |
| 15 | 0.27 | 0.34 | 0.31 | 0.20 | -0.20 | -0.24 | -0.89 | -0.62 |

Table 2. Values of Frequency Response Functions $h_{HX}$, $h_{HY}$ for No Preview Case

| P | Subject II | | | | Subject I | | | |
|---|---|---|---|---|---|---|---|---|
| | $h_{HX}$(ph) | t | $h_{HY}$(ph) | t | $h_{HY}$(ph) | t | $h_{HY}$(ph) | t |
| 1 | 14.39 | 9.61 | -0.89 | -0.18 | -0.50 | -1.81 | -2.79 | -1.48 |
| 2 | -9.08 | -2.49 | -3.68 | -0.37 | -0.11 | -0.09 | 3.30 | 1.34 |
| 3 | -6.23 | -1.21 | 5.84 | 0.51 | 0.77 | 0.64 | .12 | 0.05 |
| 4 | 10.54 | 1.75 | 1.76 | 0.20 | 0.34 | 0.28 | -1.03 | -0.42 |
| 5 | -4.22 | -0.66 | - | - | 0.11 | 0.09 | 0.17 | 0.07 |
| 6 | -6.34 | -0.97 | -5.26 | -0.58 | -0.04 | -0.03 | 0.06 | 0.02 |
| 7 | 4.61 | 0.96 | 0.28 | 0.03 | 0.99 | 0.81 | -2.50 | -0.99 |
| 8 | - | - | - | - | 0.78 | 0.67 | -2.11 | -0.82 |
| 9 | 0.83 | 0.19 | -3.35 | -0.64 | 1.48 | 1.38 | -0.29 | -0.11 |
| 10 | 2.23 | 0.52 | - | - | 0.29 | 0.27 | -1.40 | -0.54 |
| 11 | - | - | 7.65 | 0.92 | -0.03 | -0.03 | 1.04 | 0.42 |
| 12 | 0.73 | 0.15 | 8.99 | 0.78 | 0.09 | 0.09 | -1.96 | -0.75 |
| 13 | -1.16 | -0.17 | -10.37 | -1.19 | 1.12 | 1.13 | -1.42 | -0.49 |
| 14 | -3.36 | -0.52 | - | - | 0.15 | 0.15 | 0.64 | 0.22 |
| 15 | -2.49 | -0.37 | 5.35 | 0.60 | 0.55 | 0.57 | -1.72 | 0.59 |
| 16 | 2.55 | 0.39 | -4.09 | -0.35 | -0.05 | -0.05 | -0.10 | -0.03 |
| 17 | 0.02 | 0.00 | -3.07 | -0.28 | -0.39 | -0.39 | 0.45 | 0.15 |
| 18 | - | - | 1.68 | 0.15 | -0.38 | -0.38 | 2.10 | 0.70 |
| 19 | 1.04 | 0.38 | -0.77 | -0.09 | -0.04 | -0.04 | -0.67 | -0.24 |
| 20 | 1.79 | 0.92 | 0.19 | 0.06 | -1.37 | -1.63 | 3.10 | 2.07 |

correspond to two experimental conditions used for each of the two subjects. It is apparent from these data and calculated t-statistics that the smaller the absolute value of p the more significant are the impulse response terms. The values of $h_{HX}$ and $h_{HY}$ for both subjects do not have any obvious similarity except that for larger P values, the $h_{HX}$ and $h_{HY}$ values, in most cases decrease somewhat. This is to be expected and the general model formulation is based on such an assumption.

The values of the square of the multiple correlation coefficient, $R^2$, for regressions with zero intercept about the origin were obtained from the computer output. In addition, the values of the square of the multiple correlation coefficient $R'^2$ about the sample mean of $R_{XC}(qh)$ was computed. The values of $R'^2$, which corresponds to the nonzero intercept case, were obtained from the relationship

$$R'^2 = 1 - \frac{\sum_{q=0}^{M} \hat{\varepsilon}_q^{\,2}}{\sum_{q=0}^{M} [R_{XC}(qh) - \overline{R}_{XC}]^2} \qquad (6.1)$$

where

$$\overline{R}_{XC} = \frac{1}{M+1} \sum_{q=0}^{M} R_{XC}(qh) \qquad (6.2)$$

and the $\hat{\varepsilon}_q$ denote the fitted residuals for the regression equation.

The values given in Table 3 for $R^2$ and $R'^2$ are seen to be very close, due to the fact that the mean values $\overline{R}_{XC}$ were found to

Table 3. Values of $R^2$ and $R'^2$ for Both Subjects in the Two Different Task Conditions

| Subject | Bandwidth Frequency | Preview 0 sec | | Preview 3 sec | |
|---|---|---|---|---|---|
| | | $R^2$ | $R'^2$ | $R^2$ | $R'^2$ |
| I | 0.5 | 0.62 | 0.63 | 0.93 | 0.93 |
| II | 0.5 | 0.96 | 0.64 | 0.89 | 0.89 |

be close to zero (except for Subject II in the no-preview condition for which the two values of $R^2$ and $R'^2$ are significantly different). These values of $R'^2$ indicate an excellent fit for conditions of 3 seconds-preview for the two subjects and a rather fair fit for the zero-preview condition. In addition, the power spectral densities for the residuals in the regressions for different preview conditions for both subjects were obtained as shown in Figures 15, 16, 17, and 18. Considering these figures (15 through 18) the power spectral densities are somewhat constant for values over 0.8 cps for all subjects at different preview conditions. It seems that for the first subject there are peaks of residuals for both preview and no-preview conditions in the interval between 0.4 to 0.6 cps, while for the second subject, the peaks are in a somewhat lower interval. Note that these residual power spectra account partly for the nonlinear part of the human controller as well as for experimental errors. As the results show, these residuals correspond fairly well to the results for the linearity coefficient obtained in the following sections. In both cases, it seems that nonlinearity decreases somewhat in the interval from 1.0 to 1.8 cps.

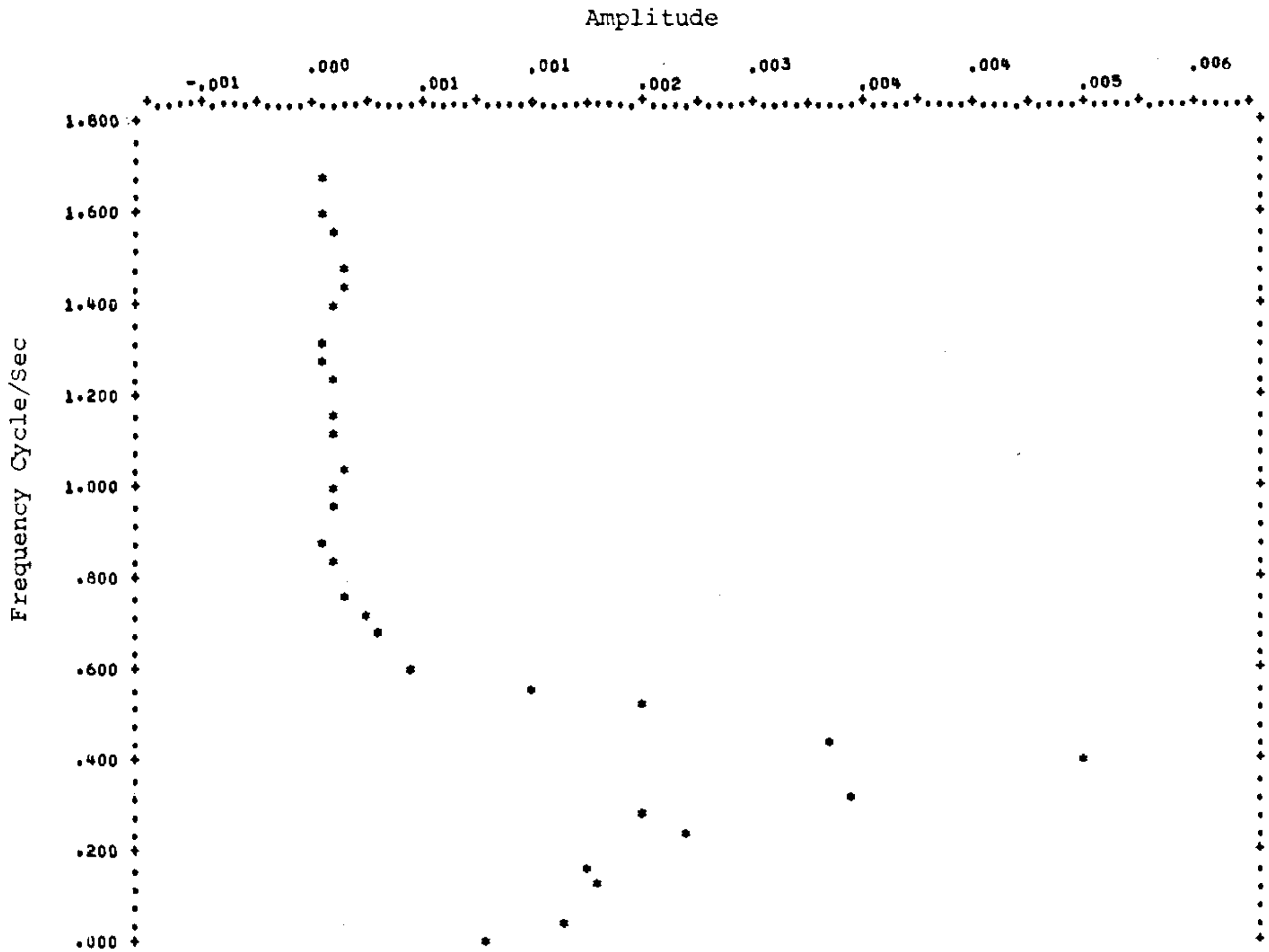


Figure 15. Power Spectral Density of Residuals for Subject I With No Preview Condition

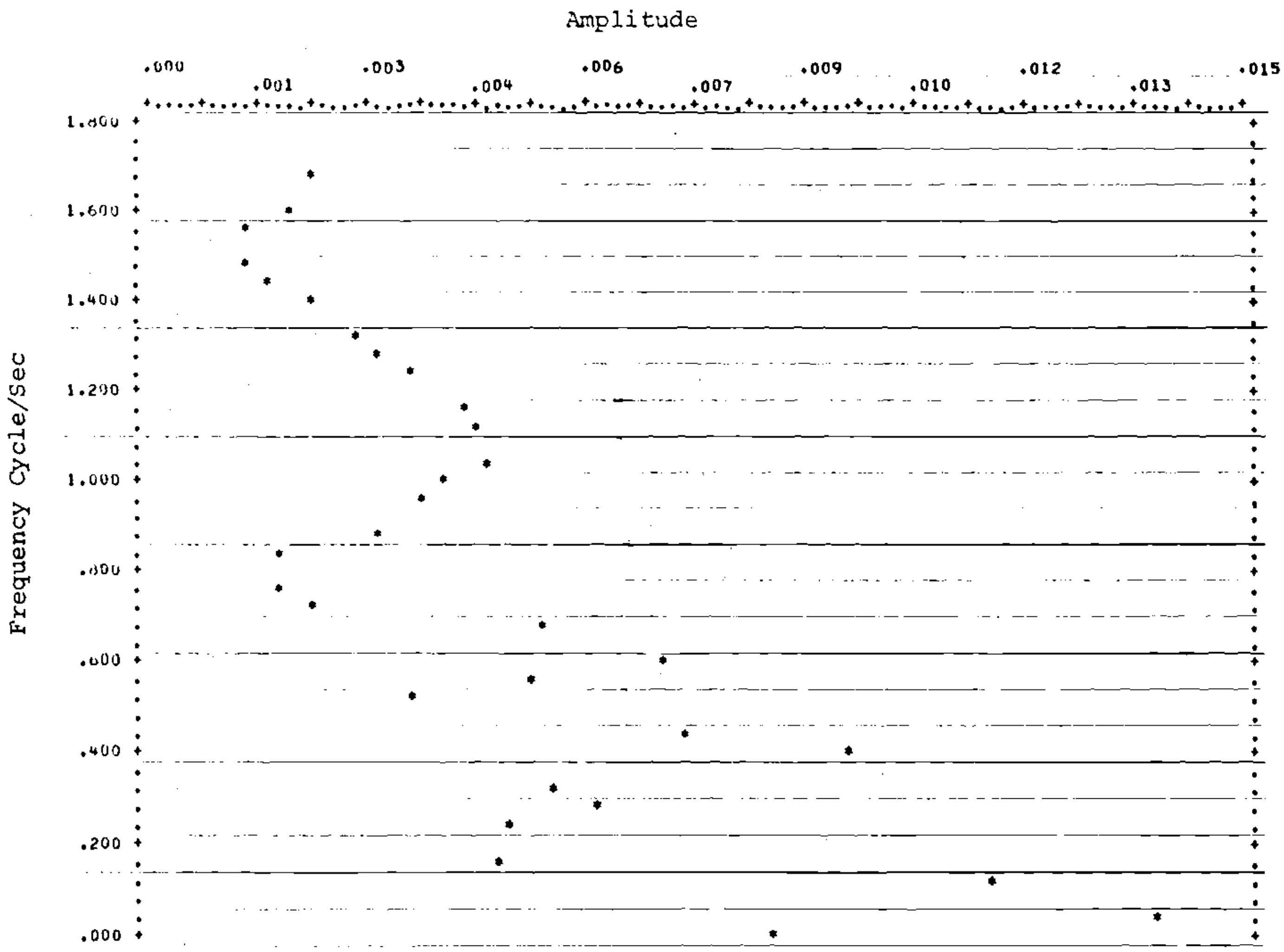


Figure 16. Power Spectral Density of Residuals for Subject II With No Preview Condition

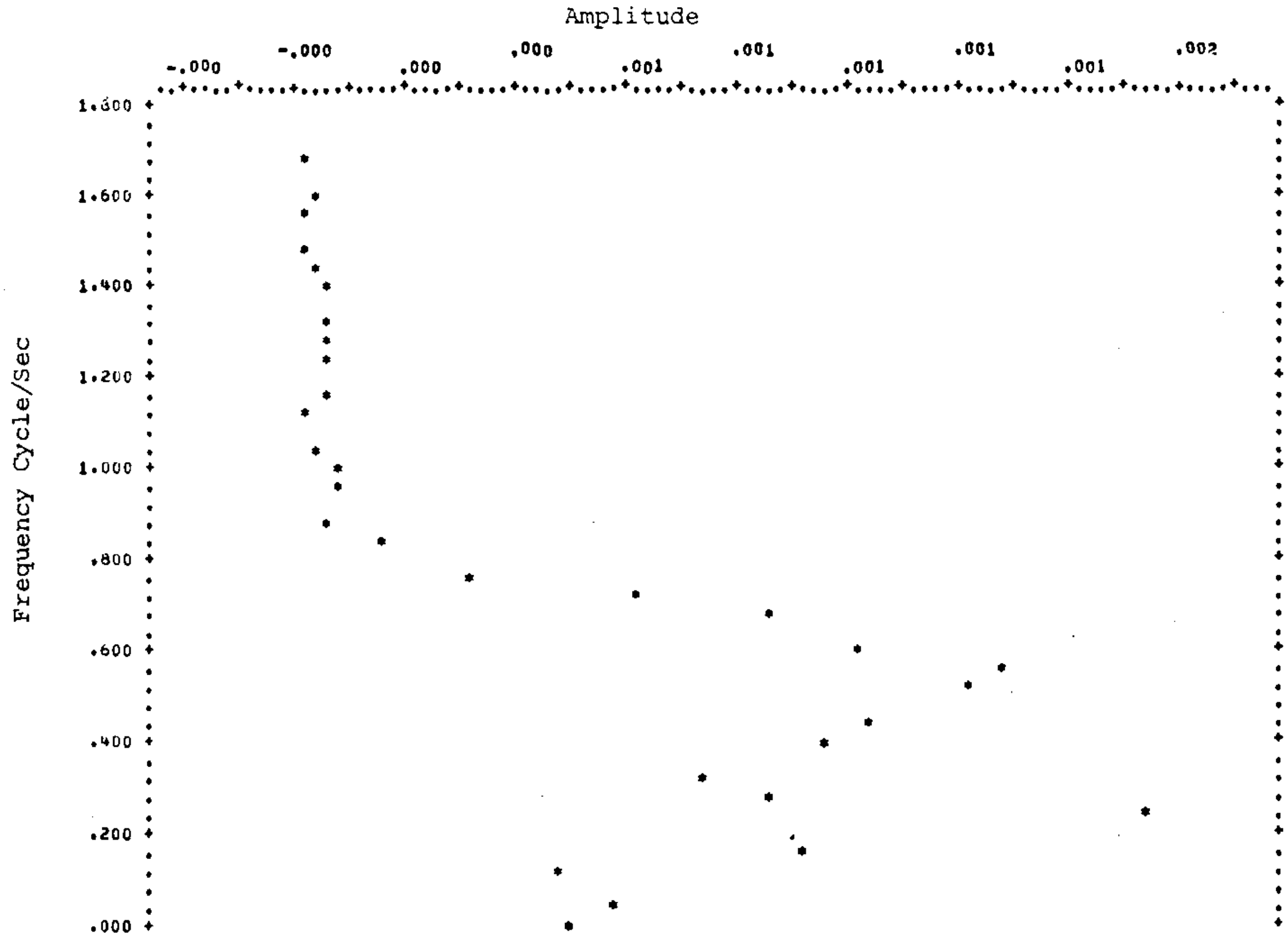


Figure 17. Power Spectral Density of Residuals for Subject I for 3 Seconds Preview Condition

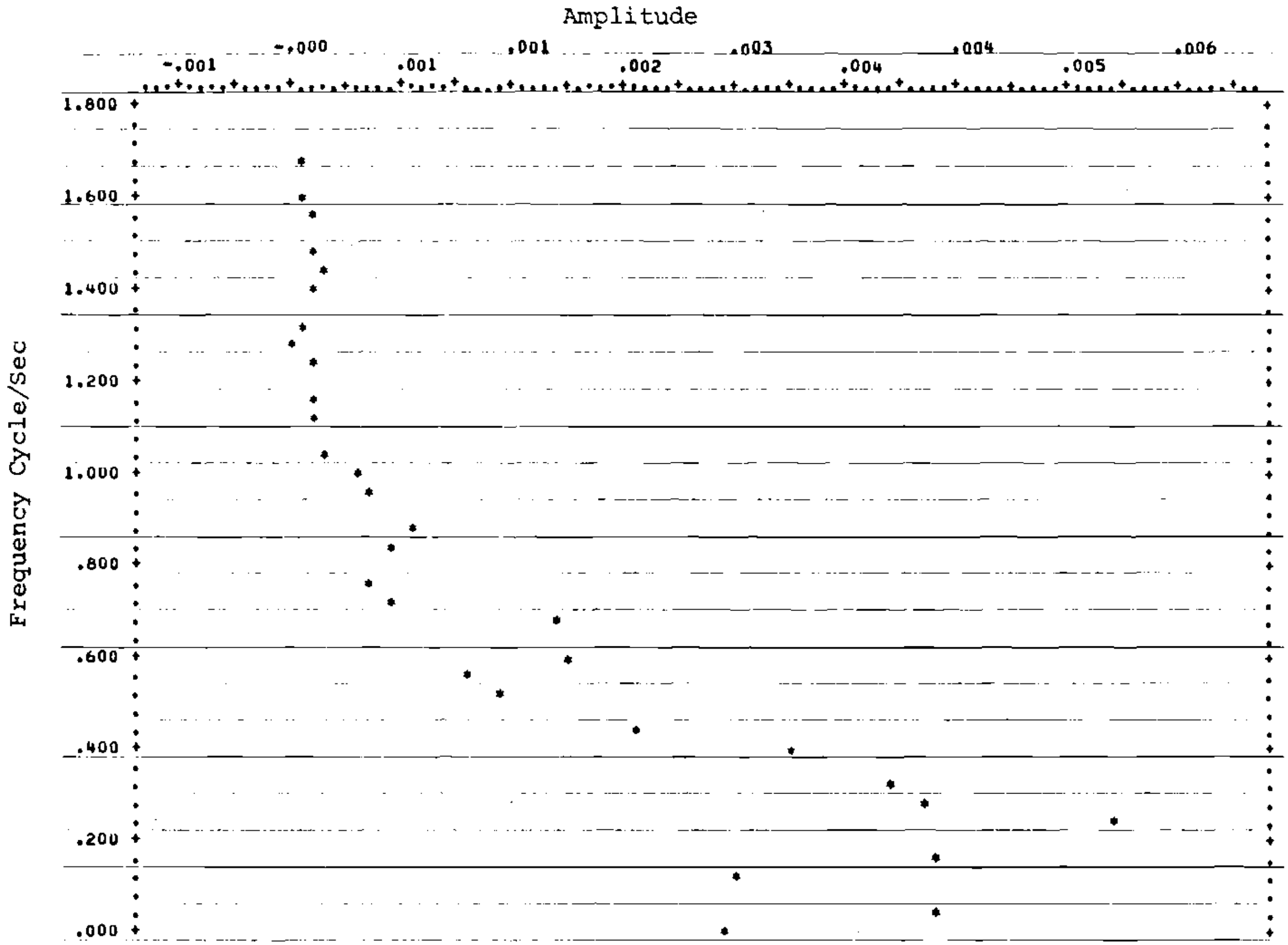


Figure 18. Power Spectral Density of Residuals for Subject II for 3 Seconds Preview Condition

## Frequency Response Data

Frequency response data were obtained for the two linear human controller elements from the estimated computer response sequences $\{h_{HX}(ph)\}$ and $\{h_{HY}(ph)\}$ in accordance with the method indicated in equations (3.8) and (3.9). A computer program was developed and used for these calculations. The resulting data are presented as Bode plots in Figures 19-26. It is impossible from these graphs to arrive at any clear inferences as to the form of the transfer functions of the two human controller components.

## The Linearity Coefficient

The determination of the linearity coefficient $\rho$ for $f_c = 0.5$ Hz for both subjects was based on the values of the quantities $H_{CE}$, $H_{HX}$, $H_{HY}$, $S_{XX}$, $S_{YY}$, $S_{rr}$, and $S_{CC}$ at different frequencies. As mentioned previously, the plant was a simple integrator with unit feedback and gain K as shown by the closed-loop system diagrammed in Figure 27.

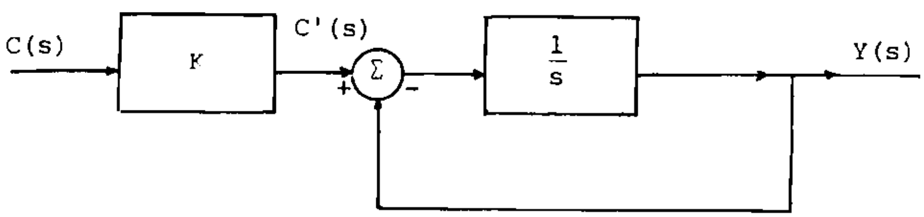


Figure 27. Closed-Loop System of Controls and Controlled Elements

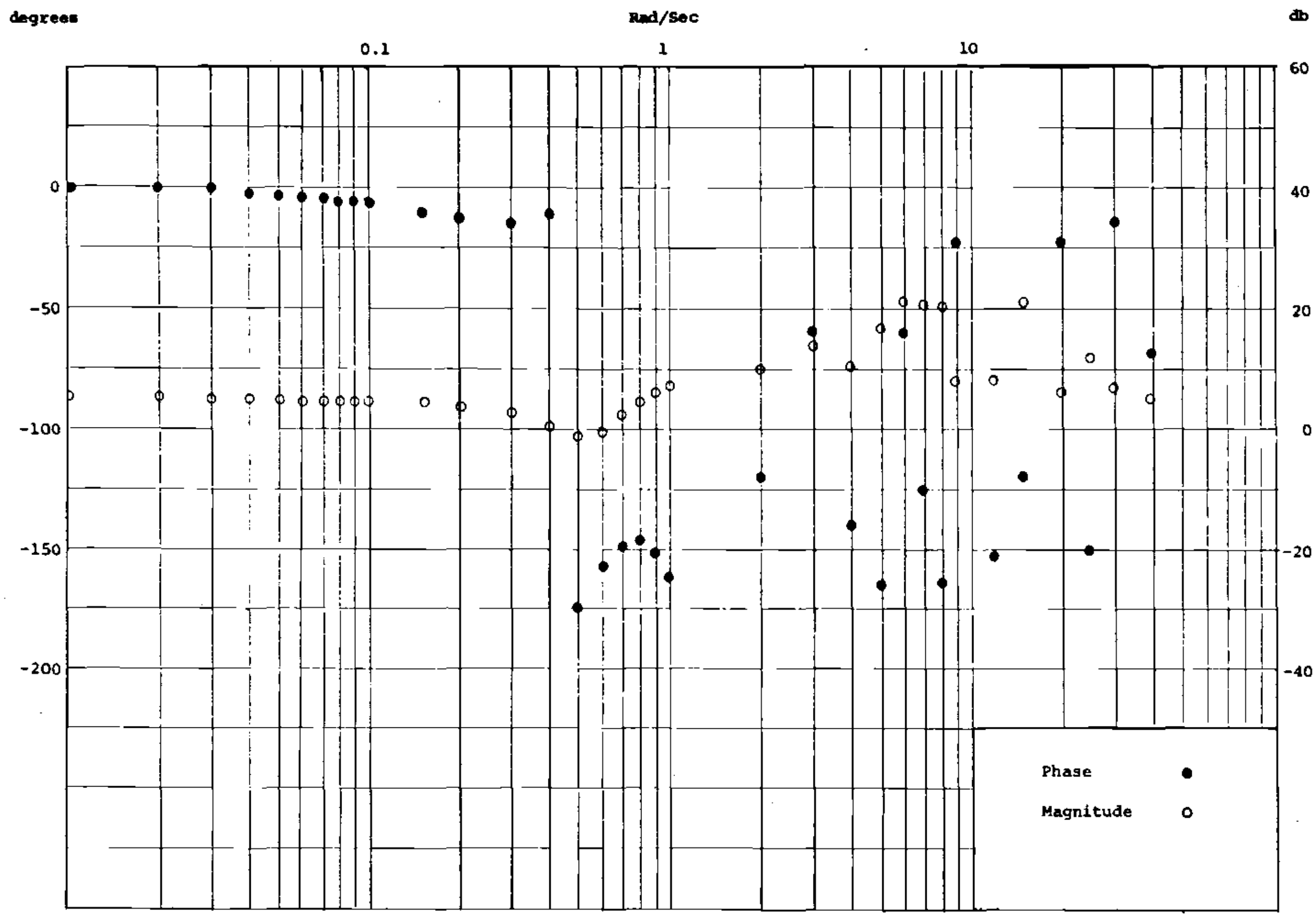


Figure 19. Bode Diagrams for $H_{HY}$ for Subject II (3 Second Preview $f_c$ = 0.5 Hz)

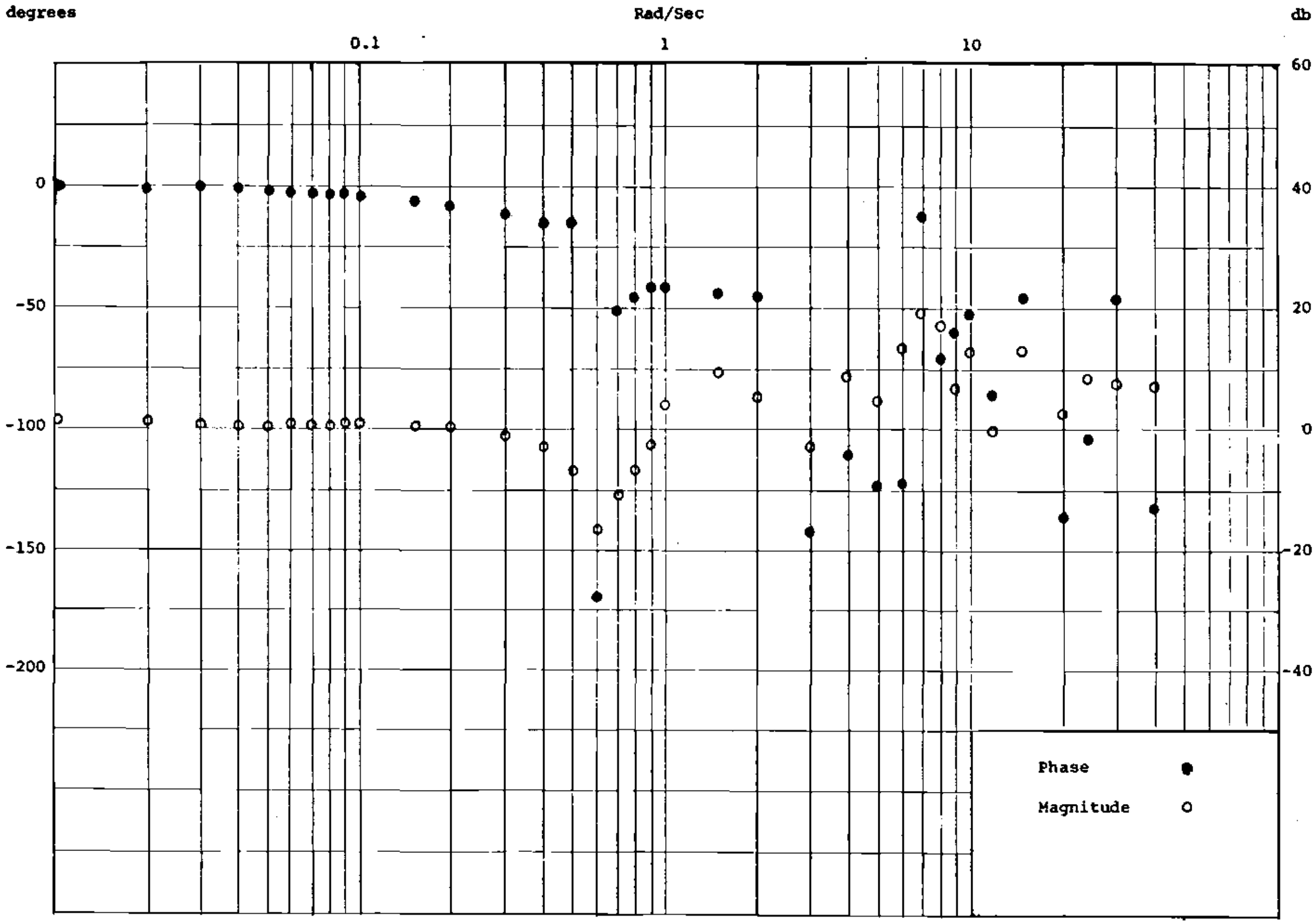


Figure 20. Bode Diagrams for $H_{HX}$ for Subject I (3 Second Preview $f_c$ = 0.5 Hz)

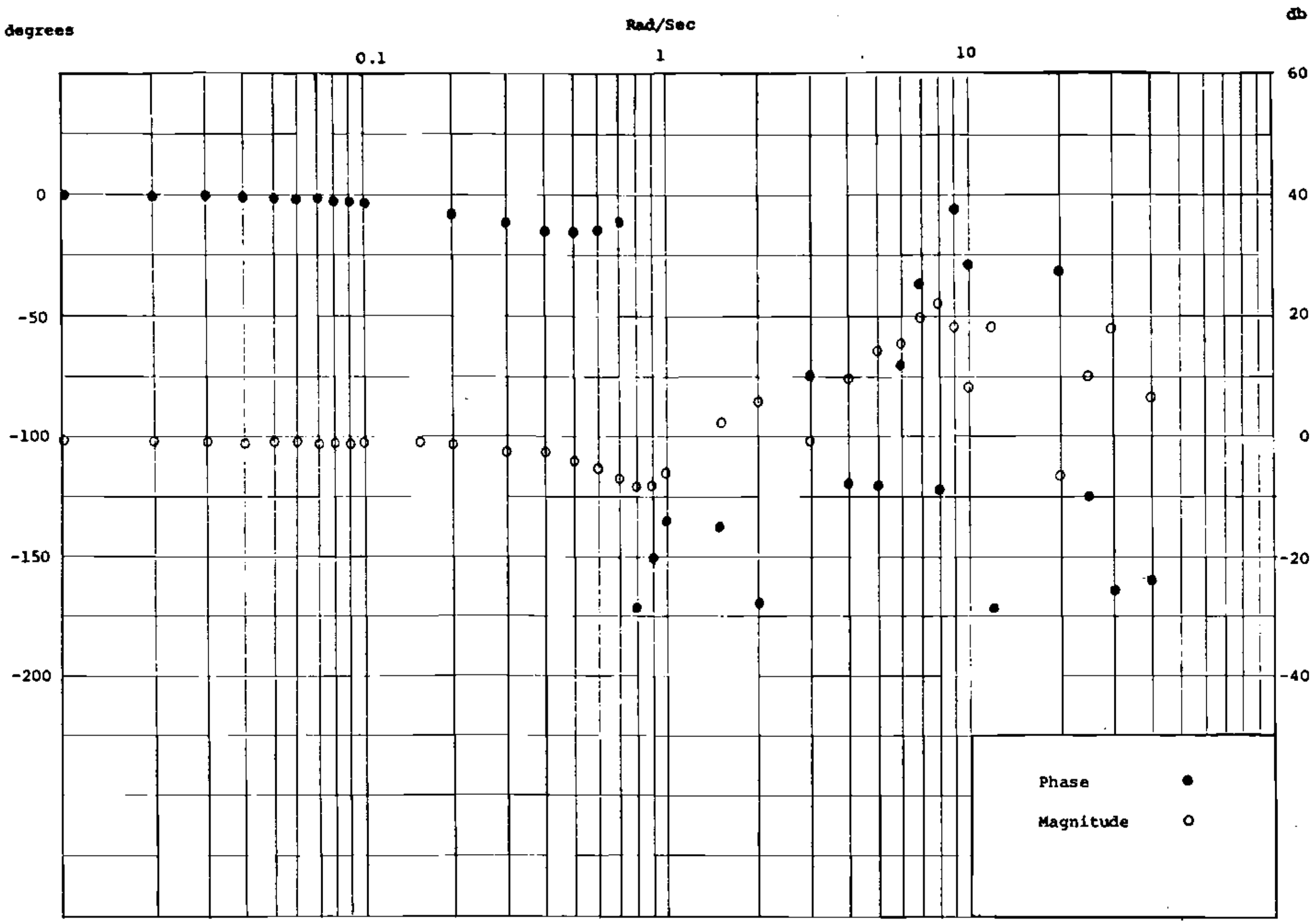


Figure 21. Bode Diagrams for $H_{HY}$ for Subject II (No Preview $f_c$ = 0.5 Hz)

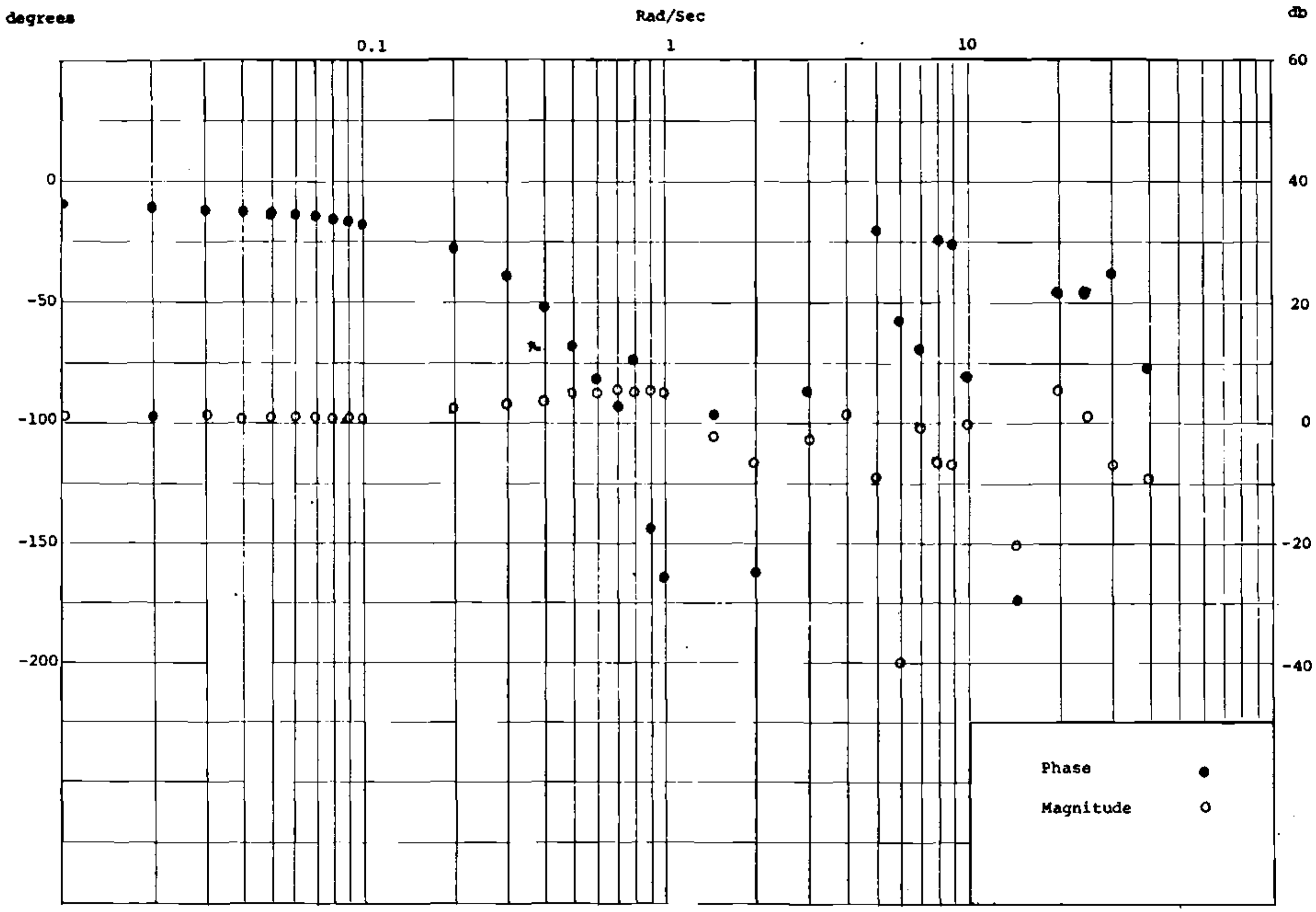


Figure 22. Bode Diagrams for $H_{HY}$ for Subject I (No Preview $f_c$ = 0.5 Hz)

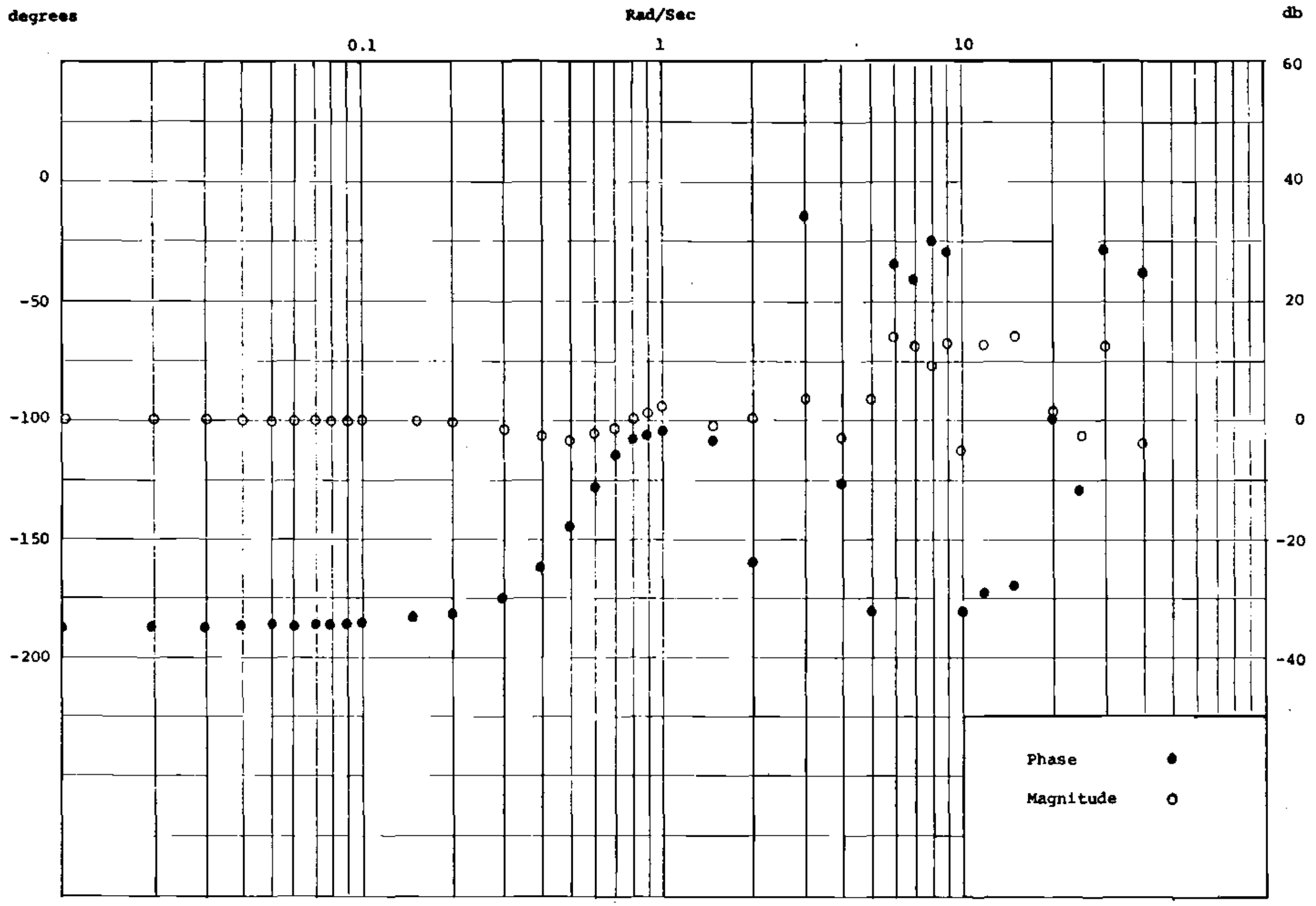


Figure 23. Bode Diagrams for $H_{HX}$ for Subject II (3 Second Preview $f_c$ = 0.5 Hz)

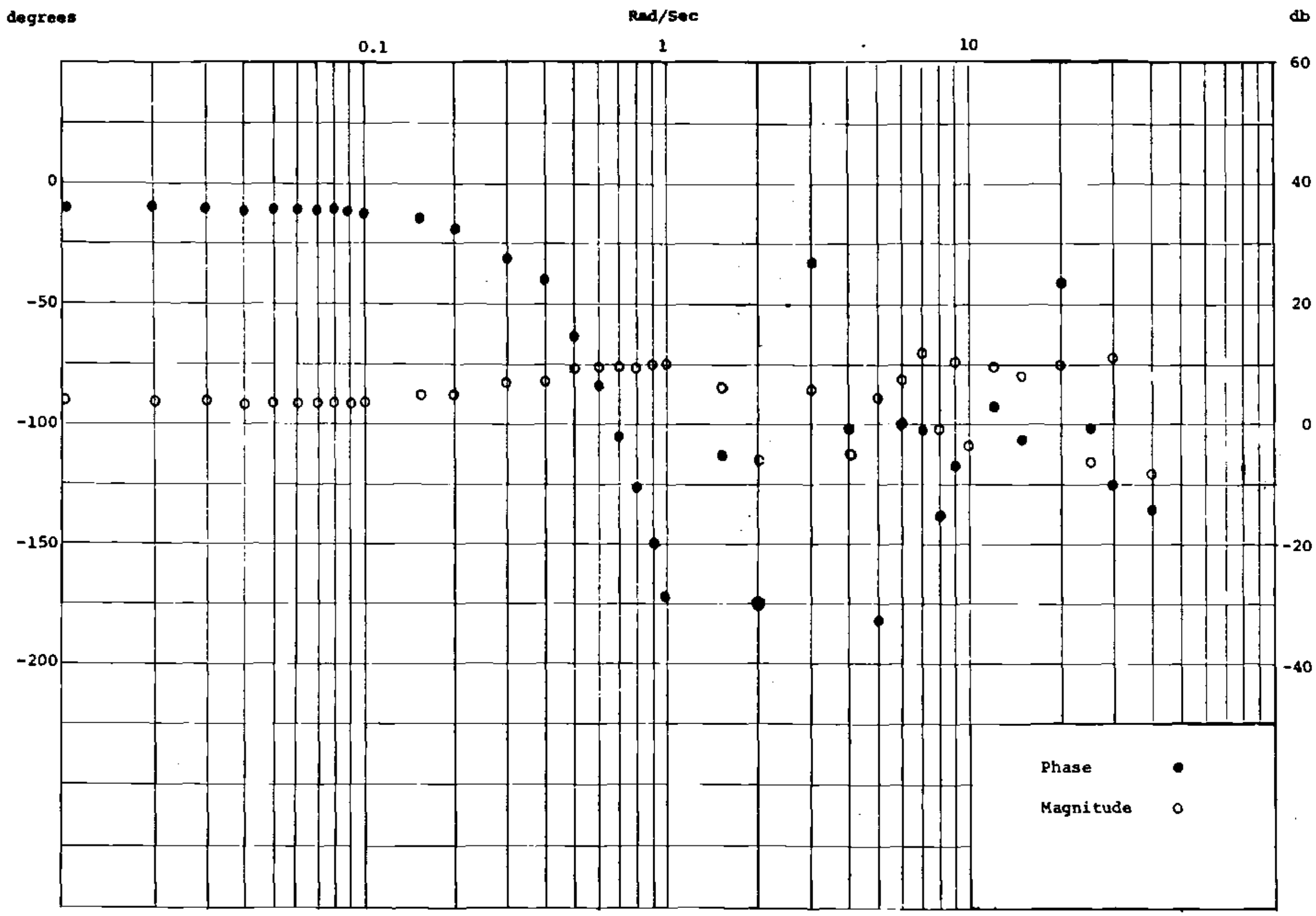


Figure 24. Bode Diagrams for $H_{HY}$ for Subject I (No Preview $f_c$ = 0.5 Hz)

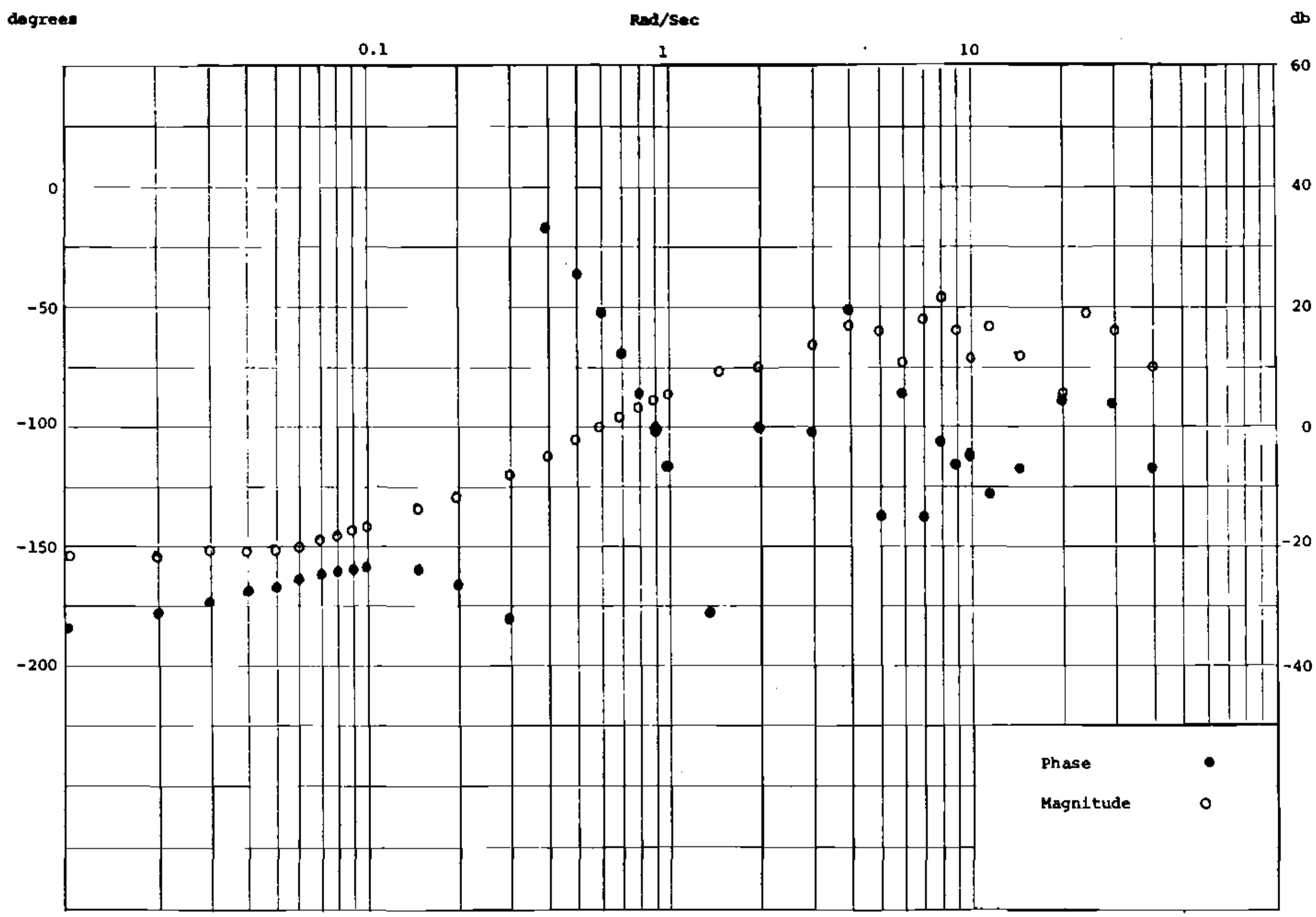


Figure 25. Bode Diagrams for $H_{HY}$ for Subject II (No Preview $f_c = 0.5$ Hz)

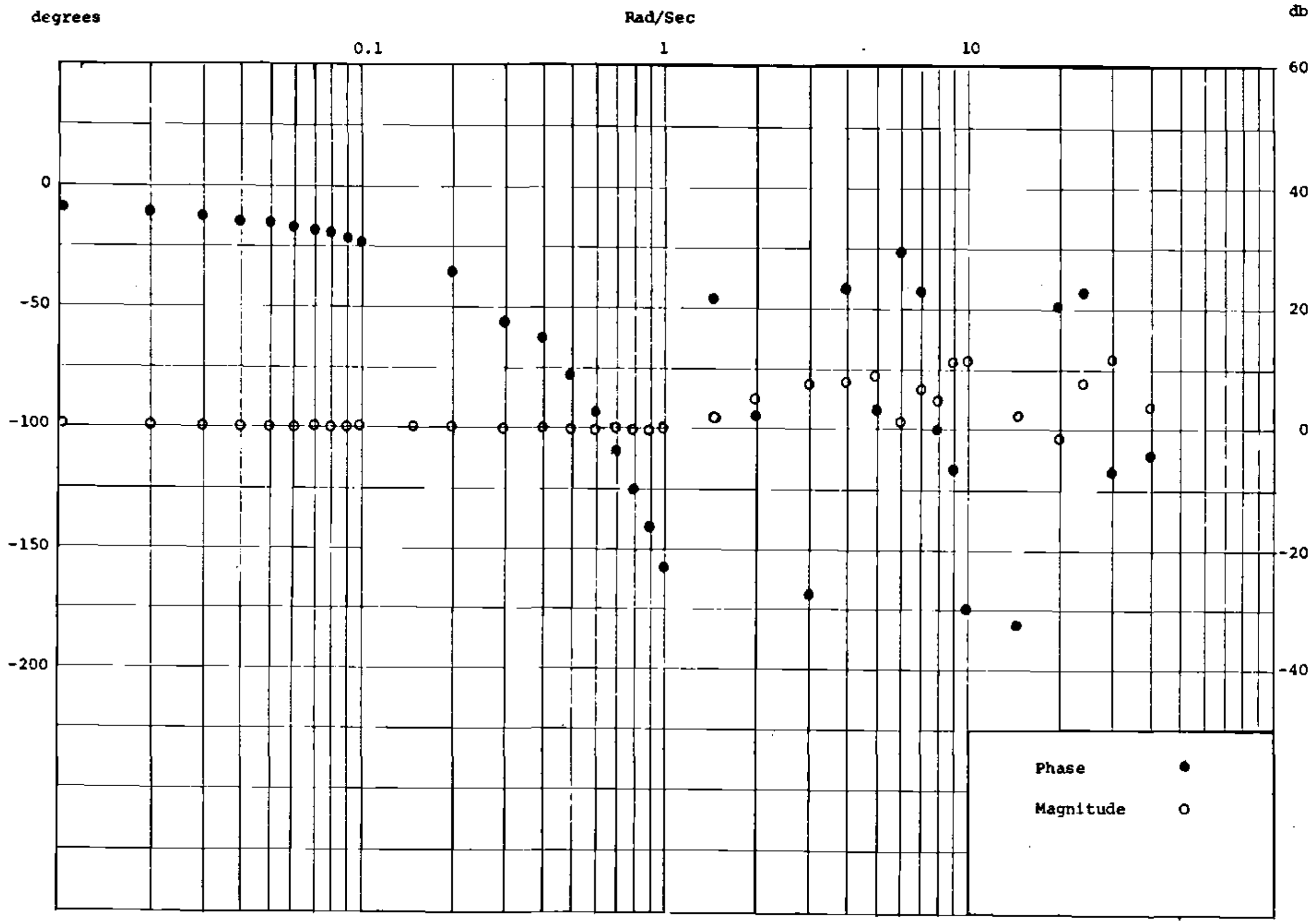


Figure 26. Bode Diagrams for $H_{HY}$ for Subject I (3 Second Preview $f_c$ = 0.5 Hz)

The closed-loop system was modified to become

$$H_{CE} = \frac{0.07}{1+S} \tag{6.3}$$

The value of K, which is the controls' proportionality constant, was obtained by finding the deviation of one of the pens on the strip chart recorder for a one-degree angle change on the joystick. The corresponding value of K was found to be 0.07. Once K was obtained it was possible to obtain $H_{CE}$ from equation (6.3) for different frequencies.

The values of the power spectral estimates $\hat{S}_{XX}(f)$ and $\hat{S}_{YY}(f)$ were obtained from the autocovariance and power spectral analyses program (BMD02T) for both subjects with different preview conditions. The values of $H_{HX}(f)$ and $H_{HY}(f)$ used were those given in Figures 19 through 26. The values that obtained for the linearity coefficient $\rho$ are listed in Table 4.

In general, one tends to have most confidence in the describing function techniques when the quasi-linear transfer function by itself provides an adequate representation of the system; that is to say, when the remnant term is relatively small. In our case, Table 4 shows that the remnant term is somewhat large, thereby suggesting that some important nonlinear effects may be occurring. As Mitchell [17] suggested, this nonlinearity could be due to such factors as: (1) noise at the operator's input, (2) noise at the operator's output, (3) unsteady behavior of the human operator, or (4) nonlinear operation and dither of the human operator.

In any event, the values of the linearity coefficients are

Table 4. Values of Linearity Coefficient and Remnant Spectral Density Function for Different Preview Conditions at Different Frequencies

| Frequency RAD/SEC | | | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1.0 | 1.5 | 2.0 | 3.0 | 4.0 | 6.0 | 8.0 | 10.0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Subject I $f_c$ = 0.5 Hz | No Preview | $S_{rr}$ | 288.38 | 135.98 | 215.50 | 139.74 | 164.04 | 154.81 | 104.36 | 166.61 | 157.39 | 141.77 | 130.37 | 151.96 | 475.91 | 176.71 | 159.31 | 265.27 | 203.02 |
| | | $\rho$ | -0.23 | -0.20 | -0.20 | -0.11 | -0.20 | -0.26 | 0.11 | 0.10 | 0.11 | 0.44 | 0.47 | 0.09 | 0.14 | 0.65 | 0.21 | 0.16 | 0.01 |
| | 3 sec Preview | $S_{rr}$ | 78.75 | 94.80 | 108.62 | 173.90 | 131.40 | 123.94 | 107.71 | 139.93 | 125.11 | 95.47 | 329.70 | 470.41 | 387.97 | 182.55 | 372.96 | 272.55 | 202.44 |
| | | $\rho$ | -0.13 | -0.16 | -0.20 | 0.07 | 0.08 | -0.06 | 0.21 | 0.15 | 0.09 | 0.37 | 0.47 | 0.17 | 0.19 | 0.63 | 0.26 | 0.13 | 0.01 |
| Subject II $f_c$ = 0.5 Hz | No Preview | $S_{rr}$ | 184.80 | 99.11 | 100.42 | 52.53 | 73.85 | 113.10 | 95.43 | 54.38 | 215.77 | 231.26 | 219.07 | 1020.67 | 654.04 | 165.15 | 40.42 | 20.92 | 19.48 |
| | | $\rho$ | 0.02 | 0.01 | 0.00 | 0.22 | 0.17 | 0.12 | 0.34 | 0.29 | 0.19 | 0.41 | 0.33 | 0.00 | 0.37 | 0.59 | 0.33 | 0.34 | 0.05 |
| | 3 sec Preview | $S_{rr}$ | 29.37 | 93.34 | 274.58 | 302.12 | 348.63 | 138.58 | 185.64 | 563.24 | 383.11 | 702.75 | 334.60 | 145.52 | 526.67 | 346.38 | 197.69 | 74.72 | 146.50 |
| | | $\rho$ | 0.10 | 0.10 | 0.10 | 0.08 | 0.02 | 0.00 | 0.22 | 0.15 | 0.08 | 0.46 | 0.41 | 0.06 | 0.17 | 0.68 | 0.21 | 0.05 | 0.00 |

small except at $\omega = 4.0$ rad/sec and in the region $1.0 \leq \omega \leq 1.5$ rad/sec. This, and the fact that some of the values of the linearity coefficient for low frequencies are negative, might suggest that our model may not be very accurate for the entire range considered, although it may be quite acceptable for certain frequency intervals.

## Error Characteristics

In order to compare the performance of the subjects at different bandwidth frequencies for different task conditions, the mean squared error (MSE) between the signals x(t) and y(t) at each 1.5 sec sample point was computed from

$$MSE = \frac{1}{T}\int_0^T e^2(t)\,dt \qquad (6.4)$$

where

$$e(t) = x(t) - y(t) \qquad (6.5)$$

Equation (6.4) can be approximated as

$$\frac{1}{T}\int_0^T e^2(t)\,dt = \frac{1}{N}\sum_{k=1}^{N} e^2(k\Delta t) \qquad (6.6)$$

with N = 50 and $\Delta t$ equal to 1.5 second or 0.5 cm on the strip chart recorder. The MSE values obtained for different experimental conditions are summarized in Table 5.

As seen from the data in Table 5, the first subject performed slightly better than the second subject in most cases. In those few cases for which the second subject performed better, the difference

Table 5. Mean Square Error for Different Preview Conditions

| Subject | Bandwidth Frequency Hz | No Preview Condition | 1-5 Seconds Preview Condition | 3 Seconds Preview Condition |
|---|---|---|---|---|
| I | $f_c = 0.50$ | 2.16 | 0.78 | 0.89 |
| | $f_c = 0.15$ | 0.25 | 0.07 | 0.04 |
| II | $f_c = 0.50$ | 3.50 | 1.00 | 0.86 |
| | $f_c = 0.15$ | 0.52 | 0.06 | 0.07 |

was significant. The MSE was considerably smaller for the preview cases for both subjects than for the no preview case. The two preview conditions (1.5 second and 3 seconds) tested did not result in significant differences in the two subjects' performances in terms of MSE.

Comparing the two different bandwidth frequencies used for the experiment, there is an immediate decrease in MSE for higher frequency conditions. In the cases of 1.5 Hz bandwidth frequency, the track (y(t)) is very similar to the course (x(t)) in the general shape and follows it closely, usually with a small time lag and some amplitude error. At the 0.5 Hz bandwidth frequency and for both subjects, the track maintained the general shape and form of the course but the lag became large and a substantial error in amplitude appeared.

# CHAPTER VII

## CONCLUSIONS AND RECOMMENDATIONS

This study has considered the effect of preview or anticipation on the human controller in pursuit tracking. The experiments of this investigation demonstrated that the imposition of preview in tracking tasks has a significant effect on the mean square error for different experimental conditions.

The characteristics of the human controller in pursuit tracking have been studied using servo techniques, and the human controller elements have been identified in the time domain based on linear statistical regression theory. The power spectra for the residual errors in the linear regression models have been estimated. The Bode diagrams showing frequency response data for the human controller elements were drawn; however, these diagrams did not show a specific pattern for estimating the transfer functions of the human controller.

The remnant power spectral density was obtained and the linearity coefficient was calculated for different frequencies. Although the results were not very satisfactory, they correspond reasonably well to the results obtained from the residual power spectra which indicated higher linearities in certain frequency regions.

A comparison of the tracking performance of the two subjects revealed that they performed the required tasks much better at a lower bandwidth frequency of the input. The performances of the two subjects were somewhat similar except for the no-preview condition, for which the first subject produced smaller tracking errors. All tracking models exhibited the hesitancy property resulting from a reaction time lag. When preview was introduced, this lag seemed to be reduced significantly.

Perhaps the most important recommendation that can be made based on this experimental work is that further investigation be made to determine the feasibility of using analog-to-digital conversion devices to supplant the cumbersome, time-consuming, and inaccurate manual procedure used in this study to make the necessary conversions. It is possible to use a graph pen sonic digitizen to digitalize the curves obtained from tracking, but care must be taken to run the pen on the curves at a constant speed.

One useful extension of this experimental work would be to consider the effect of preview or anticipation on the human controller in compensatory tracking, and then to compare the results for compensatory tracking with the results of pursuit tracking. Such a study would obviously require more sophisticated peripheral equipment than was necessary for the work described herein.

Finally, it is possible to include more preview constraints on tracking, and to consider both higher and lower bandwidth frequencies than the ones considered in this experiment.

# APPENDIX

## INSTRUCTION TO SUBJECTS

### A. General Considerations

The purpose of this experiment is to determine the effect of preview or anticipation on human controller behavior in tracking tasks. The curve already drawn on the chart is used to show the path which the vehicle should follow. The vehicle is represented by the analog computer, and the output of the vehicle is displayed by the blue pen on the strip chart recorder. You will control the vehicle by moving the joystick that has been placed in the right corner of the table next to the recorder. The movement of the joystick (right and left only) corresponds to movement of pens on the strip chart recorder.

The horizontal axis of the recorder is the time scale and the vertical axis is the position scale. By moving the joystick right and left, you will cause the two pens of the strip chart recorder to move in the same direction as you have moved the stick. (Note that you are concerned only with the blue pen.) With the joystick exactly at the center, the vehicle on the strip chart pen will travel in a straight line at the center of each path.

### B. Experiment

In this experiment your task is to control the vehicle so that it follows, as accurately as possible, the random curve already drawn. You must follow the random curve (red) with vehicle output (blue). Two different frequencies have been used for the random input signal, and the strip chart recorder will travel at the same speed (1200 cm/hr) at all times.

The different constraints of the experiment are the distances that you will see ahead of the strip chart pen. These distances, which vary for different cases, are called preview. In this experiment we will see three different previews for our two frequencies, a total of six different cases.

## C. Lab Procedure

You will be seated in front of the strip chart recorder with your right hand on the joystick. Initially, you will be given a practice period of three minutes. For each case you will be given a one-minute practice and at the end of each trial you will be given four minutes of rest period. Before a trial begins, you will have sufficient time to observe the initial position and place the joystick as desired for your initial control input. If, for example, in the pursuit case the blue pen initially is to the right of the random signal, you can move the joystick to the left. You will be notified when to start and when to stop. Do your best, and do not be discouraged. The experimenter will be present in the room during the experiment; before the experiment begins, he will answer only general questions. The total duration of each case is nine minutes.

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