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EXTENSION OF HUMAN DESCRIBING FUNCTION MODELS TO STEP PLUS RANDOM APPEARING INPUTS

Jack Dexter Fisher

Air Force Institute of Technology
Wright Patterson Air Force Base, Ohio

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AIR FORCE INSTITUTE OF TECHNOLOGY

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THESIS

Jack D. Fisher
Captain USAF

GE/EE/69S-2

SCHOOL OF ENGINEERING

WRIGHT-PATTERSON AIR FORCE BASE, OHIO

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THESIS

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Jack D. Fisher, B.S.E.E.
Captain USAF

Graduate Electrical Engineering

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Preface

This study is an attempt to determine human operator models used in predicting the performance of human trackers when operating control systems with Gaussian noise plus step inputs. Performance measurements of human trackers operating control systems can be used to establish the parameters of the describing function model. Therefore, a major portion of this thesis deals with the collection and analysis of data from tracker controlled systems with Gaussian inputs, with step inputs, and with combined step and Gaussian inputs.

I wish to express my appreciation to Ronald O. Anderson, Control Analysis Group Leader, Air Force Flight Dynamics Laboratory for his sponsorship, interest, and continued assistance throughout all phases of this study. Special thanks is given to Paul E. Pietrzak of the Control Criteria Branch, Air Force Flight Dynamics Laboratory for his help with the analog simulations and for recording the Gaussian inputs on reproducable magnetic tape. Appreciation is extended to Major Russell A. Hannen for his understanding guidance and helpful suggestions. I am indebted to my three classmates, Captains Allan M. Dickson, Ronald L. Shillcutt, and John R. Starkie for their interest and their many hours of assistance as tracking subjects. Also, thanks is given to Lieutenant Commander Robert H. Wehr for inking several figures.

Finally, I wish to extend my appreciation and love to my wife and four children for their patience, understanding and encouragement.

Jack D. Fisher

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List of Symbols

a	Break frequency (radians per second)
c_m	Control system output of the model system (volts)
c_p	Control system output of the piloted system (volts)
e	Control system total error (volts)
e_p	Control system error of the piloted system (volts)
e_m	Control system error of the model system (volts)
e_s	Control system error due to the step input (volts)
e_g	Control system error due to the random noise input (volts)
$\overline{e^2}$	Mean squared error (volts squared)
σ_i^2	Variance of the random noise input (volts squared)
σ_o^2	Variance of the output (volts squared)
IAE	Time integral of absolute error (volts-seconds)
IES	Time integral of error squared (volts^2-seconds)
ITAE	Time integral of time weighted absolute error(volts-seconds^2)
ITES	Time integral of time weighted error squared(volts^2-seconds^2)
$\bar{K}$	K_pK
K	Controlled element gain
K_p	Human tracker gain
K_N	System gain at $s = 0$.
r_s	Step input to the control system (volts)
r	Total input to the control system (volts)
R_g	Gaussian input to the control system (volts)
τ'	Pure time delay constant (seconds)
τ	Effective time delay constant (seconds)

T_I	Lag time constant (seconds)
T_L	Lead time constant (seconds)
T_N	Neuromuscular lag (seconds)
Y_c	Controlled element transfer function
Y_p	Human pilot describing transfer function

ABSTRACT

A study was made of describing function models of human trackers while operating control systems with Gaussian plus step inputs. The parameters in the describing function model were adjusted using existing parameter adjustment rules and experimental data. Four performance measures were determined from the experimental data to assess their usefulness in adjusting the parameters of human pilot describing function models.

The experiments were run using three subjects with varied levels of flying experience. Each subject was given the single task of controlling a system with one of three different controlled elements; K, K/S, K/S^2. Data were collected on each subject for each system with a single step input, Gaussian input, and Gaussian plus step input. Comparisons of the output of the piloted systems and the model systems were made, and suggestions for applications to the controlled element dynamics were offered.

EXTENSION OF HUMAN DESCRIBING FUNCTION MODELS TO STEP PLUS RANDOM APPEARING INPUTS

I. Introduction

Background

In the past several years, interest has been generated in man-machine systems with particular emphasis on determining the role and response of man in the system. Mathematical models, which imitate human behavior during a particular task, have been developed. Men such as Elkind, McRuer, and Graham have gained distinction in the growing area of human response modeling. The United States Air Force has an obvious interest in this area because of the relationship between man, the pilot, and the machine, the airplane.

The Air Force Flight Dynamics Laboratory at Wright-Patterson Air Force Base has been conducting in-house studies and contracting for research in the area of human response. Of particular interest at present is the development of a model that would predict the response of a pilot in a one-step landing system. A one-step landing system would allow a pilot, flying along a glide path towards a runway, to make one major change in his flight path before touchdown. A prediction of the proper altitude at which to make this change is dependent on the characteristics of the aircraft and the response of the pilot. The mathematical equations representing the aircraft characteristics are known, since the formulation of appropriate transfer functions is normally accomplished during the design and construction of the aircraft. The mathematical equations representing the responses of the pilot in particular tasks are being developed as data is accumulated from the experiments of many individual in this field. Accurate models, which could predict pilot response, would be of benefit in performing handling qualities and manual control analysis during aircraft development, construction, and modification. Pilot models would also be useful for determining the feasibility of performing a particular aircraft manuver such as a one-step landing, without actually flying the aircraft.

In a one-step landing, although only one major change in flight path is needed, minor adjustments must be made to prevent the aircraft from being blown off the glide path by wind gusts. Human pilot describing function models have been developed for predicting pilot performance in controlling a single loop system in the presence of Gaussian input signals, representing wind gusts. (Ref 9). Adjustment rules for setting the parameters of the model are well defined and used extensively. (Ref 11). Application of the describing function model has been applied to nonlinear systems (Ref 6), and to systems with step inputs (Ref 14). However, few data are presently available for determining pilot performance in a situation such as the one-step landing system where the input to the system is a Gaussian random disturbance plus a command step signal. A preliminary study was done at the Air Force Flight Dynamics Laboratory (Ref 1 & 3). Also, a dual mode pilot model (surge model) has been proposed (Ref 5) and some results for random inputs plus "step-like discontinuities" are available. However, only the pure gain controlled element was considered, and the model is fairly complicated.

The Problem

An evaluation of the existing human pilot describing function model is necessary to determine how well, if at all, the model predicts the performance of a pilot in a system which has Gaussian plus step inputs. A determination of the best performance criteria to use in adjusting the model parameters is also necessary. The relationship between the performance measures and adjustment rules used for a system with Gaussian input and the measures and rules used for a system with step inputs should be determined. Therefore, the purpose of this thesis is to collect performance data by observing and modeling human subjects operating single axis control systems. The collection and analysis of these data will provide for a better understanding of performance and necessary model adjustments in systems which have Gaussian plus step signals applied.

The Objectives

The objectives of this thesis are: (1) to collect, analyze, and correlate performance measure data of three subjects operating systems with Gaussian inputs, step inputs, and combined Gaussian plus step inputs, (2) to study the existing human pilot describing function model and determine a method of adjusting its parameters from accumulated data on actual pilot performance, (3) to develop techniques for combining the performance measure for a system with Gaussian input with the performance measure for a system with a step input to obtain the performance measure for a system with Gaussian plus step inputs, and (4) to evaluate the usefulness of the existing pilot model and adjustment rules for predicting the output of a manned system when Gaussian plus step signals are applied.

Approach

The first step was to collect data on the performance of three subjects operating a simple single axis compensatory tracking task. Each subject has a different level of flying proficiency, but each was given the same operating instructions. The experiments were sequenced from easy to difficult. Measurements were taken for three systems, excited first with step signals, then Gaussian signals, and then step and Gaussian signals.

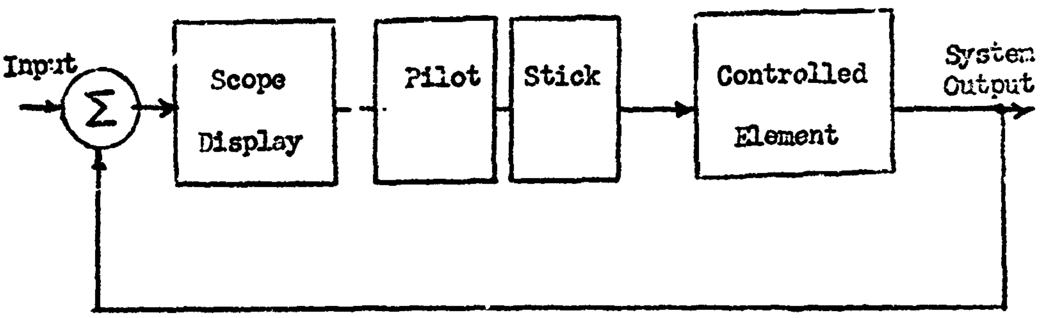
The second step was to program the pilot describing function model on the analog computer so that data for determining the model characteristics could be collected. Graphs were prepared to show the effect of parameter variation on model performance. Root locus analysis was conducted to show trends in modeled system dynamics. The determination of model characteristics was accomplished so that a comparison with actual pilot performance would be possible.

The third step was the correlation of data. An attempt was made to match human performance with model performance by using appropriate model adjustments. The final step was to compare the system output of the adjusted model with the system output of the piloted model when operated simultaneously. Real time recordings were taken.

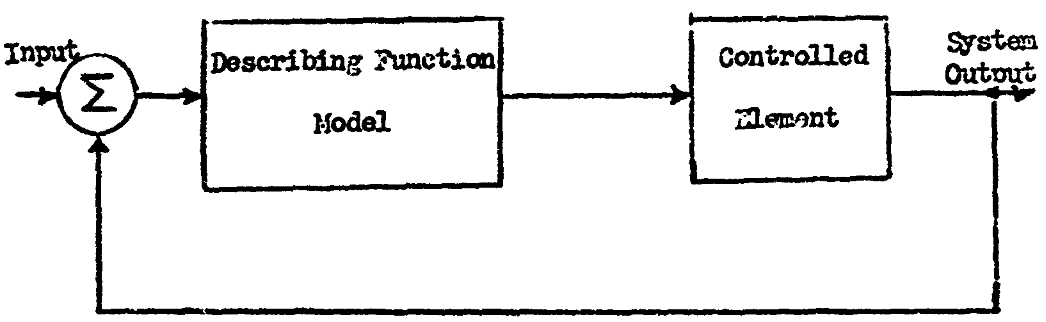
Scope

It should be emphasized that this thesis is not a study of the development of a new pilot model. The study is limited to the collection and analysis of data, the evaluation of the existing human describing function model with parameter variation, and the comparison of piloted and model systems with Gaussian plus step inputs. All experiments with human subjects and the model will be conducted for systems with one of three controlled elements and a single unity feedback loop. The analog computer is used in the simulation of both systems. A block diagram of the piloted and model systems is shown in Figure 1. Three controlled elements; K, K/S, and K/S^2 are used. No attempt was made to use aircraft dynamic equations.

Four performance measurements were studied: (1) the time integral of error squared, (2) the time integral of time weighted error squared, (3) the time integral of absolute error, and (4) the time integral of time weighted absolute error. A performance measurement is an evaluation of how well a system operates; how well the output follows the input, or how small the error can be maintained over a given time period. The time integral of error squared has been used successfully to evaluate the performance of human trackers in systems with Gaussian inputs. The purpose of studying additional performance measures was to evaluate their usefulness for systems with step, and Gaussian plus step inputs.



Piloted System



Model System

System Block Diagrams

Figure 1

II. Experimental Approach

General

The experiments were conducted in three phases. The same three subjects were used in each phase. Their flying experience is listed in Appendix F. The subjects were briefed on the purposes of the experiments. Their cooperation and interest through many hours of tests spread over several months was extremely high. All experiments were conducted in a single room with the subject seated in a student's chair. A force stick firmly attached to the chair armrest was the instrument which the subject used to affect changes on the system. The force stick is explained in Appendix A and it was used by the subject to correct for the system error. The error was displayed as a vertically displaced horizontal trace on a Tektronics oscilloscope. The subjects were told that the horizontal trace represented the pitch steering bar of an aircraft. They were instructed to keep the trace level with a guide line taped to the scope display. The force applied to the stick was electrically coupled to the controlled element of the system. The polarity of the stick control was set similiar to an aircraft stick; i.e. force applied away from the subject caused the horizontal trace on the scope to move up, and visa versa. It was emphasized to the subjects, especially the experienced pilots, that they should control the stick in a manner similiar to the method in which they handled an actual aircraft control.

For each set of experiments, the subjects were allowed three practice runs. During these runs, the sensitivity of the stick was set for comfortable control and the brightness and focus of the horizontal oscilloscope trace were set for easy viewing. Distance between the subject and the scope display was set at five feet. The oscilloscope sensitivity was set for best utilization. It should be noted that changes of scope sensitivity within reasonable limits has very little effect on performance (Ref 14). The noise level in the room was approximately half of that which would be experienced in the cockpit of an aircraft. Subject 1 mentioned that he frequently talks during actual flying manuvers, and he asked if he would be permitted to talk during the experiments. To provide as much realism as possible, it was agreed that all subjects would be allowed to talk during the experiments if they wished. However, their performance was not discussed until all tests were completed on a particular system. On several occasions, superior performance by subject 1 was noted during tests in which he was talking frequently.

In each phase, three systems were tested. The first system tested had a pure gain controlled element, the second system had a single integrator with gain, and the third system included a double integrator with gain. The subjects completed the loop of the unity feedback control system by sensing the error on the scope and applying a correction to the controlled element with the force stick.

Phase I - Step Input

During Phase I, tests were made on each of the three systems with a single one volt step input applied. The application of the step caused a two centimeter trace displacement on the oscilloscope when set at 0.5 volts/centimeter; therefore, the scope was set at

0.5 volts/centimeter for all runs. The subjects were given warning to watch the scope display preceding the application of the step. The step was randomly applied within a time interval of thirty seconds. A maximum time of twenty seconds was given for the subjects to zero the error. The analog computer was then placed in hold and the readings were taken from the digital voltmeter. Also, real time recordings of the input, output, error, and force voltages were made. From these recordings, measurements were taken of the static time delay between the input of the step and the application of force to the stick. Twenty-five runs were made with each controlled element. For the K/S^2 controlled element, additional runs were occasionally necessary when the subject lost control due to over-reaction and oscilloscope display limitations. It was necessary to bias the stick voltage as shown in Appendix B due to a slight mechanical hysteresis.

Phase II - Gaussian Input

During this phase of experimentation, the subjects were given a tracking task with Gaussian input applied to the system. Three, second order-filtered Gaussian signals (Appendix C) were used, one with a break frequency of 0.5 radians/second, another with a break frequency of 1.0 radians/second, and the third with a break frequency of 1.5 radians/second. To ensure that each run was of equal length, the automatic hold circuit of the analog computer was employed at exactly sixty seconds from the start of the run. Reuse of each of the three signals was accomplished by employing the Sangamo magnetic tape recorder/reproducer in loop operation. The production of the Gaussian signals is discussed in Appendix C. To avoid criticism that the subjects would learn the nature of the three signals, the input was switched after each sixty second trial. Occasionally, first order-filtered signals were applied from the tape to prevent over familiarity with the three, second order-filtered signals used for the data collection.

For the signal with the 1.5 radians/second break frequency and the signal with the 0.5 radians/second break frequency, nine one-minute tests were made for each of the three controlled elements. For the signal with a 1.0 radian/second break frequency, only four one-minute tests were accomplished.

Phase III - Gaussian Plus Step Inputs

The third phase of the experiment was completed using two of the three Gaussian signals used in Phase II; the 1.5 radians/second signal and the 0.5 radians/second signal. A 1, 3, or 5 volt step was applied at some random time within the first twenty seconds of the run. Five tests for each signal applied to each of the three systems were accomplished. Therefore, each subject performed a total of ninty tests during this phase. As mentioned before, the subjects worked the easiest system first and progressed to the more difficult system. All runs were sixty seconds long. The time lapse between the beginning of the run and the application of the step was measured with a hand stop watch.

Performance Measures

The following performance measures were used to evaluate each experiment:

(1) $\int e^2\, dt$

(2) $\int te^2\, dt$

(3) $\int |e|\, dt$

(4) $\int t|e|\, dt$

The measures were programmed on the analog computer as discussed in Appendix B. One difficulty occurred with the multipliers used on the analog; non-linearity of the diodes when operated near zero volts, resulted in erroneous readings for $\int te^2\, dt$ during some experiments in Phase II and Phase III. Time was represented by volts, so it was necessary to start the time at ten rather than zero. This was accomplished by applying an initial condition of ten volts to the timing integrator. The timing problem made it impossible to read $\int te^2\, dt$ and $\int t|e|\, dt$ directly. The following development indicates how these measures were determined. Since

$$\int_0^T (t + 10)\, e^2\, dt = \int_0^T te^2\, dt + 10\int_0^T e^2\, dt\ ,$$

therefore

$$\int_0^T t\, e^2\, dt = \int_0^T (t + 10)\, e^2\, dt - 10\int_0^T e^2\, dt.$$

Similarly,

$$\int_0^T t\, |e|\, dt = \int_0^T (t + 10)\, |e|\, dt - 10\int_0^T |e|\, dt.$$

One objective of this study was to determine if a linear relationship existed between the measures recorded for the piloted systems with separate step and Gaussian inputs, and the measures recorded for the piloted systems with combined Gaussian plus step inputs. The following hypothesis was formulated for each performance measure.

IES

$$\int_0^T (e_s + e_g)^2 \, dt = \int_0^T (e_s^2 + 2e_se_g + e_g^2) \, dt$$

$$= \int_0^T e_s^2 \, dt + \int_0^T 2e_se_g \, dt + \int_0^T e_g^2 \, dt$$

If the term $\int_0^T 2e_se_g \, dt$ is small enough to ignore, then the additive relationship $\int_0^T (e_s + e_g)^2 \, dt = \int_0^T e_s^2 \, dt + \int_0^T e_g^2 \, dt$ results.

ITES

$$\int_0^T t(e_s + e_g)^2 \, dt = \int_0^T t(e_s^2 + 2e_se_g + e_g)^2 \, dt$$

$$= \int_0^T te_s^2 \, dt + \int_0^T 2te_se_g \, dt + \int_0^T te_g^2 \, dt$$

If the assumption is made that $\int_0^T 2te_se_g \, dt$ is very small, then $\int_0^T t(e_s + e_g)^2 \, dt$ will approximately equal $\int_0^T te_s^2 \, dt + \int_0^T te_g^2 \, dt$. However, knowledge of the time when the step input is applied, is required to determine the value $\int_0^T te_s^2 \, dt$. It appears that the complications involved in determining this value would eliminate the use of this performance measure for determining model parameter values in a system with Gaussian plus step inputs.

IAE

$$\int_0^T |e_s + e_g|\, dt \leq \int_0^T (|e_s| + |e_g|)\, dt$$

If the assumption is made that the error due to the step input is normally of the same polarity as the error due to the Gaussian signal then the absolute value of the sum will equal the sum of the absolute values. If the subject was maintaining the error at an extremely low level when the step was applied, then equality of the above might be possible. Although the assumptions for equality were doubted before experimentation, the measurements were taken to clarify the issue.

ITAE

$$\int_0^T t|\varepsilon_s + e_g|\, dt \leq \int_0^T t|e_s|\, dt + \int_0^T t|e_g|\, dt$$

The same assumption must be made for this measure as made for the IAE. The time-varying aspect of this relationship further increases the computational difficulties in using this measure to determine the parameters of a model system forced with Gaussian plus step signals. However, the ITAE is possibly a good performance measure for a system with step inputs.

III. Describing Function Model and Analog Simulation

The Existing Model

The human pilot acts, in general, as a nonlinear and time-varying device in a control system. To develop a model to respond in a manner similar to that of a pilot, is a difficult task. However, a human describing function model has been developed which simulates pilot responses in a control system when random Gaussian signals are applied. (Ref 11). The general quasi-linear model appears as a LaPlace transformed equation,

$$Y_p(s) = \frac{K_p e^{-\tau' S}(T_L S + 1)}{(T_I S + 1)(T_N S + 1)} ,$$

with $S = jw$ since this is a describing function. The pure time delay is represented by $e^{-\tau' S}$, the gain by K_p, the general lead term as T_L, the general lag term as T_I, and the first-order lag time constant approximation of the neuromuscular system as T_N. The neuromuscular lag approximation is often eliminated and the pure time delay term, τ' is modified to include the neuromuscular time constant. The result is an effective time delay term $e^{-\tau S}$, where $\tau = \tau' + T_N$. The simplified version of the pilot describing function model, represented in LaPlace transform, is

$$Y_p(s) = \frac{K_p e^{-\tau s} (T_L S + 1)}{(T_I S + 1)} .$$

The model parameters, τ, T_L, T_I, and K_p are appropriately adjusted for the type of system being controlled. In a control system, where the controlled element is pure gain, the lead time constant, if any, is extremely small in relationship to the lag term, and thus can be eliminated. When the controlled element is K/S, the lead and lag time constants are equal or zero, and with a K/S^2 controlled element, the lag, if any, is small in relation to the lead time constant and can be eliminated. The specific model form is shown with the corresponding controlled element in Table 1.

Table 1

The Simplified Models

Controlled Element	Model
K	$Y_p = \frac{K_p \epsilon^{-\tau S}}{(T_I S + 1)}$
K/S	$Y_p = K_p \epsilon^{-\tau S}$
K/S^2	$Y_p = K_p (T_L S + 1) \epsilon^{-\tau S}$

The model parameters not only depend on the type of system, but the type of input and on the existance of physical nonlinearities. Adjustment rules governing the model operation have been developed. (Ref 11:18). Since the first consideration of the human operator is to maintain stability, the model parameters must be set for stable operation. The second consideration of the human operator is the maintenance of good low frequency operation by generating lag, if necessary. After adjusting for good low frequency operation, the pilot then generates lead, if necessary, to improve high frequency response. With the parameters, T_I, T_L, and τ, partially adjusted, the gain, K_p, is then set to the optimum operating level. It is thought that the operator adjusts gain to minimize the mean-squared error. The formulated rules also include certain invariance properties. First, the operator adjusts his gain to compensate for variations of the controlled element gain, thus over-all system gain remains relatively constant. Second, system cross-over frequency is invariant with changes of input bandwidth, provided the input bandwidth is less than the cross-over frequency. Third, when the bandwidth increases to, and goes beyond, the cross-over frequency, the operator, varies operation to maintain stability and good low frequency response. This appears as a reduction in operator gain and lead, and is known as regression.

Model Simulation

Assuming that the existing model was applicable to the experiments performed in this study, a method for identifying the appropriate model values was necessary. To facilitate matching the model with the subjects, the model was simulated on the analog computer, and a series of tests were run to determine changes in the mean-squared error, as the parameter settings were varied. To program the analog computer, it was necessary to use an approximation to the pure time delay. The first order Pade' approximation was chosen, because of its constant amplitude characteristics for all frequencies. However, the phase difference between the Pade' approximation, and the actual time delay, becomes pronounced as frequency is increased. The LaPlace transform of the Pade' approximation is $\dfrac{(1 - 0.5\tau S)}{(1 + 0.5\tau S)}$.

A root locus study was conducted to determine the appropriate parameter settings for the analog simulated model. Settings causing unstable operation were identified. The root loci of both the model with Pade' approximation and the human describing function with pure time delay were computed. Loci diagrams are shown in Figures 2-33. The plots were programmed on the IBM 7094 Digital Computer and drawn on the Cal-Comp plotter. The parameter settings used for each plot were chosen from a range of values considered in previous studies (Ref 11), and are listed in Table 2. The title for the human describing function model plots with pure time delay was shortened to "Human Describing Model." The title for the simulated model plots using the Pade' approximation is "Analog Simulated Model."

The gain for optimum operation of the model, minimum mean error-squared of the simulated model with a second order filtered Gaussian input having a break frequency of 1.5 radians per second, is identified on both the analog simulated plots and the human describing function plots. The following observations were made from the root locus study: At the gain setting for minimum mean error-squared of the simulated model,

1) the undamped natural angular frequency of the human describing function was less than that of the simulated model,

2) the damping factor of the human describing function was less than the damping factor of the pure gain controlled element model with small lag constants, and greater than the damping factor of the model with larger lag constants,

3) for large lead constants in the system with the K/S^2 controlled element, the damping factor was greater for the simulated model, and for small lead constants, the damping factor was greater, and

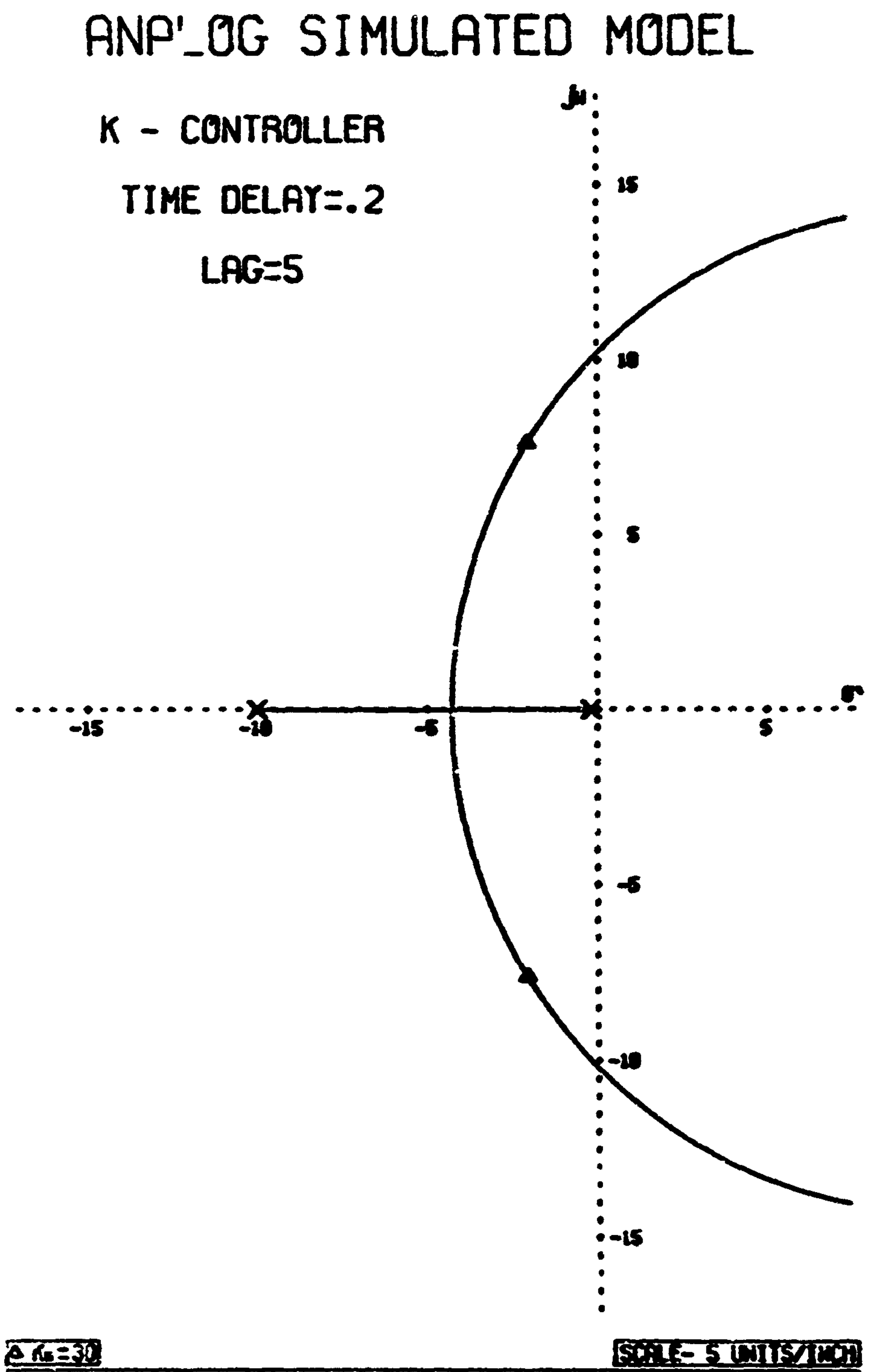
Table 2

A List of The Root Locus Figures

Figures	Type System	Time Delay	Lead	Lag
2 & 3	K	0.2	0.0	5.0
4 & 5	K	0.2	0.0	3.0
6 & 7	K	0.2	0.0	1.0
8 & 9	K	0.3	0.0	5.0
10 & 11	K	0.3	0.0	3.0
12 & 13	K	0.3	0.0	1.0
14 & 15	K/S	0.2	0.0	0.0
16 & 17	K/S	0.3	0.0	0.0
18 & 19	K/S^2	0.2	0.5	0.0
20 & 21	K/S^2	0.2	1.0	0.0
22 & 23	K/S^2	0.2	3.0	0.0
24 & 25	K/S^2	0.2	5.0	0.0
26 & 27	K/S^2	0.3	0.5	0.0
28 & 29	K/S^2	0.3	1.0	0.0
30 & 31	K/S^2	0.3	3.0	0.0
32 & 33	K/S^2	0.3	5.0	0.0

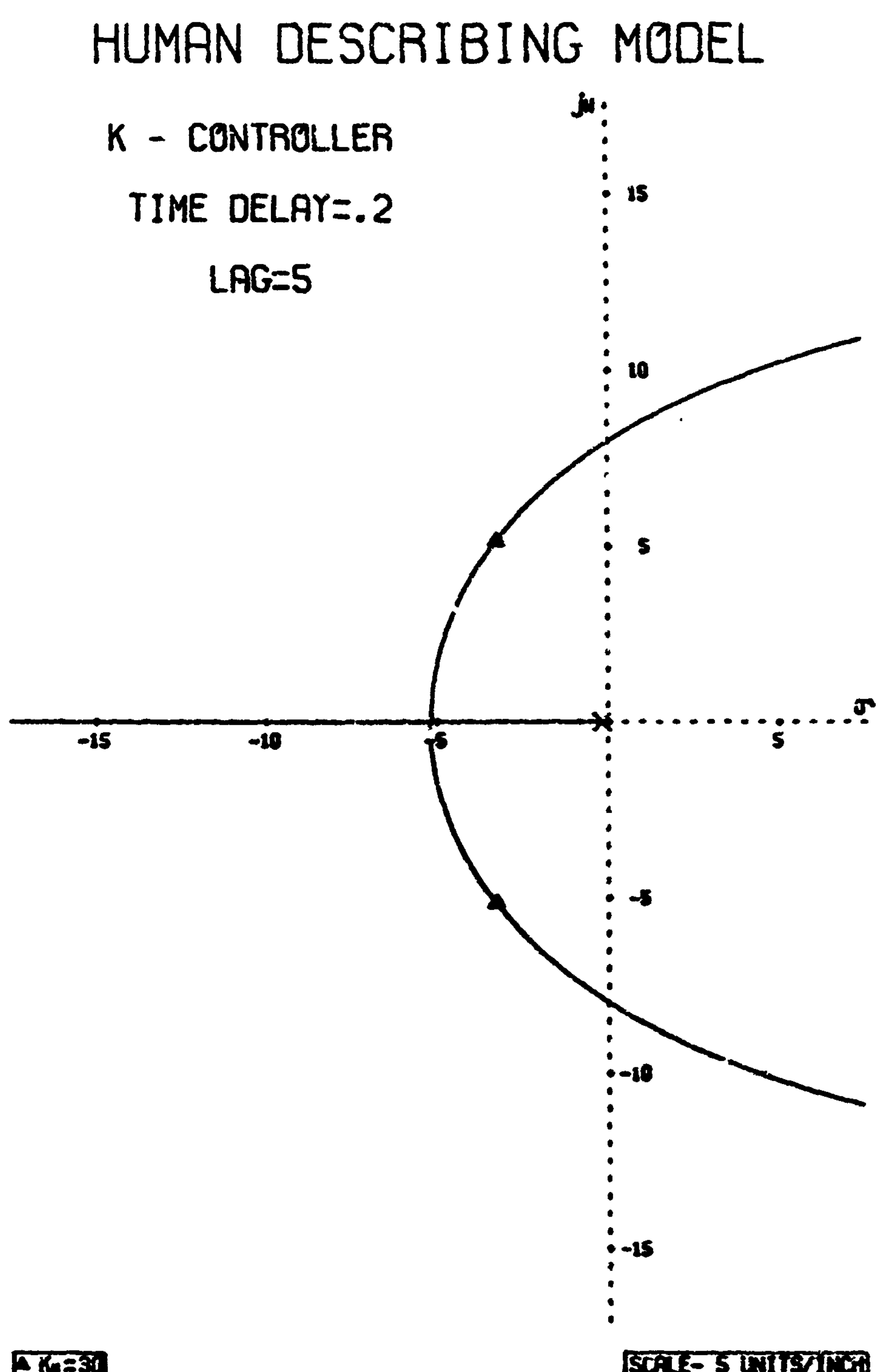
4) at low frequencies, the model is a good representation of the human describing function model.

These results may be of some value to investigators who have used, or are using, the Pade' approximation.



$$Y_P\ Y_C = \frac{-K_1(S-10)}{(S+0.2)(S+10)}$$

FIGURE 2 - ROOT LOCUS



$$Y_P Y_C = \frac{Ke^{-0.2T}}{(S+0.2)}$$

FIGURE 3 - ROOT LOCUS

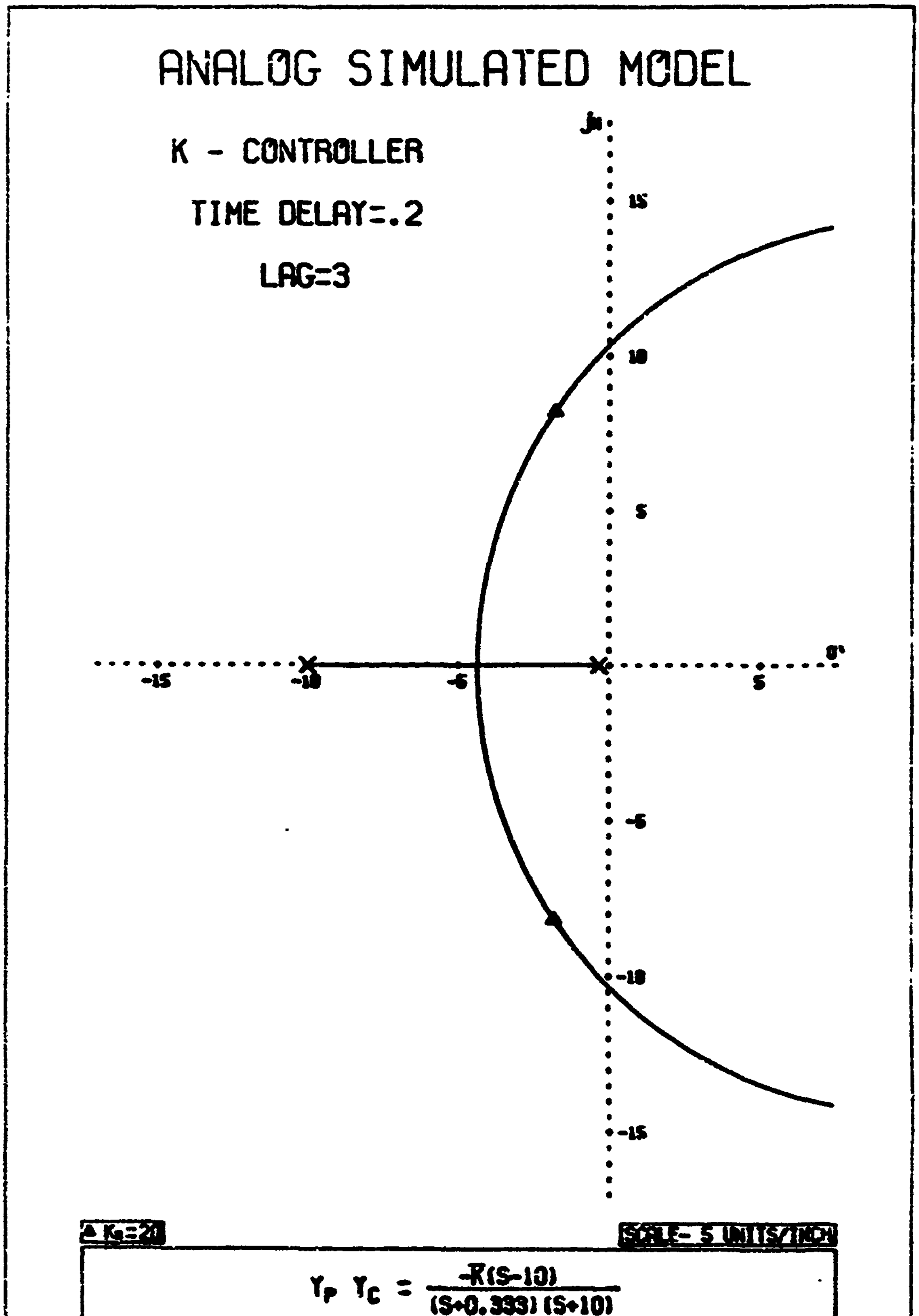
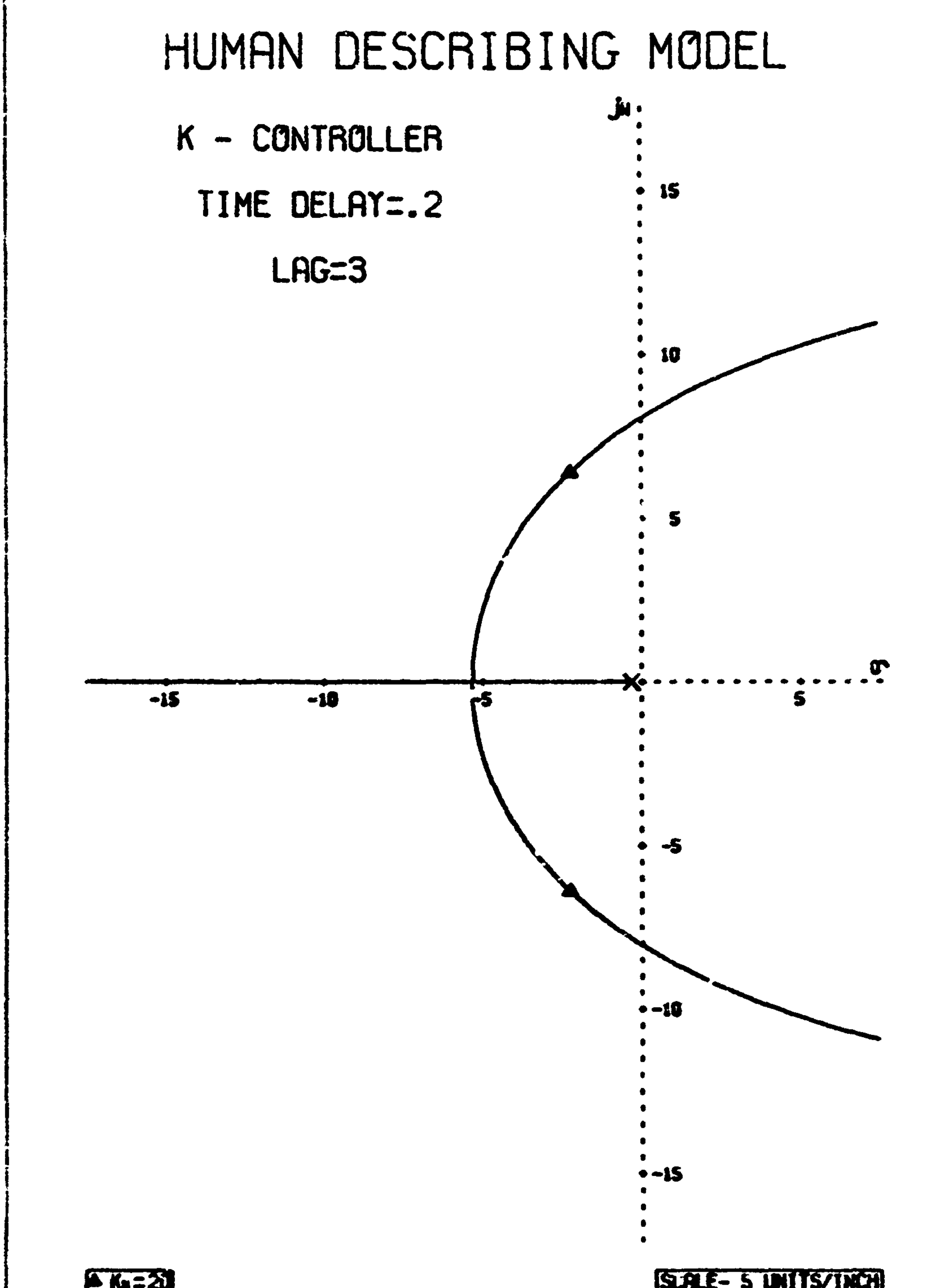


FIGURE 4 - ROOT LOCUS



$$Y_P \, Y_C = \frac{Ke^{-0.2T}}{(S+0.333)}$$

FIGURE 5 - ROOT LOCUS

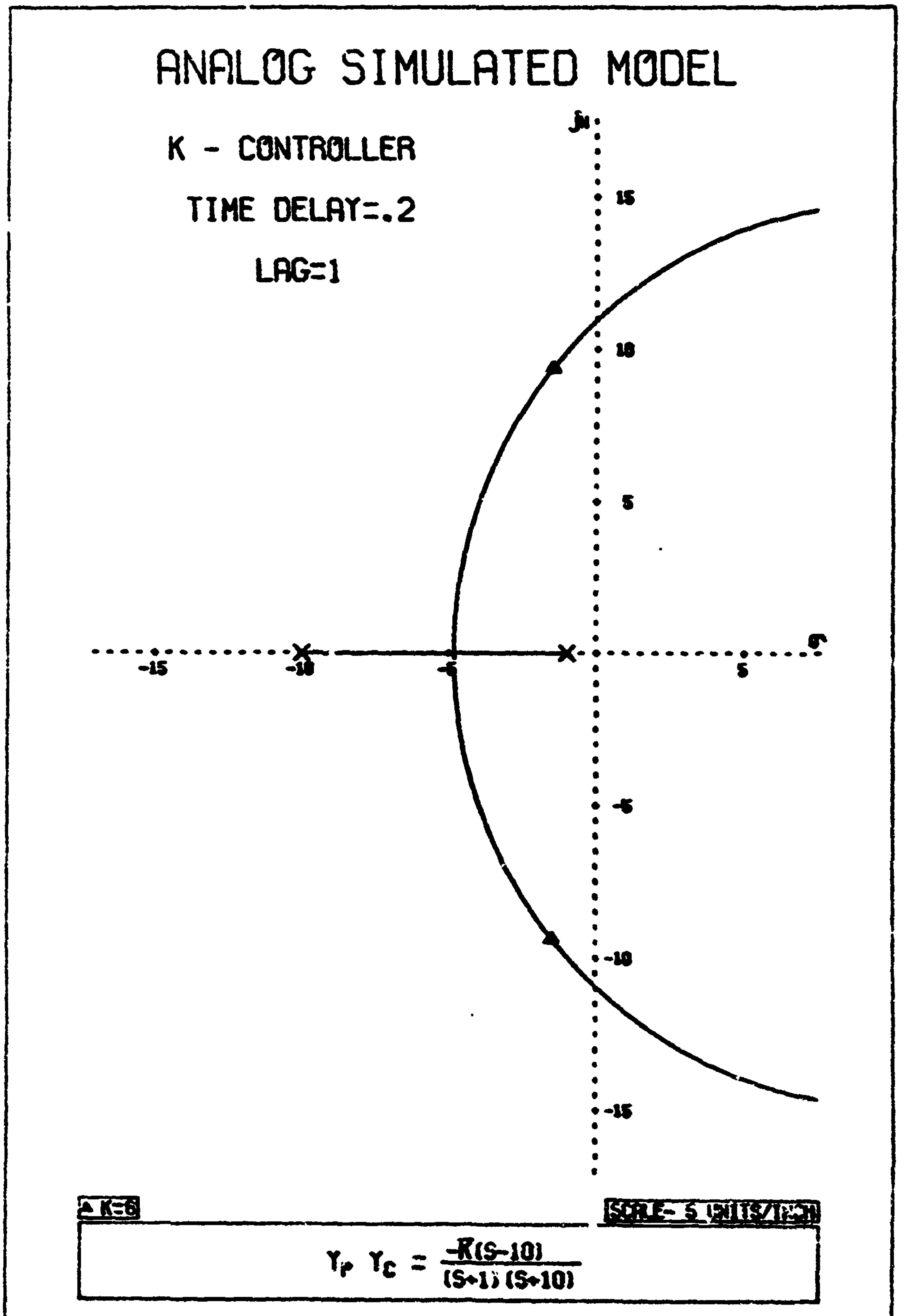


FIGURE 6 - ROOT LOCUS

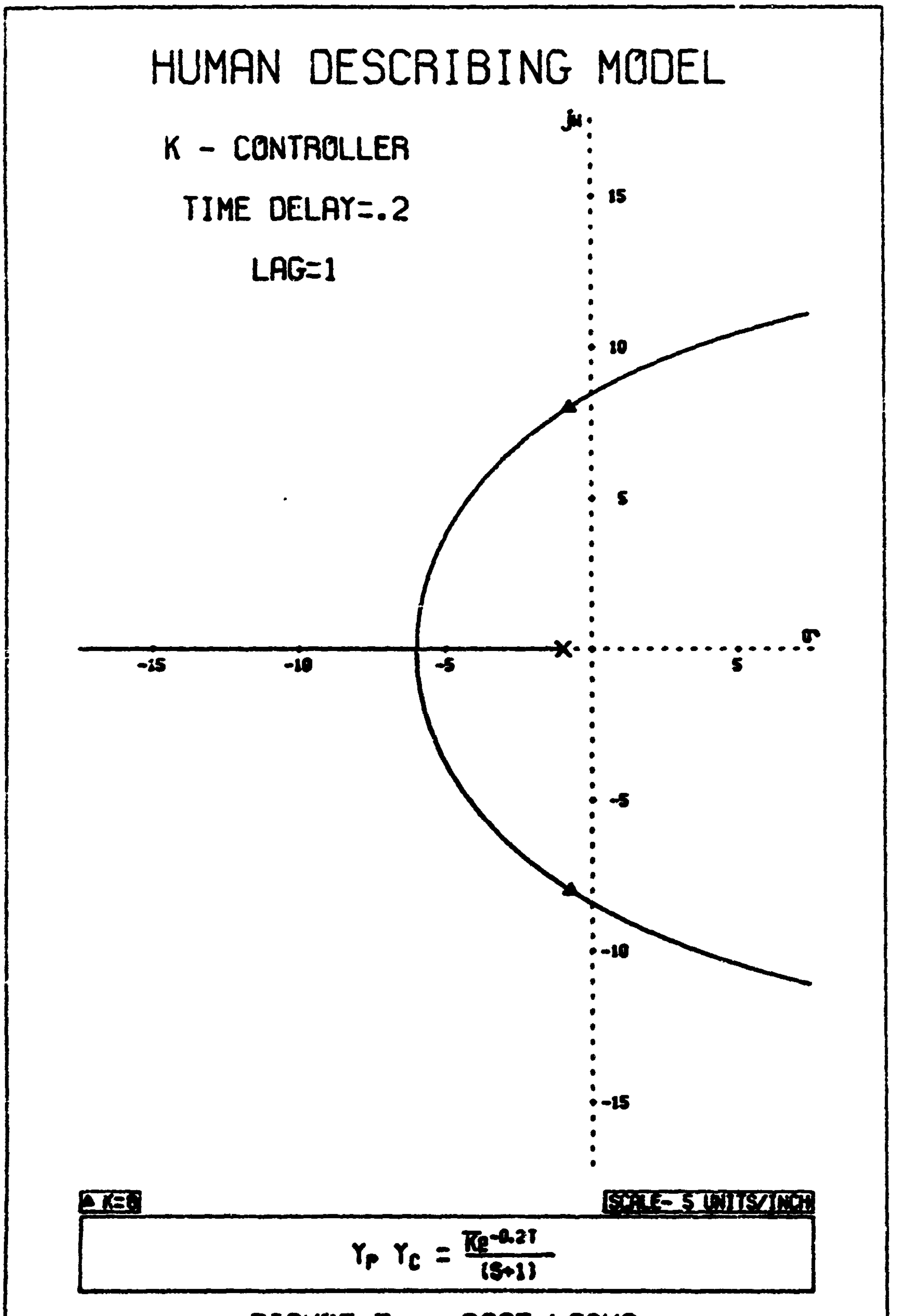


FIGURE 7 - ROOT LOCUS

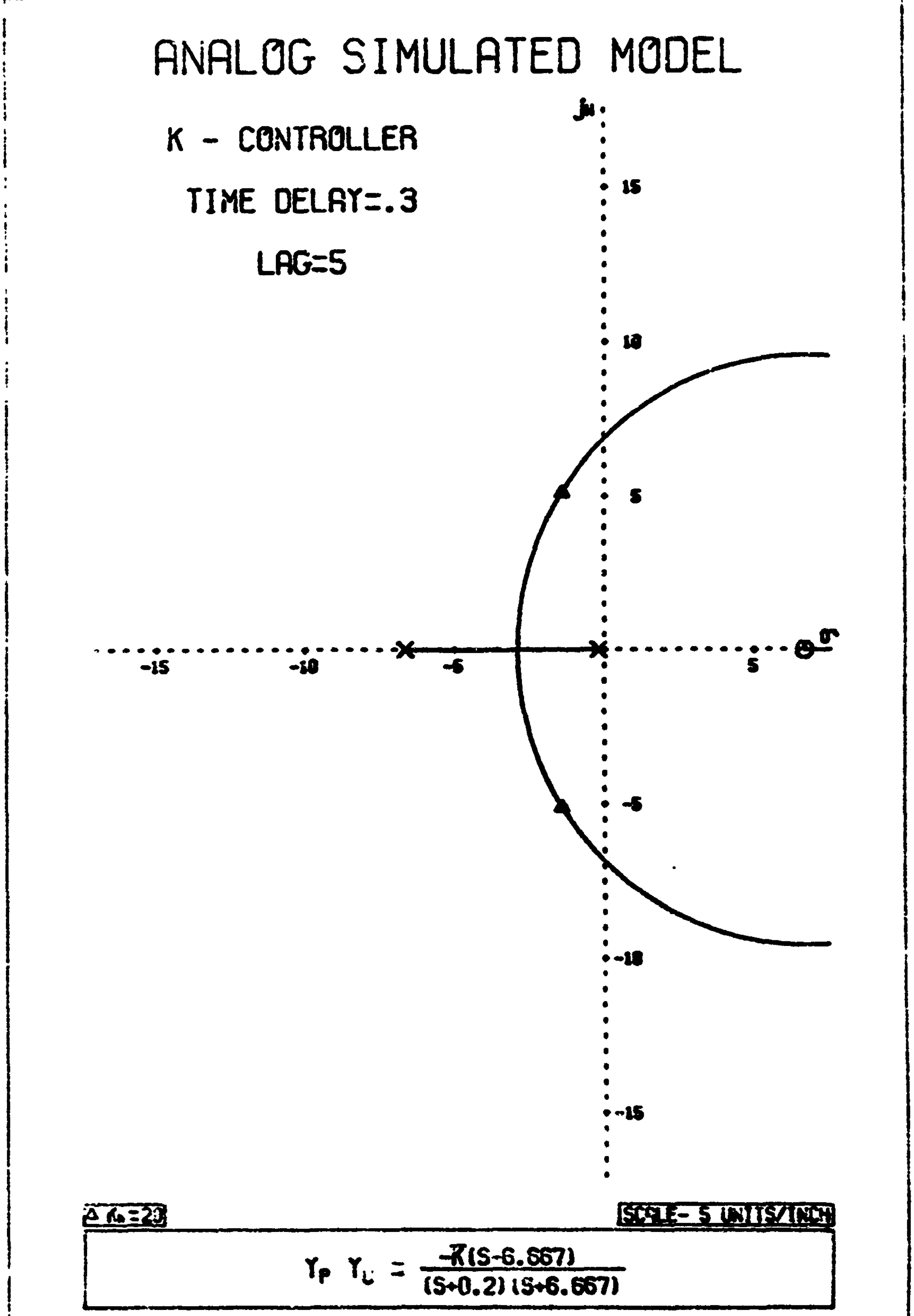


FIGURE 8 - ROOT LOCUS

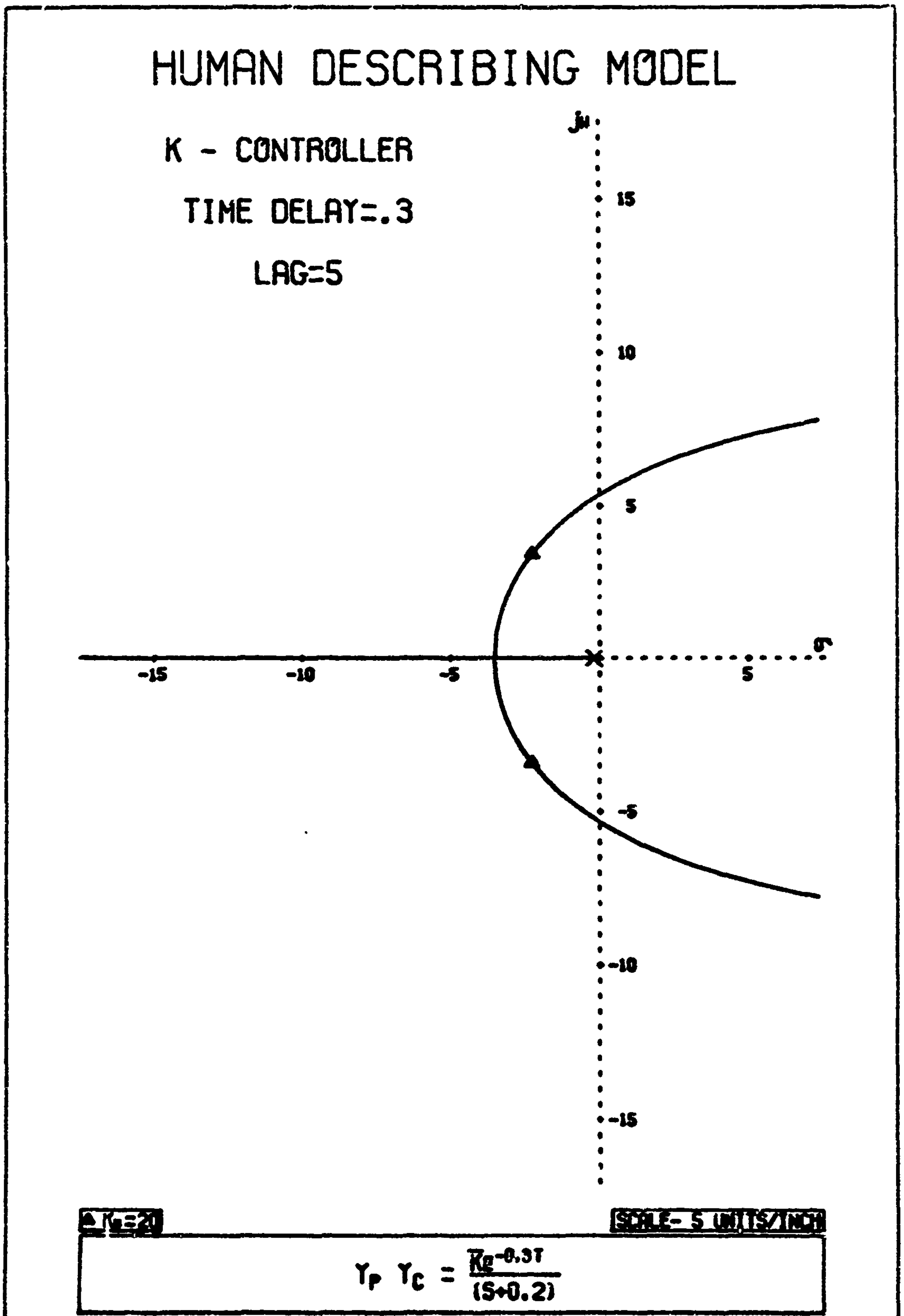
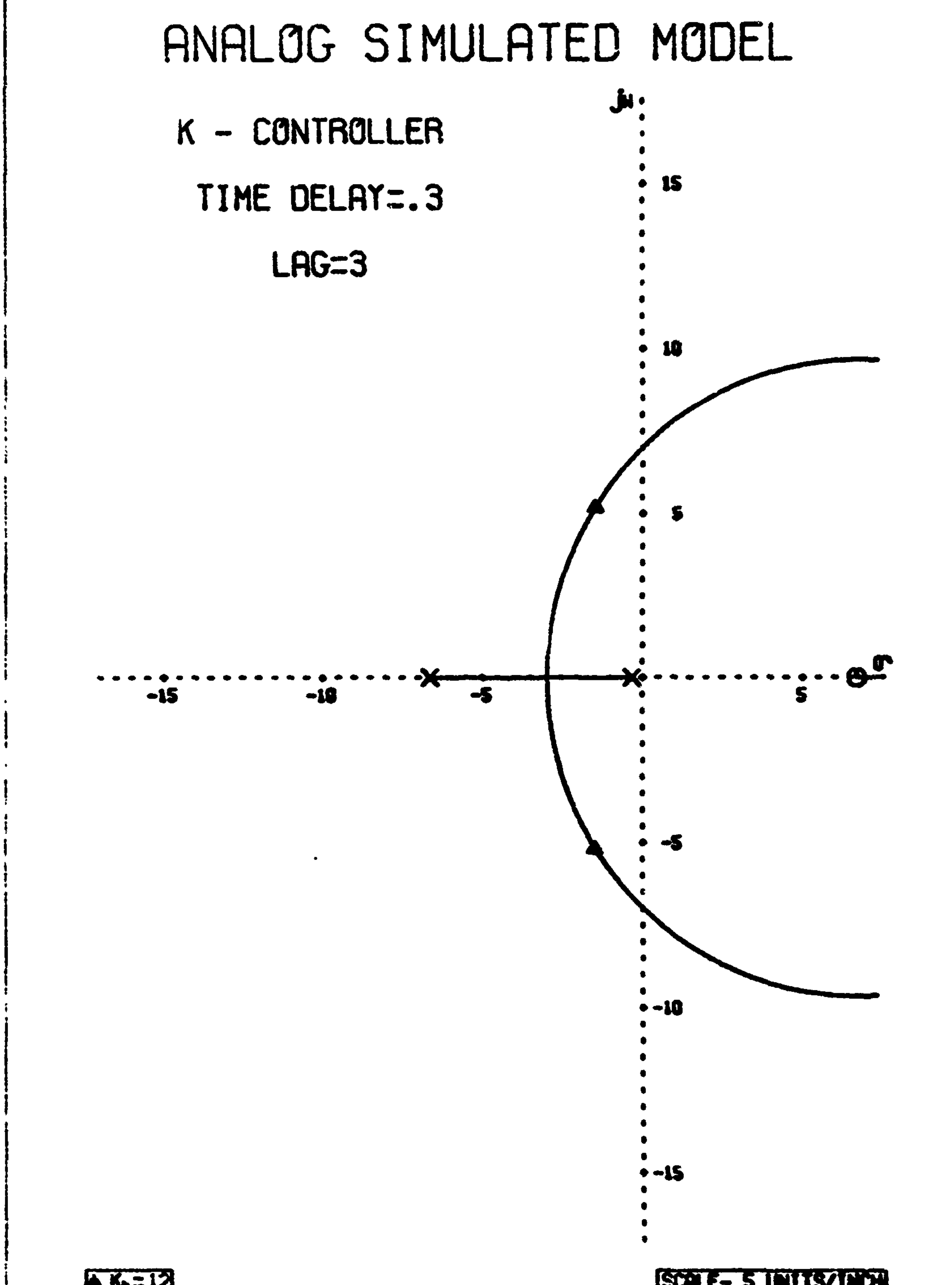


FIGURE 9 - ROOT LOCUS



$$Y_P\, Y_C = \frac{-K(S-6.667)}{(S+0.333)(S+6.667)}$$

FIGURE 10 - ROOT LOCUS

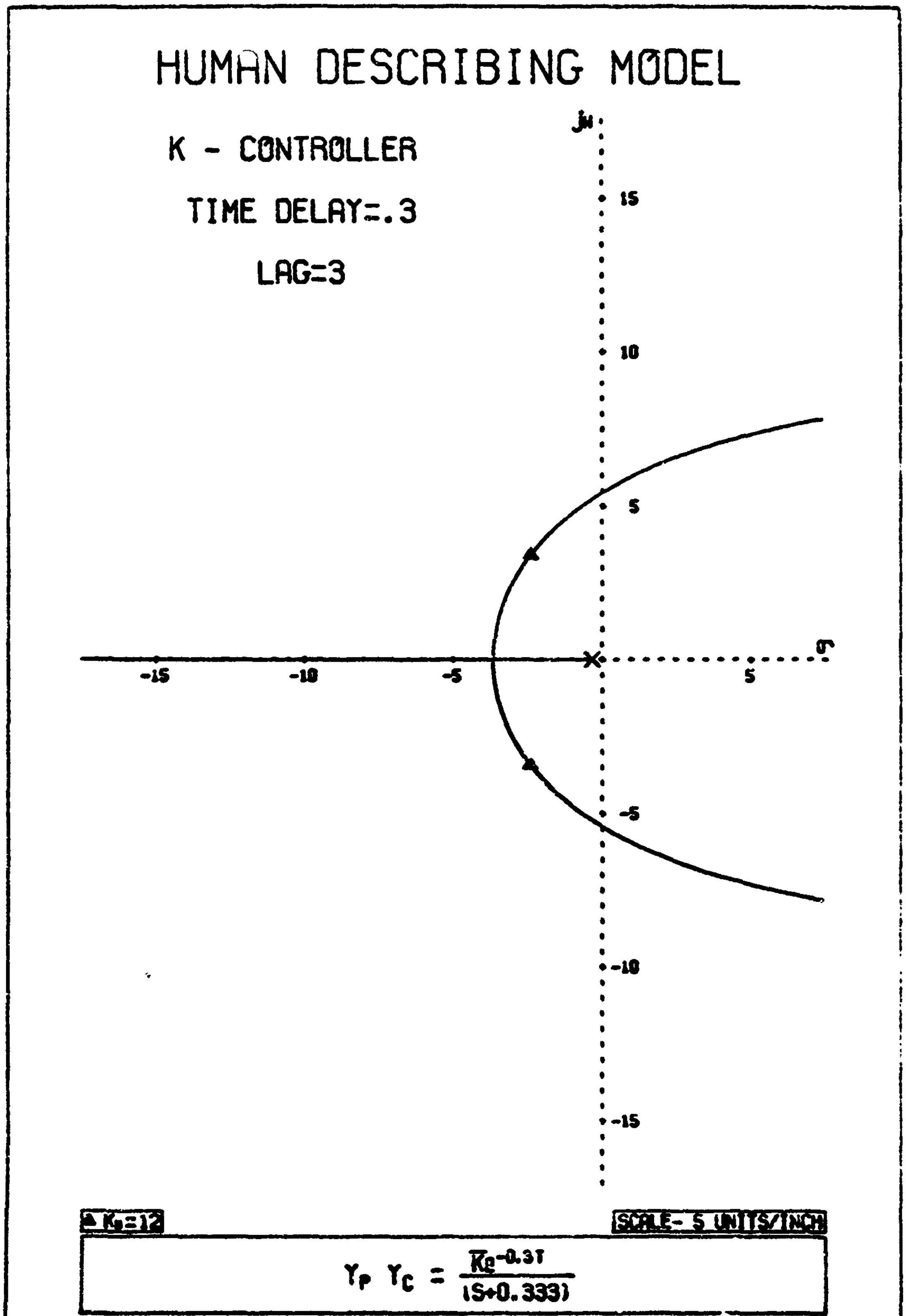
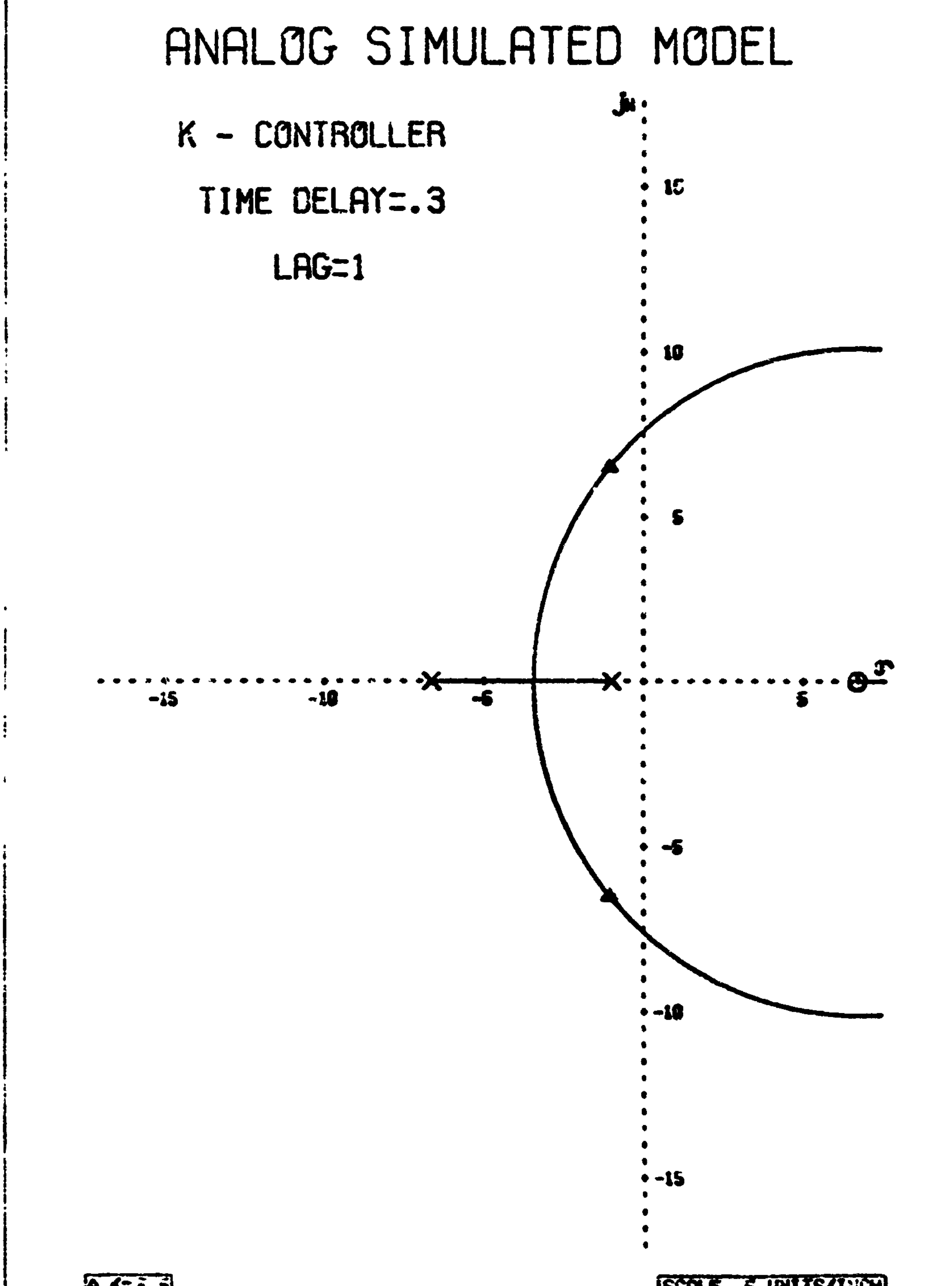


FIGURE 11 - ROOT LOCUS



$$Y_p\ Y_C = \frac{-K(S-6.667)}{(S+1)(S+6.667)}$$

FIGURE 12 - ROOT LOCUS

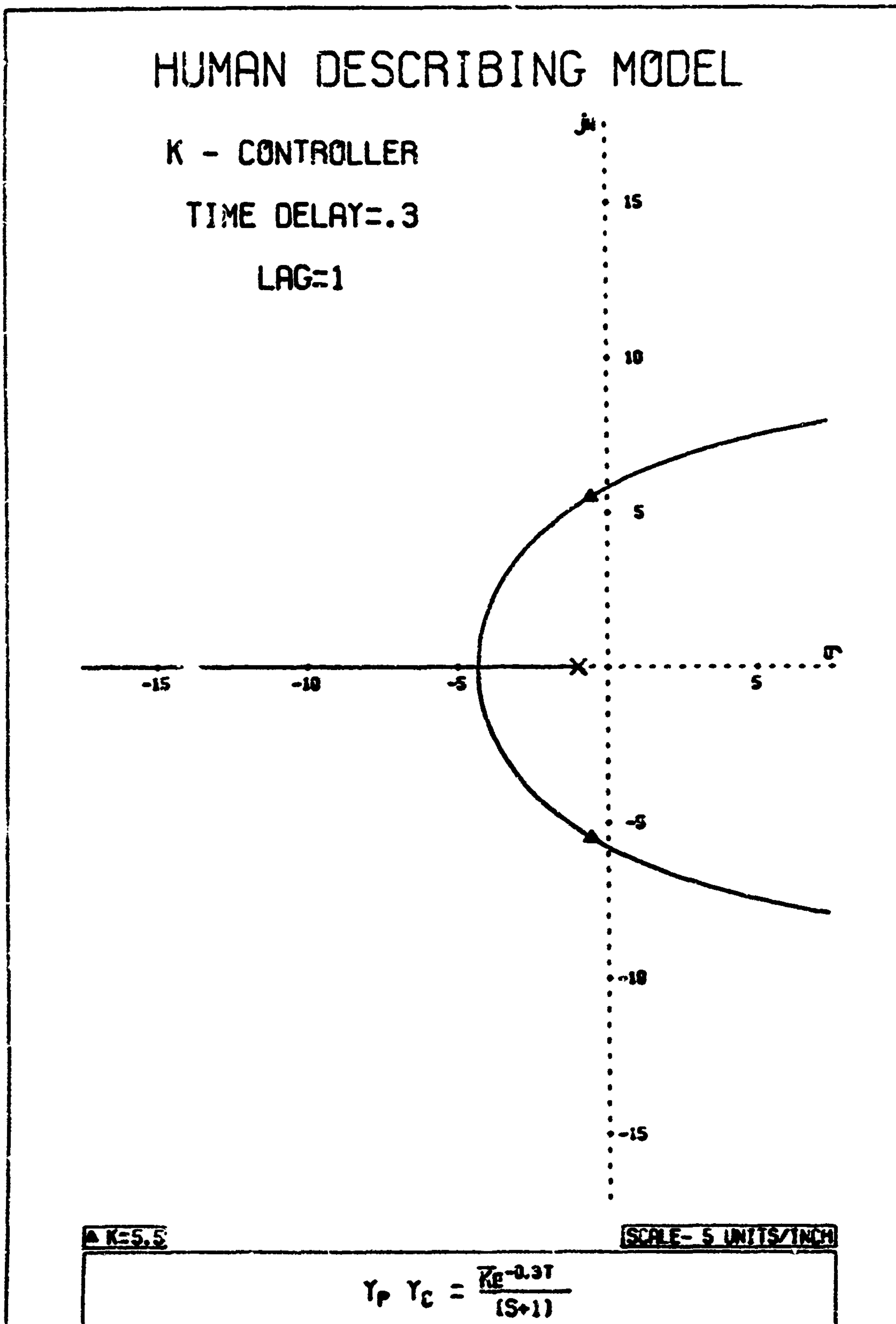


FIGURE 13 - ROOT LOCUS

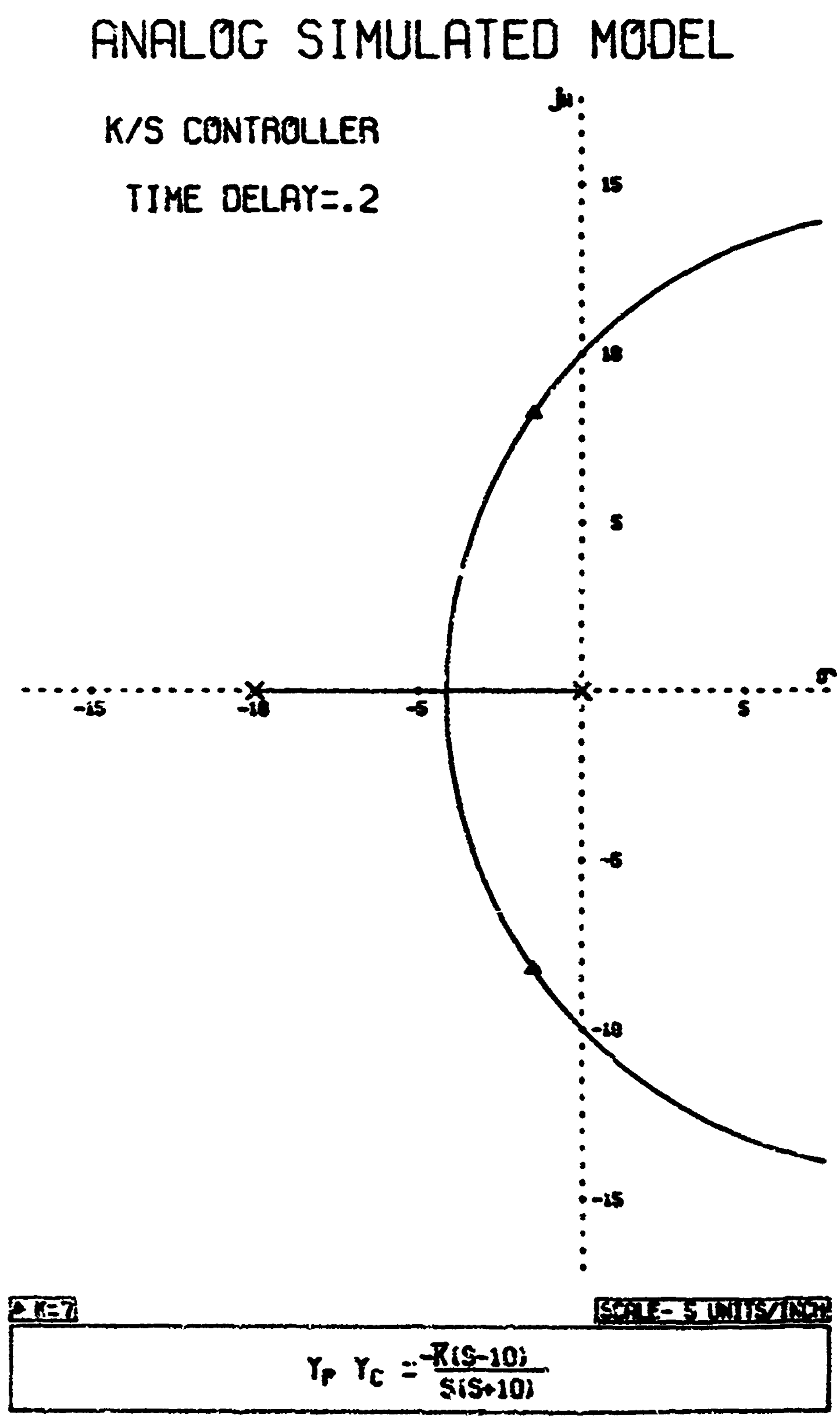


FIGURE 14 - ROOT LOCUS

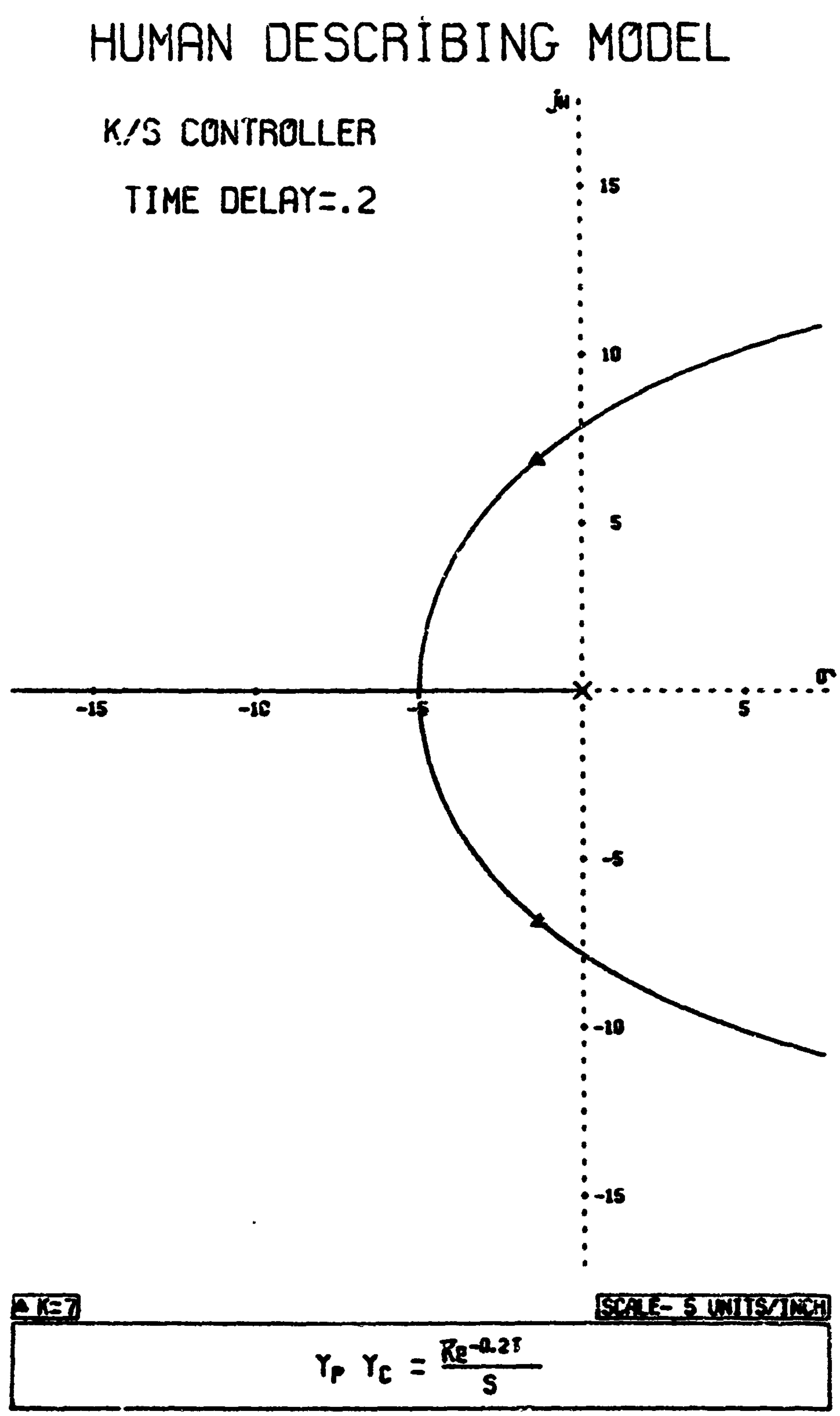
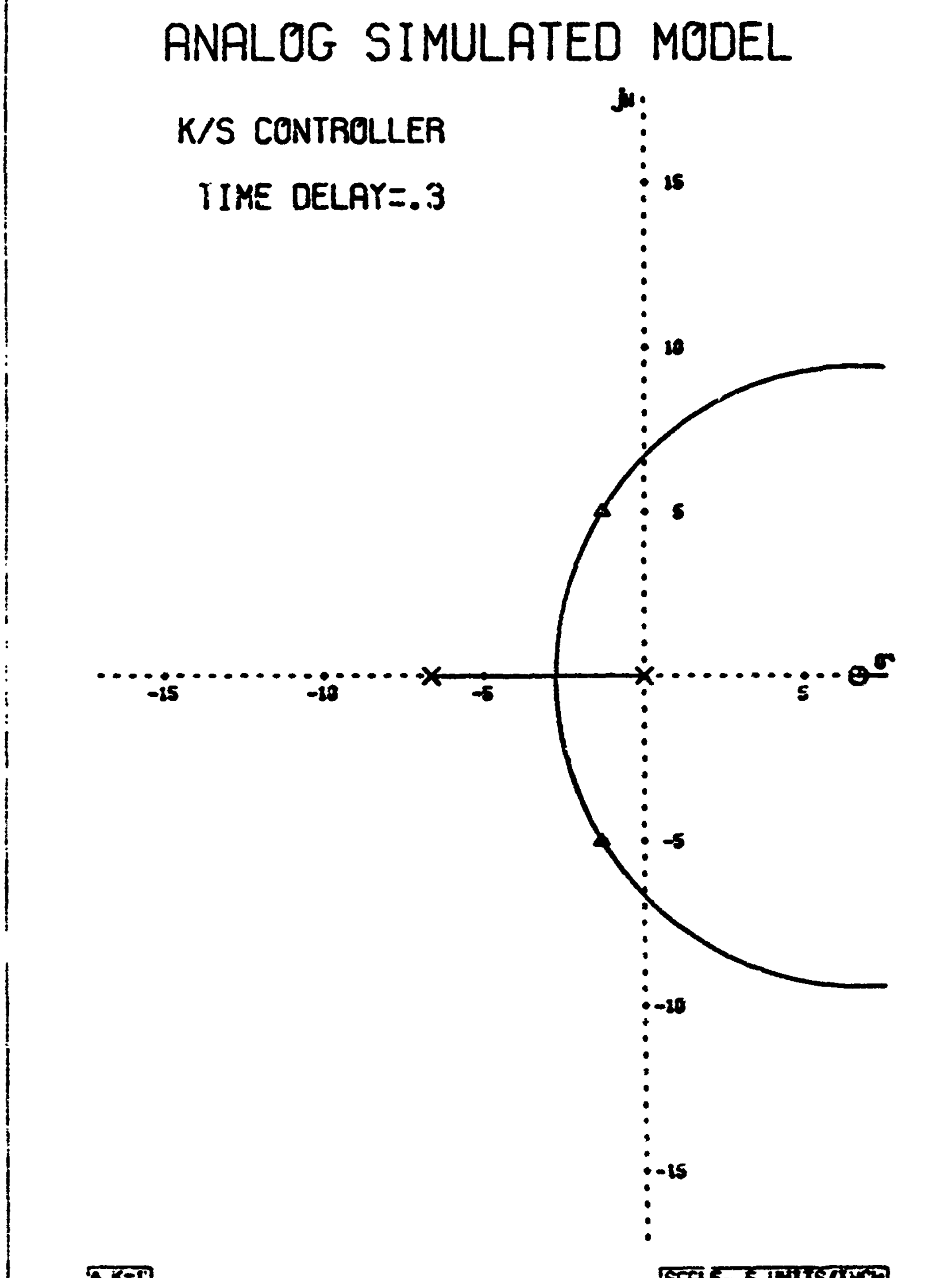


FIGURE 15 - ROOT LOCUS



$$Y_P \, Y_C = \frac{-K(S-6.667)}{S(S+6.667)}$$

FIGURE 16 - ROOT LOCUS

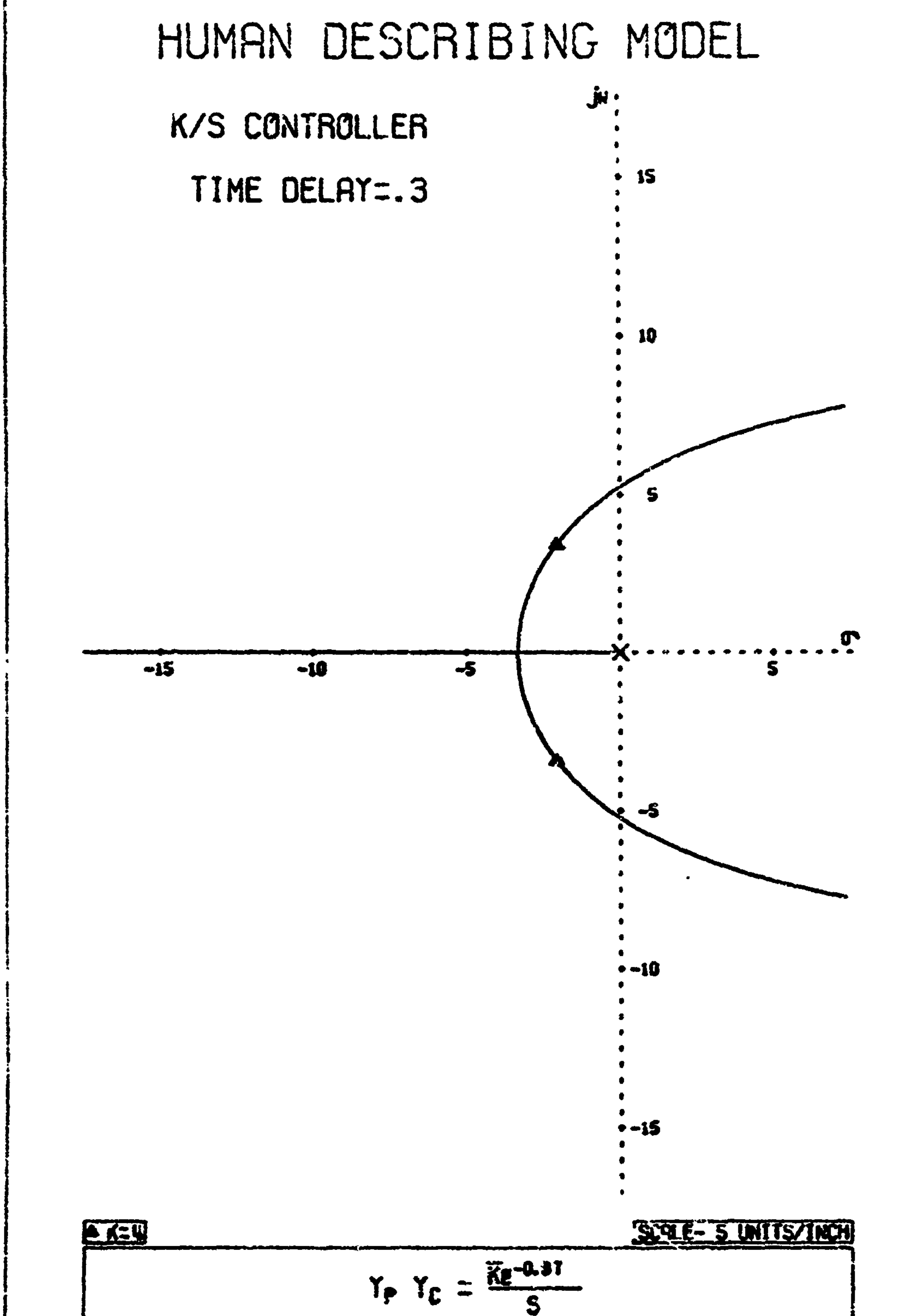
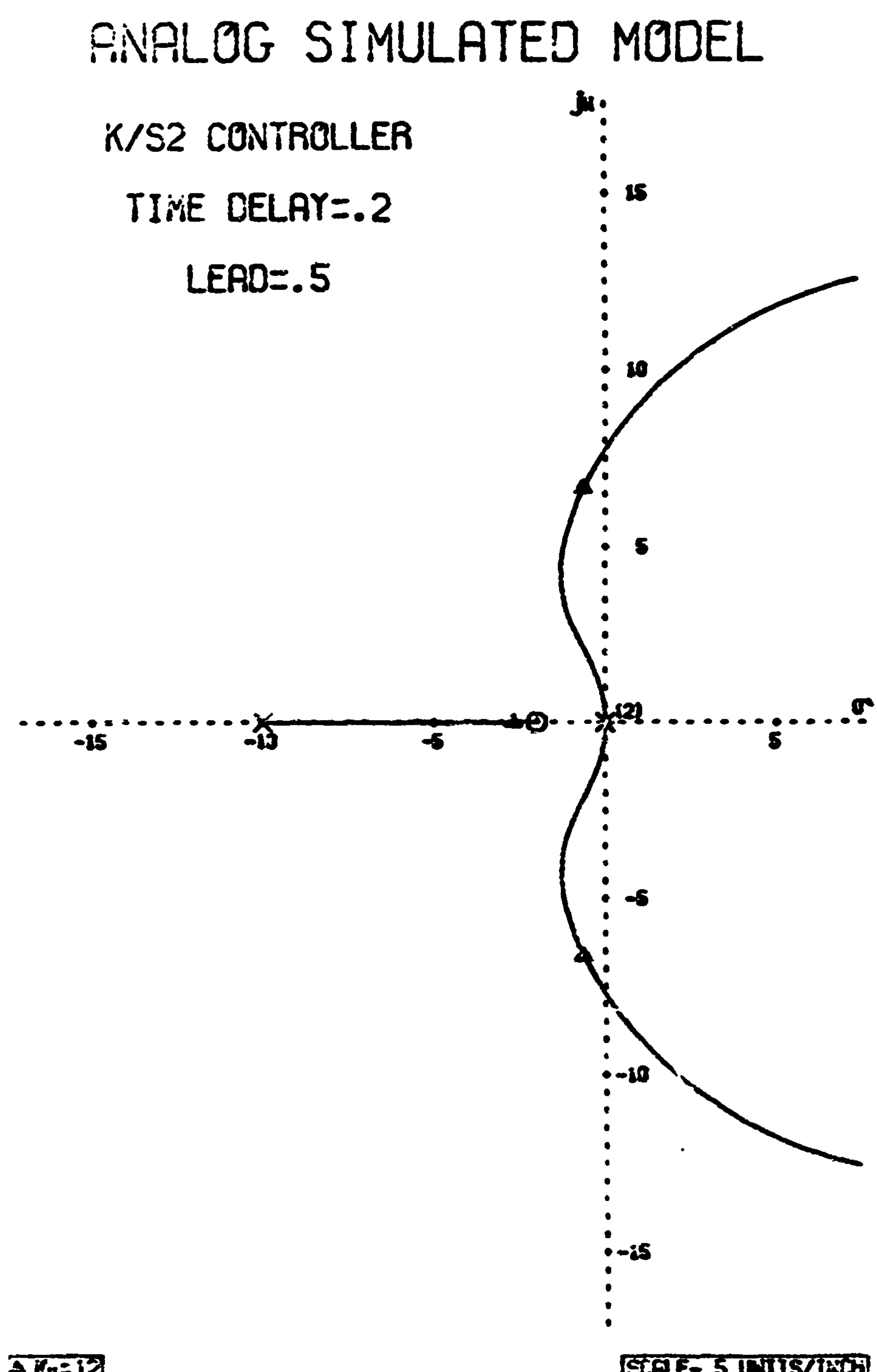


FIGURE 17 - ROOT LOCUS



$$Y_P Y_C = \frac{-K(S+2)(S-10)}{S^2(S+10)}$$

FIGURE 18 - ROOT LOCUS

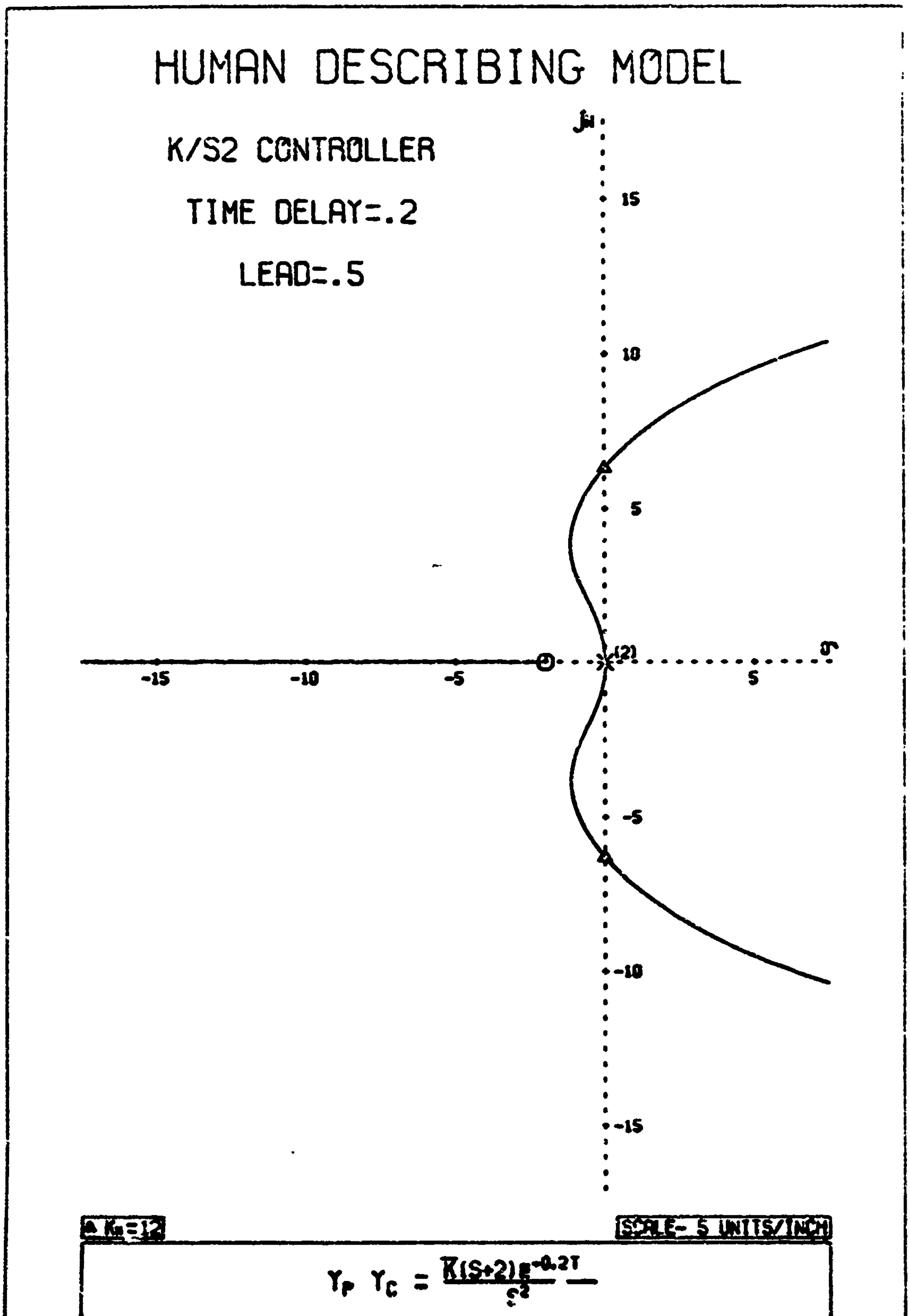
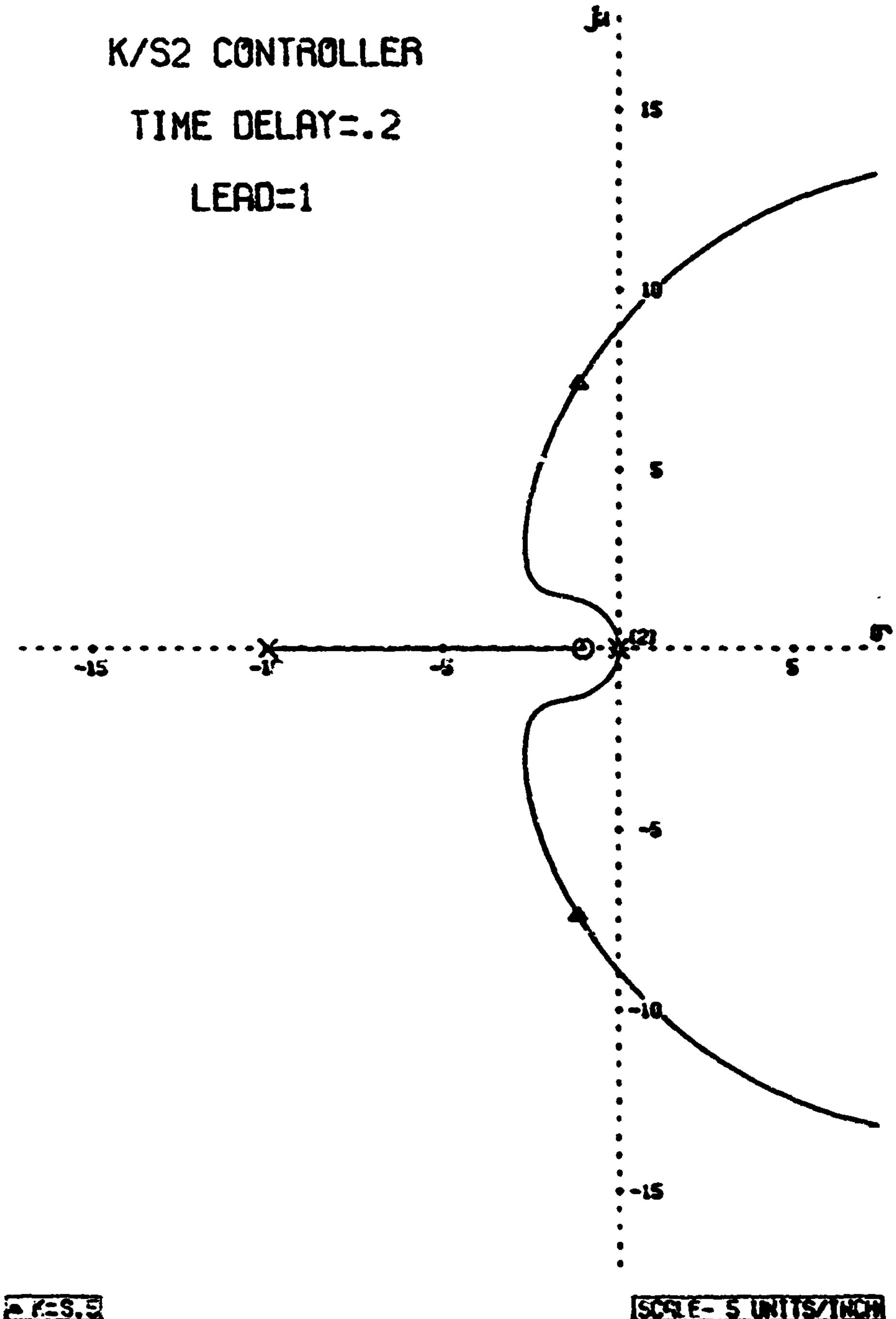


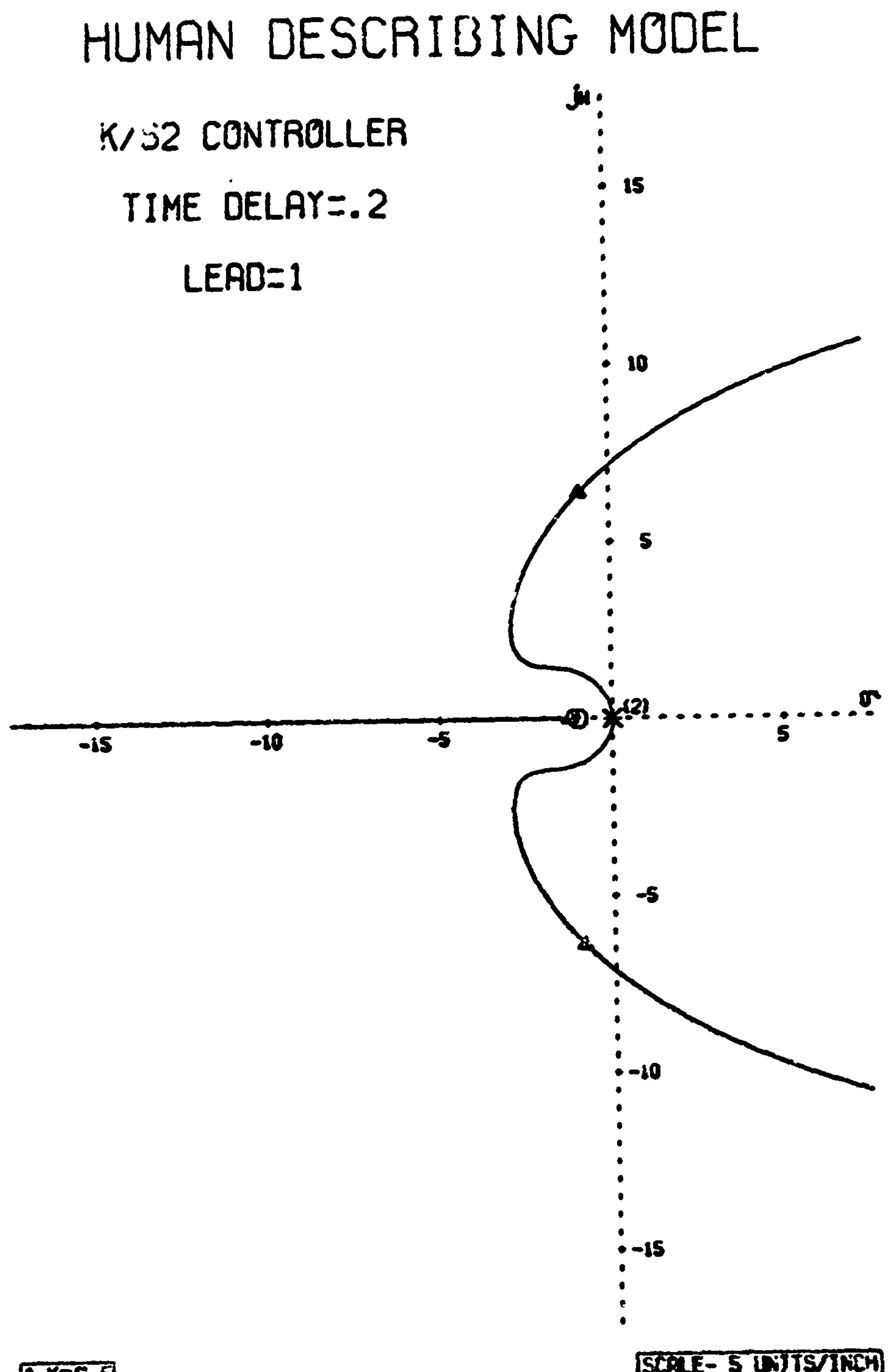
FIGURE 19 - ROOT LOCUS

ANALOG SIMULATED MODEL



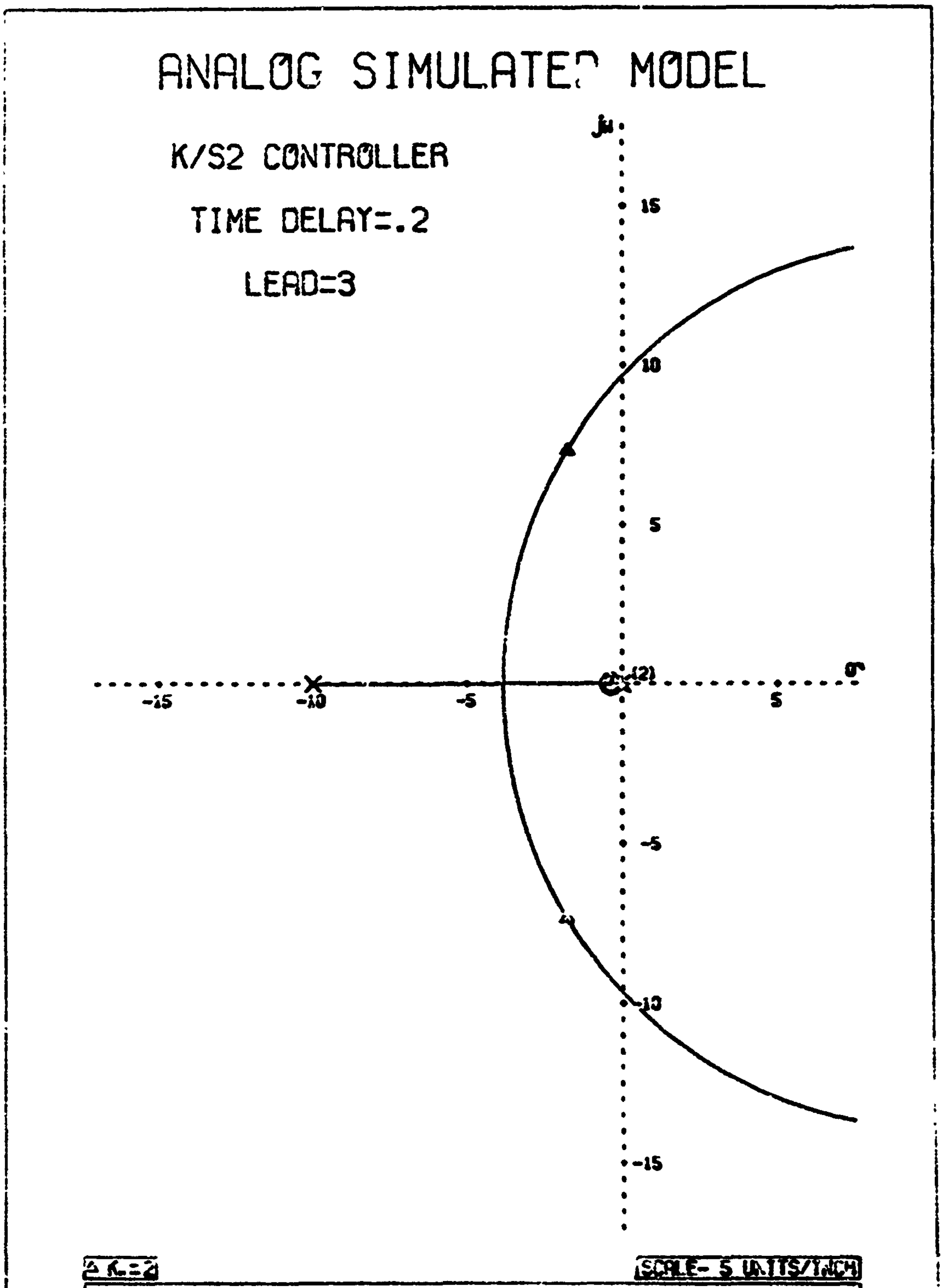
$$Y_P \; Y_C = \frac{-K(S+1)(S-10)}{S^2(S+10)}$$

FIGURE 20 - ROOT LOCUS



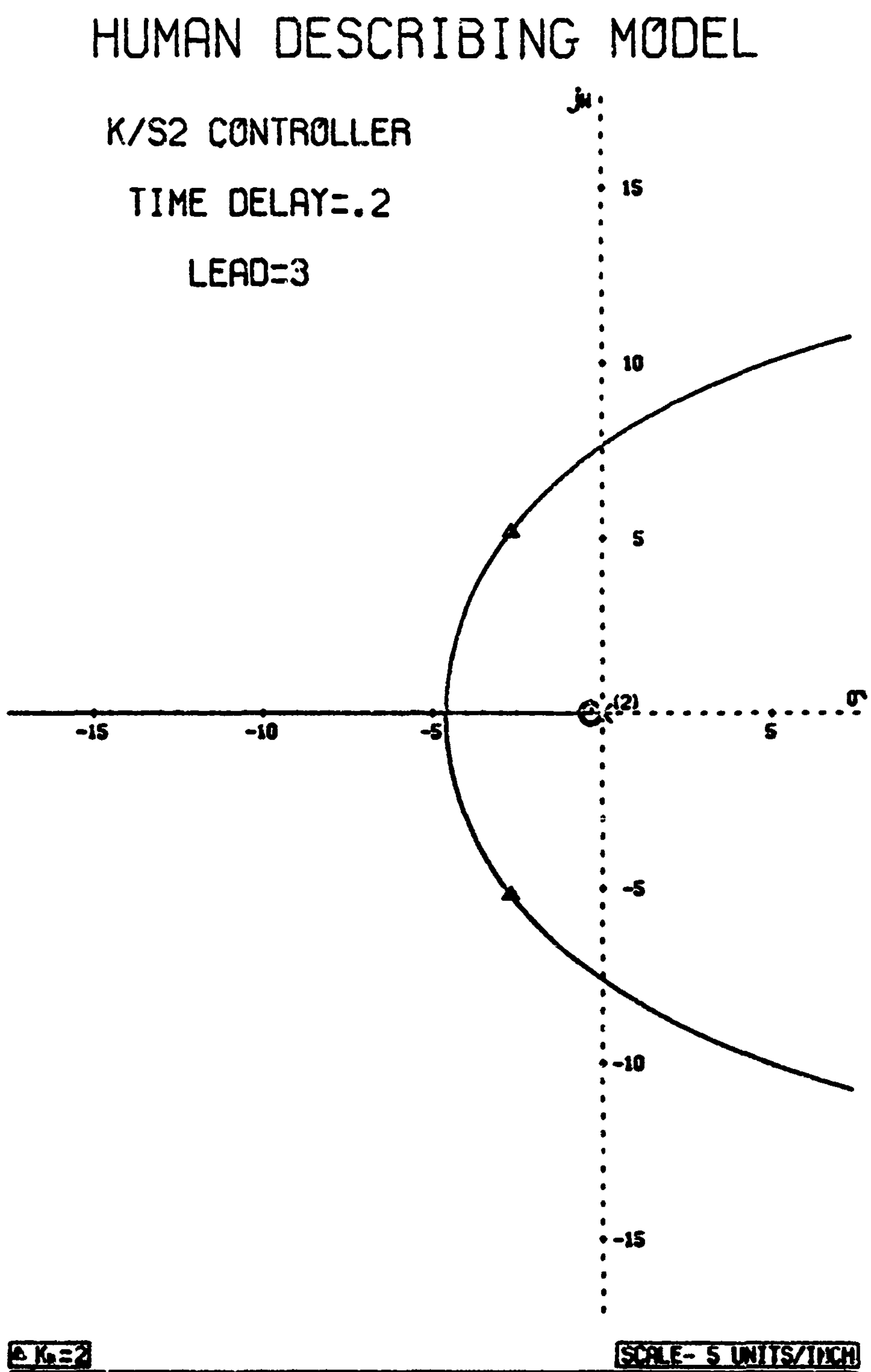
$$Y_P\ Y_C = \frac{K(S+1)e^{-0.2T}}{S^2}$$

FIGURE 21 - ROOT LOCUS



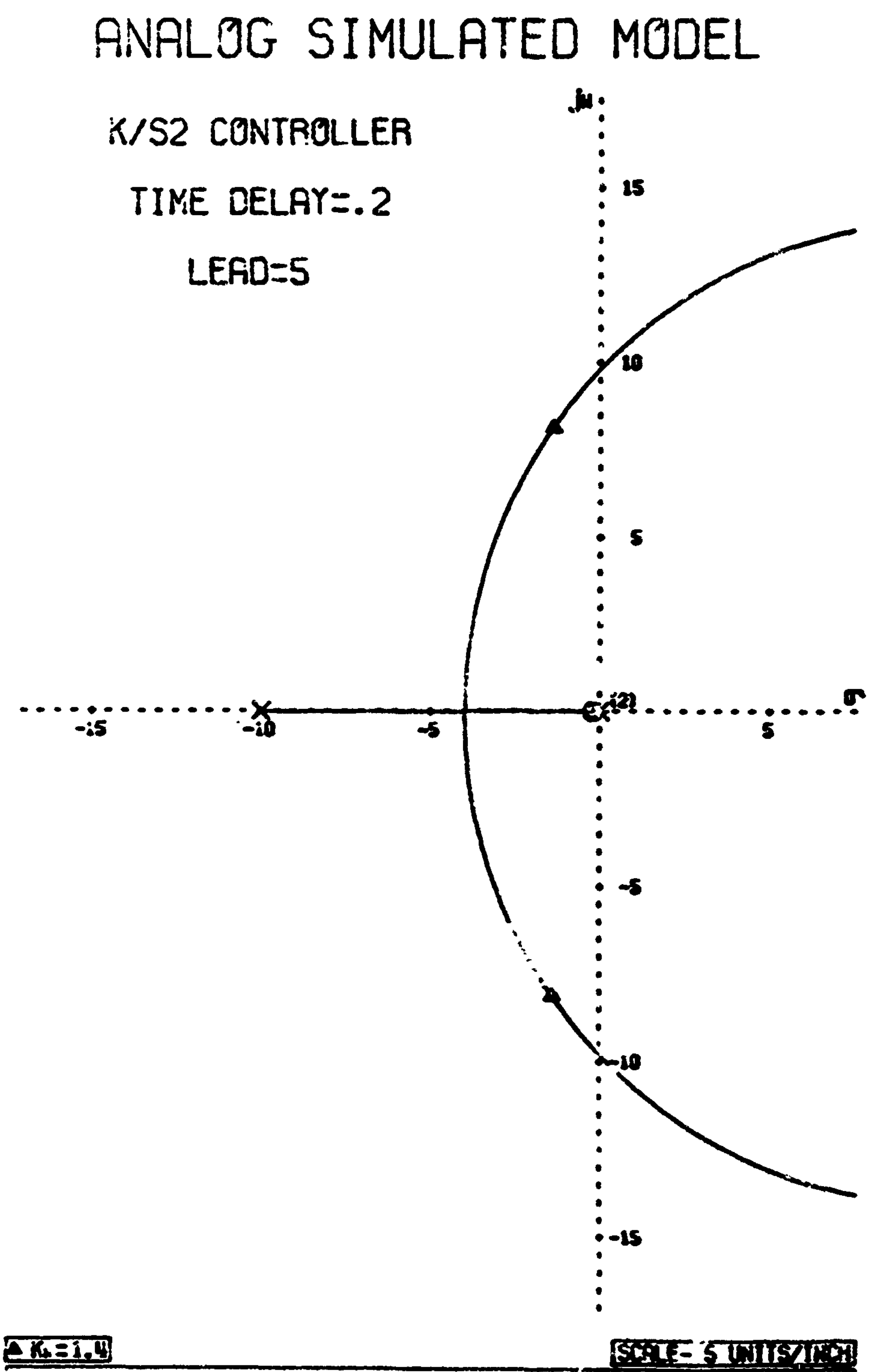
$$Y_P \, Y_C = \frac{-K(S+0.333)(S-10)}{S^2(S+10)}$$

FIGURE 22 - ROOT LOCUS



$$Y_p \, Y_c = \frac{K(S+0.333)e^{-0.2T}}{S^2}$$

FIGURE 23 - ROOT LOCUS



$$Y_P\, Y_C = \frac{-\overline{K}(S+0.2)(S-10)}{S^2(S+10)}$$

FIGURE 24 - ROOT LOCUS

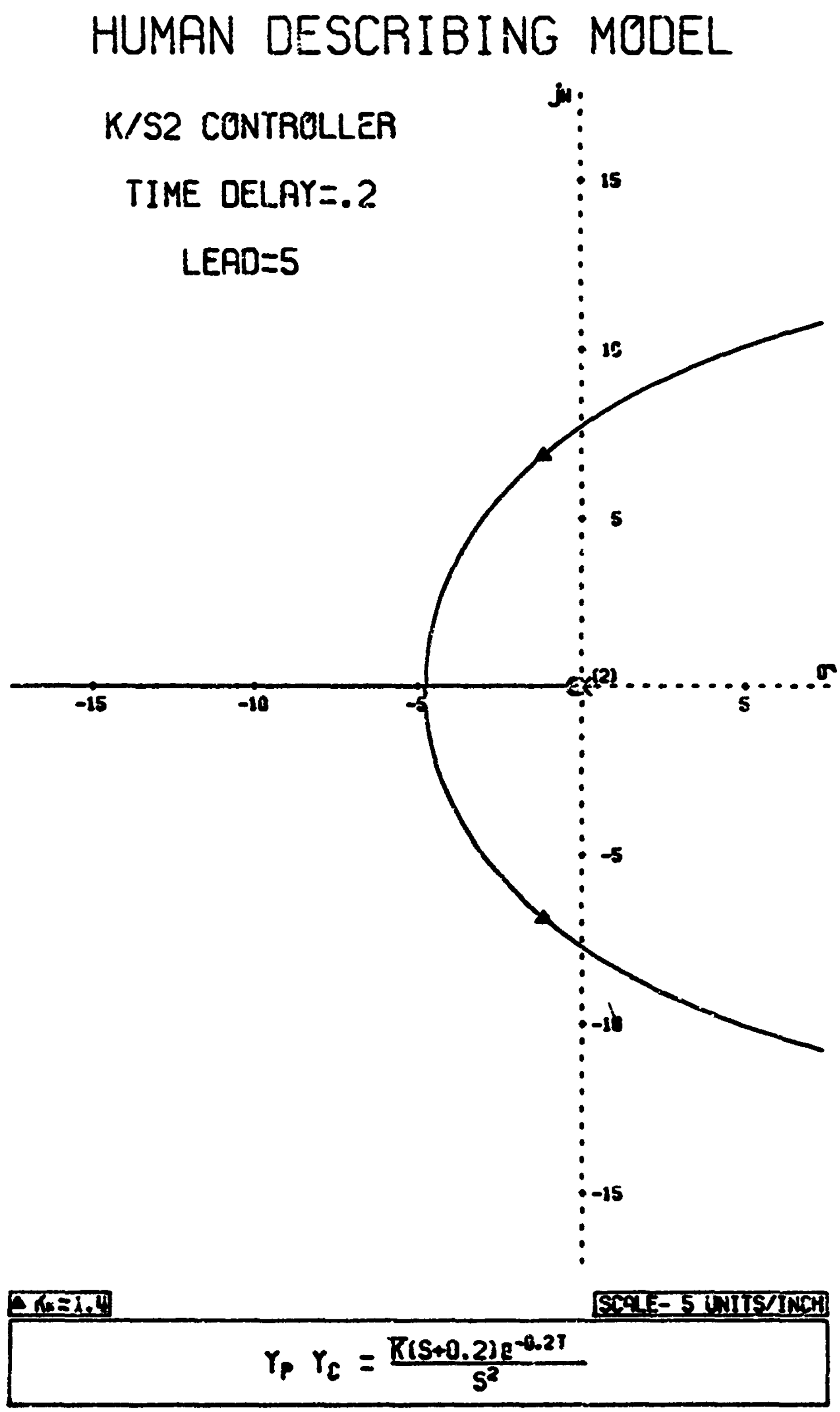
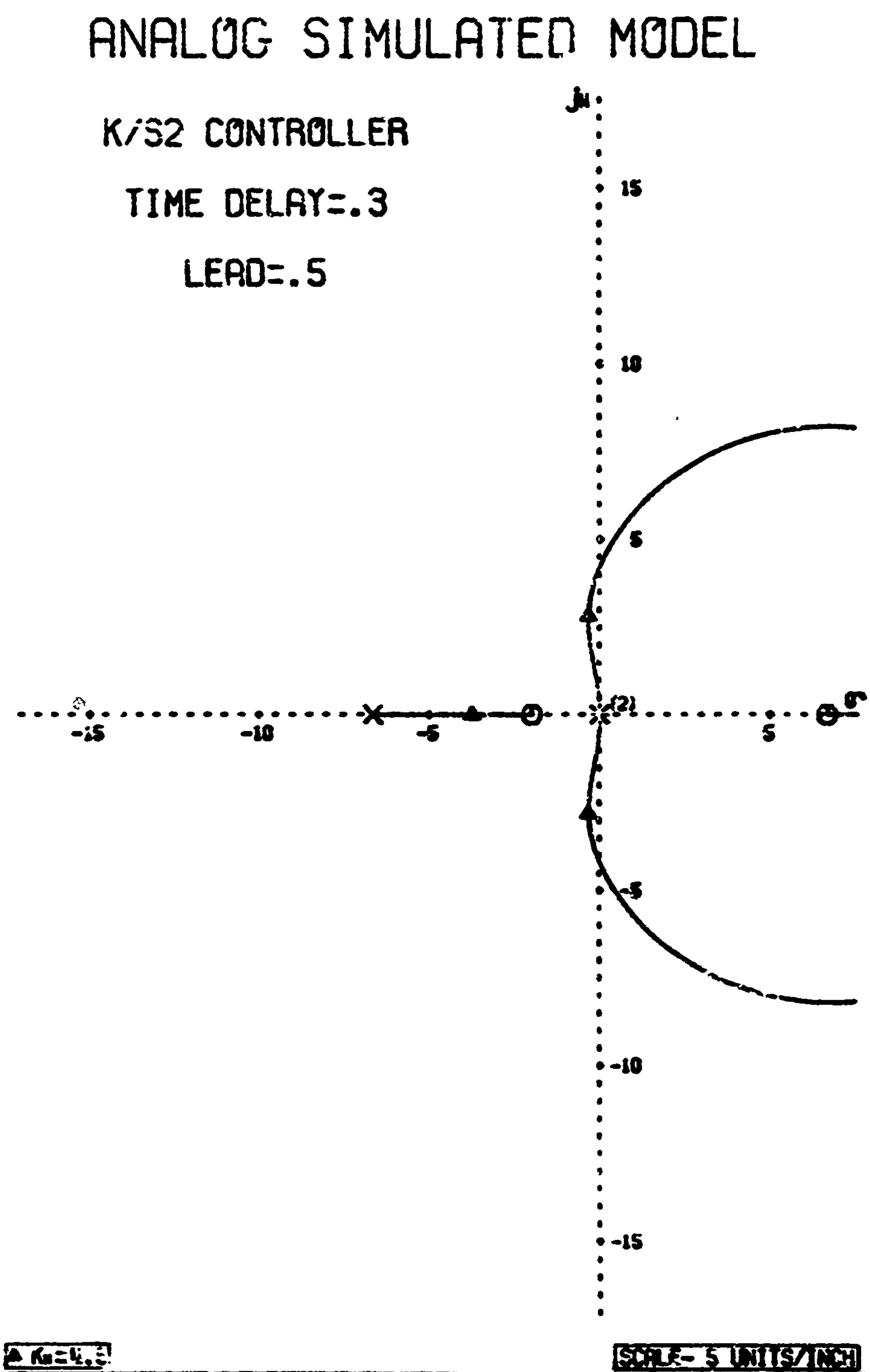


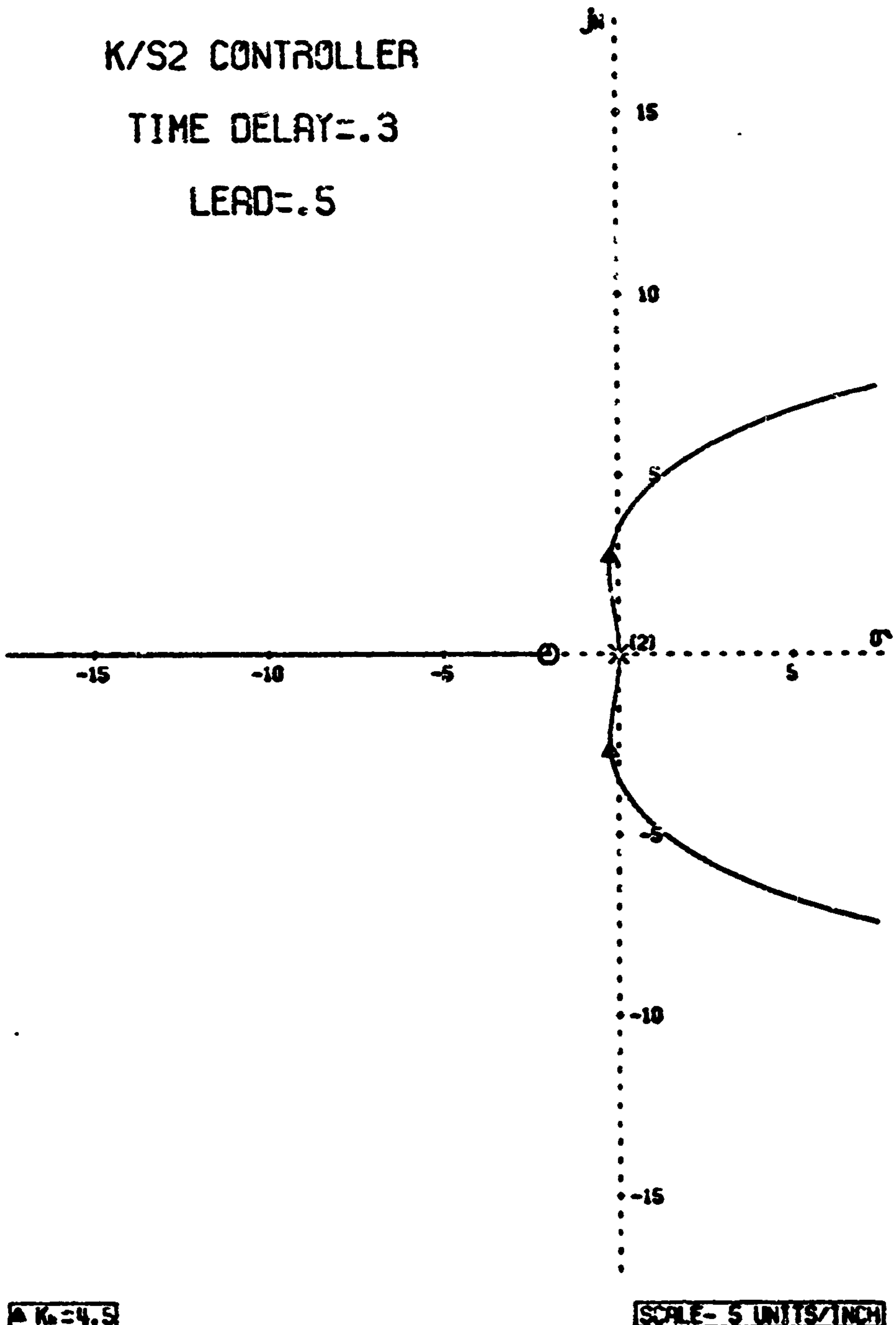
FIGURE 25 - ROOT LOCUS



$$Y_P\,Y_C = \frac{-K(S-6.667)(S+2)}{S^2(S+6.667)}$$

FIGURE 26 - ROOT LOCUS

HUMAN DESCRIBING MODEL



$$Y_P \, Y_C = \frac{\overline{K}(S+2)e^{-0.3T}}{S^2}$$

FIGURE 27 - ROOT LOCUS

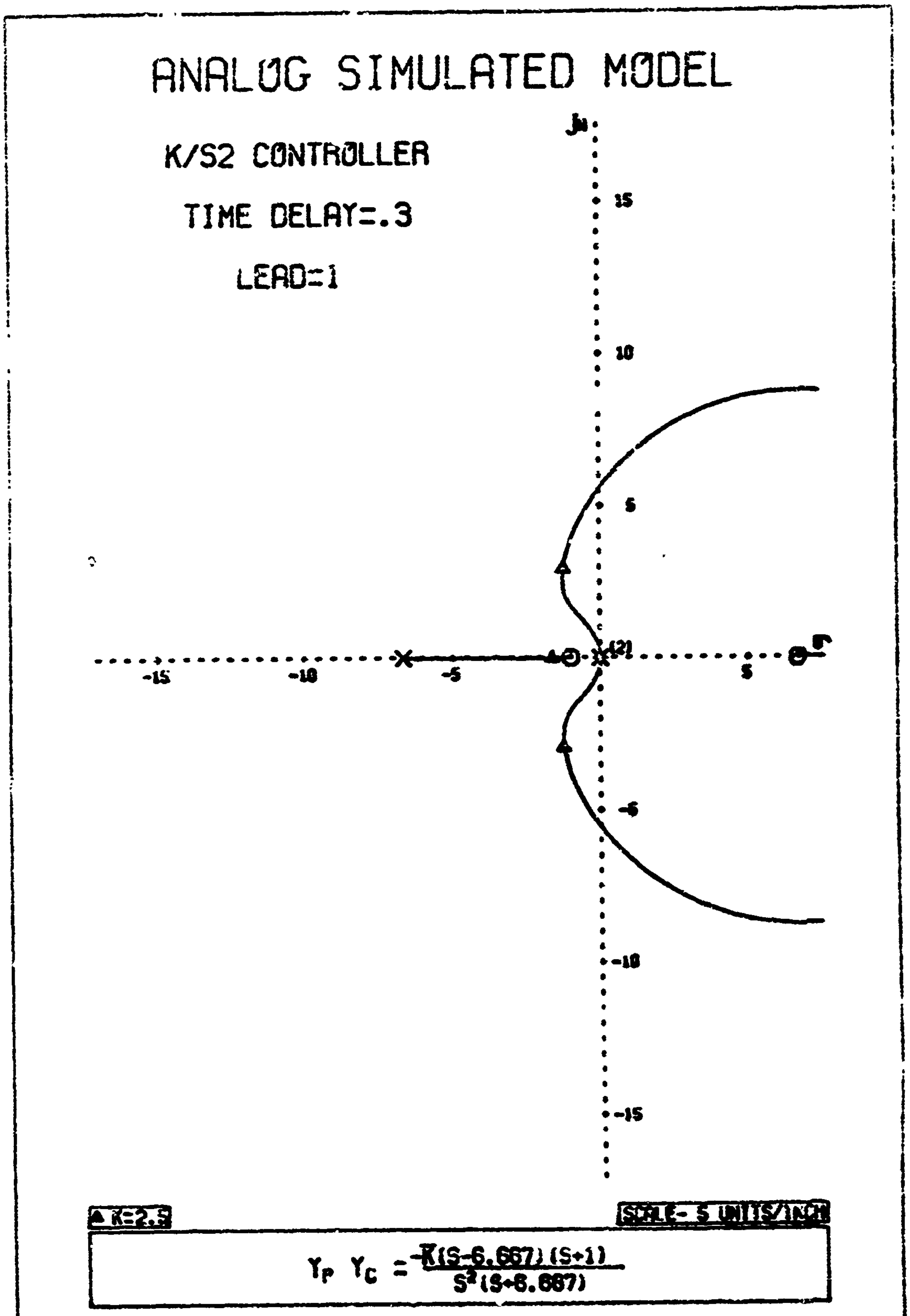


FIGURE 28 - ROOT LOCUS

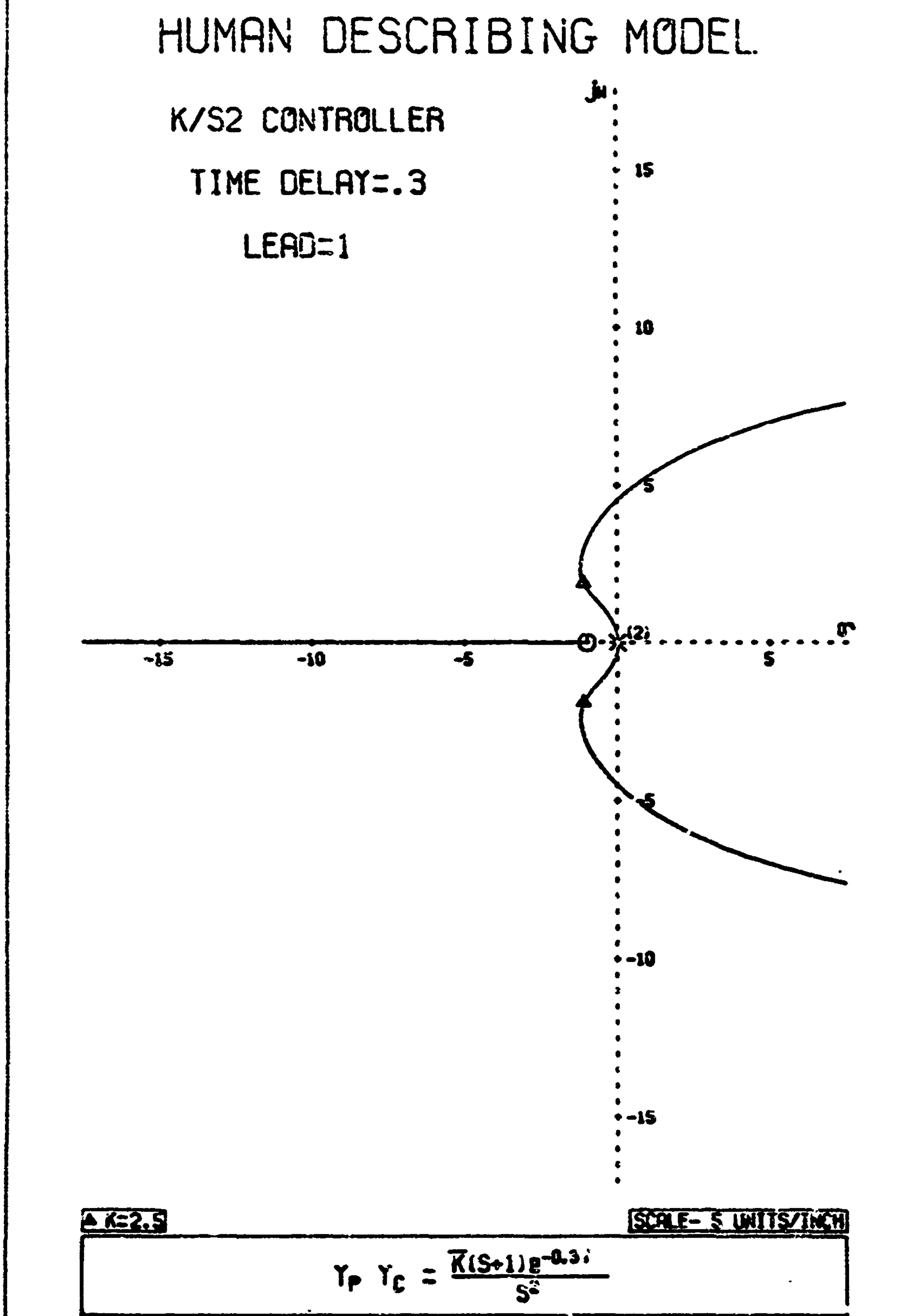
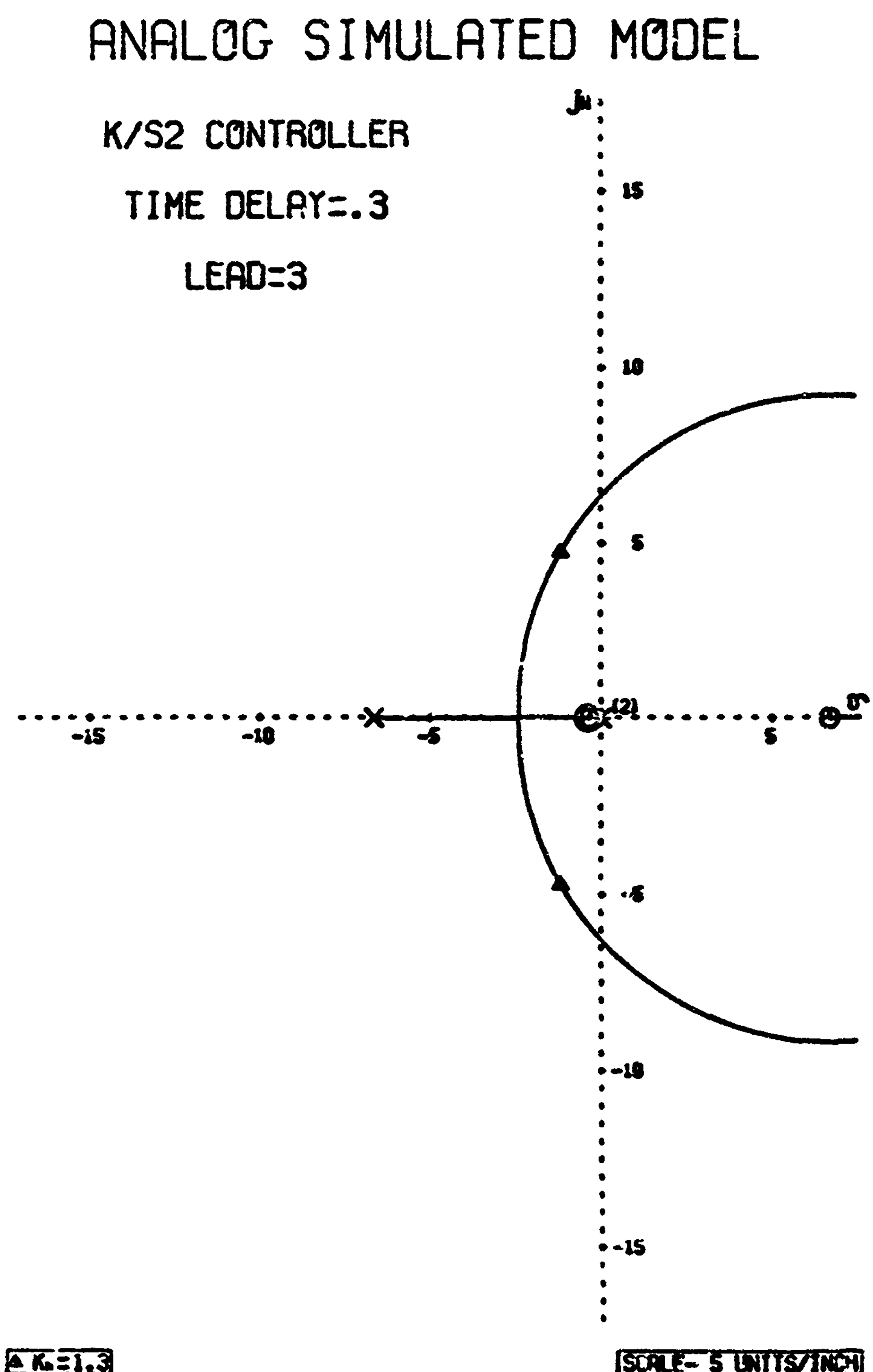
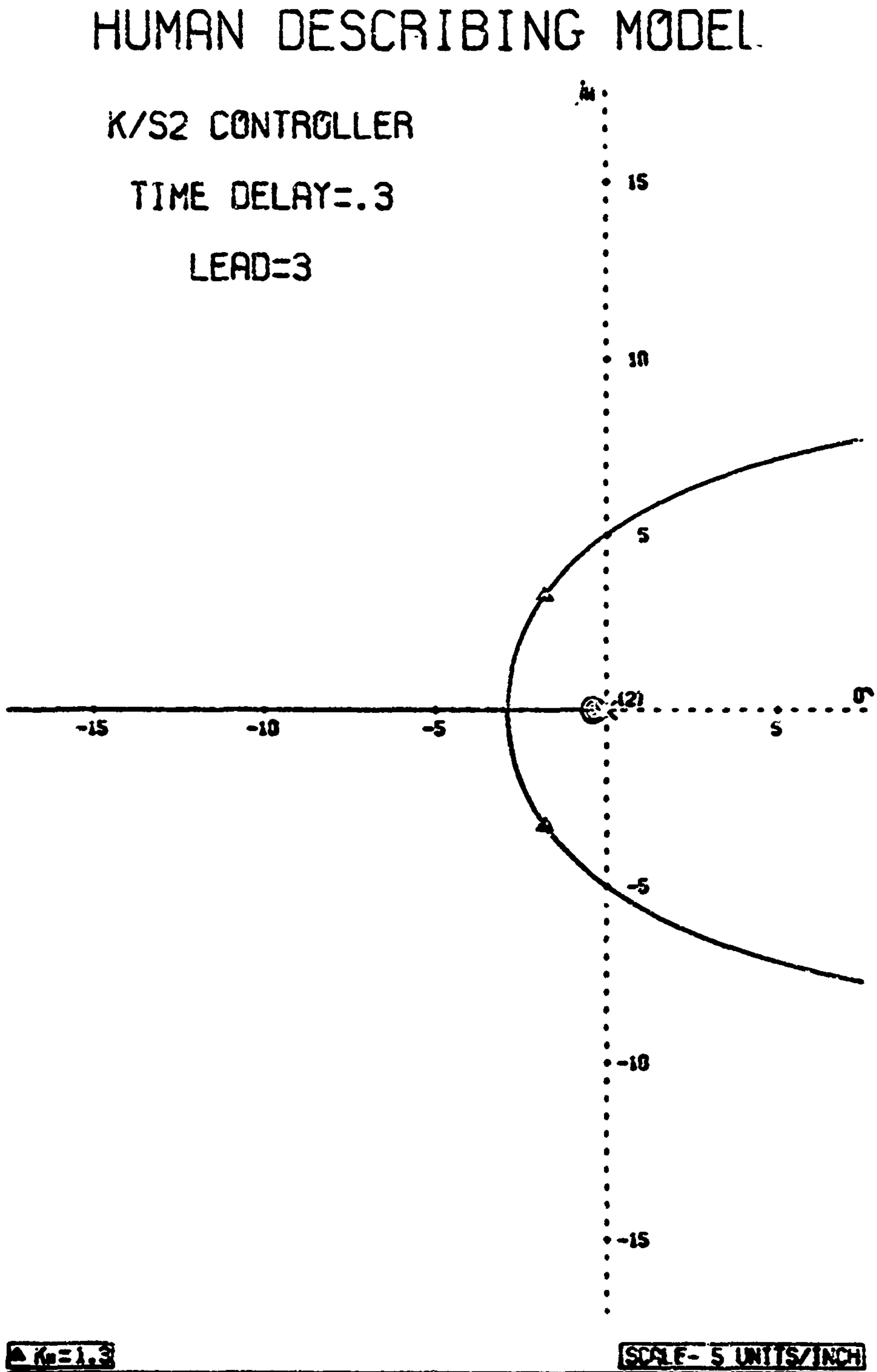


FIGURE 29 - ROOT LOCUS



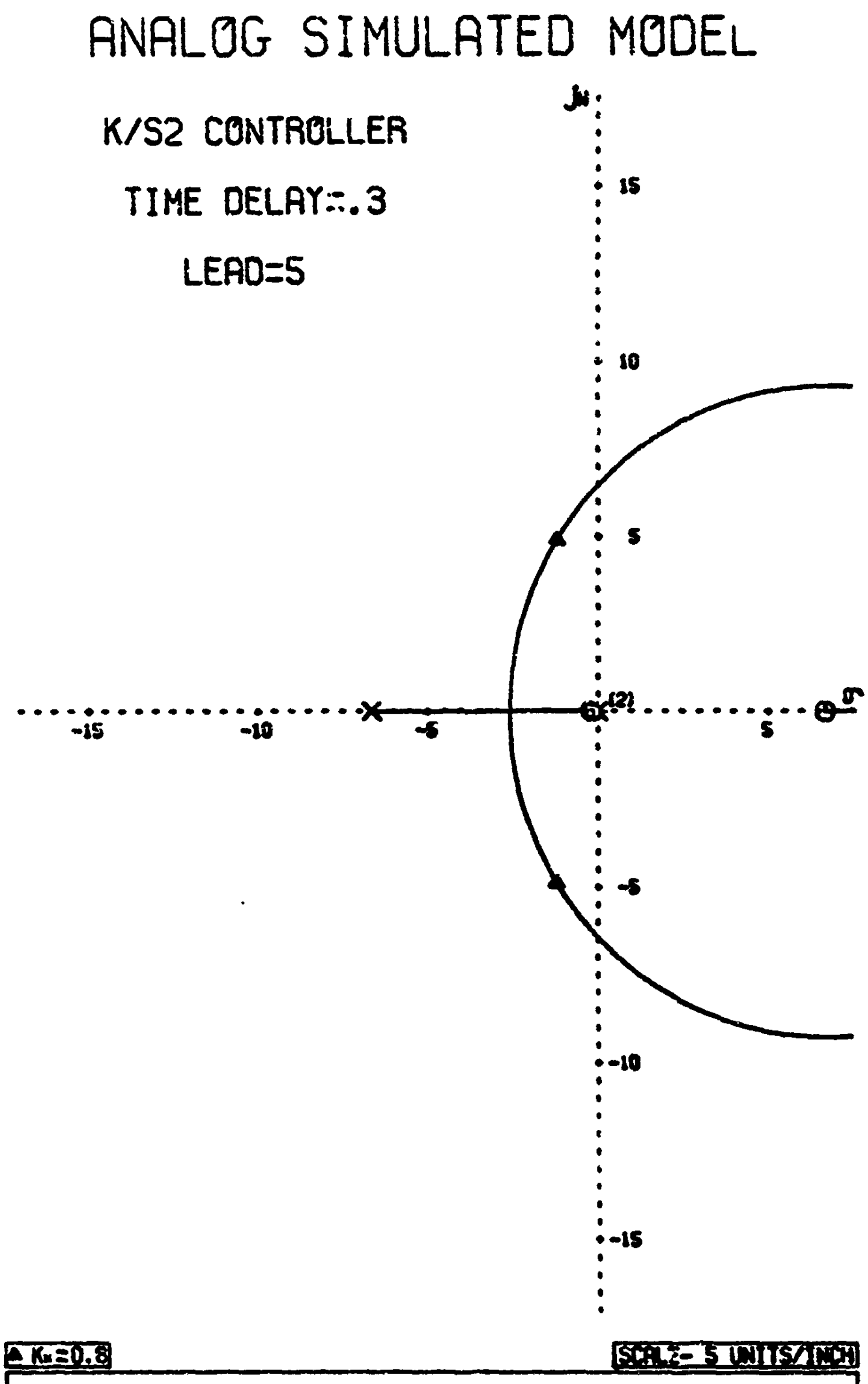
$$Y_P\ Y_C = \frac{-K(S-6.667)(S+0.333)}{S^2(S+6.667)}$$

FIGURE 30 - ROOT LOCUS



$$Y_P \, Y_C = \frac{K(S+0.333)e^{-0.3T}}{S^2}$$

FIGURE 31 - ROOT LOCUS



$$Y_P\,Y_C = \frac{-K(S-6.667)(S+0.2)}{S^2(S+6.667)}$$

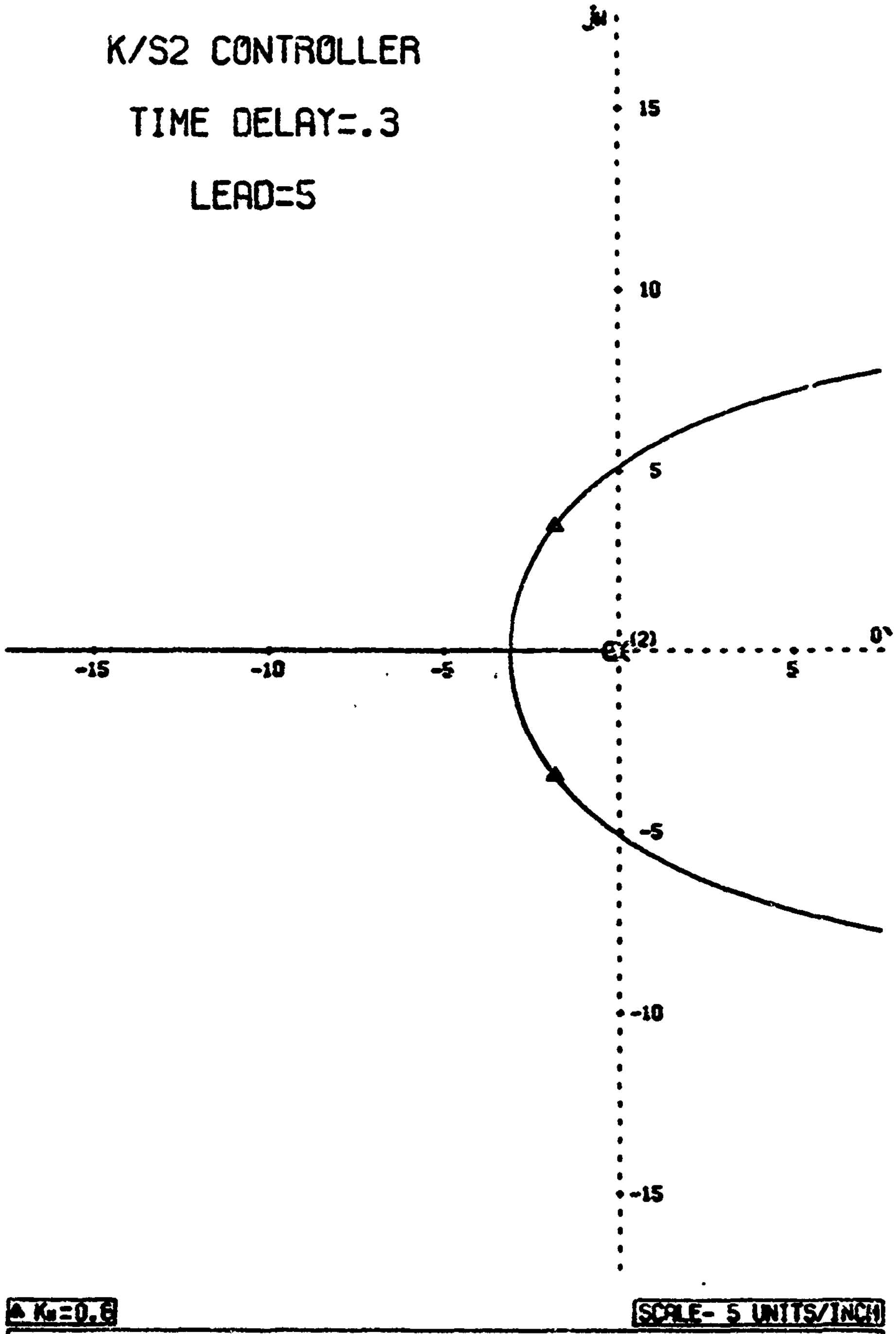
FIGURE 32 - ROOT LOCUS

HUMAN DESCRIBING MODEL

K/S2 CONTROLLER

TIME DELAY=.3

LEAD=5



$$Y_P \, Y_C = \frac{\overline{K}(S+0.2)e^{-0.3T}}{S^2}$$

FIGURE 33 - ROOT LOCUS

Variations in Model Characteristics

A set of characteristic curves was developed to show the effects of parameter variations on the performance of the analog simulated model. The input signal used was Gaussian white noise through a second order filter (Appendix C) with a break frequency of 1.5 radians per second. The mean squared error (called error squared in the following) divided by the input variance was plotted against the model system gain. The data used to plot the curves were obtained on the analog computer.

The system with a pure gain controlled element was prepared first. Five curves, representing gain variations for five different lag time constants are shown in Figure 34. The values of lag selected are consistent with values necessary for good low frequency response. If the time delay and lag time constant are known, the gain necessary for minimum error squared can be easily determined from the appropriate characteristic curve. The gain which causes model instability is also found easily by observing the rapid rise in the error squared as gain is increased. In Figure 34, the delay time is 0.2 seconds. Similar curves were plotted in Figure 35, but the time delay was increased to 0.3 seconds. As the time delay is increased, the gain for minimum error squared decreases and the minimum error squared increases. The gain for unstable operation varies inversely with the time delay. However, it was observed that the gain for minimum error squared and the gain for unstable operation vary directly with the lag time constant. Therefore, an increase in the time delay and an increase in the lag time constant would have a balancing effect on the gain for minimum error squared but an additive effect on the value of minimum error squared.

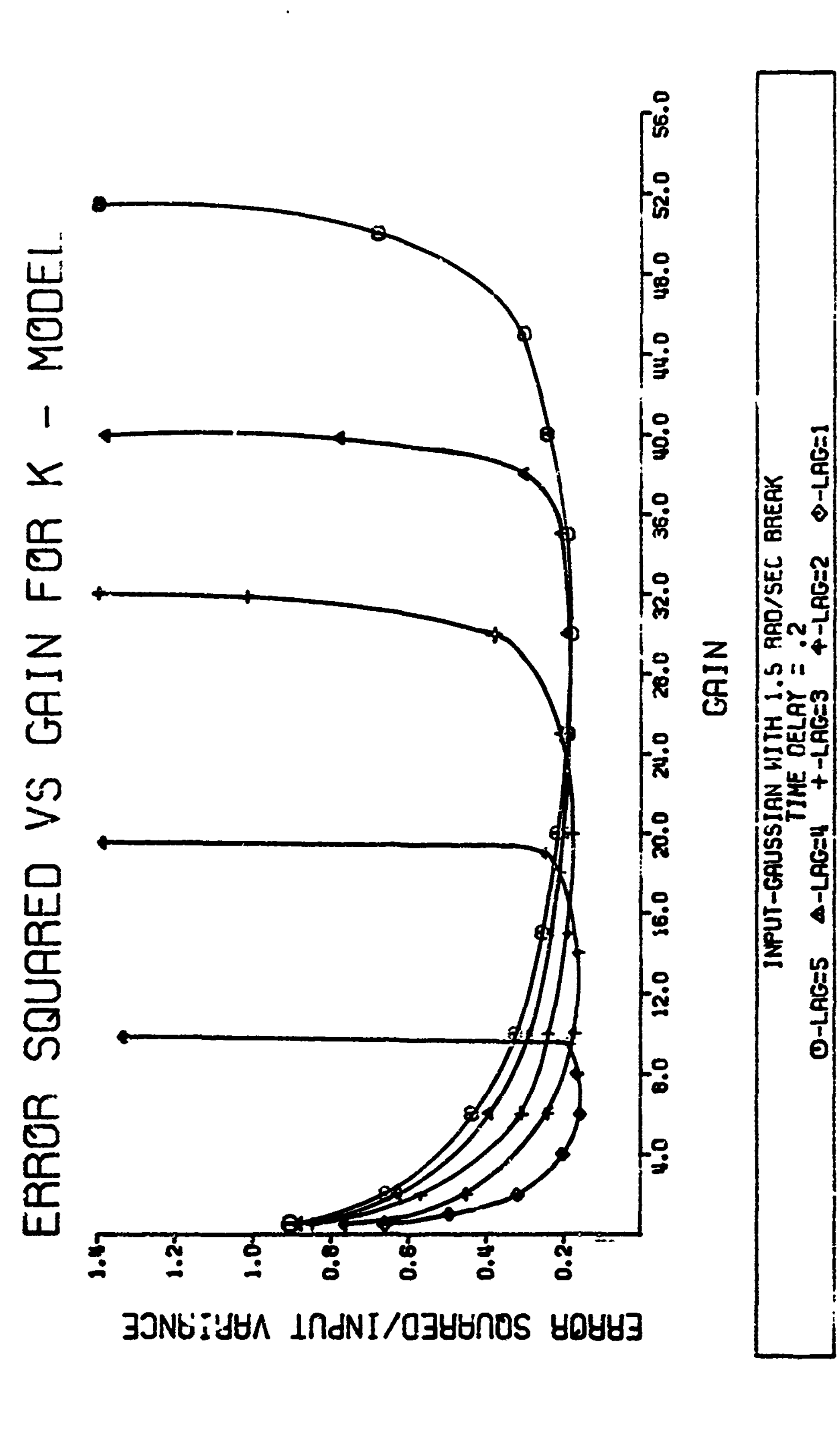

ERROR SQUARED VS GAIN FOR K - MODEL
ERROR SQUARED/INPUT VARIANCE
1.4
1.2
1.0
0.8
0.6
0.4
0.2
4.0
8.0
12.0
16.0
20.0
24.0
28.0
32.0
36.0
40.0
44.0
48.0
52.0
56.0
GAIN
INPUT-GAUSSIAN WITH 1.5 RAD/SEC BREAK
TIME DELAY = .2
⊖-LAG=5 △-LAG=4 +-LAG=3 ✢-LAG=2 ◇-LAG=1

FIGURE 34

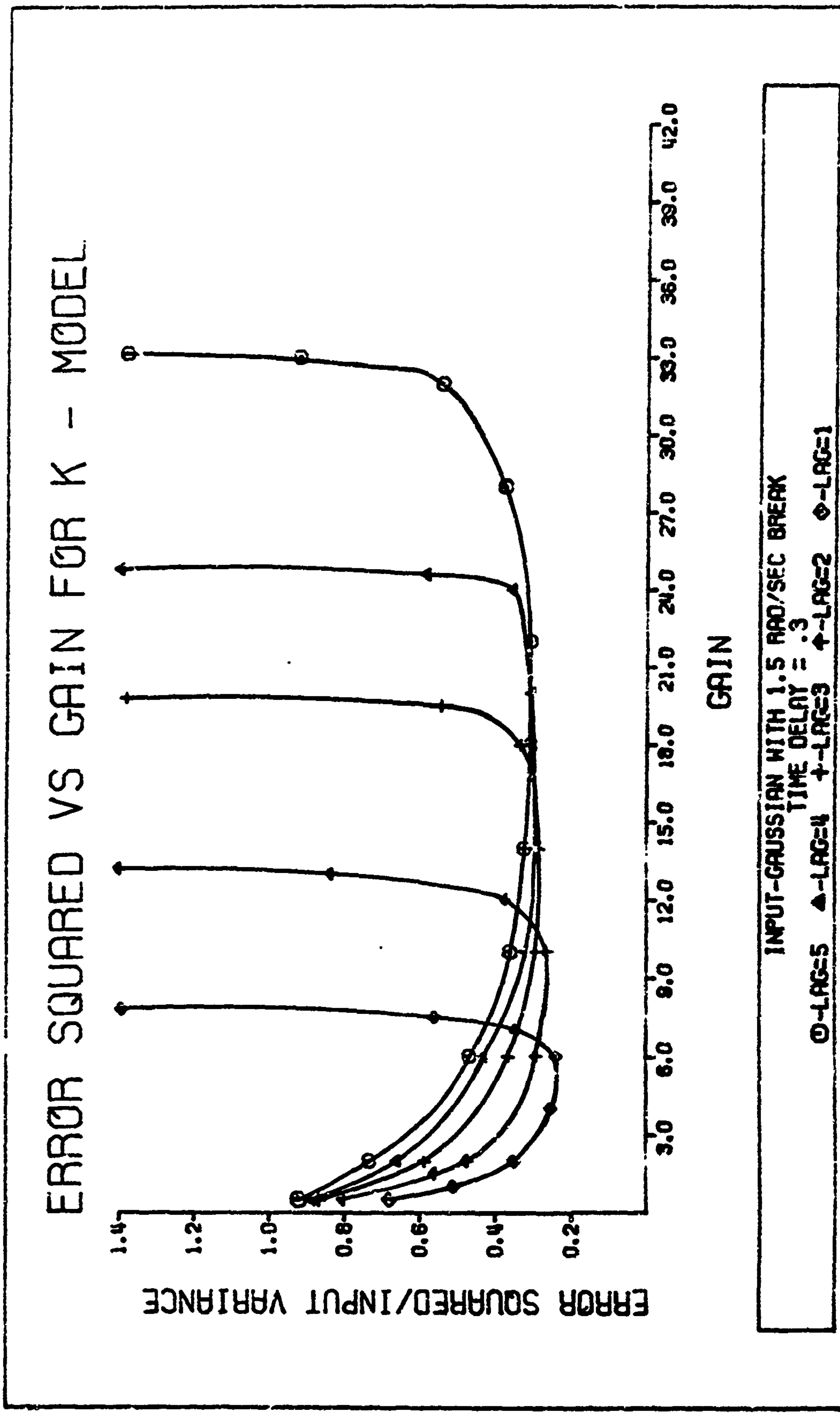

ERROR SQUARED VS GAIN FOR K - MODEL
ERROR SQUARED/INPUT VARIANCE
1.4
1.2
1.0
0.8
0.6
0.4
0.2
GAIN
3.0
6.0
9.0
12.0
15.0
18.0
21.0
24.0
27.0
30.0
33.0
36.0
39.0
42.0
INPUT-GAUSSIAN WITH 1.5 RAD/SEC BREAK
TIME DELAY = .3
⊙-LAG=5 ▲-LAG=4 +-LAG=3 ✦-LAG=2 ◇-LAG=1

FIGURE 35

Three curves, showing error squared versus gain, were plotted in Figure 35. Three different time delays were used, 0.2 seconds, 0.25 seconds, and 0.3 seconds. As the time delay was increased, the gain for minimum error squared and the gain for unstable operation decreased. As expected, the minimum error squared increased with an increase in the time delay.

The characteristic curves for the analog simulation of the model used with a K/S^2 controlled element are shown in Figure 36 and Figure 37. The gain for minimum error squared varies inversely with the lead time constant and the delay time. The minimum error squared increases with an increase in the time delay, but decreases with an increase in the lead time constant.

Use of the existing adjustment rules, the root locus diagrams, and the model characteristic curves reduces the guess-work required in predicting the model parameters for proper system response with random appearing inputs. To determine model parameters for step and random inputs, the piloted system output and appropriate performance measures must be obtained through experimentation. The necessary experimental results are discussed in the next chapter.

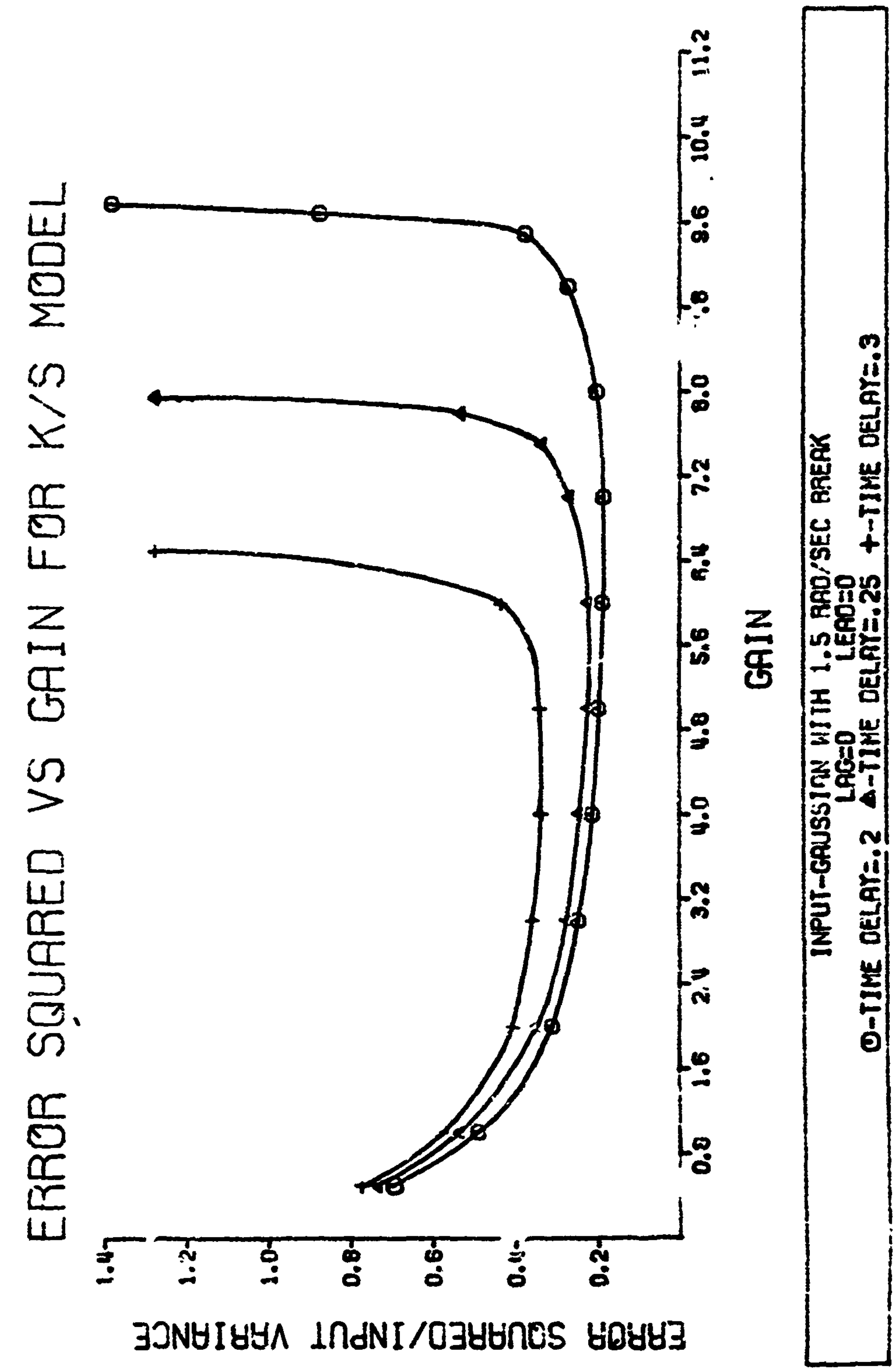

ERROR SQUARED VS GAIN FOR K/S MODEL
ERROR SQUARED/INPUT VARIANCE
1.4
1.2
1.0
0.8
0.6
0.4
0.2
GAIN
0.0
1.6
2.4
3.2
4.0
4.8
5.6
6.4
7.2
8.0
8.8
9.6
10.4
11.2
INPUT-GAUSSIAN WITH 1.5 RAD/SEC BREAK
LAG=0 LEAD=0
⊖-TIME DELAY=.2 ▲-TIME DELAY=.25 +-TIME DELAY=.3

FIGURE 36

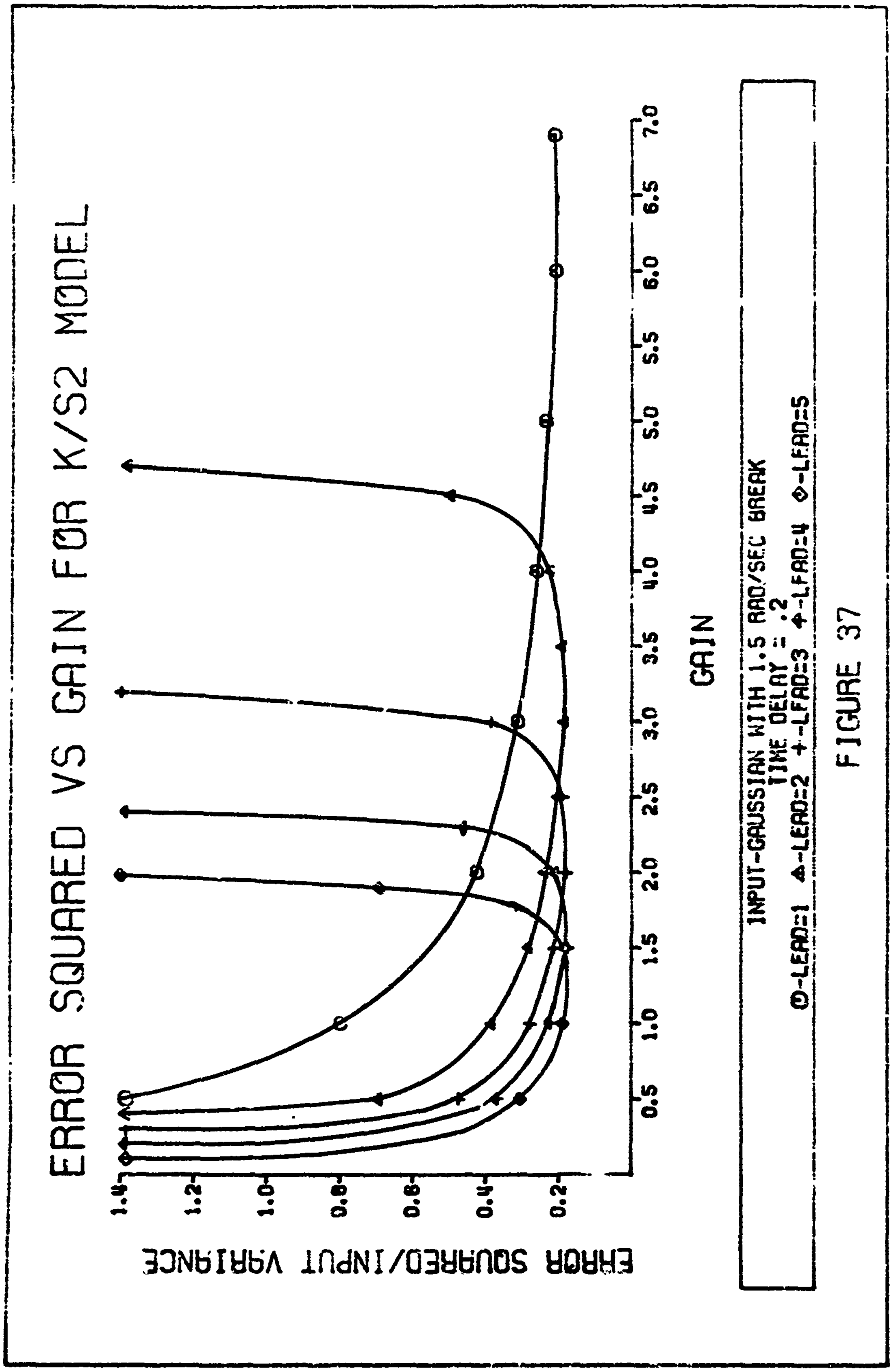

ERROR SQUARED VS GAIN FOR K/S2 MODEL
ERROR SQUARED/INPUT VARIANCE
1.4
1.2
1.0
0.8
0.6
0.4
0.2
GAIN
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
INPUT-GAUSSIAN WITH 1.5 RAD/SEC BREAK
TIME DELAY = .2
⊙-LEAD=1 ▲-LEAD=2 +-LEAD=3 ✦-LEAD=4 ◇-LEAD=5

FIGURE 37

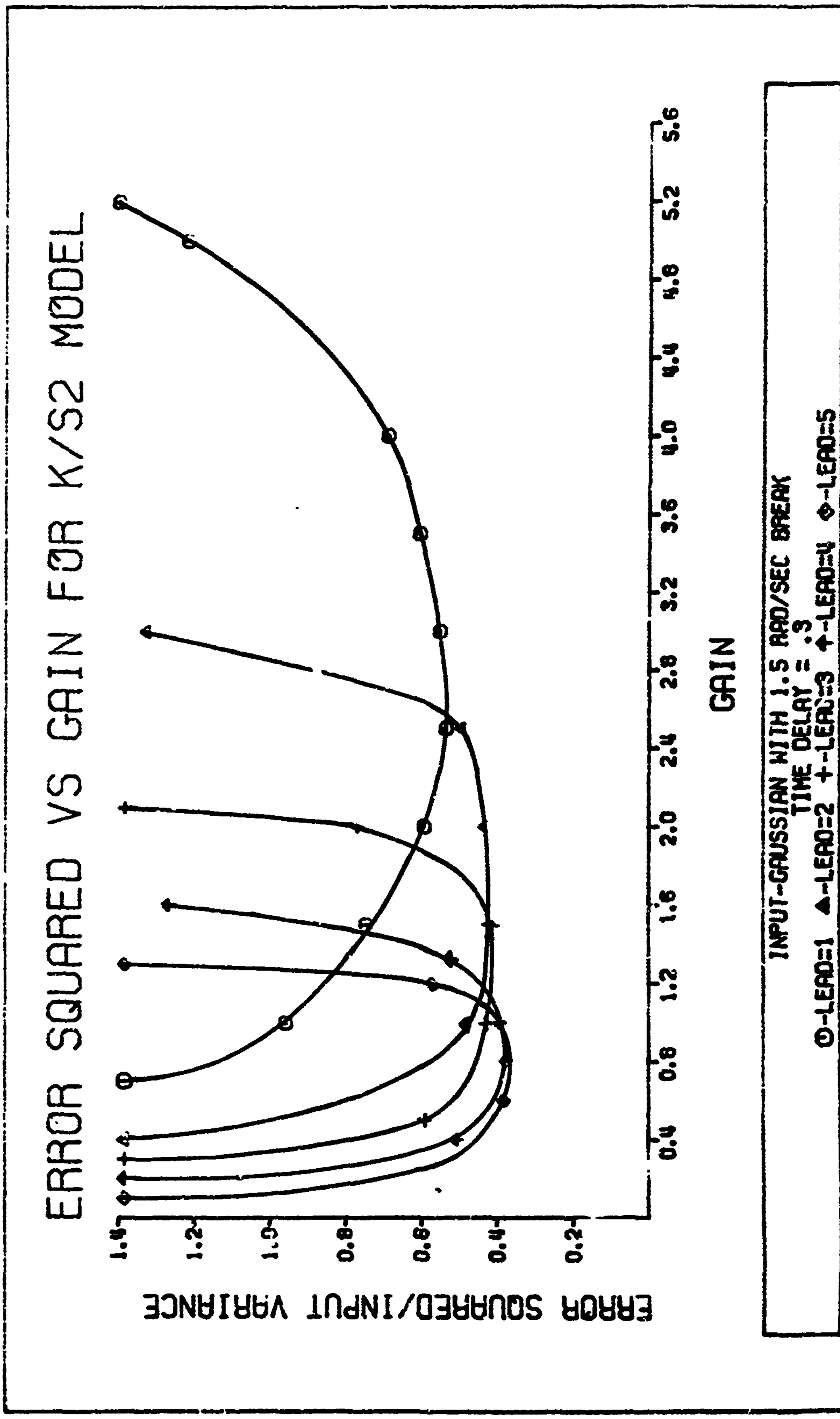

ERROR SQUARED VS GAIN FOR K/S2 MODEL
ERROR SQUARED/INPUT VARIANCE
1.4
1.2
1.0
0.8
0.6
0.4
0.2
GAIN
0.4
0.8
1.2
1.6
2.0
2.4
2.8
3.2
3.6
4.0
4.4
4.8
5.2
5.6
INPUT-GAUSSIAN WITH 1.5 RAD/SEC BREAK
TIME DELAY = .3
LEAD=1 LEAD=2 LEAD=3 LEAD=4 LEAD=5

FIGURE 38

IV. Experimental Results

In this chapter, the data collected from each experimental phase are analyzed, and observations and results are presented. The details of the experimental procedures were previously presented in Chapter II. The use of the performance measures for setting model parameters is discussed at the end of this chapter.

Phase I - Step Input

Four performance measures were taken for each step input. A time recording of the output, the error, and the force stick movement was made for each trial run. The average static delay time, the time between the application of the step and the first movement of the force stick, was computed for all tests. All data are listed in Appendix D. The average delay time for the three subjects was approximately 0.26 seconds, which approximately agrees with the results of Reference 14. The low individual average delay time of 0.23 seconds was noted for subject 1 while operating the K/S^2 controlled system. The high average of 0.32 seconds was computed for subject 3 on the K/S^2 controlled system. The absence of any trends in the static time delay values, indicates that the reaction time of the individual subject was more related to his alertness on the day of the test than on the controlled element used. The only conclusion that can be made from the computed date, is that flying experience and a small static delay time apparently are related.

Correlation coefficients for each performance measure, and for the static delay time were computed from the data collected on the

Table 3

Correlation Coefficients of Experimental Data For Systems With K Controlled Elements and Step Inputs

Subject 1

	IES	ITES	IAE	ITAE	Time Delay
IES	1.000	.935	.796	.173	.934
ITES		1.000	.800	.237	.924
IAE			1.000	.728	.753
ITAE				1.000	.171

Subject 2

	IES	ITES	IAE	ITAE	Time Delay
IES	1.000	.748	.721	.000	.714
ITES		1.000	.639	.044	.623
IAE			1.000	.676	.284
ITAE				1.000	-.332

Subject 3

	IES	ITES	IAE	ITAE	Time Delay
IES	1.000	.389	.436	.119	.813
ITES		1.000	.943	.901	.099
IAE			1.000	.941	.143
ITAE				1.000	-.164

Table 4

Correlation Coefficients of Experimental Data For Systems With K/S Controlled Elements and Step Inputs

Subject 1

	IES	ITES	IAE	ITAE	Time Delay
IES	1.000	.904	.829	.000	.507
ITES		1.000	.831	.083	.523
IAE			1.000	.545	.326
ITAE				1.000	-.188

Subject 2

	IES	ITES	IAE	ITAE	Time Delay
IES	1.000	.959	.714	-.085	.455
ITES		1.000	.827	.122	.473
IAE			1.000	.634	.423
ITAE				1.000	.076

Subject 3

	IES	ITES	IAE	ITAE	Time Delay
IES	1.000	.980	.940	.783	.303
ITES		1.000	.976	.873	.260
IAE			1.000	.947	.241
ITAE				1.000	.157

Table 5

Correlation Coefficients of Experimental Data For Systems With K/S^2 Controlled Elements and Step Inputs

Subject 1

	IES	ITES	IAE	ITAE	Time Delay
IES	1.000	.929	.880	.639	.394
ITES		1.000	.955	.791	.534
IAE			1.000	.894	.514
ITAE				1.000	.474

Subject 2

	IES	ITES	IAE	ITAE	Time Delay
IES	1.000	.894	.779	.388	.038
ITES		1.000	.960	.740	.147
IAE			1.000	.875	.205
ITAE				1.000	.251

Subject 3

	IES	ITES	IAE	ITAE	Time Delay
IES	1.000	.690	.798	.370	-.107
ITES		1.000	.720	.638	-.015
IAE			1.000	.799	-.094
ITAE				1.000	-.078

twenty-five runs made by each subject operating each of tho controlled elements. The coefficients were computed by using the data from Tables D-1 through D-6 of Appendix D in the equation,

$$\text{Correlation Coefficient} = \frac{E\left[X_1X_2\right] - \bar{X}_1\bar{X}_2}{\sqrt{E\left[(X_1 - \bar{X}_1)^2\right]*E\left[(X_2 - \bar{X}_2)^2\right]}}$$

The computed coefficients are presented in Tables 3 through 5. A decrease in the correlation between the time delay and the performance measures was noted as the order of the controlled element was increased. Of the four performance measures taken, the IES and the ITES were better correlated to the static delay time. In general, the correlations were highest for the subjects with flying experience. It should be noted that minimum time has also been suggested as a performance measure (Ref 12:68). However, observed pilot "conservatism" (Ref 1) seems to rule out this measure.

The correlation between each of the performance measures was computed and also shown in Tables 3 through 5. If high correlation existed between any two performance measures, the more difficult to compute could be eliminated from the useful list of measures. The correlations between the IES and the ITES, between the IES and IAE, and between the ITES and the IAE were all found to be relatively high. Since minimizing the IES is included as an adjustment rule of the existing human describing function model with random inputs, and because the IES is relatively easy to compute and measure, this performance measure was given priority consideration over the other measures. Therefore, the ITES and the IAE were eliminated as practical performance measures for a system with step inputs.

The correlation between the IES and the ITAE was found to be relatively low, even negative in some cases. An investigation of the model system with step inputs was undertaken to determine whether the gain should be set for the minimum ITAE or for minimum IES. From a study of time recordings of the system outputs, the following observations were made:

1) The experienced pilots were conservative in operating the force stick. The result is an overdamped system output.

2) Setting the gain of the human describing function model for minimum error squared, results in an underdamped system output.

3) Setting the gain of the human describing function model for minimum ITAE results in a slightly overdamped system output.

4) Therefore, setting the gain of the model for minimum ITAE resulted in a better match of the model system output with the experienced piloted system output.

5) Setting the gain of the model below the value necessary for minimum IES, gave the same results as setting the gain of the model for minimum ITAE (Approximately 85% of gain for minimum IES).

6) Subject 3, who had no flying experience, was less conservative than the other two subjects. The output from systems operated by Subject 3 showed less dampening than the experienced pilot system output.

7) Setting the gain of the model with a pure gain controlled element slightly below the gain for minimum IES resulted in a relatively good match of the unexperienced piloted system and the model system output.

8) Subject 3 had difficulty maintaining control of the system with a K/S^2 controlled element. His erratic behavior made comparison with the model difficult.

It should be remembered that human response is, in general, time varying, and therefore a perfect match between the output of the model system and the output of the piloted system is impossible. Regression (Ref 11:19) due to the high frequency components of a step input is offered as a possible reason why the human subjects operate the system at a gain below the value necessary for minimum error squared. The damped effects of a reduced gain can be observed in the real time recordings shown in Appendix E. Operating a model system at the gain setting for minimum ITAE results in a greater dampening effect than operating at the gain setting for minimum IES (Ref 19:48), and provides a close match between the model system output and the piloted system output. Therefore, the ITAE is proposed as a useful performance measure for systems with step inputs.

Phase II - Gaussian Input

The experiments conducted during this phase were accomplished to establish a set of values to be used in Phase III. However, correlation coefficients were computed to compare performance measures. In almost all cases, the correlation among the four performance measures was extremely high, averaging above 0.85. As might be expected, the two subjects with flying experience performed better than the subject with no flying experience. In several cases, the error squared was so small that invalid readings, resulting from nonlinear operation of the multiplier used to obtain the ITES, were recorded. Therefore, the ITES was eliminated as a useful performance measure.

In an attempt to match the model system and the experienced piloted system outputs, the gain of the model was adjusted very slightly below the value of gain necessary for minimum error squared. When the Gaussian with a high filtered break frequency was used, a smoothing tendency was noted in the outputs of the systems controlled by the experienced pilots. (Appendix E). Also, the more experienced pilots appeared to introduce more lead into the system with the K/S^2 controlled element. A lead time constant of four was assumed for the experienced pilots, whereas a lead time constant of about one was assumed for the subject with no flying experience. Summarizing the results of this phase, the existing adjustment rules were verified with the small exception that the experienced pilots appeared to operate with a gain very slightly below the gain necessary for minimum error squared. See the real time recordings in Appendix E.

Phase III - Gaussian Plus Step Inputs

The data collected during this phase were analyzed and compared with the data from previous phases. Each performance measure was analyzed separately. It should be noted that the step time in Tables D-16 through D-33 was the time interval between the beginning of the run and the application of the step.

IES

The values of IES were averaged and the variance was computed for each set of five, one minute runs. The IES for the 3 volt step was determined by multiplying the IES for the 1 volt step in Tables D-1 through D-6 by 9. A multiplier of 25 was used to obtain the IES for the 5 volt step. To verify these values, several sample measurements were taken with 3 and 5 volt steps actually applied to the system. The averaged $\int e_s^2\, dt$ for each of the 1, 3, and 5 volt step inputs was added to the averaged $\int e_g^2\, dt$ for the Gaussian inputs; then, the sum was compared with the averaged $\int e^2\, dt$ computed during this phase. The results for each subject operating each of the three controlled elements are shown in Table 6. The absolute difference between the summed value and the combined value of the system with Gaussian plus step inputs was compared with the combined standard deviation of the three error measures. For the cases where the absolute difference was less than the combined standard deviation, the assumption, that the $\int 2e_s e_g\, dt$ term was small enough to be neglected, was considered valid. Values satisfying this validity test are marked with an asterick in Table 6. From the calculations and comparisons, the following observations were made:

1) For most of the cases tested, the $\int e_g^2\, dt + \int e_s^2\, dt$ was within one standard deviation of the $\int e^2\, dt$.

2) In general, the $\int e^2\, dt$ was slightly more then the $\int e_g^2\, dt + \int e_s^2\, dt$ due to the ommission of $\int 2e_s e_g\, dt$.

3) Because the experienced pilots were able to maintain a small error for the Gaussian input, the continuous time multiplication of the error due to the Gaussian input with the error due to the step input was maintained at a very low level.

From the above observations, the assumption that the sum of the $\int e_s^2\, dt$ and the $\int e_g^2\, dt$ will fairly well predict the $\int e^2\, dt$ for a system with Gaussian plus step inputs, is validated.

Table 6

Comparison of IES For The Step Input and IES For The Gaussian Input With IES For The Combined Step and Gaussian Input

System	a (σ_i)	Sub	For 1 volt step		For 3 volt step		For 5 volt step	
			Summed	Combined	Summed	Combined	Summed	Combined
K	0.5 (1.44)	1	3.412	3.552	6.700	9.048	12.301	18.785
		2	4.221	4.421*	8.061	7.604*	15.741	16.286*
		3	13.862	17.011*	17.006	34.964*	23.294	51.032
K	1.5 (0.56)	1	5.288	6.486*	8.276	10.248	15.177	18.987
		2	6.848	7.604*	10.688	11.707*	18.368	18.752*
		3	9.049	10.400*	12.193	19.112	18.481	39.558
K/S	0.5 (1.44)	1	5.324	5.592*	9.804	7.752	18.764	15.720
		2	6.472	7.684*	12.232	14.286*	23.752	27.328*
		3	12.695	12.787*	21.583	20.141*	39.359	45.514*
K/S	1.5 (0.56)	1	6.005	5.979*	10.485	9.196*	19.445	18.082*
		2	11.201	13.084*	16.961	17.918*	28.481	34.722*
		3	15.465	15.640*	24.353	25.975*	42.129	43.568*
K/S^2	0.5 (1.44)	1	39.357	41.918*	44.929	51.884*	55.873	63.261*
		2	36.291	41.575*	45.147	43.775*	62.869	61.719*
		3	42.406	50.859*	54.310	66.821*	78.118	87.768*
K/S^2	1.5 (0.56)	1	45.924	51.646*	51.396	55.832*	62.340	71.259*
		2	42.234	50.309*	51.090	59.863*	68.802	82.943*
		3	58.709	65.600*	70.613	89.966*	94.421	96.966*

* Indicates that the two values are within one standard deviation of the computed data.

It should be noted that the "additive results" appear to work over a wide range for $\int e_g^2\,dt \approx \int e_s^2\,dt$. A general range of values is indicated from the data collected for Subject 1. Cases ranged from:

$$0.245\ (K,1v) \leq \int e_s^2\,dt \leq (0.913)(25)\ (K/S^2,5v)$$

and

$$2.450\ (K,a=0.5) \leq \int e_g^2\,dt \leq 51.3\ (K/S^2,a=1.5)$$

<u>IAE</u>

The values of IAE were averaged and the variance was computed for each set of five, one minute runs. To obtain the IAE for a 3 volt step, the IAE for a 1 volt step was multiplied by 3, and to obtain the IAE for a 5 volt step, the IAE for a 1 volt step was multiplied by 5. The averaged $\int |e_s|\,dt$ for each of the 1, 3, and 5 volt step inputs was added to the averaged $\int |e_g|\,dt$ for the Gaussian inputs; then, the sum was compared with the averaged $\int |e|\,dt$ computed during this phase. The results for each subject operating each of the three controlled elements are shown in Table 7. The absolute difference between the summed value and the combined value of the system with Gaussian plus step inputs was compared with the combined standard deviation of the three error measures. For the cases where the absolute different was less than the combined standard deviation, the assumption, that $\int |e|\,dt$ approximately equals $\int |e_s|\,dt + \int |e_g|\,dt$, was considered valid. Values satisfying this validity test are marked with an asterick in Table 7. From the calculations and comparisons, the following observations were made:

1) For most of the cases tested, the $\int |e_g|\,dt + \int |e_s|\,dt$ was within one standard deviation of the $\int |e|\,dt$.

Table 7

Comparison of IAE For The Step Input and IAE For The Gaussian Input With IAE For The Combined Step and Gaussian Input

System	a (σ_i)	Sub	For 1 volt step		For 3 volt step		For 5 volt step	
			Summed	Combined	Summed	Combined	Summed	Combined
K	0.5 (1.44)	1	11.319	13.695	12.660	15.448	13.955	16.888
		2	11.602	11.722*	13.264	12.531*	14.926	14.720*
		3	20.914	21.762*	22.780	27.434*	24.446	34.065
K	1.5 (0.56)	1	15.313	15.343*	16.631	16.937*	17.949	17.844*
		2	15.608	16.091*	17.270	18.036*	18.932	18.709*
		3	18.497	19.295*	20.263	23.442*	22.129	27.082*
K/S	0.5 (1.44)	1	13.195	12.947*	14.997	12.676	16.799	13.501
		2	15.250	15.880*	17.364	18.322*	19.478	19.836*
		3	23.177	23.208*	26.575	23.126*	29.973	27.503*
K/S	1.5 (0.56)	1	15.049	14.594*	16.851	15.821*	18.653	17.019*
		2	20.505	21.206*	22.619	22.522*	24.733	25.688*
		3	24.022	23.625*	27.400	28.366*	30.818	31.040*
K/S^2	0.5 (1.44)	1	37.753	39.221*	40.265	42.865*	42.777	42.008*
		2	35.983	37.316*	39.367	39.512*	42.751	42.811*
		3	40.017	42.543*	45.491	46.411*	50.965	49.402*
K/S^2	1.5 (0.56)	1	40.329	41.918*	42.841	42.733*	45.353	44.232*
		2	36.401	41.493	39.785	44.651	43.169	48.421*
		3	47.612	48.383*	53.086	56.693*	58.560	55.084*

* Indicates that the two values are within one standard deviation of the computed data.

2) In general, the $\int |e|\,dt$ was slightly less than the $\int |e_g|\,dt$ + $\int |e_s|\,dt$ as would be expected from the mathematical relationship, $\int |e_s + e_g|\,dt \leq \int (|e_s| + |e_g|)\,dt$.

3) If the error due to the Gaussian input was maintained at a low level when the step was applied, the sum of the individual IAEs would equal the combined IAE. However, the same relationship would be true if the step error was of the same polarity as the error of the Gaussian was when the step was applied.

From the above observations, the assumption that the sum of $\int |e_s|\,dt$ and $\int |e_g|\,dt$ will fairly well predict $\int |e|\,dt$ for a system with Gaussian plus step inputs, is validated.

A study of the correlation coefficients between the IAE and the IES of a system with step plus Gaussian inputs demonstrated that the two measures perform the same evaluation of the subject's performance. In almost all cases, the correlation coefficient was above 0.85. Therefore, it was determined that the IES was a better performance measure to use because of its acceptance as a measure of performance for system with Gaussian inputs.

ITES

As mentioned before, the ITES was impossible to determine for some runs, because the error squared was maintained at a very low level causing nonlinear operation of the analog multiplier circuit. Therefore, the ITES was eliminated from consideration as a useful performance measure of piloted systems with Gaussian plus step inputs.

ITAE

Computational difficulties in determining the effects of time on this performance measure prohibit its usefulness.

From the analysis of all data, the conclusion is made that the IES is the best performance measure to use in evaluating the operation of the piloted system with Gaussian plus step inputs.

Adjusting the Model Parameters

The final step in this study was to adjust the parameters of the analog simulated model, and record the outputs of the model and piloted systems when both were operated simultaneously. One major difficulty in properly matching the piloted and model system outputs for step inputs was the distortion caused by the use of the Pade' approximation of the real time delay. The phase difference at high frequencies between the Pade' approximation and the real time delay resulted in a dip in the model output when there should have been none. This distortion was especially apparent for the model system with the pure gain controlled element.

Despite the difficulties associated with the Pade' approximation in the analog simulated system, the following parameter setting were determined:

1) The lag time constant was set at 3 seconds for the model with a pure gain controlled element. This value was previously determined by others (Ref 11:46), and was found to provide the proper lag for the experiments of this study.

2) The time delay was determined from data collected during Phase I to be approximately 0.3 seconds for all models with step inputs. From earlier studies (Ref 11), the time delay for the K and K/S systems with random inputs is 0.2 seconds, and the time delay for the K/S^2

system with random inputs is 0.4 seconds. An overall compromise for the step plus Gaussian case is the selection of a time delay of 0.3 seconds.

3) The lead time constant for the model with the K/S^2 controlled element was selected between 1 and 5 seconds. For a model used to predict the response of an experienced pilot, the lead time constant was set at 4 seconds, and for the response prediction of the subject with no flying experience, the lead time constant was set at 1 second.

4) The best gain setting for a system with step inputs was found to be for minimum ITAE or approximately 85% below the setting for minimum IES. For Gaussian plus small step inputs, the gain setting should be slightly below the value for minimum error squared. As the step is increased in relationship to the Gaussian input, the gain should be decreased toward the value which would provide minimum ITAE for a single step input. This technique for setting the gain of a system with step plus Gaussian inputs is more applicable for predicting the response of an experienced pilot than for predicting the response of an unexperienced pilot. The subject with no flying experience appeared to always operate close to the gain setting necessary for minimum IES in respect to time history responses.

Real time recordings of the piloted system and model system outputs and errors are shown in Appendix E.

V. Summary and Conclusions

The conclusions, supported by the analysis of data collected during the experimental study, are summarized in this chapter. First, it was found that the existing human describing function model is useful in predicting the response of a pilot in systems with Gaussian plus one step inputs. The use of the existing adjustment rules, model characteristic curves, and performance data on human trackers was necessary to adjust the model parameters for proper model prediction of the actual pilot response.

Second, the adjustment rule, stating that human subjects attempt to minimize their mean squared error, should be modified slightly to account for the conservative response of an experienced pilot when he is operating a control device in a manner similar to the way he operates an aircraft control. The gain of a model representing an experienced pilot in a system with step inputs, should be set to a value that is approximately 85% of the value necessary for minimum mean squared error. The decrease in gain of the model will provide increased dampening, thus, indicating the conservative nature of pilot response.

Third, it was found that operating a system with step inputs at minimum ITAE was similar to operating a system with the gain set at 85% of the value necessary for minimum IES. Therefore, use of the minimum ITAE is recommended for adjusting the gain of a model in a system with step inputs.

A technique suggested for the adjustment of model gain in a system with step plus Gaussian inputs is to reduce the gain below the value necessary for minimum IES as the step input is increased in relationship with the Gaussian input. For a small step in relation to the random input, the gain should be set between 90% and 95% of the value necessary for minimum IES. For a large step in relation to the random input, the gain should be set between 85% and 90% of the value necessay for minimum IES. This technique is especially useful for predicting the response of an experienced pilot.

Finally, the summed values of the IES found from the system with step inputs and the IES found from the system with Gaussian inputs is a relatively close approximation of the IES of a system with step plus Gaussian inputs. There is every reason to believe that the results of this study could be applied to systems composed of aircraft-like dynamics.

VI. Recommendations

The following recommendations are suggested for expanding the results of this study.

1) Verify that the same technique of reducing gain can be used for systems having controlled elements representing actual aircraft dynamics, and step plus random signals applied.

2) Study the effects of applying random signals plus other deterministic signals such as ramps or sine waves.

3) Study the effects of applying an additional Gaussian signal, simulating pilot remnant, directly to the controlled element. Perhaps, a pilot remnant input with the step plus random input pilot model could be used to predict repeatability aspects of the responses.

4) Investigate the use of delay tapes to replace the Pade' approximation of the pure time delay in the analog model simulation of a system with step inputs.

5) Conduct further statistical studies to determine the response differences between experienced pilots and non-pilots, when performing specialized tasks related to aircraft control.

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Appendix A

Equipment Description

Analog Computer

Use of an Applied Dynamics Analog Computer, Model AD-2-64 PB, was made throughout this investigation. This is a precision electronics differential analyzer capable of solving both linear and nonlinear ordinary differential equations. It contains 64 operational amplifiers, 24 of which may be used as integrators. The unit also contains 80 coefficient pots, 16 electronic multipliers, 8 diode function generators, and 20 special diode networks. (Ref 2).

Digital Voltmeter

A Nonlinear System, Model 4206 Digital Voltmeter was used. This unit was installed as a part of the AD-64PB computer and featured automatic range and polarity control. The meter has a 10 megohm input impedance and an accuracy of ± 0.02 percent of full scale and a resolution of ± 0.01 percent of full scale on each range. (Ref 16).

Hand Control

A Measurements Systems, Model 435 Hand Control, mounted in a student's chair, was used for the pilot tracking portion of this investigation. This is an a.c. powered force-stick tranducer which produces phase reversing a.c. voltages converted to d.c. proportional to applied force in two axes. Its essential features are zero back-lash, low hysteresis, and drift, and linear output vs. force applied. (Ref 13).

Magnetic Tape Recorder/Reproducer

A Sangamo Electric Company, Model 4784 Magnetic Tape Recorder/ Reproducer was used to reproduce several 60 second gaussian noise signals for input to the analog computer. The Recorder/Reproducer is a seven channel, eight speed magnetic tape device with the capability of reel to reel or loop operation. The system consists of six major assemblies: A control panel, an a.c. control box, a power supply drawer, a tape transport panel, a vacuum panel, and a plug-in module chasis. An important feature is the employment of a unique vacuum tensioning and cleaning system to maintain precise tape tension at the head while cleaning the tape to reduce drop outs and oxide buildup. (Ref 17).

Noise Generator

An Elgenco Model 311A Noise Generator was used to produce the signals which were stored on magnetic tape for reuse throughout the experiment. This unit is a stable source of random noise of mean less than 50 millivolts. Its output has an amplitude probability distribution that is Gaussian to less than plus or minus one percent and the output spectrum is uniform to plus or minus 0.1 db from 0 to 35 cycles per second. (Ref 7).

Oscilloscope

In this investigation a Tektronics Type RM35A Oscilloscope was used to present tracking error. This oscilloscope together with a type CA plug-in preamplifier provided rise time capability of 0.023 microseconds with a band pass from d.c. to 15 megacycles per second. The oscilloscope has a usable viewing area of 6x10 centimeters with a range of 0.05 volts per centimeter to 20 volts per centimeter. (Ref 18).

Recorder

Real time recordings were made with a Beckman, Type SC-2 Dynograph, Direct Writing Recorder. This is an eight channel unit capable of recording bi-polar signals on rectilinear paper with a sensitivity of 50 millivolts per division to 10 volts per division. Input impedance is 1 megohm and frequency response is flat from d.c. to 42 cycles per second. (Ref 4).

Appendix B

Analog Computer Program

The analog computer was used for all experiments. Both the piloted system and the model system, along with all performance measures, were programed on one analog board. The analog schematic for both the piloted systems and the model systems is shown in Figure B-1. The input circuit, the timing circuit, and the automatic sixty second hold circuit, are shown in Figure B-2. Figure B-3 is the schematic of all performance measure circuitry. Switches available on the computer were used extensively to change controlled elements, and the signals applied.

Systems

The schematic of the piloted system is pictured in the top half of Figure B-1. The schematic for the model system is shown in the bottom half of Figure B-1. Since a pure time delay in the form $e^{-\tau s}$ is impossible to program, a first order Pade' approximation was selected because it presents zero db gain at all frequencies. (Ref 15:218)

Seperate program sections were prepared for each controlled element and combined with the pilot model. The controlled element represented by K is programed together with the lag term of the pilot model. In all cases the controlled element gain was chosen to be unity. The combined term is $K_p/(T_I S + 1)$. For the controlled element K/S, the combined term is K_p/S, and for the controlled element, K_p/S^2, the combined term is $K_p(T_L S + 1)/S^2$.

Table 1 indicates the potentiometer settings for both systems. The numbers inclosed in the triangles indicate the line connections on the strip recorder.

Timing, Hold, and Input

The timing circuit is set for linear operation by the application of a 10 volt initial condition to the integrator. One volt represents one second. The sixty second hold circuit is also a timing circuit. Both the hold circuit and the timing circuit were checked often during experimentation to insure synchronous, accurate operation. The input circuit was designed so that circuit changes between experiments were minimized. The potentiometer settings are shown in Table B-2.

Performance Measures

Performance data were collected from the circuitry represented by the schematic in Figure B-3. The diode multipliers with the most linear characteristics were selected for the experiments.
Known voltages were input into each performance measure circuit for a one minute interval, and the circuits were calibrated by using potentiometers.

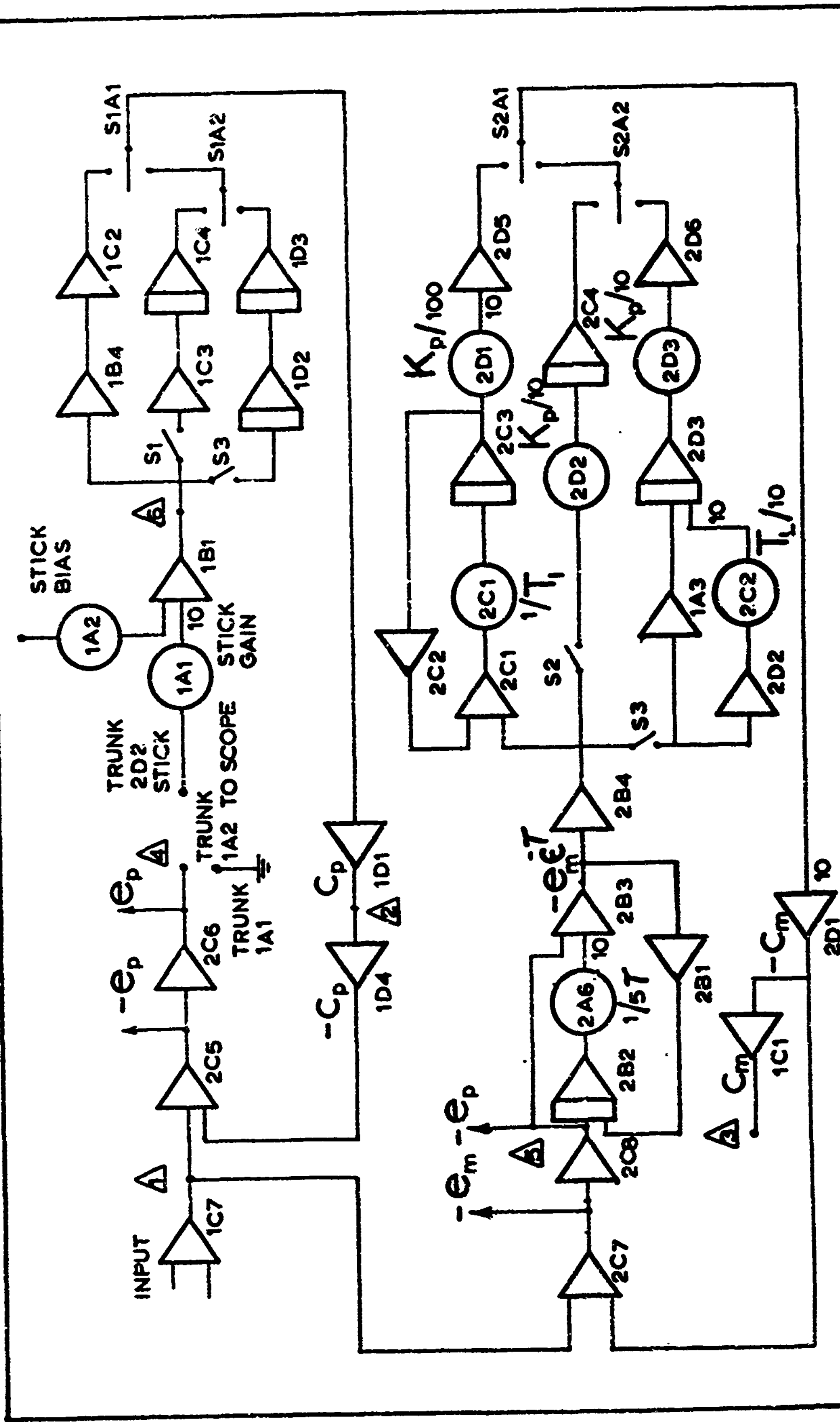


Figure B-1 Piloted System and Model System Analog Diagrams

Table B-1

Potentiometer Values for Figure B-1

Quantity	Potentiometer	Sample Setting
Stick Gain	1A1	1.000
Stick Bias	1A2	.003
$1/5\tau$	2A6	.667
$1/T_I$	2C1	.333
$T_L/10$	2C2	.300
$K_p/100$	2D1	.120
$K_p/10$	2D2	.450
$K_p/10$	2D3	.130

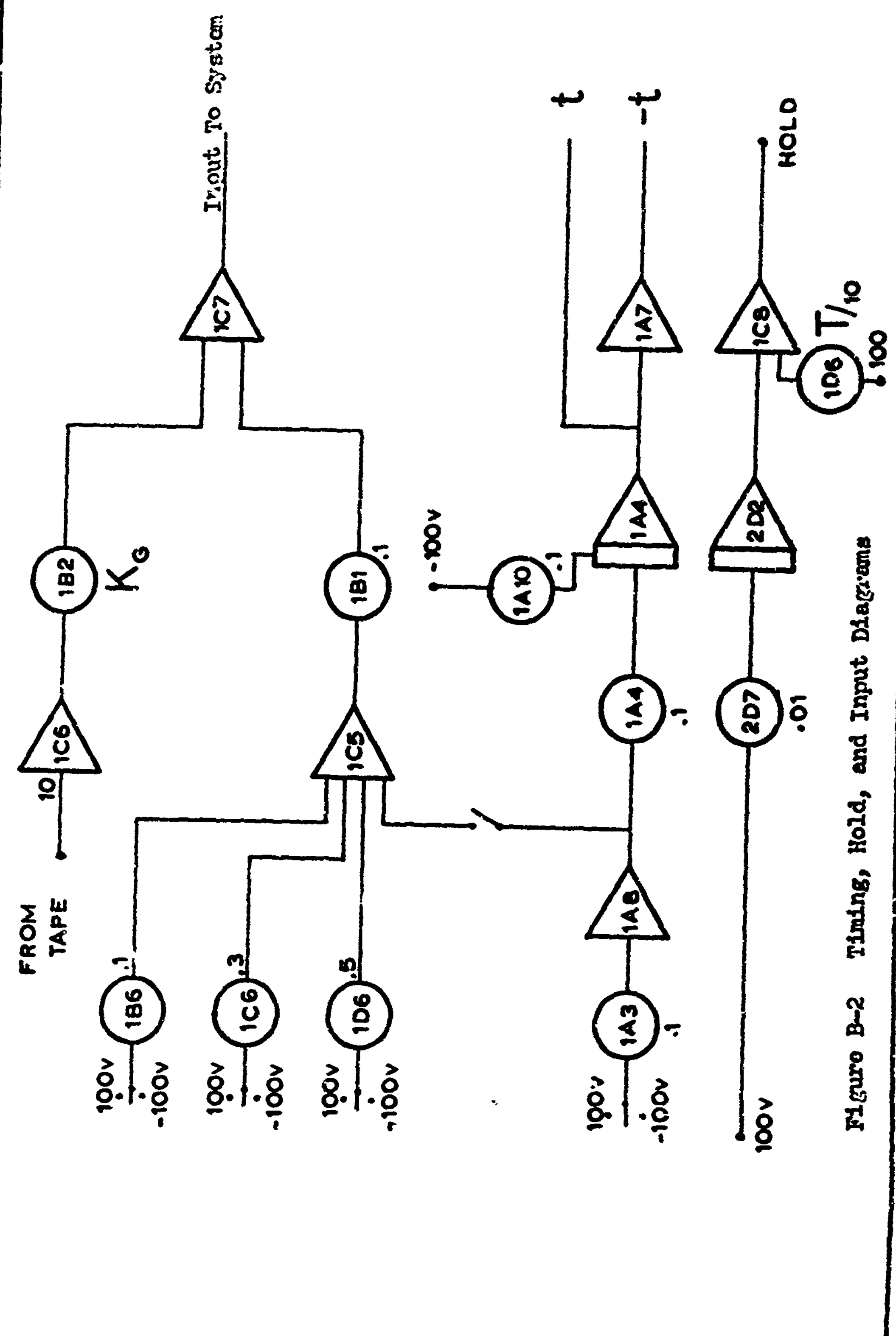


Figure B-2 Timing, Hold, and Input Diagrams

Table B-2

Potentiometer Values for Figure B-2

Quantity	Potentiometer	Setting
$\dot{t}/10$	1A3	.100
$\dot{t}/10$	1A4	.100
$t_o/100$	1A10	.100
$\dot{t}/100$	2D7	.010
$t_h/100$	1D6	.600
$r_s/10$	1B6	.100
$r_s/10$	1C6	.300
$r_s/10$	1D6	.500
$r_s/10$	1B1	.100
$R_g/10$	1B2	Variable .272 or .562

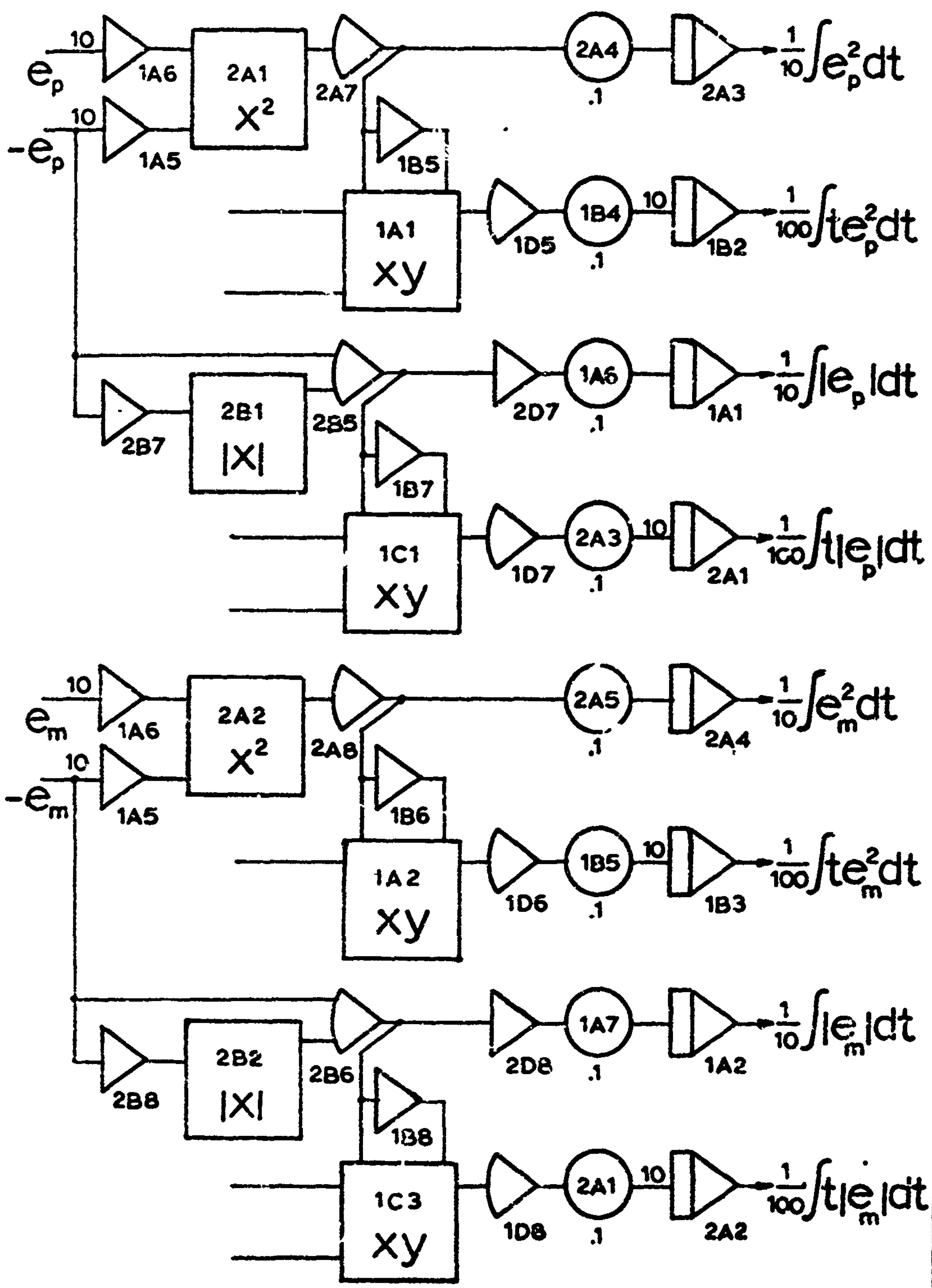


Figure 3-3 Performance Measures

Table B-3

Potentiometer Values for Figure B-3

Quantity	Potentiometer	Approximate Setting
$IAE_m/10$	1A6	.100
$IAE_p/10$	1A7	.100
$ITES_m/100$	1B4	.100
$ITES_p/100$	1B5	.100
$ITAE_m/100$	2A1	.100
$ITAE_p/100$	2A3	.100
$IES_m/10$	2A4	.100
$IES_p/10$	2A5	.100

Appendix C

Analog Gaussian Input Tape Recordings

The signal recordings used in the Phase II and III experiments are shown in Figure C-1. The following procedure was used to obtain these signals. First, white noise from the Elgenco Model 311A Noise Generator was fed to a second order filter, which was programmed on the analog computer. Then, the filtered Gaussian signal was processed through a fader and reproduced on the appropriate tape channel of the Sangamo Model 4784 Magnetic Tape Recorder/Reproducer. Fading was accomplished to eliminate step signals at the beginning of the input tape.

The equation used to program the second order filter is

$$y(s) = \frac{K\, x(s)}{(S + a)^2} ,$$

where y(s) represents the Gaussian output, and x(s) represents the white noise input. The analog schematic of the filter is shown in Figure C-2, and the potentiometer settings are shown in Table C-1.

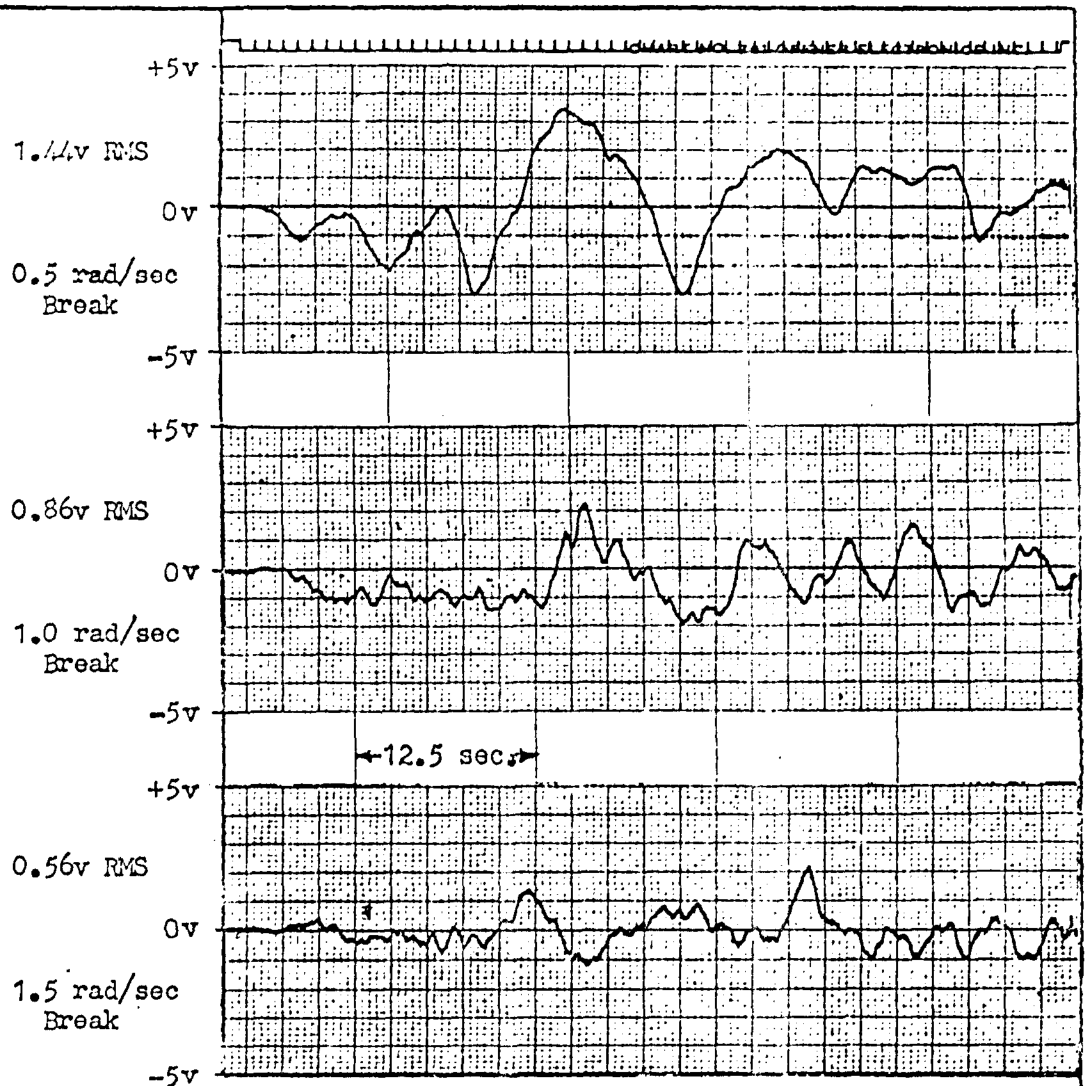


Figure C-1 Input Signals

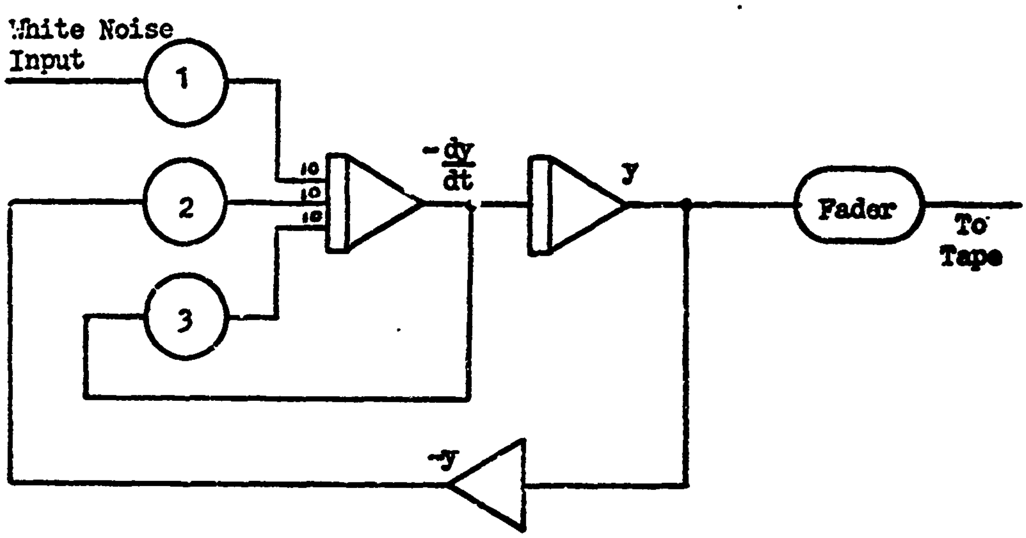


Figure C-2 Analog Simulation of the Second Order Filter

Table C-1

Potentiometer Settings for Figure C-2

Quantity	Pot.	Settings For The Following Break Frequencies		
		0.5 rad/sec	1.0 rad/sec	1.5 rad/sec
$K/10a^2$	1	Gain/10	Gain/10	Gain/10
$2a/10$	3	.100	.200	.300
$a^2/10$	2	.025	.100	.225

Appendix D

Experimental Data

A listing of all data is presented here to save those who wish to continue research on this topic many tedious hours of laboratory time. The data also provide model designers with a first step comparison of their model system performance with piloted system performance.

The mean, variance, and standard deviation were computed, and these values are presented with the experimental measurements. Tables D-1 through D-6 list data gathered and analyzed during Phase I of the study. The first column is measured in volts^2-seconds, the second column in volts^2-seconds^2, the third column in volts-seconds, the fourth column in volts-seconds^2, and the last column, the delay time, is measured in tenths of a second. Tables D-7 through D-24 list data gathered and analyzed during Phase II, and Tables D-25 through D-33 list data gathered and analyzed during Phase III. The step time, the interval between the beginning of the run and the application of the step in the Phase III experiments, is measured in seconds. The same four units of measure are used for the first four columns in Tables D-7 through D-33 as were used in Tables D-1 through D-6.

A "0." appearing in any of the tables, indicates that no measurement was taken, or that the measurement was invalid due to multiplier nonlinearity.

Table D-1

SUBJECT 1 - PERFORMANCE MEASURES FOR K CONTROLLER
INPUT - 1 VOLT STEP

	IES	ITES	IAE	ITAE	DELAY TIME
	0.740	0.840	1.112	2.550	5.9
	0.319	0.239	0.535	1.430	2.9
	0.430	0.372	0.635	1.270	3.2
	0.341	0.253	0.592	1.580	2.5
	0.402	0.324	0.653	1.590	2.7
	0.462	0.356	0.686	1.430	3.8
	0.448	0.372	0.798	2.120	3.1
	0.300	0.141	0.463	1.070	2.2
	0.400	0.240	0.631	1.520	2.9
	0.255	0.149	0.515	1.580	2.3
	0.245	0.042	0.603	2.270	2.2
DATA	0.334	0.146	0.546	1.470	2.4
	0.307	0.183	0.560	1.560	2.5
	0.299	0.102	0.747	2.650	2.2
	0.295	0.198	0.475	1.080	3.0
	0.333	0.239	0.756	2.530	2.5
	0.318	0.225	0.625	1.870	2.5
	0.362	0.222	0.778	2.450	3.0
	0.407	0.389	0.783	2.210	3.5
	0.281	0.194	0.632	2.060	2.2
	0.300	0.212	0.672	2.160	2.2
	0.340	0.083	0.532	1.320	2.6
	0.427	0.399	0.754	1.920	4.0
	0.454	0.373	0.792	2.070	3.8
	0.229	0.180	0.600	2.260	2.2
MEAN	0.361	0.259	0.659	1.841	2.9
VARIANCE	0.010	0.024	0.018	0.217	0.7
STD. DEV.	0.102	0.154	0.136	0.465	0.8

SUBJECT 1 - PERFORMANCE MEASURES FOR K/S CONTROLLER
INPUT - 1 VOLT STEP

	IES	ITES	IAE	ITAE	DELAY TIME
	0.576	0.525	0.924	2.440	2.5
	0.612	0.582	1.105	3.390	2.6
	0.684	0.637	0.969	2.150	2.3
	0.583	0.553	1.019	2.810	2.1
	0.645	0.696	1.040	2.550	2.0
	0.785	0.982	1.200	2.740	3.2
	0.693	0.747	0.986	1.940	2.9
	0.658	0.674	1.022	2.360	2.1
	0.716	0.723	1.032	2.080	2.3
	0.695	0.706	0.966	1.790	2.9
	0.675	0.740	0.924	1.640	2.5
D. [illegible]	0.642	0.612	0.904	1.740	2.6
	0.614	0.625	0.859	1.500	2.8
	0.526	0.488	0.750	1.420	2.0
	0.571	0.603	0.846	1.660	2.3
	0.613	0.580	0.876	1.650	3.3
	0.532	0.696	0.979	2.550	2.3
	0.378	0.413	0.800	2.440	2.1
	0.415	0.372	0.752	1.920	2.2
	0.354	0.395	0.822	2.700	2.0
	0.415	0.472	0.800	2.270	2.1
	0.426	0.485	0.766	2.030	2.2
	0.396	0.444	0.736	2.020	2.4
	0.367	0.388	0.698	1.920	2.3
	0.425	0.501	0.752	1.930	2.6
MEAN	0.560	0.586	0.901	2.146	2.4
VARIANCE	0.016	0.020	0.016	0.216	0.1
STD. DEV.	0.125	0.140	0.127	0.4[illegible]	0.4

Table D-2

SUBJECT 1 - PERFORMANCE MEASURES FOR K/S2 CONTROLLER INPUT - 1 VOLT STEP					
	IES	ITES	IAE	ITAE	DELAY TIME
DATA	0.688	0.896	1.174	3.120	2.4
	0.54[illegible]	0.651	1.145	3.760	2.1
	0.894	1.322	1.672	5.240	2.0
	0.716	1.296	1.608	5.580	2.7
	0.801	1.195	1.396	4.040	2.2
	0.593	0.800	1.109	3.120	2.1
	0.787	1.048	1.260	3.120	2.1
	0.739	1.117	1.298	3.520	2.5
	0.879	1.451	1.596	5.020	2.7
	0.659	1.107	1.404	4.710	2.5
	0.534	0.687	1.021	2.910	2.1
	0.791	1.053	1.229	2.920	2.3
	0.500	0.729	1.103	3.650	2.6
	0.668	1.128	1.282	3.740	2.8
	0.785	1.081	1.520	4.960	2.6
	0.872	1.221	1.439	3.930	2.2
	0.913	1.524	1.635	5.110	2.4
	0.900	1.620	1.844	6.280	2.5
	0.709	0.867	1.046	2.120	2.6
	0.454	0.474	0.920	2.700	2.1
	0.602	0.803	1.059	2.830	2.0
	0.526	0.614	0.999	2.600	2.2
	0.509	0.590	0.908	4.160	2.1
	0.530	0.681	0.960	2.330	2.0
	0.441	0.516	0.781	1.990	1.8
MEAN	0.684	0.979	1.256	3.738	2.3
VARIANCE	0.021	0.101	0.075	1.272	0.1
STD. DEV.	0.146	0.317	0.273	1.128	0.3

Table D-3

SUBJECT 2 - PERFORMANCE MEASURES FOR K CONTROLLER
INPUT - 1 VOLT STEP

	IES	ITES	IAE	ITAE	DELAY TIME
DATA	0.456	0.474	0.786	2.120	2.8
	0.471	0.357	0.792	2.110	2.9
	0.475	0.391	0.769	1.920	3.0
	0.624	0.710	0.929	1.710	3.2
	0.430	0.337	0.780	2.210	2.2
	0.509	0.495	0.860	2.190	3.2
	0.421	0.356	0.809	2.420	2.2
	0.400	0.367	0.750	2.130	2.4
	0.382	0.380	0.803	2.600	2.3
	0.465	0.410	0.822	2.140	2.3
	0.476	0.477	0.877	2.350	2.7
	0.507	0.474	0.826	1.920	2.9
	0.540	0.561	0.868	1.960	3.2
	0.432	0.439	0.806	2.220	2.5
	0.508	0.549	0.873	2.180	2.6
	0.596	0.632	0.866	1.670	4.5
	0.587	0.648	0.953	2.260	3.2
	0.516	0.514	0.864	2.150	3.0
	0.505	0.921	0.833	1.750	3.4
	0.443	0.361	0.633	1.110	2.8
	0.413	0.415	0.722	1.820	2.7
	0.367	0.342	0.656	1.690	2.9
	0.572	0.729	1.071	3.080	3.1
	0.405	0.444	0.832	2.470	2.4
	0.506	0.519	1.004	2.980	2.8
MEAN	0.480	0.492	0.831	2.126	2.8
VARIANCE	0.004	0.020	0.009	0.164	0.2
STD. DEV.	0.067	0.141	0.094	0.406	0.5

SUBJECT 2 - PERFORMANCE MEASURES FOR K/S CONTROLLER
INPUT - 1 VOLT STEP

	IES	ITES	IAE	ITAE	DELAY TIME
DATA	0.973	1.228	1.436	3.130	2.9
	0.816	0.972	1.151	2.210	2.6
	0.763	0.840	1.090	2.030	2.5
	0.675	0.682	0.954	1.740	2.5
	0.631	0.702	1.031	2.370	2.6
	0.815	0.942	1.090	1.800	3.0
	0.651	0.657	0.875	1.370	2.9
	0.739	0.798	1.084	2.140	3.0
	0.691	0.769	0.949	1.570	2.1
	0.551	0.514	0.930	2.080	2.8
	0.720	0.837	1.082	2.160	3.8
	0.718	0.809	0.983	1.600	3.0
	0.411	0.534	1.038	3.470	2.9
	0.758	0.862	1.128	2.300	3.3
	0.651	0.688	1.092	2.440	2.6
	0.622	0.590	0.852	1.370	2.9
	0.675	0.721	0.941	1.610	3.1
	0.745	0.800	1.096	2.130	3.0
	0.705	0.746	0.966	1.630	2.8
	0.841	0.969	1.148	1.980	4.2
	0.728	0.816	1.176	2.740	4.4
	0.897	1.074	1.165	1.840	4.6
	0.656	0.773	1.118	2.780	2.2
	0.611	0.602	0.834	1.360	2.1
	0.951	1.196	1.214	1.740	3.8
MEAN	0.720	0.805	1.057	2.064	3.0
VARIANCE	0.014	0.032	0.017	0.283	0.4
STD. DEV.	0.120	0.179	0.129	0.532	0.7

Table D-4

SUBJECT 2 - PERFORMANCE MEASURES FOR K/S2 CONTROLLER INPUT - 1 VOLT STEP					
	IES	ITES	IAE	ITAE	DELAY TIME
DATA	1.184	1.590	1.669	3.639	2.7
	1.206	1.770	1.779	4.170	2.2
	1.052	1.620	1.781	4.830	2.6
	0.944	1.240	1.492	3.770	2.9
	1.244	2.040	1.962	5.280	2.5
	1.034	1.350	1.398	2.700	2.1
	0.968	1.280	1.430	3.330	2.2
	1.358	2.470	2.220	6.700	2.3
	1.212	1.860	1.826	4.460	2.0
	1.135	1.740	1.712	4.140	2.1
	0.923	1.310	1.642	4.780	2.2
	0.928	1.270	1.530	4.040	2.6
	1.246	1.760	1.720	3.610	2.5
	0.934	1.260	1.490	3.790	2.2
	1.181	1.670	1.708	3.860	3.5
	1.118	1.720	1.742	4.380	2.7
	1.282	1.860	1.786	3.940	2.0
	0.899	1.250	1.528	4.170	2.6
	1.132	1.550	1.562	3.220	3.0
	1.009	1.330	1.486	3.560	2.0
	1.223	1.780	1.802	4.200	2.5
	1.180	2.230	2.112	6.660	3.5
	0.985	1.380	1.552	3.920	2.6
	1.210	1.820	1.782	4.130	2.4
	1.084	1.500	1.586	3.570	2.1
MEAN	1.107	1.626	1.692	4.194	2.5
VARIANCE	0.017	0.100	0.039	0.816	0.2
STD. DEV.	0.129	0.316	0.198	0.903	0.4

Table D-5

SUBJECT 3 - PERFORMANCE MEASURES FOR K CONTROLLER
INPUT - 1 VOLT STEP

	IES	ITES	IAF	ITAE	DELAY TIME
	0.367	0.168	0.626	1.880	3.3
	0.382	0.279	0.621	1.500	3.5
	0.280	0.170	0.584	1.940	2.8
	0.354	0.280	0.584	1.590	2.9
	0.552	0.492	0.853	2.090	5.0
	0.613	0.506	0.969	2.390	4.0
	0.626	0.751	1.036	2.800	5.5
	0.389	0.450	0.880	3.100	3.0
	0.474	0.590	1.007	3.450	3.8
	0.361	0.370	0.703	2.200	2.8
	0.433	0.510	0.880	2.880	3.6
DATA	0.377	0.280	0.639	1.710	2.8
	0.371	0.370	0.747	2.380	2.4
	0.390	0.480	0.992	3.830	2.3
	0.365	0.712	0.963	3.850	2.2
	0.366	0.821	0.968	3.920	2.2
	0.374	1.144	1.376	6.240	2.4
	0.461	1.038	1.505	6.280	3.8
	0.298	0.644	0.986	3.740	3.0
	0.302	0.280	0.688	2.420	2.5
	0.303	0.267	0.810	3.160	2.5
	0.331	0.552	0.941	3.830	2.2
	0.468	0.944	1.328	5.570	2.6
	0.334	0.512	0.864	3.300	2.5
	0.252	0.236	0.536	1.720	2.2
MEAN	0.393	0.514	0.883	3.111	3.0
VARIANCE	0.009	0.069	0.060	1.756	0.7
STD. DEV.	0.093	0.262	0.245	1.325	0.8

SUBJECT 3 - PERFORMANCE MEASURES FOR K/S CONTROLLER
INPUT - 1 VOLT STEP

	IES	ITES	IAE	ITAE	DELAY TIME
	1.457	2.970	2.690	9.640	3.0
	1.535	2.700	2.280	6.160	4.0
	1.613	2.400	2.089	5.470	3.2
	1.200	1.890	1.956	5.520	3.1
	0.817	1.007	1.332	3.370	3.4
	1.388	2.247	1.943	4.510	4.3
	1.076	1.420	1.577	3.790	4.1
	1.330	2.230	2.072	5.800	2.8
	0.944	1.239	1.373	3.010	2.7
	1.311	2.140	1.956	5.000	2.7
	1.072	1.580	1.646	4.230	2.5
DATA	0.887	1.126	1.411	3.690	2.8
	0.867	1.224	1.603	4.910	2.9
	1.136	1.760	1.824	4.950	3.0
	1.289	2.110	1.945	5.150	3.3
	1.444	2.480	2.138	5.570	3.0
	1.128	1.630	1.613	3.750	2.6
	1.355	2.140	1.878	4.210	2.8
	0.823	0.934	1.189	2.440	3.1
	0.887	1.159	1.372	3.350	3.8
	0.895	1.108	1.355	3.210	2.7
	1.012	1.380	1.534	3.740	2.4
	0.839	1.065	1.291	3.090	2.9
	1.072	1.500	1.545	3.470	3.0
	0.599	0.649	0.874	1.740	2.5
MEAN	1.111	1.684	1.699	4.391	3.1
VARIANCE	0.061	0.364	0.154	2.344	0.2
STD. DEV.	0.247	0.604	0.392	1.531	0.5

Table D-6

SUBJECT 3 - PERFORMANCE MEASURES FOR K/S2 CONTROLLER
INPUT - 1 VOLT STEP

	IES	ITES	IAE	ITAE	DELAY TIME
DATA	1.489	2.630	2.470	7.330	3.8
	1.558	3.510	3.050	10.950	3.5
	2.092	6.020	3.709	13.510	3.1
	1.524	2.470	2.160	5.120	2.5
	1.385	2.800	2.680	9.240	3.3
	1.492	2.720	2.438	7.100	3.0
	1.122	1.720	2.116	6.920	2.5
	1.229	3.400	2.833	13.810	2.6
	1.458	4.810	3.263	19.190	3.3
	1.555	2.890	2.758	8.810	2.4
	1.323	2.290	2.460	8.060	3.7
	1.520	2.590	2.736	9.060	4.0
	0.904	1.200	1.828	6.200	3.5
	1.120	1.650	2.448	7.250	3.2
	1.208	1.940	2.276	7.820	3.4
	1.130	2.910	2.141	7.110	3.5
	1.544	4.060	2.506	7.340	3.4
	1.879	2.980	3.438	11.860	3.1
	1.595	4.460	2.634	7.940	3.6
	2.005	3.710	3.320	10.560	2.9
	1.803	2.940	3.310	11.400	3.2
	1.626	3.030	2.606	7.740	3.3
	1.362	3.030	3.129	12.390	3.2
	1.642	3.860	3.216	11.990	3.1
	1.626	3.530	2.893	9.660	3.0
MEAN	1.488	3.086	2.737	9.534	3.2
VARIANCE	0.076	1.059	0.217	9.172	0.2
STD. DEV.	0.276	1.029	0.465	3.029	0.4

Table D-7

SUBJECT 1 - PERFORMANCE MEASURES FOR K CONTROLLER
INPUT - 1.44 VOLT RMS GAUSSIAN WITH .5 RADIAN CUT-OFF

	IES	ITES	IAE	ITAE
DATA	3.396	0.	11.280	392.000
	3.144	0.	11.320	416.480
	3.000	0.	10.768	384.720
	2.928	0.	10.800	368.240
	3.816	0.	11.048	391.040
	2.748	0.	10.352	369.360
	2.454	0.	9.280	333.520
	3.378	0.	11.568	415.600
	2.592	0.	9.520	296.160
MEAN	3.051	0.	10.660	374.124
VARIANCE	0.166	-0.	0.569	1335.189
STD. DEV.	0.408	-0.	0.755	36.540

SUBJECT 1 - PERFORMANCE MEASURES FOR K CONTROLLER
INPUT - .86 VOLT RMS GAUSSIAN WITH 1 RADIAN CUT-OFF

	IES	ITES	IAE	ITAE
DATA	5.920	74.560	13.941	516.240
	5.344	52.880	13.590	499.680
	5.280	67.680	14.400	503.640
	6.920	121.920	15.345	567.540
MEAN	5.866	79.260	14.319	521.775
VARIANCE	0.432	667.992	0.433	735.543
STD. DEV.	0.658	25.846	0.658	27.121

SUBJECT 1 - PERFORMANCE MEASURES FOR K CONTROLLER
INPUT - .56 VOLT RMS GAUSSIAN WITH 1.5 RADIAN CUT-OFF

	IES	ITES	IAE	ITAE
DATA	4.896	28.640	13.392	487.850
	6.680	95.120	15.471	548.190
	6.728	96.560	15.660	551.700
	7.432	113.920	16.272	591.930
	6.496	85.600	16.110	569.790
	6.928	111.520	15.930	569.790
	5.144	53.760	13.653	600.030
	4.400	7.120	12.474	448.110
	4.640	24.160	12.924	475.200
MEAN	5.927	68.489	14.654	538.060
VARIANCE	1.163	1471.303	2.043	2623.677
STD. DEV.	1.078	38.358	1.429	51.222

Table D-8

SUBJECT 1 - PERFORMANCE MEASURES FOR K/S CONTROLLER
INPUT - 1.44 VOLT RMS GAUSSIAN WITH .5 RADIAN CUT-OFF

	IES	ITES	IAE	ITAE
DATA	5.300	0.	12.960	446.000
	4.540	0.	12.130	416.900
	5.200	0.	12.600	429.800
	4.650	0.	12.000	416.100
	4.400	0.	12.150	416.600
	4.940	0.	12.420	414.000
	5.110	0.	12.860	430.600
	4.160	0.	11.520	399.200
	4.580	0.	12.010	412.100
MEAN	4.764	0.	12.294	420.144
VARIANCE	0.136	-0.	0.187	161.297
STD. DEV.	0.369	-0.	0.433	12.700

SUBJECT 1 - PERFORMANCE MEASURES FOR K/S CONTROLLER
INPUT - .86 VOLT RMS GAUSSIAN WITH 1 RADIAN CUT-OFF

	IES	ITES	IAE	ITAE
DATA	11.344	244.320	18.909	633.150
	10.672	243.040	18.666	630.630
	11.208	266.880	19.620	671.310
	10.024	219.680	18.576	626.760
MEAN	10.812	243.480	18.943	640.462
VARIANCE	0.270	278.725	0.168	322.371
STD. DEV.	0.520	16.695	0.410	17.955

SUBJECT 1 - PERFORMANCE MEASURES FOR K/S CONTROLLER
INPUT - .56 VOLT RMS GAUSSIAN WITH 1.5 RADIAN CUT-OFF

	IES	ITES	IAE	ITAE
DATA	4.938	70.620	13.696	466.240
	5.916	124.140	14.832	525.360
	4.728	80.160	13.168	475.280
	5.460	93.420	14.376	502.480
	5.934	133.860	14.816	534.880
	6.384	143.820	15.224	538.800
	5.676	118.680	13.904	501.920
	5.088	86.640	13.872	490.480
	4.884	77.280	13.440	463.120
MEAN	5.445	103.180	14.148	499.840
VARIANCE	0.290	655.796	0.436	730.715
STD. DEV.	0.538	25.609	0.660	27.032

Table D-9

SUBJECT 1 - PERFORMANCE MEASURES FOR K/S2 CONTROLLER
INPUT - 1.44 VOLT RMS GAUSSIAN WITH .5 RADIAN CUT-OFF

	IES	ITES	IAE	ITAE
DATA	44.415	1363.050	36.140	1176.600
	47.349	1496.610	42.500	1310.000
	30.402	1051.380	33.040	1125.600
	41.220	1297.800	37.290	1220.100
	38.709	1204.110	35.850	1155.500
	31.950	1028.700	34.150	1132.500
	36.216	1272.240	36.090	1199.100
	35.604	1265.760	35.100	1221.000
	43.092	1504.080	38.310	1317.900
MEAN	38.773	1275.970	36.497	1206.478
VARIANCE	29.248	25071.236	6.675	4343.153
STD. DEV.	5.408	158.339	2.584	65.903

SUBJECT 1 - PERFORMANCE MEASURES FOR K/S2 CONTROLLER
INPUT - .86 VOLT RMS GAUSSIAN WITH 1 RADIAN CUT-OFF

	IES	ITES	IAE	ITAE
DATA	58.860	2313.400	44.050	1574.500
	67.200	2414.000	49.710	1641.900
	62.040	2019.600	45.760	1466.400
	61.700	2015.000	46.750	1496.500
MEAN	62.450	2190.500	46.567	1544.825
VARIANCE	9.045	31266.062	4.225	4697.500
STD. DEV.	3.008	176.822	2.055	68.538

SUBJECT 1 - PERFORMANCE MEASURES FOR K/S2 CONTROLLER
INPUT - .56 VOLT RMS GAUSSIAN WITH 1.5 RADIAN CUT-OFF

	IES	ITES	IAE	ITAE
DATA	47.730	1753.700	38.950	1355.500
	38.000	1360.000	37.490	1305.100
	27.210	887.900	32.800	1121.000
	53.400	1996.000	42.320	1452.800
	48.410	2040.900	39.460	1462.400
	51.310	1899.900	39.710	1410.900
	44.680	1728.200	38.320	1358.800
	50.130	1859.700	42.690	1466.100
	46.290	1625.100	39.920	1351.800
MEAN	45.240	1683.489	39.073	1364.933
VARIANCE	58.056	116803.860	7.482	10327.875
STD. DEV.	7.619	341.766	2.735	101.626

Table D-10

SUBJECT 2 - PERFORMANCE MEASURES FOR K CONTROLLER
INPUT - 1.44 VOLT RMS GAUSSIAN WITH .5 RADIAN CUT-OFF

	IES	ITES	IAE	ITAE
DATA	3.256	0.	10.052	310.800
	4.928	0.	13.398	377.230
	3.883	0.	10.633	331.380
	3.536	0.	10.766	313.180
	4.713	0.	12.124	339.780
	4.367	0.	11.690	338.520
	4.070	0.	11.095	328.020
	2.486	0.	8.736	264.950
	2.431	0.	8.442	267.960
MEAN	3.741	0.	10.771	319.091
VARIANCE	0.716	-0.	2.198	1118.416
STD. DEV.	0.846	-0.	1.483	33.443

SUBJECT 2 - PERFORMANCE MEASURES FOR K CONTROLLER
INPUT - .86 VOLT RMS GAUSSIAN WITH 1 RADIAN CUT-OFF

	IES	ITES	IAE	ITAE
DATA	14.850	282.100	20.490	678.500
	9.180	130.200	18.160	618.900
	10.110	100.200	20.040	598.600
	8.600	71.200	18.120	566.900
MEAN	10.685	145.925	19.202	615.725
VARIANCE	6.073	6616.377	1.154	1656.984
STD. DEV.	2.464	81.341	1.074	40.706

SUBJECT 2 - PERFORMANCE MEASURES FOR K CONTROLLER
INPUT - .56 VOLT RMS GAUSSIAN WITH 1.5 RADIAN CUT-OFF

	IES	ITES	IAE	ITAE
DATA	5.620	15.900	14.200	512.500
	6.720	48.800	14.750	522.700
	5.920	15.300	14.480	501.700
	6.320	36.400	14.950	525.500
	6.760	37.600	15.870	524.900
	5.240	0.	13.700	466.100
	9.040	118.100	16.590	539.200
	6.040	10.200	14.360	486.400
	5.650	0.	14.090	471.500
MEAN	6.368	31.367	14.777	505.611
VARIANCE	1.119	1200.433	0.749	593.826
STD. DEV.	1.058	34.647	0.865	24.369

Table D-11

SUBJECT 2 - PERFORMANCE MEASURES FOR K/S CONTROLLER
INPUT - 1.44 VOLT RMS GAUSSIAN WITH .5 RADIAN CUT-OFF

	IES	ITES	IAE	ITAE
DATA	5.420	0.	14.060	443.100
	5.500	0.	14.310	476.100
	6.130	0.	14.700	467.800
	5.960	0.	14.330	457.500
	7.520	44.200	15.780	505.100
	5.680	0.	14.260	466.000
	4.580	0.	12.610	428.000
	5.790	0.	14.120	448.600
	5.190	0.	13.570	455.900
MEAN	5.752	4.911	14.193	460.900
VARIANCE	0.576	192.952	0.637	427.274
STD. DEV.	0.759	13.891	0.798	20.671

SUBJECT 2 - PERFORMANCE MEASURES FOR K/S CONTROLLER
INPUT - .86 VOLT RMS GAUSSIAN WITH 1 RADIAN CUT-OFF

	IES	ITES	IAE	ITAE
DATA	18.900	461.700	26.990	859.100
	21.860	616.400	28.580	964.200
	18.420	494.000	25.650	890.500
	23.140	660.200	29.180	987.200
MEAN	20.580	558.075	27.600	925.250
VARIANCE	3.920	6806.266	1.908	2734.578
STD. DEV.	1.980	82.500	1.381	52.293

SUBJECT 2 - PERFORMANCE MEASURES FOR K/S CONTROLLER
INPUT - .56 VOLT RMS GAUSSIAN WITH 1.5 RADIAN CUT-OFF

	IES	ITES	IAE	ITAE
DATA	9.380	176.800	19.400	704.200
	9.880	172.900	18.620	643.400
	9.650	169.600	18.440	636.900
	9.750	164.800	18.520	642.400
	10.900	187.000	19.420	648.200
	13.090	293.900	21.720	742.800
	12.960	257.000	21.580	704.600
	9.260	117.600	18.410	596.400
	9.460	132.300	18.920	620.000
MEAN	10.481	185.767	19.448	659.878
VARIANCE	2.051	2802.314	1.514	1966.865
STD. DEV.	1.432	52.937	1.231	44.349

Table D-12

SUBJECT 2 - PERFORMANCE MEASURES FOR K/S2 CONTROLLER
INPUT - 1.44 VOLT RMS GAUSSIAN WITH .5 RADIAN CUT-OFF

	IES	ITES	IAE	ITAE
DATA	37.110	1029.900	36.600	1126.000
	46.010	1489.900	38.550	1263.500
	34.780	974.200	35.080	1131.200
	33.470	1007.300	35.090	1154.100
	36.290	1098.000	33.520	1083.800
	24.000	604.700	29.450	935.500
	39.340	1156.600	35.240	1175.600
	29.280	732.200	30.530	923.700
	36.470	1221.300	34.560	1204.400
MEAN	35.184	1034.900	34.291	1110.867
VARIANCE	33.768	60192.597	7.098	11696.139
STD. DEV.	5.811	245.342	2.664	108.149

SUBJECT 2 - PERFORMANCE MEASURES FOR K/S2 CONTROLLER
INPUT - .86 VOLT RMS GAUSSIAN WITH 1 RADIAN CUT-OFF

	IES	ITES	IAE	ITAE
DATA	55.080	1914.200	45.250	1525.500
	53.480	1600.200	44.950	1406.500
	50.600	1709.000	41.420	1438.800
	50.340	1649.600	44.010	1455.900
MEAN	52.375	1718.250	43.907	1456.675
VARIANCE	3.958	14282.687	2.272	1893.656
STD. DEV.	1.989	119.510	1.507	43.516

SUBJECT 2 - PERFORMANCE MEASURES FOR K/S2 CONTROLLER
INPUT - .56 VOLT RMS GAUSSIAN WITH 1.5 RADIAN CUT-OFF

	IES	ITES	IAE	ITAE
DATA	37.656	1223.040	33.060	1147.400
	40.416	1230.240	34.260	1115.400
	39.792	1337.280	35.380	1216.200
	45.660	1629.000	36.190	1278.100
	37.104	1343.760	32.300	1181.000
	47.520	1792.800	36.640	1343.600
	41.412	1561.080	3[illegible].580	1303.200
	37.380	1195.800	33.760	1147.400
	43.200	1690.800	34.610	1299.900
MEAN	41.127	1444.867	34.709	1225.800
VARIANCE	12.262	45339.444	1.683	6074.958
STD. DEV.	3.502	212.931	1.297	77.942

Table D-13

SUBJECT 3 - PERFORMANCE MEASURES FOR K CONTROLLER INPUT - 1.44 VOLT RMS GAUSSIAN WITH .5 RADIAN CUT-OFF				
	IES	ITES	IAE	ITAE
DATA	12.000	296.800	19.416	626.640
	20.550	522.500	21.372	679.080
	13.530	402.700	21.780	736.200
	14.605	423.950	20.280	697.800
	13.720	407.800	18.972	650.880
	12.970	357.000	20.892	689.880
	12.390	324.250	19.800	649.800
	11.960	324.800	19.842	672.780
	9.500	226.000	17.928	579.120
MEAN	13.469	365.089	20.031	664.687
VARIANCE	8.122	6538.587	1.297	1811.056
STD. DEV.	2.850	80.862	1.139	42.556

SUBJECT 3 - PERFORMANCE MEASURES FOR K CONTROLLER INPUT - .86 VOLT RMS GAUSSIAN WITH 1 RADIAN CUT-OFF				
	IES	ITES	IAE	ITAE
DATA	7.500	196.450	15.505	570.150
	8.490	241.000	16.814	614.460
	9.105	244.150	17.318	610.820
	11.690	371.100	19.320	714.000
MEAN	9.196	263.175	17.239	627.357
VARIANCE	2.401	4238.429	1.881	2804.863
STD. DEV.	1.549	65.103	1.372	52.961

SUBJECT 3 - PERFORMANCE MEASURES FOR K CONTROLLER INPUT - .56 VOLT RMS GAUSSIAN WITH 1.5 RADIAN CUT-OFF				
	IES	ITES	IAE	ITAE
DATA	8.980	244.100	18.060	625.800
	7.760	197.700	17.514	615.860
	8.560	192.700	18.284	588.560
	6.960	173.400	15.134	554.260
	11.340	343.200	20.510	734.300
	11.815	370.950	20.685	752.150
	6.530	166.500	15.386	577.640
	8.430	223.100	16.758	592.620
	7.525	182.850	16.198	565.320
MEAN	8.656	232.722	17.614	622.946
VARIANCE	2.981	4972.711	3.592	4593.889
STD. DEV.	1.726	70.517	1.895	67.778

Table D-14

SUBJECT 3 - PERFORMANCE MEASURES FOR K/S CONTROLLER
INPUT - 1.44 VOLT RMS GAUSSIAN WITH .5 RADIAN CUT-OFF

	IES	ITES	IAE	ITAE
	14.208	425.280	24.232	852.080
	14.526	314.940	23.440	710.400
	9.270	212.580	18.864	642.560
DATA	17.352	404.220	26.400	796.000
	10.368	240.780	20.688	676.320
	8.514	166.500	18.776	611.280
	11.460	274.800	22.512	743.680
	10.374	238.500	19.904	665.760
	8.184	173.280	18.488	624.720
MEAN	11.584	272.320	21.478	702.533
VARIANCE	8.679	7703.470	6.989	5874.840
STD. DEV.	2.946	87.769	2.644	76.648

SUBJECT 3 - PERFORMANCE MEASURES FOR K/S CONTROLLER
INPUT - .86 VOLT RMS GAUSSIAN WITH 1 RADIAN CUT-OFF

	IES	ITES	IAE	ITAE
	24.216	766.440	29.240	1009.200
DATA	17.628	480.120	25.960	756.400
	24.114	763.860	30.976	1027.040
	16.128	455.520	24.840	843.600
MEAN	20.521	616.485	27.754	909.060
VARIANCE	13.553	22177.758	6.075	12884.352
STD. DEV.	3.682	148.922	2.465	113.509

SUBJECT 3 - PERFORMANCE MEASURES FOR K/S CONTROLLER
INPUT - .56 VOLT RMS GAUSSIAN WITH 1.5 RADIAN CUT-OFF

	IES	ITES	IAE	ITAE
	13.884	442.800	21.712	783.375
	9.858	280.740	18.007	655.425
	13.950	404.220	22.192	744.825
DATA	18.606	596.940	24.967	851.325
	15.348	507.120	23.062	807.375
	15.018	405.720	23.227	748.725
	17.256	460.440	24.495	764.550
	16.746	354.780	26.100	730.500
	9.520	218.940	17.145	616.050
MEAN	14.354	407.967	22.323	744.683
VARIANCE	9.809	11586.085	8.130	4458.396
STD. DEV.	3.132	107.639	2.851	68.252

Table D-15

SUBJECT 3 - PERFORMANCE MEASURES FOR K/S2 CONTROLLER
INPUT - 1.44 VOLT RMS GAUSSIAN WITH .5 RADIAN CUT-OFF

	IES	ITES	IAE	ITAE
DATA	55.168	1535.520	43.128	807.120
	45.744	1395.360	38.214	1296.360
	51.072	1407.680	43.632	1277.280
	34.664	1062.960	34.650	1133.100
	42.448	928.320	38.034	1010.160
	32.224	706.560	33.858	1065.420
	42.440	999.600	37.854	1054.260
	32.728	819.120	33.210	958.500
	31.776	940.640	32.940	1033.200
MEAN	40.918	1110.640	37.280	1070.600
VARIANCE	66.607	61466.458	14.483	20547.153
STD. DEV.	8.161	247.924	3.806	143.343

SUBJECT 3 - PERFORMANCE MEASURES FOR K/S2 CONTROLLER
INPUT - .86 VOLT RMS GAUSSIAN WITH 1 RADIAN CUT-OFF

	IES	ITES	IAE	ITAE
DATA	95.040	3044.800	55.161	1698.390
	65.968	2267.520	49.473	1568.070
	72.872	2432.880	56.313	1771.470
	46.384	1484.960	39.582	1236.780
MEAN	70.066	2307.540	50.132	1568.677
VARIANCE	302.301	309375.500	43.808	42026.594
STD. DEV.	17.387	556.215	6.619	205.004

SUBJECT 3 - PERFORMANCE MEASURES FOR K/S2 CONTROLLER
INPUT - .56 VOLT RMS GAUSSIAN WITH 1.5 RADIAN CUT-OFF

	IES	ITES	IAE	ITAE
DATA	37.600	1287.200	37.674	1285.560
	45.880	1636.400	40.059	1344.510
	44.080	1609.600	39.690	1358.100
	40.048	1525.920	36.459	1284.210
	77.600	2382.400	55.620	1701.900
	47.224	1790.160	39.438	1396.620
	64.000	1821.600	48.330	1439.100
	58.400	1460.800	47.223	1288.[illegible]70
	100.160	2356.800	59.382	1511.280
MEAN	57.221	1763.431	44.875	1401.050
VARIANCE	376.394	128211.277	60.631	16544.694
STD. DEV.	19.401	358.066	7.787	128.626

Table D-.6

SUBJECT 1 - PERFORMANCE MEASURES FOR K CONTROLLER
INPUT - 1.44 VOLT RMS GAUSSIAN WITH .5 RADIAN CUT-OFF PLUS 1 VOLT STEP

	IES	ITES	IAE	ITAE	STEP TIME
DATA	3.705	0.	13.916	393.263	6.0
	3.579	0.	13.063	371.053	11.9
	3.495	0.	13.947	388.105	13.2
	3.568	0.	13.737	377.158	8.5
	3.411	0.	13.811	361.053	88.0
MEAN	3.552	0.	13.695	378.126	
VARIANCE	0.010	-0.	0.105	134.237	
STD. DEV.	0.098	-0.	0.325	11.586	

INPUT - 1.44 VOLT RMS GAUSSIAN WITH .5 RADIAN CUT-OFF PLUS 3 VOLT STEP

	IES	ITES	IAE	ITAE	STEP TIME
DATA	9.379	57.895	16.547	448.316	12.8
	9.705	20.947	15.800	393.158	8.8
	8.168	13.053	14.547	391.579	11.0
	8.295	39.368	14.926	416.842	12.0
	9.695	24.947	15.421	398.842	7.0
MEAN	9.048	31.242	15.448	409.747	
VARIANCE	0.460	250.572	0.483	452.422	
STD. DEV.	0.678	15.829	0.695	21.270	

INPUT - 1.44 VOLT RMS GAUSSIAN WITH .5 RADIAN CUT-OFF PLUS 5 VOLT STEP

	IES	ITES	IAE	ITAE	STEP TIME
DATA	22.011	237.158	17.221	433.579	13.8
	16.737	125.263	16.926	460.632	12.0
	15.221	93.474	15.768	442.947	10.0
	21.432	128.105	17.789	445.895	8.2
	18.526	90.526	16.737	393.789	6.6
MEAN	18.785	134.905	16.888	435.368	
VARIANCE	6.874	2856.176	0.440	507.700	
STD. DEV.	2.622	53.443	0.664	22.532	

Table D-17

SUBJECT 1 - PERFORMANCE MEASURES FOR K CONTROLLER
INPUT - .56 VOLT RMS GAUSSIAN WITH 1.5 RADIAN CUT-OFF PLUS 1 VOLT STEP

	IES	ITES	IAE	ITAE	STEP TIME
DATA	6.611	16.632	15.632	449.474	9.0
	7.053	21.053	16.316	466.737	6.6
	6.558	16.842	15.074	449.895	11.7
	6.400	12.000	15.337	470.421	12.3
	5.811	0.	14.358	417.579	14.2
MEAN	6.486	13.305	15.343	450.821	
VARIANCE	0.161	52.466	0.415	349.044	
STD. DEV.	0.401	7.243	0.644	18.683	

INPUT - .56 VOLT RMS GAUSSIAN WITH 1.5 RADIAN CUT-OFF PLUS 3 VOLT STEP

	IES	ITES	IAE	ITAE	STEP TIME
DATA	11.747	117.474	17.537	488.421	12.8
	10.284	75.263	17.411	475.368	12.2
	11.495	85.474	18.916	510.421	4.3
	9.347	37.263	15.884	436.316	9.6
	8.368	20.316	14.937	429.368	7.6
MEAN	10.248	67.158	16.937	467.979	
VARIANCE	1.630	1204.144	1.922	953.428	
STD. DEV.	1.277	34.701	1.386	30.878	

INPUT - .56 VOLT RMS GAUSSIAN WITH 1.5 RADIAN CUT-OFF PLUS 5 VOLT STEP

	IES	ITES	IAE	ITAE	STEP TIME
DATA	20.084	140.000	19.074	474.947	7.2
	19.705	190.000	18.905	475.263	12.7
	19.853	136.105	16.989	443.368	8.4
	18.611	81.895	17.411	439.789	5.2
	16.684	120.000	16.842	435.579	10.0
MEAN	18.987	133.600	17.844	453.789	
VARIANCE	1.583	1217.319	0.912	309.005	
STD. DEV.	1.258	34.890	0.955	17.579	

Table D-18

SUBJECT 1 - PERFORMANCE MEASURES FOR K/S CONTROLLER
INPUT - 1.44 VOLT RMS GAUSSIAN WITH .5 RADIAN CUT-OFF PLUS 1 VOLT STEP

	IES	ITES	IAE	ITAE	STEP TIME
	5.600	0.	13.147	368.526	6.5
DATA	5.663	0.	12.832	352.632	6.9
	5.547	0.	13.242	372.842	14.8
	5.579	0.	12.800	356.737	8.8
	5.568	0.	12.716	358.000	16.7
MEAN	5.592	0.	12.947	361.747	
VARIANCE	0.002	-0.	0.043	58.261	
STD. DEV.	0.043	-0.	0.208	7.633	

INPUT - 1.44 VOLT RMS GAUSSIAN WITH .5 RADIAN CUT-OFF PLUS 3 VOLT STEP

	IES	ITES	IAE	ITAE	STEP TIME
	7.158	0.	12.653	329.474	9.7
DATA	7.779	0.	13.063	356.947	5.8
	7.516	0.	12.221	331.158	13.3
	8.000	0.	12.979	348.316	10.1
	8.305	0.	12.463	337.684	7.9
MEAN	7.752	0.	12.676	340.716	
VARIANCE	0.155	-0.	0.099	109.631	
STD. DEV.	0.394	-0.	0.314	10.470	

INPUT - 1.44 VOLT RMS GAUSSIAN WITH .5 RADIAN CUT-OFF PLUS 5 VOLT STEP

	IES	ITES	IAE	ITAE	STEP TIME
	13.989	64.316	13.379	337.526	11.5
DATA	14.674	16.842	13.221	335.579	5.2
	16.442	71.684	14.232	360.737	7.7
	17.547	82.211	14.232	349.789	9.0
	15.947	100.947	12.442	303.789	13.3
MEAN	15.720	67.200	13.501	336.484	
VARIANCE	1.600	785.709	0.456	370.134	
STD. DEV.	1.265	28.031	0.676	19.239	

Table D-19

SUBJECT 1 - PERFORMANCE MEASURES FOR K/S CONTROLLER INPUT - .56 VOLT RMS GAUSSIAN WITH 1.5 RADIAN CUT-OFF PLUS 1 VOLT STEP					
	IES	ITES	IAE	ITAE	STEP TIME
DATA	6.232 5.747 5.937 6.263 5.716	0. 0. 0. 0. 0.	15.032 14.168 14.411 14.937 14.421	454.526 439.474 409.789 411.579 425.895	13.5 10.0 9.2 6.3 3.8
MEAN	5.979	0.	14.594	428.253	
VARIANCE	0.054	-0.	0.111	288.139	
STD. DEV.	0.232	-0.	0.333	16.975	
INPUT - .56 VOLT RMS GAUSSIAN WITH 1.5 RADIAN CUT-OFF PLUS 3 VOLT STEP					
	IES	ITES	IAE	ITAE	STEP TIME
DATA	8.947 8.926 8.211 10.063 9.832	25.474 28.947 27.263 31.474 41.158	14.968 14.737 16.095 16.505 16.800	407.053 417.368 449.579 436.842 454.211	13.4 11.0 8.8 6.0 5.1
MEAN	9.196	30.863	15.821	433.011	
VARIANCE	0.452	30.406	0.681	331.428	
STD. DEV.	0.673	5.514	0.825	18.205	
INPUT - .56 VOLT RMS GAUSSIAN WITH 1.5 RADIAN CUT-OFF PLUS 5 VOLT STEP					
	IES	ITES	IAE	ITAE	STEP TIME
DATA	18.474 19.821 16.558 16.484 19.074	178.632 171.368 99.789 82.842 100.000	16.084 18.421 16.126 16.821 17.642	468.632 457.895 481.263 482.526 469.789	13.9 10.5 8.2 6.8 5.6
MEAN	18.082	126.526	17.019	472.021	
VARIANCE	1.807	1610.518	0.813	82.366	
STD. DEV.	1.344	40.131	0.902	9.076	

Table D-20

SUBJECT 1 - PERFORMANCE MEASURES FOR K/S2 CONTROLLER
INPUT - 1.44 VOLT RMS GAUSSIAN WITH .5 RADIAN CUT-OFF PLUS 1 VOLT STEP

	IES	ITES	IAE	ITAE	STEP TIME
DATA	44.063	1006.737	41.453	1187.579	9.0
	51.537	1486.737	41.642	1324.632	10.3
	27.242	680.842	32.211	917.895	12.5
	37.926	986.947	39.032	1108.632	8.1
	48.821	1347.895	41.768	1267.579	[illegible].7
MEAN	41.918	1101.832	39.221	1161.263	
VARIANCE	75.218	81634.537	13.363	20136.637	
STD. DEV.	8.673	285.719	3.647	141.904	

INPUT - 1.44 VOLT RMS GAUSSIAN WITH .5 RADIAN CUT-OFF PLUS 3 VOLT STEP

	IES	ITES	IAE	ITAE	STEP TIME
DATA	66.000	1686.316	47.579	1344.211	12.2
	46.568	1205.895	40.158	1167.695	8.0
	53.589	1504.105	43.789	1298.947	10.0
	33.211	756.316	34.168	957.263	8.4
	60.053	1622.632	48.632	1385.263	4.8
MEAN	51.884	1355.053	42.865	1230.716	
VARIANCE	129.170	116856.899	27.858	24028.875	
STD. DEV.	11.365	341.843	5.278	155.012	

INPUT - 1.44 VOLT RMS GAUSSIAN WITH .5 RADIAN CUT-OFF PLUS 5 VOLT STEP

	IES	ITES	IAE	ITAE	STEP TIME
DATA	64.232	1976.632	43.074	1171.368	10.4
	47.305	872.211	34.958	924.105	8.5
	63.853	1290.947	43.011	1127.789	6.5
	47.884	808.526	38.347	980.737	4.2
	93.032	1962.316	50.653	1308.210	12.9
MEAN	63.261	1382.126	42.008	1102.442	
VARIANCE	275.722	257430.225	27.995	18870.075	
STD. DEV.	16.605	507.425	5.291	137.368	

Table D-21

SUBJECT 1 - PERFORMANCE MEASURES FOR K/S2 CONTROLLER
INPUT - .56 VOLT RMS GAUSSIAN WITH 1.5 RADIAN CUT-OFF PLUS 1 VOLT STEP

	IES	ITES	IAE	ITAE	STEP TIME
DATA	72.821	1736.000	50.716	1534.947	13.8
	48.032	1488.105	40.926	1260.211	11.0
	51.832	1803.789	41.695	1378.842	8.5
	43.905	1532.526	38.442	1297.684	4.7
	41.642	1521.474	37.811	1285.053	5.8
MEAN	51.546	1616.379	41.918	1351.347	
VARIANCE	124.296	16384.875	21.478	10009.175	
STD. DEV.	11.149	128.003	4.634	100.046	

INPUT - .56 VOLT RMS GAUSSIAN WITH 1.5 RADIAN CUT-OFF PLUS 3 VOLT STEP

	IES	ITES	IAE	ITAE	STEP TIME
DATA	55.958	1768.842	43.832	1321.684	14.3
	61.979	1654.421	43.663	1259.158	10.6
	46.147	1386.947	39.232	1166.632	8.5
	52.337	1654.526	40.916	1224.526	6.2
	60.737	1726.316	46.021	1365.053	4.4
MEAN	55.832	1640.210	42.733	1267.410	
VARIANCE	26.626	17778.800	5.689	4908.687	
STD. DEV.	5.160	133.337	2.385	70.062	

INPUT - .56 VOLT RMS GAUSSIAN WITH 1.5 RADIAN CUT-OFF PLUS 5 VOLT STEP

	IES	ITES	IAE	ITAE	STEP TIME
DATA	61.347	1498.105	40.653	1171.789	13.3
	76.000	2130.526	65.789	1349.474	7.8
	73.137	1492.842	44.211	1130.526	9.2
	52.021	990.316	38.168	1035.158	4.5
	93.789	1847.368	52.337	1285.053	10.8
MEAN	71.259	1591.832	44.232	1194.400	
VARIANCE	200.393	147179.174	23.539	12443.000	
STD. DEV.	14.156	383.639	4.852	111.548	

Table D-22

SUBJECT 2 - PERFORMANCE MEASURES FOR K CONTROLLER
INPUT - 1.44 VOLT RMS GAUSSIAN WITH .5 RADIAN CUT-OFF PLUS 1 VOLT STEP

	IES	ITES	IAE	ITAE	STEP TIME
DATA	4.558	0.	12.126	359.158	14.7
	5.032	0.	12.526	363.684	10.2
	3.979	0.	11.221	341.053	9.0
	4.263	0.	11.363	365.895	8.0
	4.274	0.	11.368	355.158	4.2
MEAN	4.421	0.	11.722	356.989	
VARIANCE	0.127	-0.	0.262	77.234	
STD. DEV.	0.356	-0.	0.512	8.788	

INPUT - 1.44 VOLT RMS GAUSSIAN WITH .5 RADIAN CUT-OFF PLUS 3 VOLT STEP

	IES	ITES	IAE	ITAE	STEP TIME
DATA	9.274	0.	12.947	363.474	9.1
	7.642	0.	13.316	401.474	13.6
	6.400	0.	11.674	350.526	7.2
	6.895	0.	11.895	343.474	4.2
	7.811	0.	12.821	374.421	9.9
MEAN	7.604	0.	12.531	366.674	
VARIANCE	0.957	-0.	0.403	416.056	
STD. DEV.	0.978	-0.	0.635	20.397	

INPUT - 1.44 VOLT RMS GAUSSIAN WITH .5 RADIAN CUT-OFF PLUS 5 VOLT STEP

	IES	ITES	IAE	ITAE	STEP TIME
DATA	20.642	226.000	16.442	469.[illegible]84	14.1
	15.284	71.368	14.789	400.421	10.8
	13.747	3.789	13.642	365.474	6.0
	17.642	56.632	15.011	394.316	7.0
	14.116	52.737	13.716	362.632	11.9
MEAN	16.286	82.105	14.720	398.505	
VARIANCE	6.595	5693.150	1.045	1493.137	
STD. DEV.	2.568	75.453	1.022	38.641	

Table D-23

SUBJECT 2 - PERFORMANCE MEASURES FOR K CONTROLLER

INPUT - .56 VOLT RMS GAUSSIAN WITH 1.5 RADIAN CUT-OFF PLUS 1 VOLT STEP

	IES	ITES	IAE	ITAE	STEP TIME
DATA	7.326	42.316	15.959	507.789	13.5
	8.505	85.053	17.411	557.263	10.1
	8.242	70.000	17.053	534.842	8.8
	6.621	12.316	14.242	486.000	8.6
	7.326	51.579	15.789	507.579	4.5
MEAN	7.604	52.253	16.091	518.695	
VARIANCE	0.468	616.991	1.239	611.944	
STD. DEV.	0.684	24.839	1.113	24.737	

INPUT - .56 VOLT RMS GAUSSIAN WITH 1.5 RADIAN CUT-OFF PLUS 3 VOLT STEP

	IES	ITES	IAE	ITAE	STEP TIME
DATA	11.474	112.211	18.316	566.105	4.7
	12.611	94.316	18.095	527.684	6.3
	10.442	89.368	17.505	541.263	8.4
	11.242	112.105	17.905	547.053	10.5
	12.768	159.684	18.358	563.579	14.7
MEAN	11.707	113.537	18.036	549.137	
VARIANCE	0.763	617.390	0.097	204.616	
STD. DEV.	0.873	24.847	0.311	14.304	

INPUT - .56 VOLT RMS GAUSSIAN WITH 1.5 RADIAN CUT-OFF PLUS 5 VOLT STEP

	IES	ITES	IAE	ITAE	STEP TIME
DATA	14.421	27.389	18.525	562.105	14.3
	14.400	34.116	19.432	534.105	11.7
	14.832	22.579	18.663	519.684	8.6
	14.800	15.863	17.663	510.105	7.2
	15.305	16.705	19.263	543.789	4.0
MEAN	14.752	23.331	18.709	533.958	
VARIANCE	0.110	46.604	0.392	332.334	
STD. DEV.	0.331	6.827	0.626	18.230	

Table D-24

SUBJECT 2 - PERFORMANCE MEASURES FOR K/S CONTROLLER
INPUT - 1.44 VOLT RMS GAUSSIAN WITH .5 RADIAN CUT-OFF PLUS 1 VOLT STEP

	IES	ITES	IAE	ITAE	STEP TIME
DATA	7.811	55.789	15.958	477.263	13.7
	7.411	48.632	16.000	476.421	10.2
	7.463	42.421	15.495	470.947	9.2
	8.305	74.947	16.400	496.000	7.2
	7.432	68.737	15.547	490.532	3.6
MEAN	7.684	58.105	15.880	482.[illegible]53	
VARIANCE	0.118	147.559	0.110	89.184	
STD. DEV.	0.343	12.147	0.332	9.444	

INPUT - 1.44 VOLT RMS GAUSSIAN WITH .5 RADIAN CUT-OFF PLUS 3 VOLT STEP

	IES	ITES	IAE	ITAE	STEP TIME
DATA	16.600	200.316	19.389	532.632	15.0
	13.074	125.263	17.516	472.000	11.4
	14.505	129.158	18.368	499.474	9.2
	15.516	145.895	19.116	526.526	6.2
	11.737	62.842	17.221	472.211	5.0
MEAN	14.286	132.695	18.322	500.568	
VARIANCE	2.977	1938.795	0.727	664.678	
STD. DEV.	1.725	44.032	0.853	25.781	

INPUT - 1.44 VOLT RMS GAUSSIAN WITH .5 RADIAN CUT-OFF PLUS 5 VOLT STEP

	IES	ITES	IAE	ITAE	STEP TIME
DATA	30.021	238.842	21.168	495.684	7.4
	23.684	111.053	19.368	467.053	4.2
	27.095	226.211	19.358	479.57[illegible]	8.4
	25.042	256.316	17.863	465.158	11.7
	30.800	445.263	21.421	589.263	13.6
MEAN	27.328	255.537	19.836	499.347	
VARIANCE	7.573	11602.225	1.725	2140.187	
STD. DEV.	2.752	107.714	1.314	46.262	

Table D-25

SUBJECT 2 - PERFORMANCE MEASURES FOR K/S CONTROLLER
INPUT - .56 VOLT RMS GAUSSIAN WITH 1.5 RADIAN CUT-OFF PLUS 1 VOLT STEP

	IES	ITES	IAE	ITAE	STEP TIME
	15.147	363.789	23.147	751.474	16.0
DATA	13.895	247.263	21.895	646.842	11.6
	11.716	218.737	20.084	630.947	10.0
	13.505	280.[illegible]05	21.053	646.632	5.6
	11.158	194.842	19.853	595.474	3.2
MEAN	13.084	260.947	21.206	654.274	
VARIANCE	2.135	3456.483	1.471	2712.612	
STD. DEV.	1.461	58.792	1.213	52.083	

INPUT - .56 VOLT RMS GAUSSIAN WITH 1.5 RADIAN CUT-OFF PLUS 3 VOLT STEP

	IES	ITES	IAE	ITAE	STEP TIME
	17.684	[illegible]31.684	23.421	719.895	4.7
DATA	16.853	231.684	22.168	642.947	5.9
	20.211	324.737	22.895	664.316	8.8
	18.463	341.684	22.453	655.579	11.6
	16.379	277.263	21.674	617.158	14.4
MEAN	17.918	301.411	22.52[illegible]	659.979	
VARIANCE	1.822	1705.489	0.359	1150.362	
STD. DEV.	1.350	41.298	0.599	33.917	

INPUT - .56 VOLT RMS GAUSSIAN WITH 1.5 RADIAN CUT-OFF PLUS 5 VOLT STEP

	IES	ITES	IAE	ITAE	STEP TIME
	33.579	683.263	27.495	830.316	14.3
DATA	44.000	683.158	28.547	753.263	11.2
	32.000	402.526	24.253	639.579	9.2
	33.389	410.737	25.000	674.211	7.0
	30.642	251.053	23.147	577.158	4.5
MEAN	34.722	486.147	25.688	6[illegible]4.9[illegible]5	
VARIANCE	22.644	29123.315	4.086	7819.081	
STD. DEV.	4.759	170.656	2.021	88.426	

Table D-26

SUBJECT 2 - PERFORMANCE MEASURES FOR K/S2 CONTROLLER
INPUT - 1.44 VOLT RMS GAUSSIAN WITH .5 RADIAN CUT-OFF PLUS 1 VOLT STEP

	IES	ITES	IAE	ITAE	STEP TIME
DATA	47.811	1671.368	39.811	1252.421	3.7
	42.842	1356.942	37.432	1154.316	6.2
	32.842	1003.158	33.558	1046.526	8.3
	45.695	1543.053	40.579	1300.526	11.5
	38.684	1145.789	35.200	1056.421	14.4
MEAN	41.575	1344.042	37.316	1162.042	
VARIANCE	28.416	60483.525	7.097	10381.137	
STD. DEV.	5.331	245.934	2.664	101.888	

INPUT - 1.44 VOLT RMS GAUSSIAN WITH .5 RADIAN CUT-OFF PLUS 3 VOLT STEP

	IES	ITES	IAE	ITAE	STEP TIME
DATA	42.032	1189.158	38.305	1115.895	14.4
	39.011	934.105	37.432	1018.316	10.4
	49.568	1167.474	40.011	1065.158	8.7
	58.084	1337.053	42.547	1169.263	6.5
	46.042	1088.000	39.263	1057.895	5.7
MEAN	46.947	1143.158	39.512	1085.305	
VARIANCE	43.775	17409.587	3.062	2725.900	
STD. DEV.	6.616	131.945	1.750	52.210	

INPUT - 1.44 VOLT RMS GAUSSIAN WITH .5 RADIAN CUT-OFF PLUS 5 VOLT STEP

	IES	ITES	IAE	ITAE	STEP TIME
DATA	49.684	1382.105	38.716	1156.000	14.2
	58.674	1458.526	41.221	1172.000	10.4
	52.411	1235.895	40.558	1102.842	9.5
	68.453	1403.895	44.926	1197.053	5.5
	75.874	1567.579	48.632	1325.263	2.8
MEAN	61.019	1409.600	42.811	1190.632	
VARIANCE	96.801	11662.600	12.546	5484.075	
STD. DEV.	9.839	107.994	3.542	74.055	

Table D-27

SUBJECT 2 - PERFORMANCE MEASURES FOR K/S2 CONTROLLER
INPUT - .56 VOLT RMS GAUSSIAN WITH 1.5 RADIAN CUT-OFF PLUS 1 VOLT STEP

	IES	ITES	IAE	ITAE	STEP TIME
DATA	51.789	1517.895	43.442	1274.000	3.4
	65.547	2803.474	43.789	1533.684	6.9
	44.126	1617.684	39.084	1286.000	9.2
	40.989	1409.053	38.663	1261.789	10.0
	49.095	1637.684	42.484	1346.737	15.5
MEAN	50.309	1797.158	41.493	1340.442	
VARIANCE	72.191	259785.574	4.773	10189.375	
STD. DEV.	8.497	509.692	2.185	100.942	

INPUT - .56 VOLT RMS GAUSSIAN WITH 1.5 RADIAN CUT-OFF PLUS 3 VOLT STEP

	IES	ITES	IAE	ITAE	STEP TIME
DATA	56.274	1654.105	44.358	1293.263	11.3
	53.411	1482.737	42.537	1223.053	14.2
	66.716	2213.895	43.853	1361.474	9.4
	63.947	1876.316	48.147	1424.842	6.2
	58.968	1652.421	44.358	1293.263	6.8
MEAN	59.863	1775.895	44.651	1319.179	
VARIANCE	23.792	63589.725	3.501	4707.425	
STD. DEV.	4.878	252.170	1.871	68.611	

INPUT - .56 VOLT RMS GAUSSIAN WITH 1.5 RADIAN CUT-OFF PLUS 5 VOLT STEP

	IES	ITES	IAE	ITAE	STEP TIME
DATA	98.421	2772.632	55.874	1666.526	10.5
	79.484	2469.368	49.895	1569.474	13.7
	58.358	3300.632	38.979	1030.211	8.4
	77.326	1769.895	46.484	1303.579	7.0
	101.126	1898.210	50.874	1352.316	4.0
MEAN	82.943	2442.147	48.421	1384.421	
VARIANCE	243.628	318949.500	31.327	49371.825	
STD. DEV.	15.609	564.756	5.597	222.198	

Table D-28

SUBJECT 3 - PERFORMANCE MEASURES FOR K CONTROLLER
INPUT - 1.44 VOLT RMS GAUSSIAN WITH .5 RADIAN CUT-OFF PLUS 1 VOLT STEP

	IES	ITES	IAE	ITAE	STEP TIME
DATA	13.811	254.000	22.274	666.211	15.8
	18.242	374.211	22.695	716.211	11.8
	23.516	476.632	22.926	650.421	3.6
	14.116	182.211	19.926	523.263	9.4
	15.368	264.737	20.989	572.632	5.7
MEAN	17.011	310.358	21.762	625.747	
VARIANCE	13.030	10680.670	1.291	4750.791	
STD. DEV.	3.610	103.347	1.136	68.926	

INPUT - 1.44 VOLT RMS GAUSSIAN WITH .5 RADIAN CUT-OFF PLUS 3 VOLT STEP

	IES	ITES	IAE	ITAE	STEP TIME
DATA	63.968	1415.053	28.221	764.526	14.2
	27.011	467.263	25.905	657.368	10.4
	18.032	210.632	20.653	532.947	9.0
	33.516	853.263	31.832	975.368	6.9
	32.295	624.421	30.558	829.158	3.9
MEAN	34.964	714.126	27.434	751.874	
VARIANCE	240.099	166630.437	15.608	22588.569	
STD. DEV.	15.495	408.204	3.951	150.295	

INPUT - 1.44 VOLT RMS GAUSSIAN WITH .5 RADIAN CUT-OFF PLUS 5 VOLT STEP

	IES	ITES	IAE	ITAE	STEP TIME
DATA	56.842	997.895	32.653	774.526	9.2
	38.379	566.632	28.074	688.632	10.4
	30.789	516.421	30.737	782.105	6.3
	62.316	1155.789	37.874	1011.789	4.2
	66.832	1340.105	40.989	942.737	14.2
MEAN	51.032	915.368	34.065	839.958	
VARIANCE	196.114	105158.137	22.284	14123.512	
STD. DEV.	14.004	324.281	4.721	118.842	

Table D-29

SUBJECT 3 - PERFORMANCE MEASURES FOR K CONTROLLER
INPUT - .56 VOLT RMS GAUSSIAN WITH 1.5 RADIAN CUT-OFF PLUS 1 VOLT STEP

	IES	ITES	IAE	ITAE	STEP TIME
DATA	9.811 9.263 9.368 13.579 9.979	189.053 134.947 153.684 238.842 161.053	17.747 17.695 20.063 22.747 18.221	562.737 514.421 529.158 634.316 527.895	3.9 7.2 9.2 11.0 13.7
MEAN	10.400	175.516	19.295	553.705	
VARIANCE	2.597	1305.013	3.724	1878.331	
STD. DEV.	1.612	36.125	1.930	43.340	

INPUT - .56 VOLT RMS GAUSSIAN WITH 1.5 RADIAN CUT-OFF PLUS 3 VOLT STEP

	IES	ITES	IAE	ITAE	STEP TIME
DATA	19.347 15.905 14.442 20.705 25.158	326.632 181.579 222.000 331.368 354.316	23.284 21.305 21.495 25.589 25.537	625.053 543.053 591.295 657.579 670.105	13.1 10.1 8.9 6.3 4.3
MEAN	19.112	283.179	23.442	617.537	
VARIANCE	14.248	4667.246	3.476	2125.747	
STD. DEV.	3.775	68.317	1.365	46.106	

INPUT - .56 VOLT RMS GAUSSIAN WITH 1.5 RADIAN CUT-OFF PLUS 5 VOLT STEP

	IES	ITES	IAE	ITAE	STEP TIME
DATA	35.663 40.337 34.463 47.958 39.368	620.842 737.684 510.737 480.967 288.000	26.926 28.738 29.253 27.168 23.305	691.789 770.316 702.105 571.684 527.684	14.2 11.4 8.8 7.1 4.8
MEAN	39.558	527.642	27.082	652.716	
VARIANCE	22.466	22539.690	4.363	7998.969	
STD. DEV.	4.740	150.132	2.089	89.437	

Table D-30

SUBJECT 3 - PERFORMANCE MEASLRES FOR K/S CONTROLLER INPUT - 1.44 VOLT RMS GAUSSIAN WITH .5 RADIAN CUT-OFF PLUS 1 VOLT STEP					
	IES	ITES	IAE	ITAE	STEP TIME
DATA	13.484 11.463 14.021 13.663 11.305	238.632 240.000 295.368 254.105 230.737	22.042 19.979 21.684 22.411 29.926	598.947 598.737 634.421 624.947 467.158	14.4 10.9 7.4 9.4 5.2
MEAN	12.787	251.768	23.208	584.842	
VARIANCE	1.345	531.965	11.976	3661.622	
STD. DEV.	1.160	23.064	3.461	60.511	
INPUT - 1.44 VOLT RMS GAUSSIAN WITH .5 RADIAN CUT-OFF PLUS 3 VOLT STEP					
	IES	ITES	IAE	ITAE	STEP TIME
DATA	22.747 20.884 18.621 24.726 13.726	344.526 341.895 238.947 290.632 173.579	21.874 25.179 21.779 25.432 21.368	544.737 629.895 568.105 581.158 546.632	13.5 10.0 8.5 7.0 4.3
MEAN	20.141	277.916	23.126	574.105	
VARIANCE	14.366	4219.337	3.200	963.103	
STD. DEV.	3.790	64.956	1.789	31.034	
INPUT - 1.44 VOLT RMS GAUSSIAN WITH .5 RADIAN CUT-OFF PLUS 5 VOLT STEP					
	IES	ITES	IAF	ITAE	STEP TIME
DATA	34.463 43.189 35.326 54.674 59.916	319.474 465.789 450.842 781.684 1050.316	25.747 27.053 24.411 30.937 29.368	607.684 648.842 571.158 667.895 725.895	3.9 6.2 9.2 12.1 15.0
MEAN	45.514	613.621	27.503	644.295	
VARIANCE	104.525	70764.269	5.624	2785.109	
STD. DEV.	10.224	266.016	2.371	52.774	

Table D-31

SUBJECT 3 - PERFORMANCE MEASURES FOR K/S CONTROLLER
INPUT - .56 VOLT RMS GAUSSIAN WITH 1.5 RADIAN CUT-OFF PLUS 1 VOLT STEP

	IES	ITES	IAE	ITAE	STEP TIME
DATA	16.579	415.263	23.800	768.737	5.8
	16.137	392.842	24.674	720.842	7.2
	12.937	300.421	21.105	654.316	10.3
	17.179	340.842	25.200	684.009	11.2
	15.368	399.474	23.347	711.684	13.0
MEAN	15.640	369.768	23.625	707.916	
VARIANCE	2.176	1826.072	2.007	1465.094	
STD. DEV.	1.475	42.733	1.417	38.277	

INPUT - .56 VOLT RMS GAUSSIAN WITH 1.5 RADIAN CUT-OFF PLUS 3 VOLT STEP

	IES	ITES	IAE	ITAE	STEP TIME
DATA	21.442	478.211	25.779	771.789	4.6
	27.589	415.263	28.926	726.316	7.4
	26.095	421.579	28.958	707.789	10.1
	28.095	553.789	28.989	771.158	12.0
	26.653	566.526	29.179	790.316	16.1
MEAN	25.975	487.074	28.366	753.474	
VARIANCE	5.624	4057.719	1.681	966.031	
STD. DEV.	2.372	63.700	1.297	31.081	

INPUT - .56 VOLT RMS GAUSSIAN WITH 1.5 RADIAN CUT-OFF PLUS 5 VOLT STEP

	IES	ITES	IAE	ITAE	STEP TIME
DATA	41.726	757.474	28.737	757.263	13.0
	38.600	608.947	30.832	729.158	11.1
	46.484	653.053	32.653	750.316	8.7
	42.821	600.842	32.684	781.579	6.2
	48.211	751.579	30.295	744.737	9.8
MEAN	43.568	674.379	31.040	752.611	
VARIANCE	11.738	4601.687	2.241	295.631	
STD. DEV.	3.426	67.936	1.497	17.194	

Table D-32

SUBJECT 3 - PERFORMANCE MEASURES FOR K/S2 CONTROLLER
INPUT - 1.44 VOLT RMS GAUSSIAN WITH .5 RADIAN CUT-OFF PLUS 1 VOLT STEP

	IES	ITES	IAE	ITAE	STEP TIME
DATA	63.905	1612.526	48.168	1312.000	4.8
	49.095	1455.368	41.747	1270.947	8.6
	40.116	1133.579	37.853	1076.211	12.0
	53.032	1886.526	43.505	1367.053	22.5
	48.147	1372.210	41.442	1217.158	6.5
MEAN	50.859	1492.042	42.543	1248.674	
VARIANCE	60.161	62867.000	11.283	9851.337	
STD. DEV.	7.756	250.733	3.359	99.254	

INPUT - 1.44 VOLT RMS GAUSSIAN WITH .5 RADIAN CUT-OFF PLUS 3 VOLT STEP

	IES	ITES	IAE	ITAE	STEP TIME
DATA	74.442	4356.632	51.011	1424.632	12.3
	88.126	4346.105	52.274	1348.842	10.4
	49.411	3679.579	41.737	1275.263	8.5
	60.989	3644.842	42.547	1049.263	5.3
	61.137	3837.053	44.484	1172.000	15.1
MEAN	66.821	3972.842	46.411	1254.000	
VARIANCE	176.288	99729.399	19.203	17440.725	
STD. DEV.	13.277	315.800	4.382	132.063	

INPUT - 1.44 VOLT RMS GAUSSIAN WITH .5 RADIAN CUT-OFF PLUS 5 VOLT STEP

	IES	ITES	IAE	ITAE	STEP TIME
DATA	93.305	4279.579	52.126	1308.210	5.0
	90.726	4207.474	51.147	1244.316	8.3
	76.284	3715.053	44.779	1133.263	9.7
	104.379	4295.158	53.389	1575.579	12.3
	74.147	3815.368	45.568	1335.895	14.5
MEAN	87.768	4062.526	49.402	1319.453	
VARIANCE	126.547	60813.000	12.487	21261.900	
STD. DEV.	11.249	246.603	3.534	145.815	

Table D-33

SUBJECT 3 - PERFORMANCE MEASURES FOR K/S2 CONTROLLER

INPUT - .56 VOLT RMS GAUSSIAN WITH 1.5 RADIAN CUT-OFF PLUS 1 VOLT STEP

	IES	ITES	IAE	ITAE	STEP TIME
DATA	67.179	2475.579	46.000	1525.263	17.7
	64.568	2145.895	50.274	1518.316	13.8
	56.105	2076.842	46.105	1491.579	10.2
	55.684	2064.211	44.032	1424.947	7.5
	82.463	2797.474	55.505	1678.632	4.1
MEAN	65.600	2312.000	48.[illegible]	1527.747	
VARIANCE	88.484	81346.449	16.[illegible]	6947.475	
STD. DEV.	9.407	285.213	4.101	83.352	

INPUT - .56 VOLT RMS GAUSSIAN WITH 1.5 RADIAN CUT-OFF PLUS 3 VOLT STEP

	IES	ITES	IAE	ITAE	STEP TIME
DATA	71.116	2297.263	52.305	1586.421	4.7
	93.116	2725.684	59.737	1719.474	6.8
	79.189	2687.053	52.863	1595.579	9.5
	108.842	2446.316	61.347	1536.000	11.6
	97.568	3563.263	57.211	1808.947	14.7
MEAN	89.966	274[illegible].916	56.693	1649.284	
VARIANCE	179.098	192592.199	13.023	10017.725	
STD. DEV.	13.383	438.853	3.609	100.089	

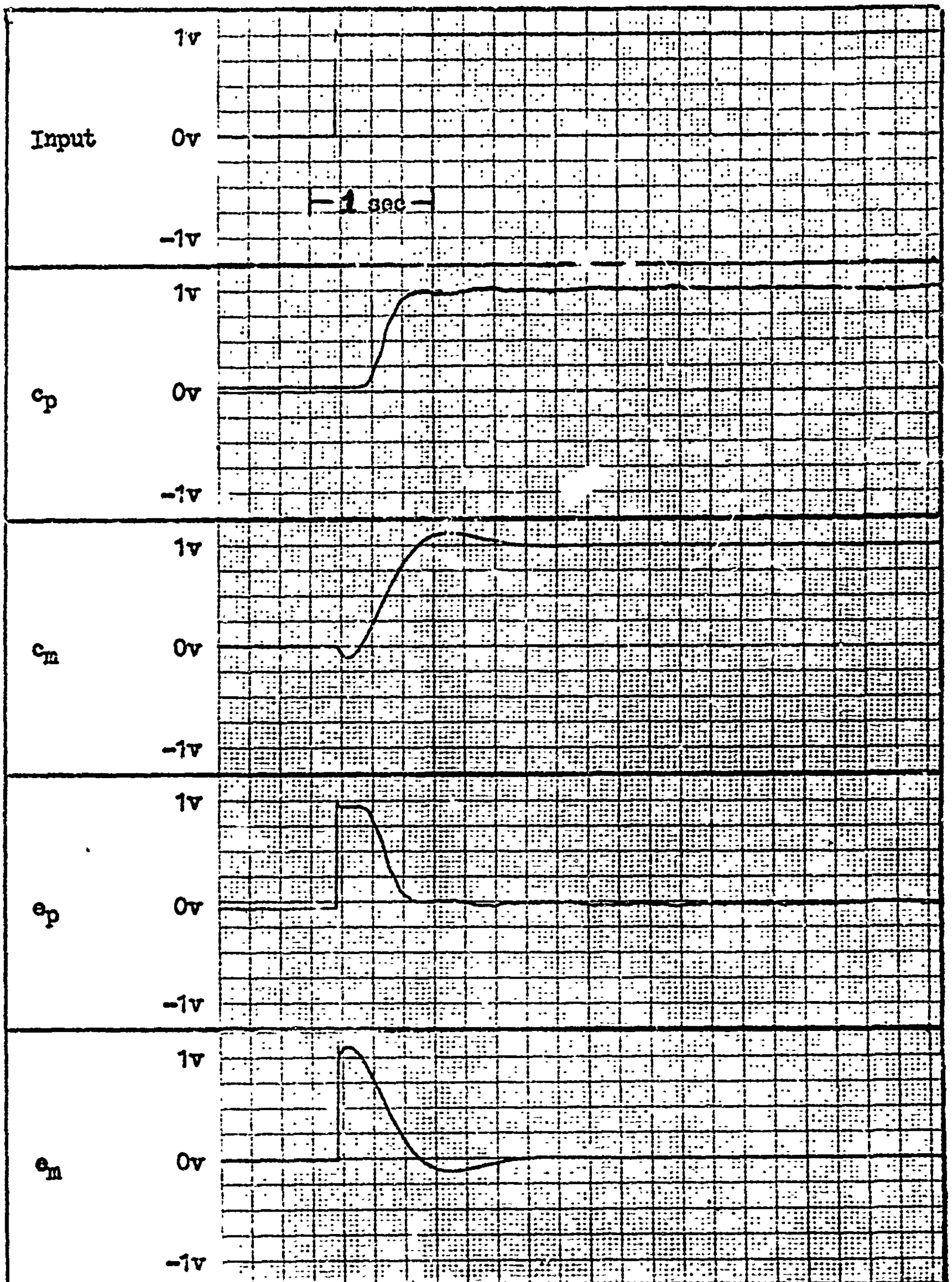
INPUT - .56 VOLT RMS GAUSSIAN WITH 1.5 RADIAN CUT-OFF PLUS 5 VOLT STEP

	IES	ITES	IAE	ITAE	STEP TIME
DATA	82.000	2051.579	49.179	1375.579	14.3
	102.832	2985.368	58.484	1623.579	10.9
	115.053	2338.947	60.179	1438.210	8.0
	75.368	1844.211	49.453	1356.000	7.2
	109.579	2393.684	58.126	1511.368	5.2
MEAN	96.966	2322.758	55.084	1460.947	
VARIANCE	242.211	149378.199	22.672	9562.075	
STD. DEV.	15.563	386.495	4.761	97.786	

Appendix E

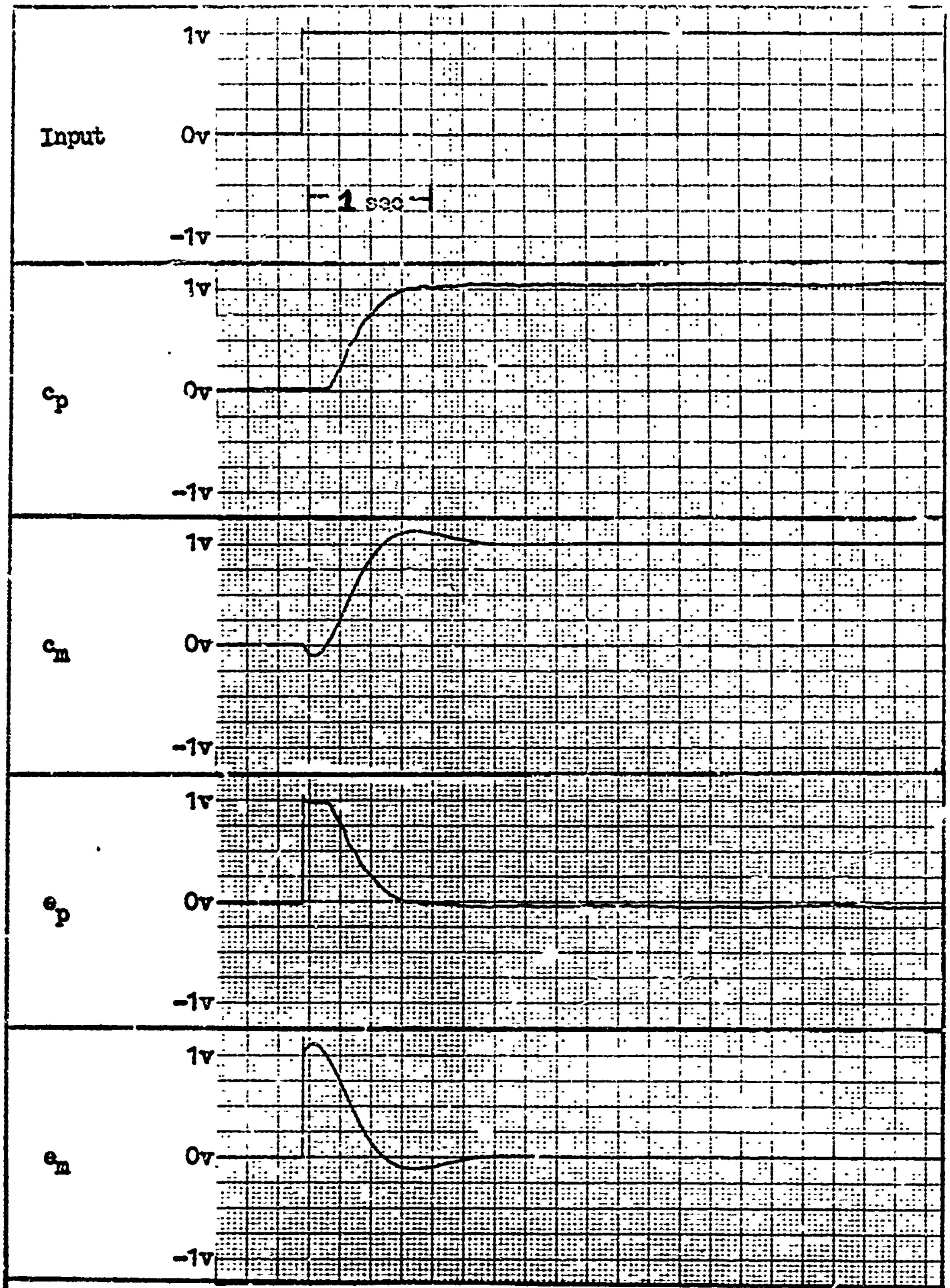
Real Time Recordings from the Analog Programs

The following are real time recordings made with both piloted and model systems operating simultaneously. The input, output and error signals are shown. Figures E-1 through E-6 show the output and error with a step input. Figures E-7 through E-13 show the output and error with a Gaussian, and Figures E-14 through E-20 show the output and error with combined inputs.



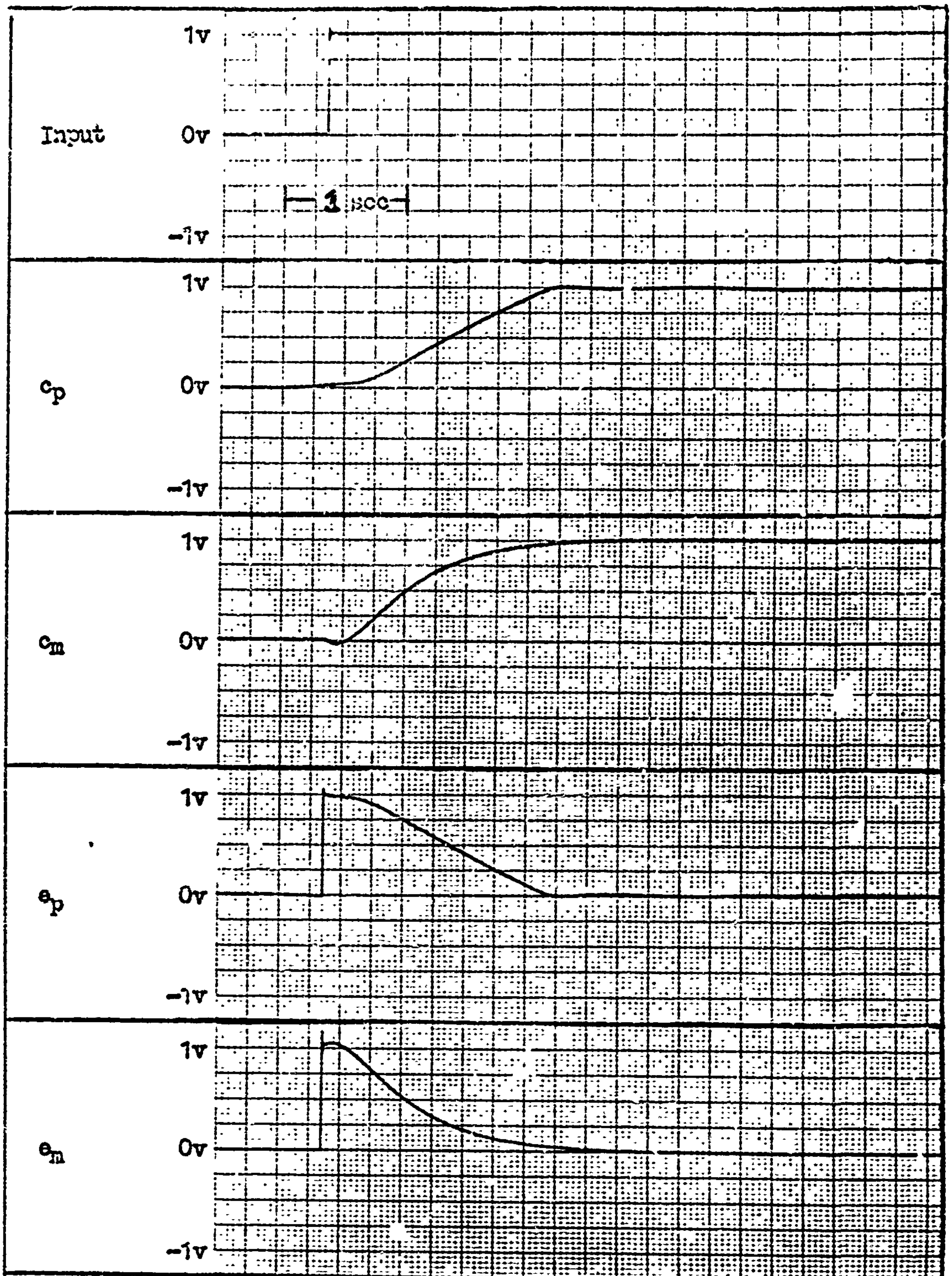
Subject 1 - K System: $\Upsilon = 0.2$, $T_I = 3$, $X_p = 10$

Figure E-1



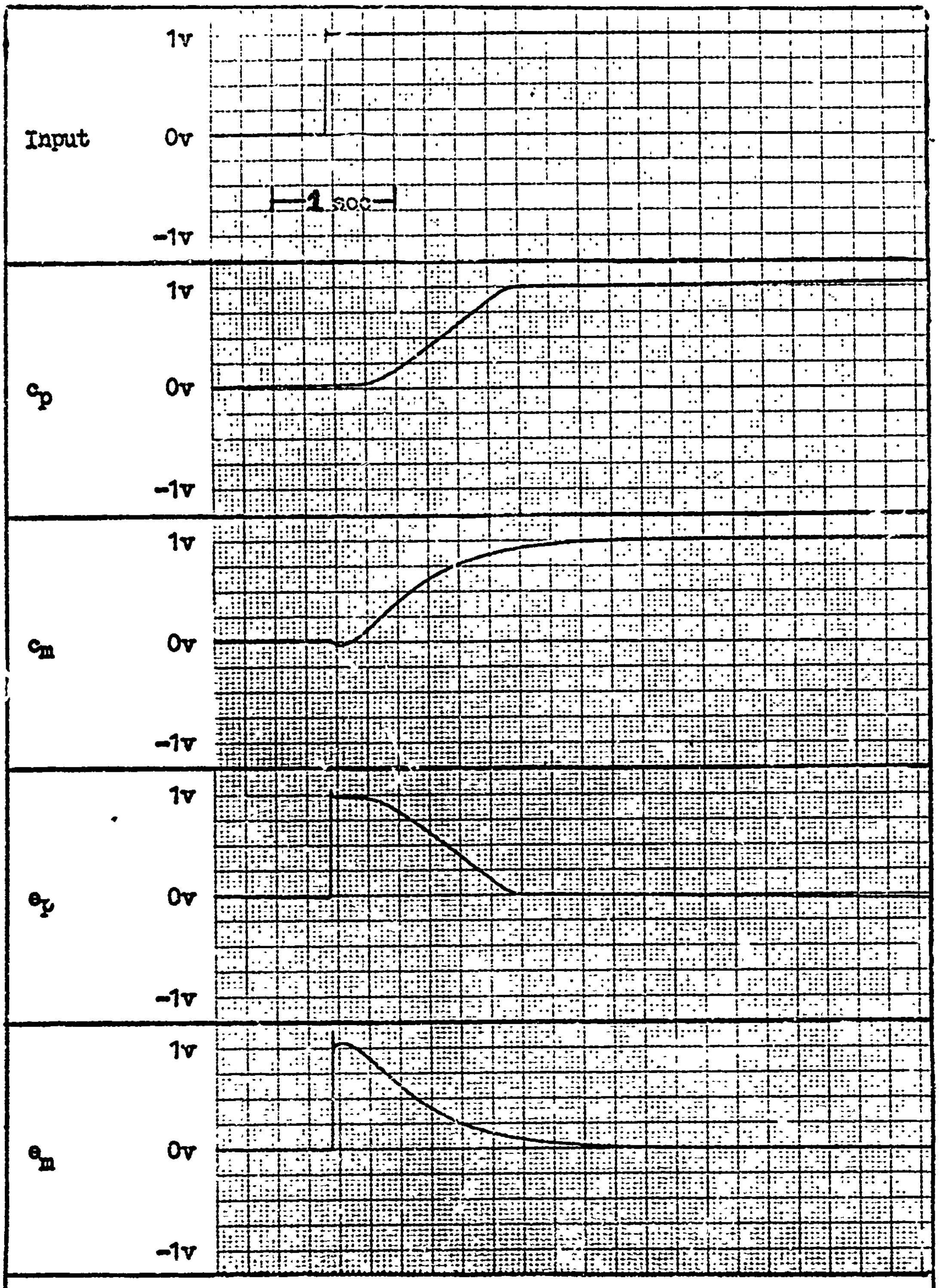
Subject 2 - K System: $\tau = 0.2$, $T_I = 3$, $K_p = 10$

Figure E-2



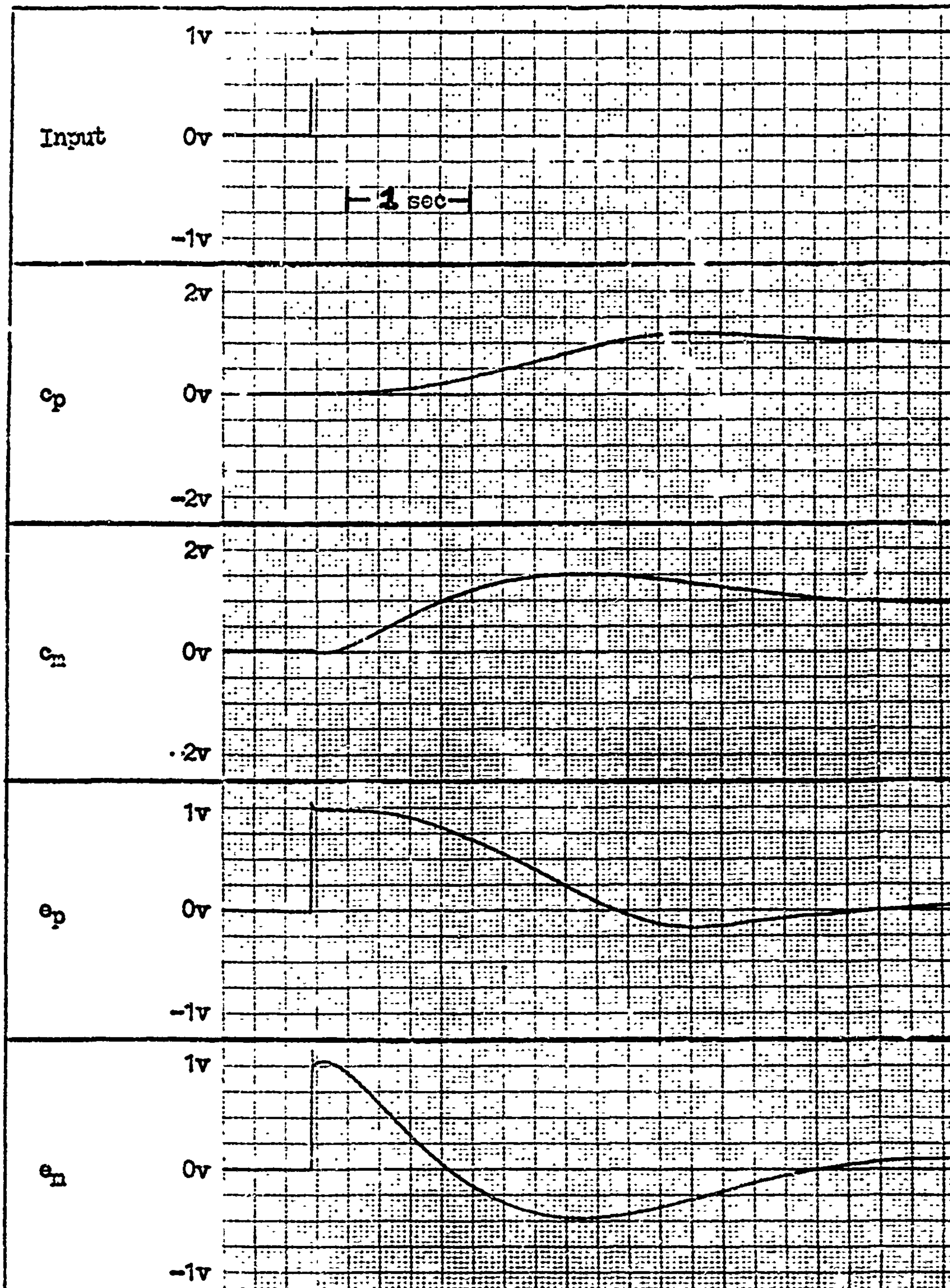
Subject 1 - K/S System: $\tau = 0.2$, $K_p = 3$

Figure E-3



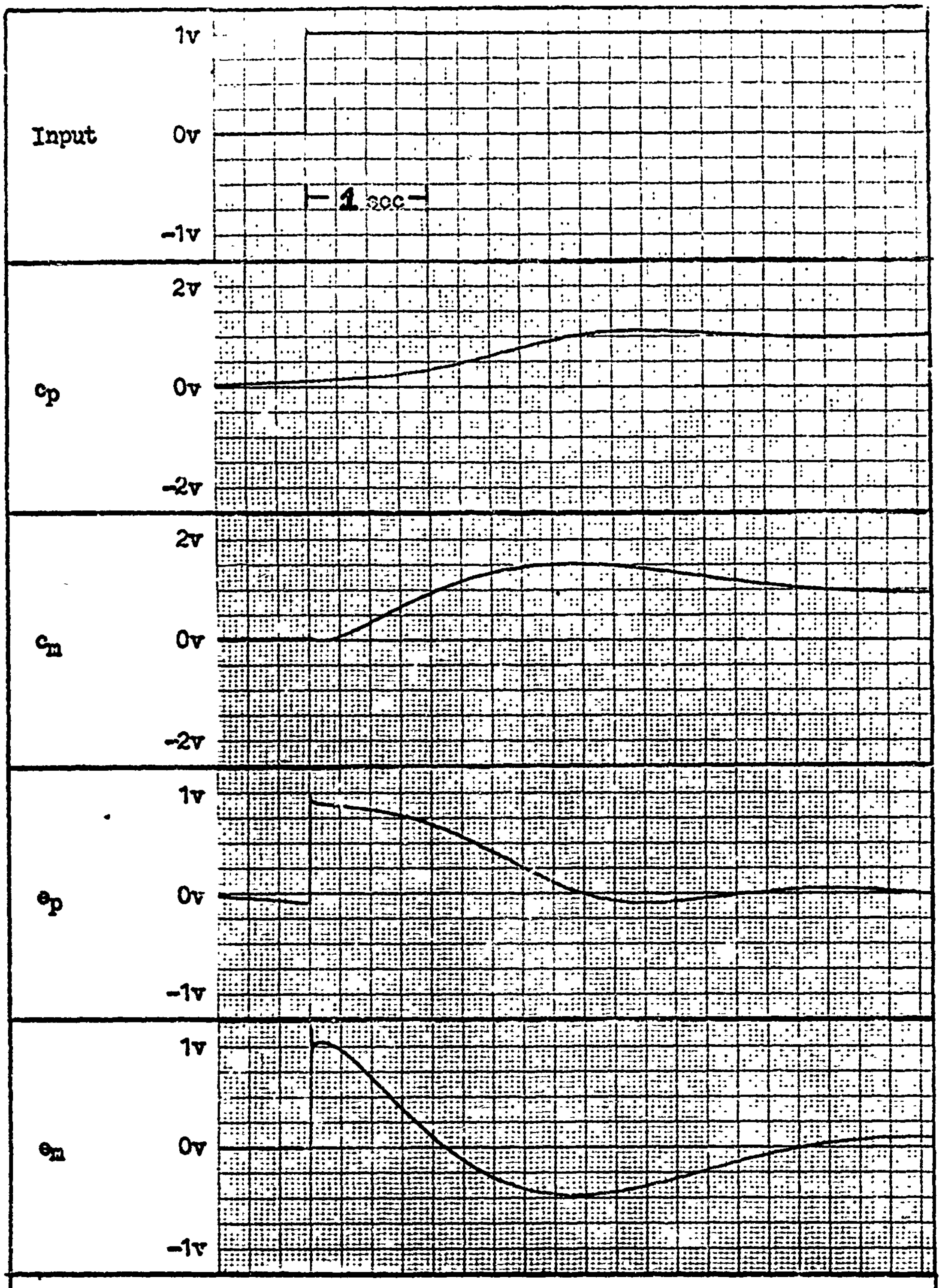
Subject 2 - K/S System: $\Upsilon = 0.2$, $K_p = 3$

Figure E-4



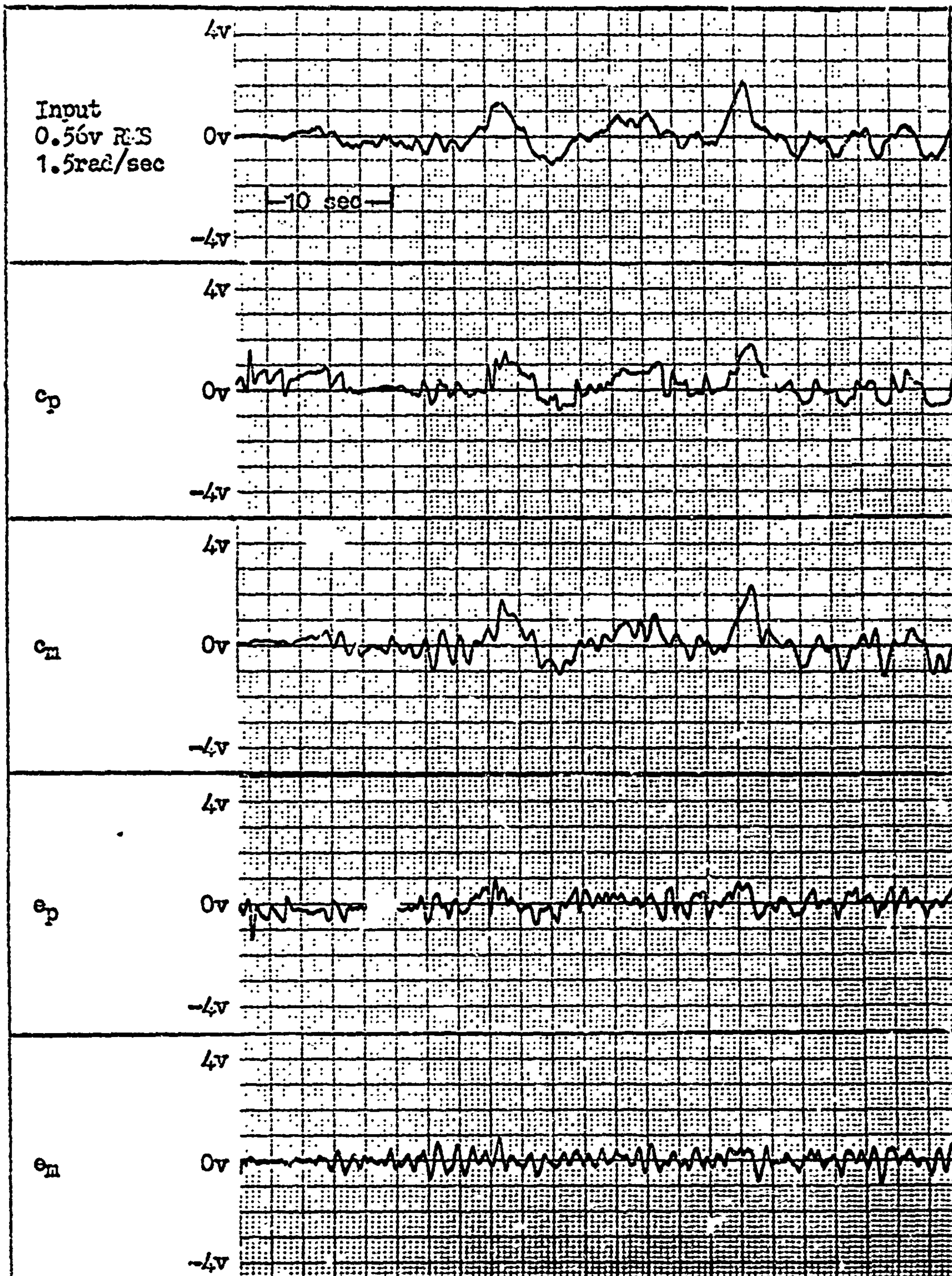
Subject 1 - K/S^2 System: $\Upsilon = 0.2$, $T_L = 1$, $K_p = 2$

Figure E-5



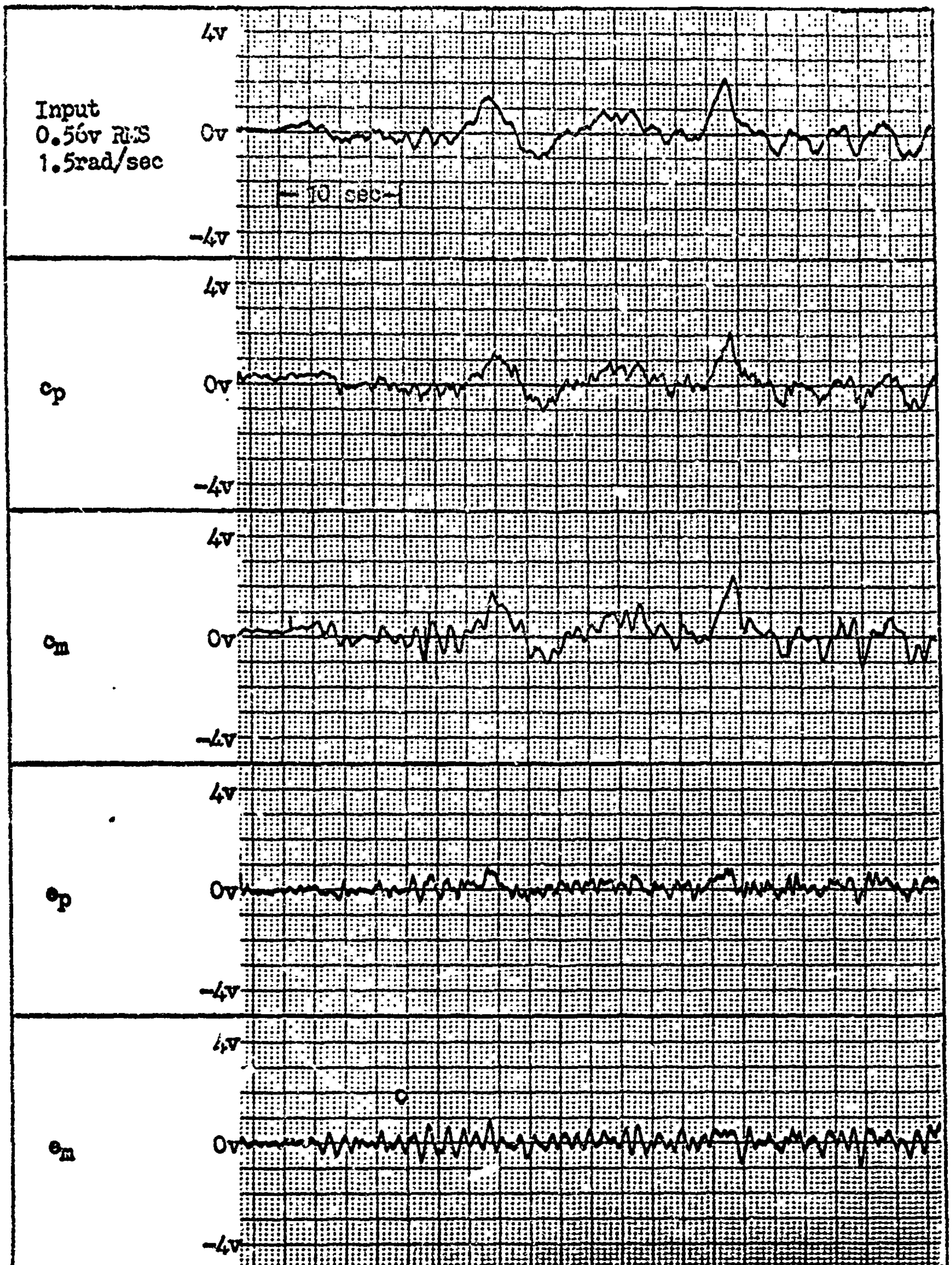
Subject 2 - K/S^2 System: $\Upsilon = 0.2$, $T_L = 1$, $K_p = 2$

Figure E-6



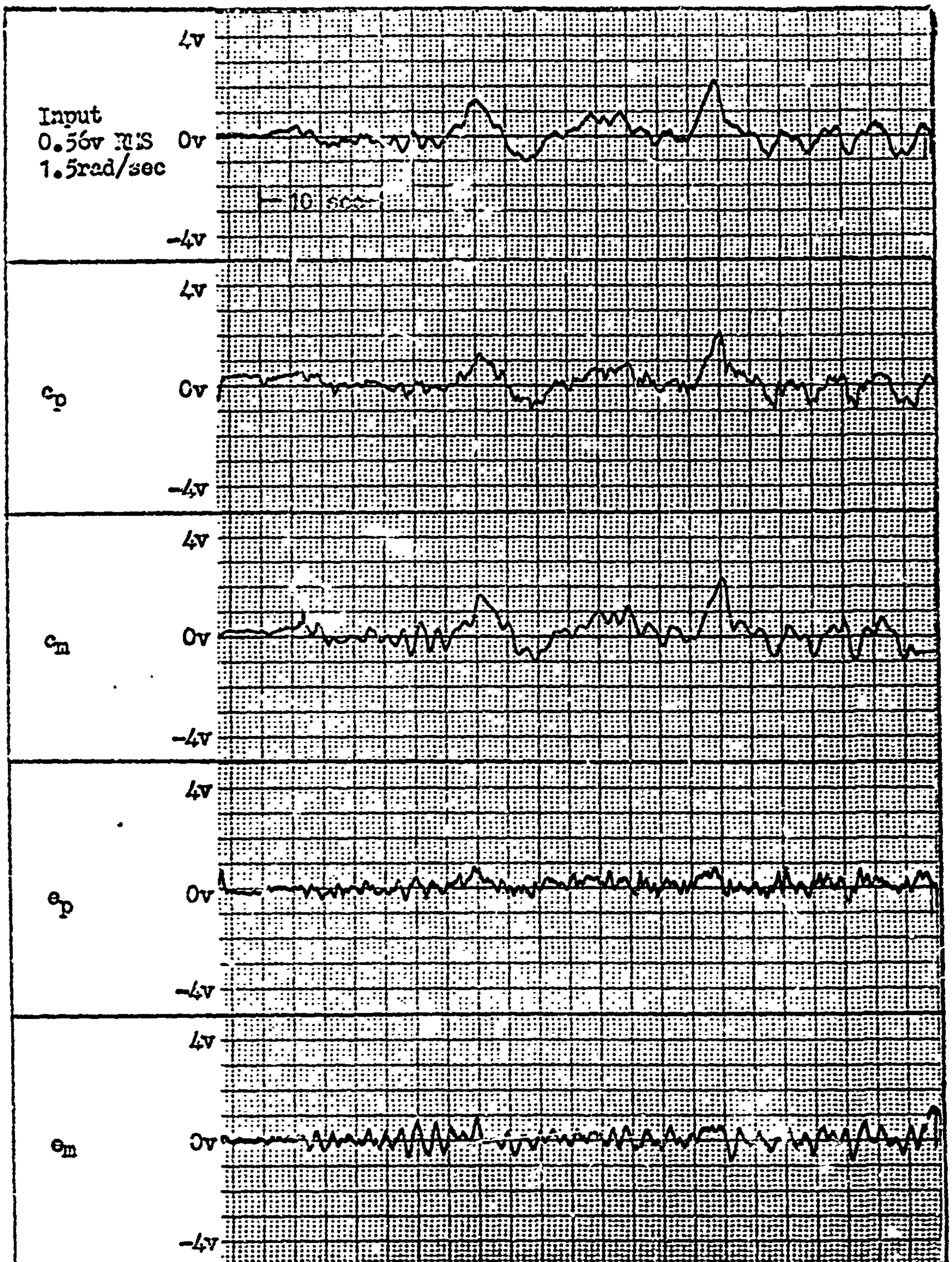
Subject 1 - K System: $\tau = 0.3$, $T_I = 3$, $K_p = 15$

Figure E-7



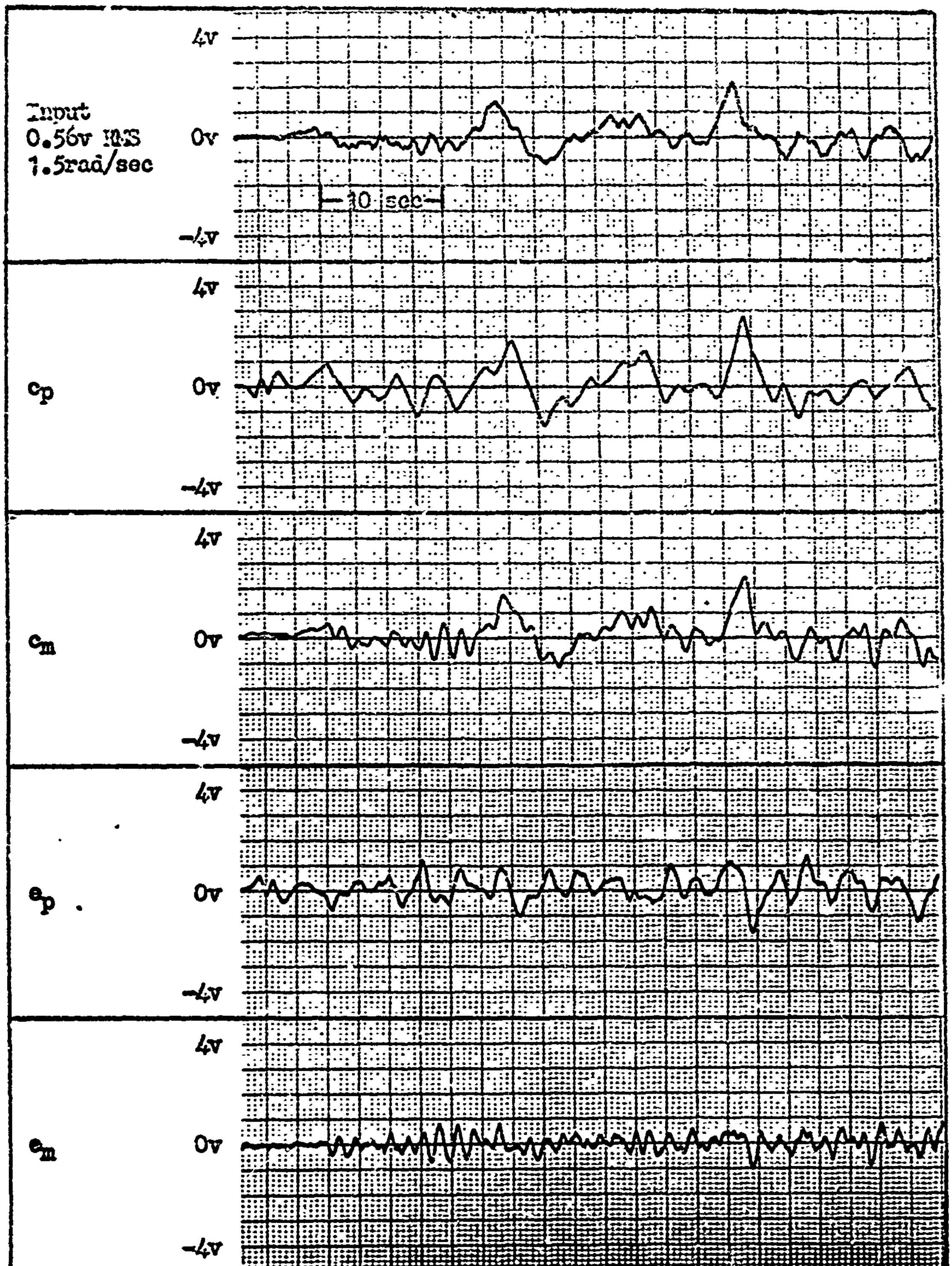
Subject 2 - K System: $\tau = 0.3$, $T_I = 3$, $K = 15$

Figure E-8



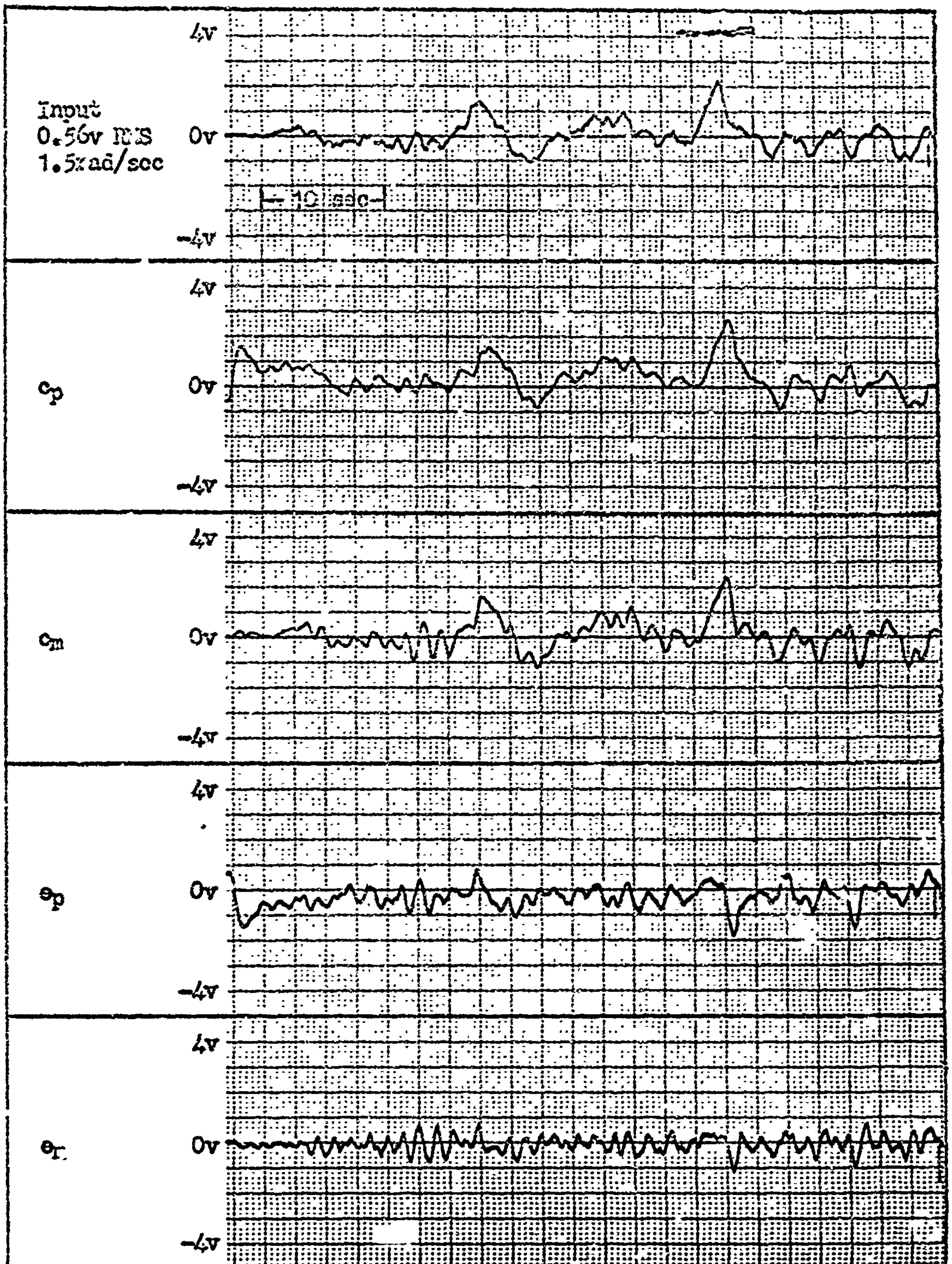
Subject 2 - X System: $\tau = 0.3$, $T_I = 3$, $K_p = 12$

Figure E-9



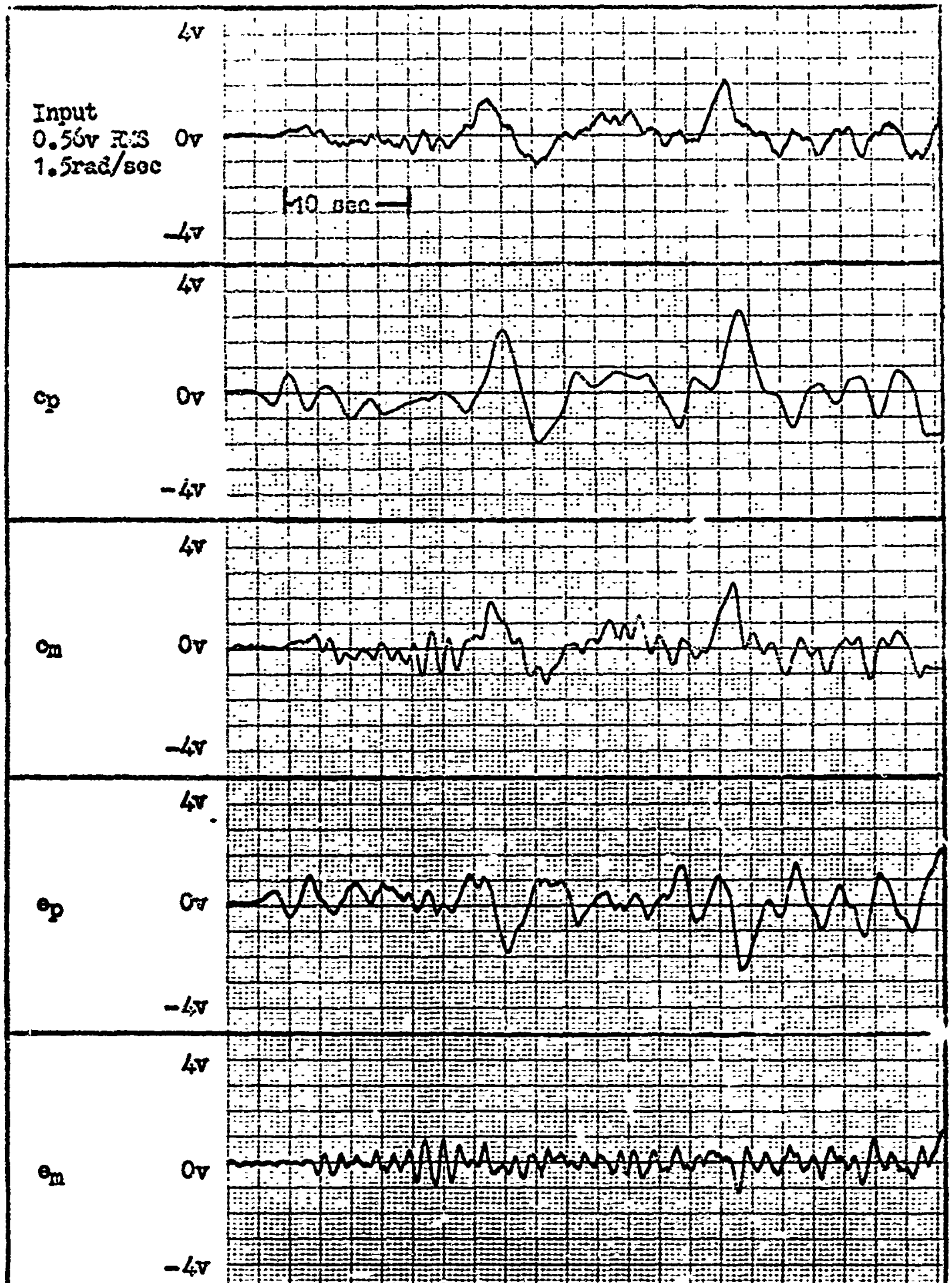
Subject 1 - K/S System: $\tau = 0.3$, $K_p = 4$

Figure E-10



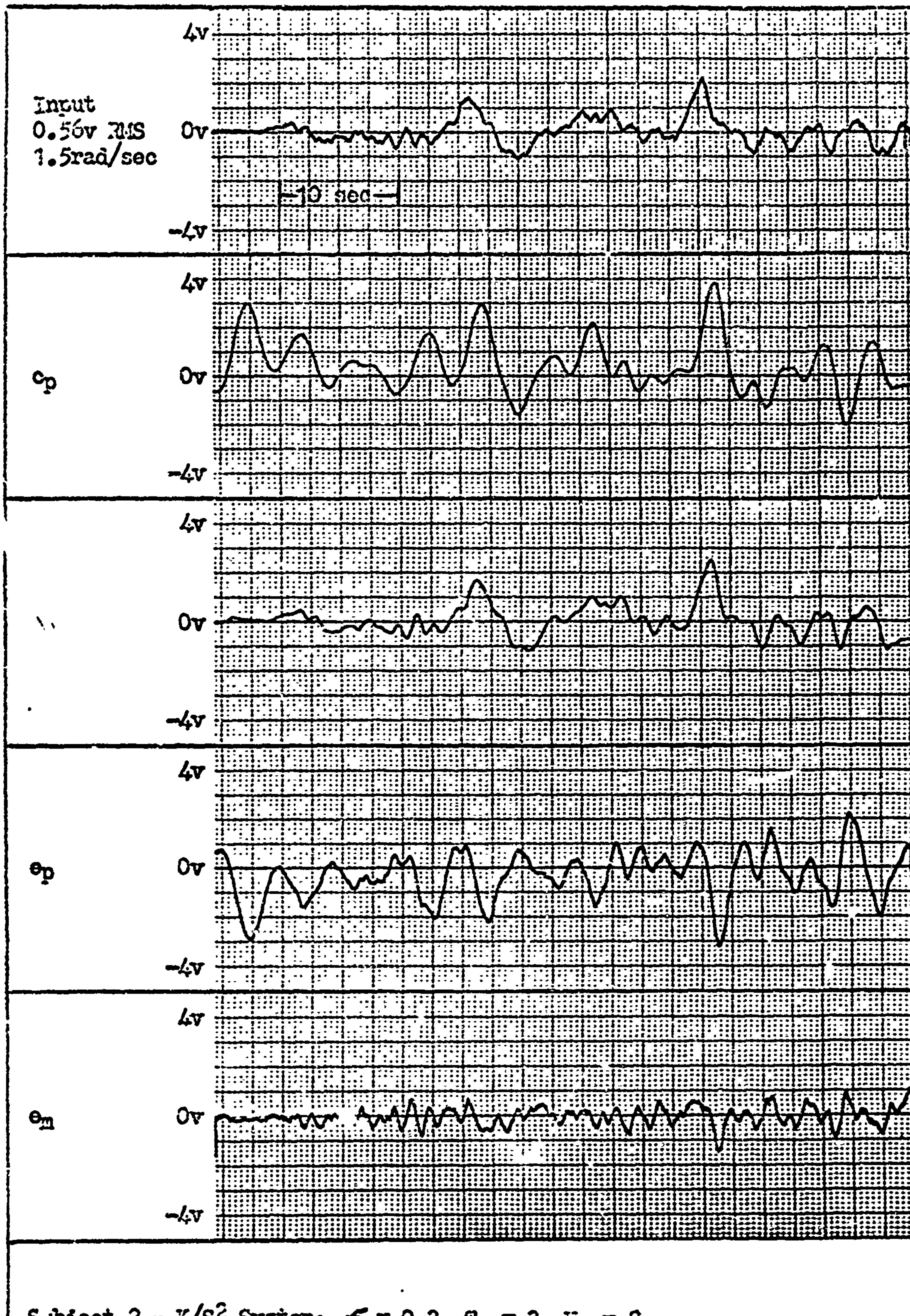
Subject 2 - K/S System: $\gamma = 0.3$, $K_p = 4$

Figure E-11



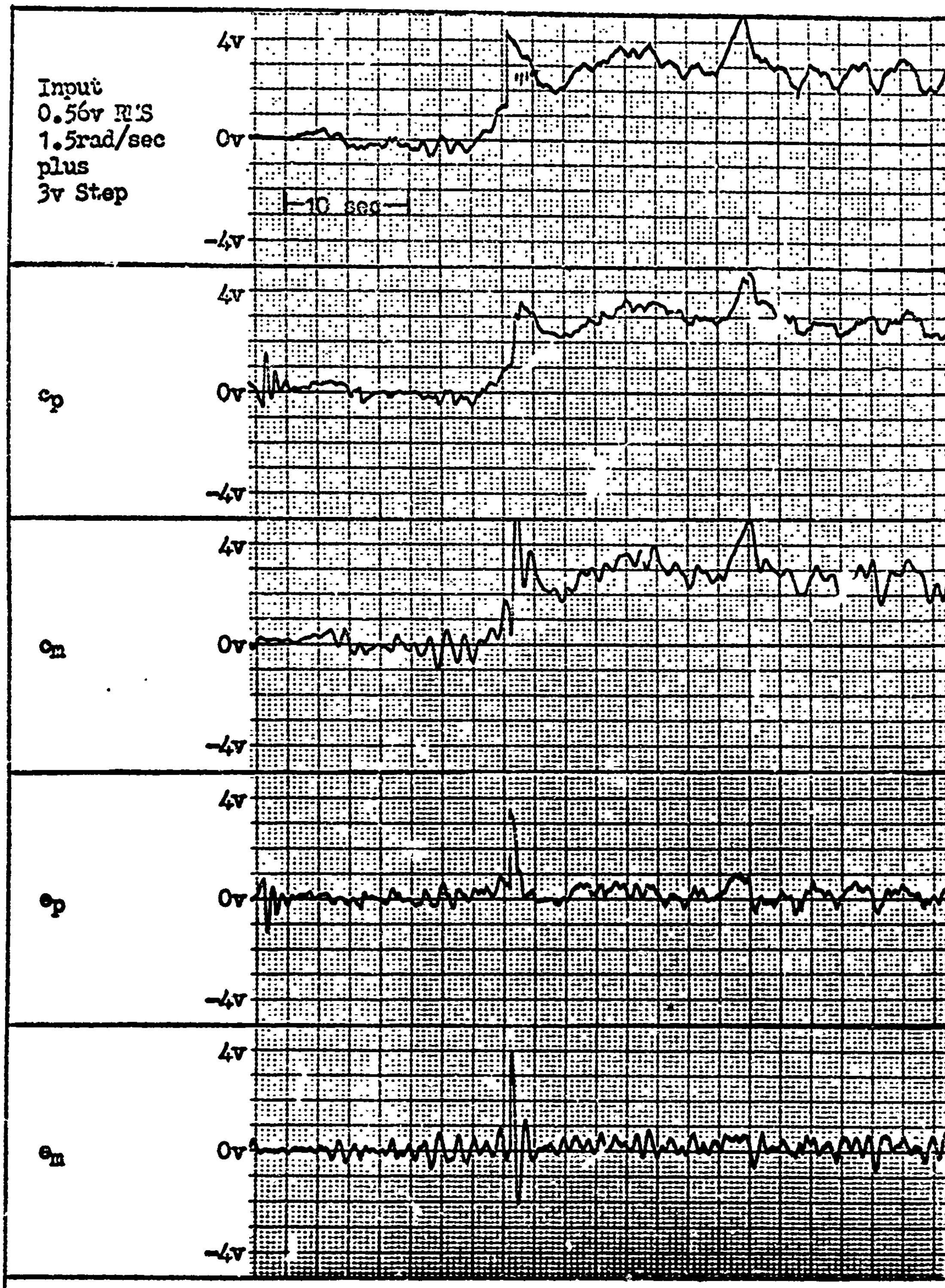
Subject 1 - K/S^2 System: $\tau = 0.3$, $T_L = 3$, $K_p = 15$

Figure E-12



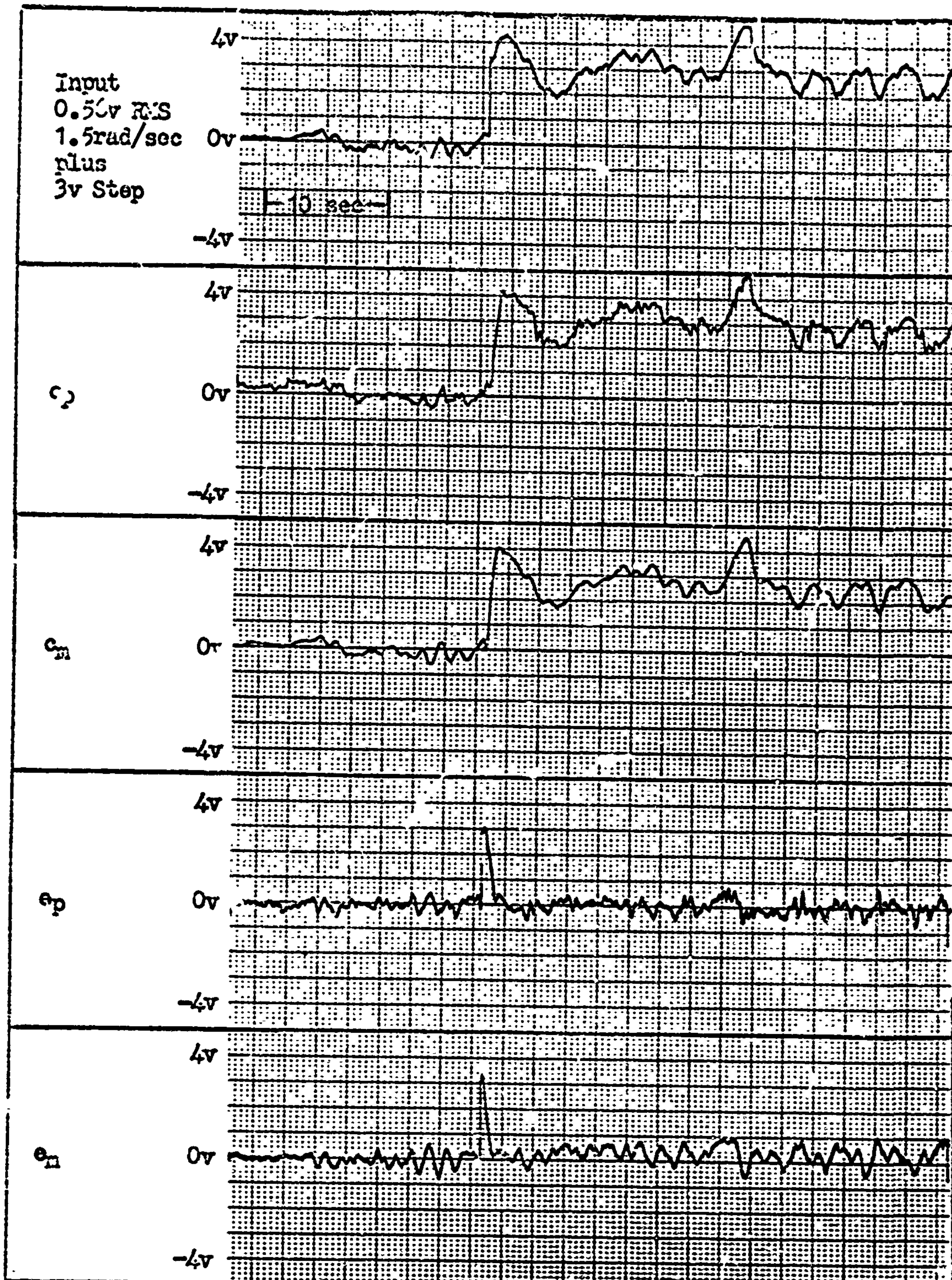
Subject 2 - K/S^2 System: $\tau = 0.3$, $T_L = 3$, $K_p = 8$

Figure E-1



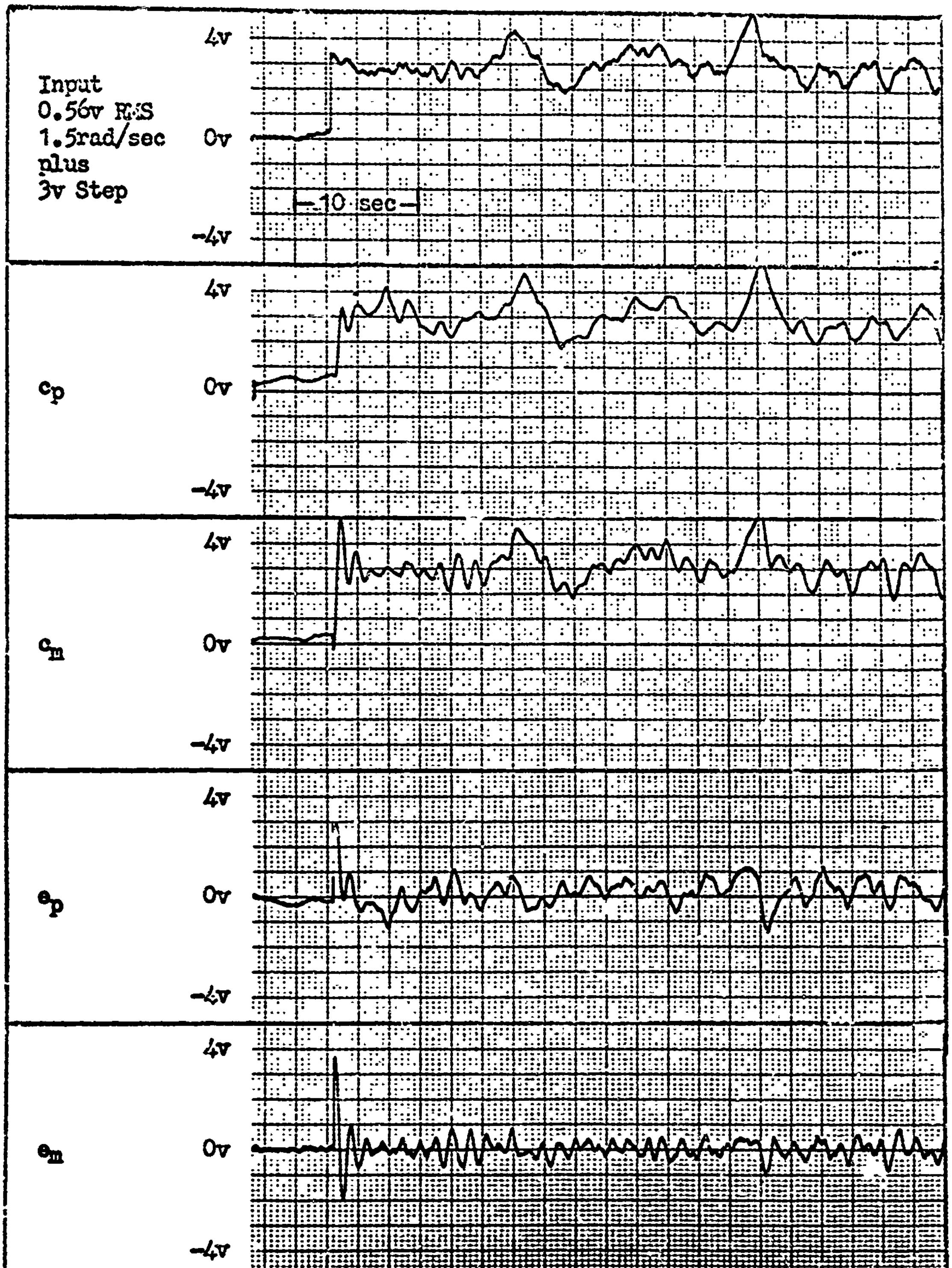
Subject 1 – K System: $\tau = 0.3$, $T_L = 3$, $K_p = 15$

Figure E-14



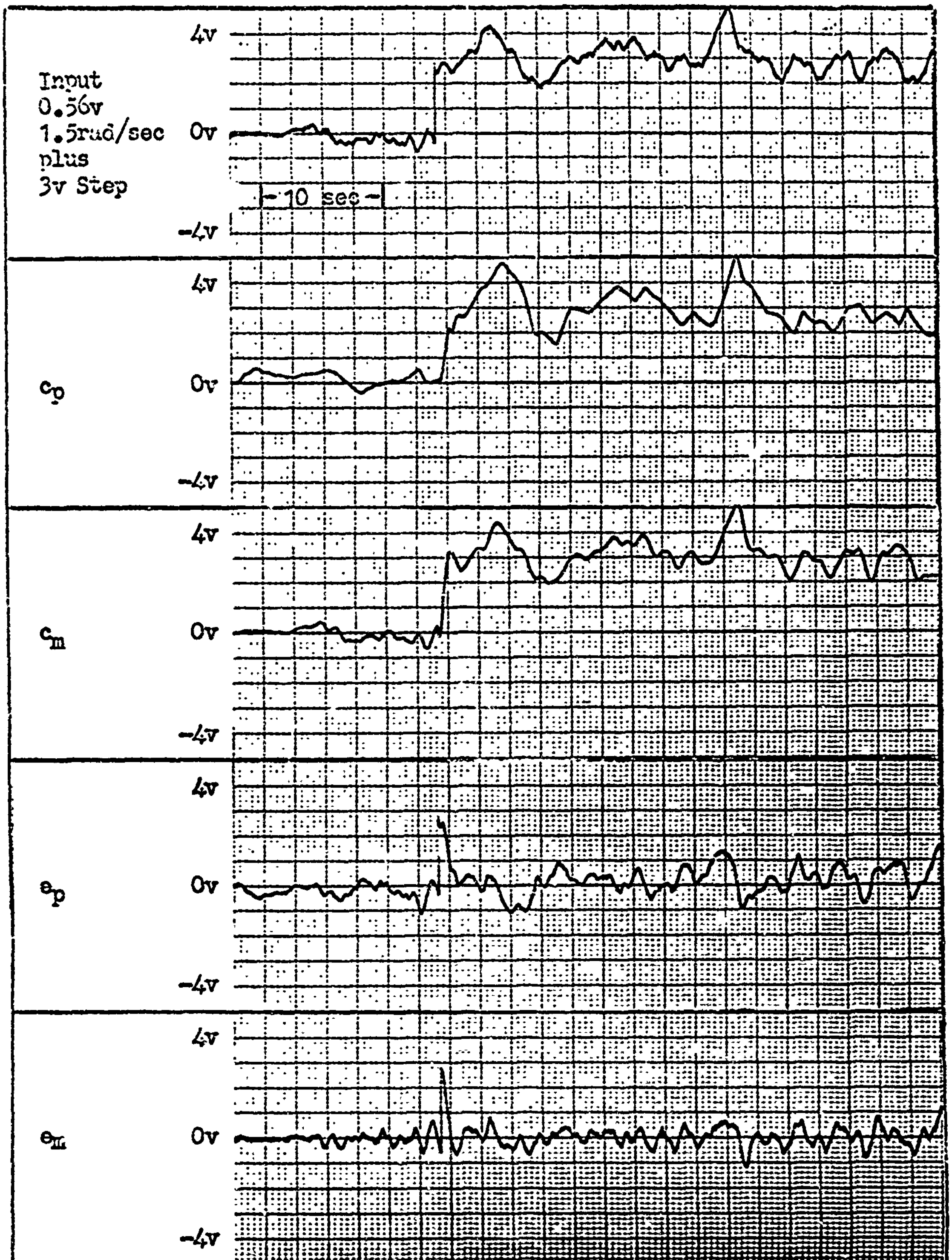
Subject 2 - K System: $\gamma = 0.3$, $T_I = 3$, $K_p = 8$

Figure E-15



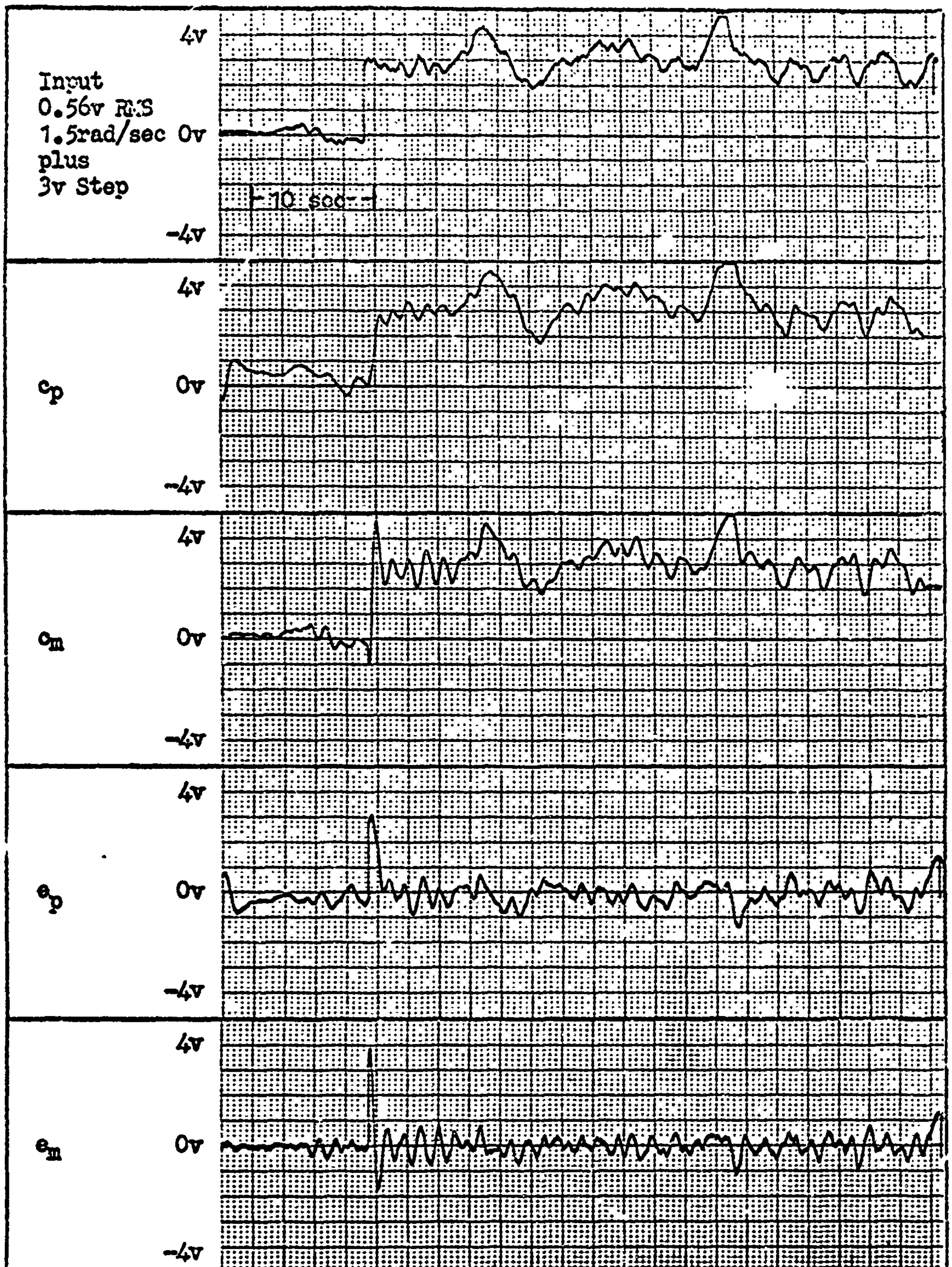
Subject 1 - K/S System: $\tau = 0.3$, $K_p = 4$

Figure E-16



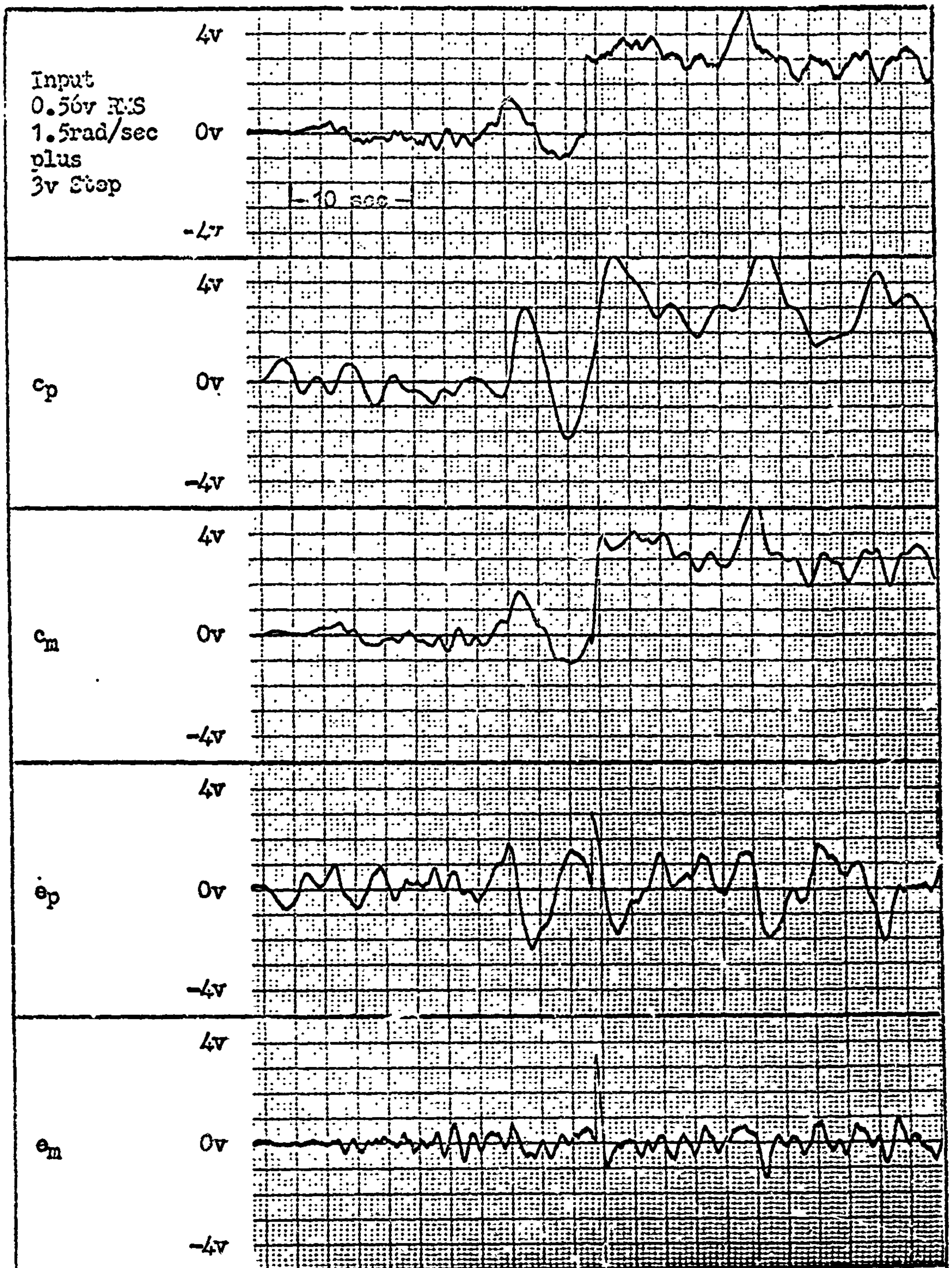
Subject 1 - K/S System: $\tau = 0.3$, $K_p = 2$

Figure E-17



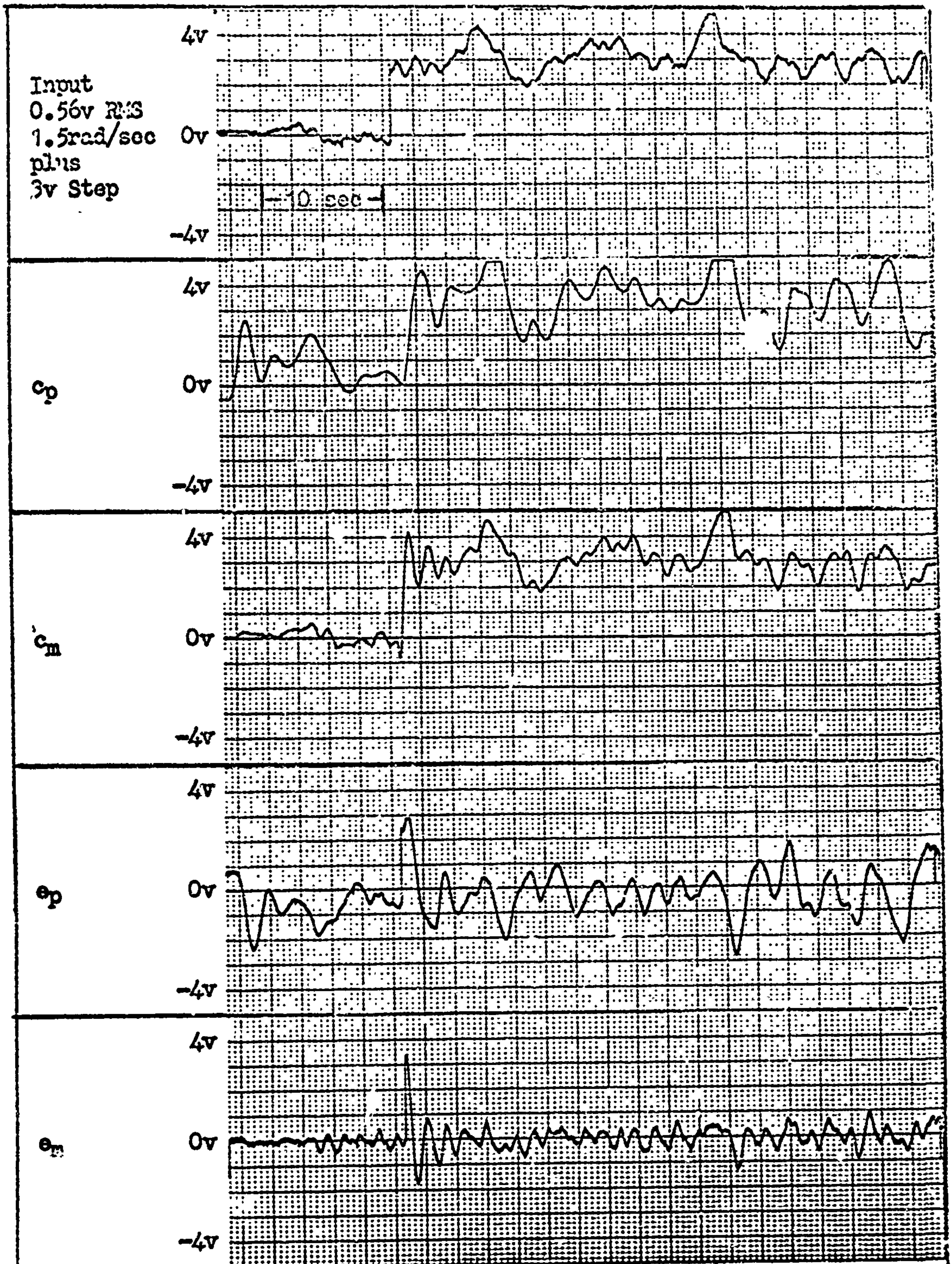
Subject 2 - K/S System: $\gamma = 0.3$, $K_p = 4$

Figure E-18



Subject 1 - K/S^2 System: $\tau = 0.3$, $T_L = 3$, $K_p = 7$

Figure E-19



Subject 2 - K/S^2 System: $\tau = 0.3$, $T_L = 4$, $K_p = 8$

Figure E-20

Appendix F

List of Tracking Subjects

Subject	Experience
1	USAF pilot with 9 years experience in tactical fighter and transport.
2	Private pilot with instrument training for his commercial license in single engine aircraft.
3	No flying experience.

Note: All subjects had limited task training with only three practice runs before data was taken.

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13. ABSTRACT

A study was made of describing function models of human trackers while operating control systems with Gaussian plus step inputs. The parameters in the describing function model were adjusted using existing parameter adjustment rules and experimental data. Four performance measures were determined from the experimental data to assess their usefulness in adjusting the parameters of human pilot describing function models.

The experiments were run using three subjects with varied levels of flying experience. Each subject was given the single task of controlling a system with one of three different controlled elements; K, K/S, K/S^2. Data were collected on each subject for each system with a single step input, Gaussian input, and Gaussian plus step input. Comparisons of the output of the piloted systems and the model systems were made, and suggestions for applications to the controlled element dynamics were offered.

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