HELICOPTER CONTROL:
A MULTI-LOOP MANUAL CONTROL SYSTEM

by

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George R. Friedman

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ABSTRACT

The human operator's performance in a high order, multi-loop task, typified by the helicopter, is studied using the method of average responses. This method permits a time domain, transient input analysis. A cascade model configuration for the human operator is proposed. In this configuration, the first human operator model controls attitude. This model is identical to that of the single-loop model for the same dynamics and consists of a lead time constant of 5 seconds, a neuromuscular lag of .1 second, and a pure time delay of .28 seconds. The attitude reference for the attitude control loop is provided by a second cascade human operator model consisting of a one second lead operating on the position error. A general programming system for average response experiments, using the GPS 290T Hybrid Computer, is described.

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CHAPTER 1

INTRODUCTION

Most manual control studies in the past have emphasized control of simple dynamic systems. The most thorough study was that of McRuer, Krendel, Graham, and Reisner. They conducted extensive experiments on system dynamics, up to second order, with random-appearing inputs and showed that, for most applications, the following quasi-linear describing function was satisfactory:

$$Y_P = K_P \frac{T_L j\omega+1}{T_I j\omega+1} \frac{e^{-j\omega\tau}}{T_N j\omega+1}$$

The pure time delay and lag of T_N seconds constitutes a minimal description of the neuromuscular system. A more precise model for the neuromuscular system would add a second order, high frequency lag and a low frequency lag-lead. The equalizer time constants, T_L and T_I, are adjusted for the particular dynamics in accordance with certain adjustment rules. This thesis indicates that the model can be generalized to include discrete, transitory inputs, if the input is non-predictable. Responses to discontinuous inputs, such as steps, can be predicted, if the lead term is modified so it does not respond to the discontinuity with an impulse.

Past studies have indicated the difficulty the human operator has in controlling systems of higher order than second. Many more complicated systems exist for human operators to control. Among these are the single thrust vehicles, such as the helicopter, VTOL's, and LEM. The ability of the human pilot to control these vehicles indicates that he is able to use more information than can be presented as a single coordinate on a screen in a manual control experiment.

The helicopter has been selected as an example of such a higher order system. The dynamics are of fourth order and can be factored conveniently into two systems: the attitude dynamics and the positional dynamics. Each of these is a difficult second order task. To control the helicopter system, the pilot then should find it necessary to use attitude information in addition to position error, as has been verified by helicopter pilots.

Stapleford, McRuer, and Magdaleno considered an aircraft bank angle tracking task for studying multi-loop manual control. The spectral analysis techniques and equipment limited the model configurations that could be studied. In this thesis, the multi-loop helicopter control task is studied using the method of average responses. This time domain approach permitted the study of transitory responses and time-sequenced operations.

Helicopter control was studied with the intention of seeing how the single loop models of the human operator can be modified to predict multi-loop behavior. It was found that in the multi-loop task the high frequency portion of the system is controlled as in a single loop task. An additional low frequency loop then can be closed about a simple human operator model. The output of this outer loop model provides a reference for the inner, high frequency system.

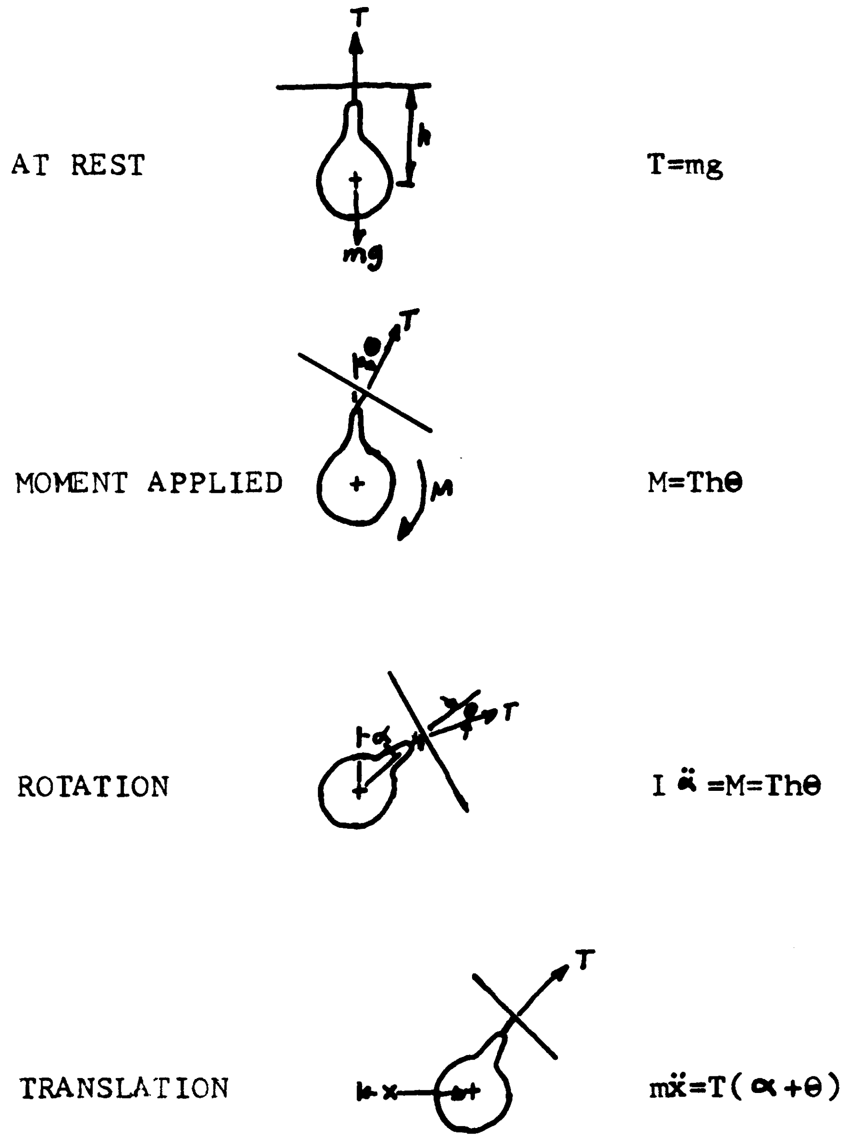
Model configurations for the helicopter and pilot are discussed in Chapter 2. A cascade model is proposed, since the human operator was observed to respond sequentially, first controlling roll angle error and then correcting for position errors. Chapter 3 discusses the average response method. This method consists of forming a statistical ensemble of responses to some input and then computing the ensemble average. The input consists of a random signal plus a deterministic signal. That portion of the average response due to the random input averages out to zero for a sufficient number of sampled responses. This thesis demonstrates that this method is a valuable tool, permitting system identification with a minimum of equipment. The method is independent of the model configuration selected. Chapter 4 discusses the use of the GPS 290T Hybrid Computer in performing the on-line experiments with immediate data reduction. Chapter 5 discusses the results of experiments on the second order system and compares them with previous spectral analysis results. Chapter 6 discusses the results of the fourth order, multi-loop system experiments. Chapter 7 discusses linear models for the second and fourth order responses. The simple human operator models for the multi-loop task justify the selection of a cascade configuration.

CHAPTER 2

HELICOPTER AND PILOT MODELS

The hovering helicopter serves as a good example of a multi-loop manual control system. The dynamics are fourth order in either of the two horizontal directions and second order in the vertical direction. The helicopter, as well as any other single thrust vehicle such as LEM, produces horizontal motion by tilting the thrust vector from the vertical. In the helicopter, the following sequence of events takes place. Through the cyclic control stick, the rotor plane is tilted relative to the helicopter body. Because the thrust vector no longer passes through the center of gravity of the vehicle, the vehicle rotates. This response, the roll or pitch angle, is a second order response to the stick or rotor plane angle. The tilted thrust vector now has a horizontal component which produces an acceleration. This results in the horizontal position being a second order response to the roll or pitch angle and a fourth order response to the input stick motion. Because of the difficulty of controlling this system, various mechanical linkage methods are used to reduce the roll response to first order. More recently, work by R. H. Miller has centered on reducing the control task to that of a first order system. Figure 2.1 illustrates a simplified approach to these dynamics.

Observation of helicopter pilots leads to two important points. The first is that roll and pitch angle information



$$\ddot{\alpha} = \frac{Th}{I}\,\theta \qquad \ddot{x} = \frac{T}{m}\,\alpha = g\,\alpha$$

FOR THE SIKORSKY S-58 HELICOPTER,

$mg = 11{,}900$ lbf $\qquad I = 5{,}900$ slug-ft^2
$h = 8$ ft

$\ddot{\alpha} = 16\,\theta$ deg/sec^2 $\qquad \ddot{x} = .56\,\alpha$ ft/sec^2

HELICOPTER MOTION FOR SMALL ANGLES
AND SMALL VELOCITIES

Figure 2.1

is essential for any control at all. The pilot gets this information from bodily sensations and observation of the horizon. With this information, a good helicopter pilot can hover within a foot of a selected point. Because of this need, helicopter flying can be extremely difficult at night or in cloudy weather. The second observation is that control is exercised in such a way that roll rate and translational velocity remain small.

The manual control task of the pilot has two parts: sensing of those variables necessary for control and the generation of a control response as input to the system that results in both stability and desirable handling characteristics.

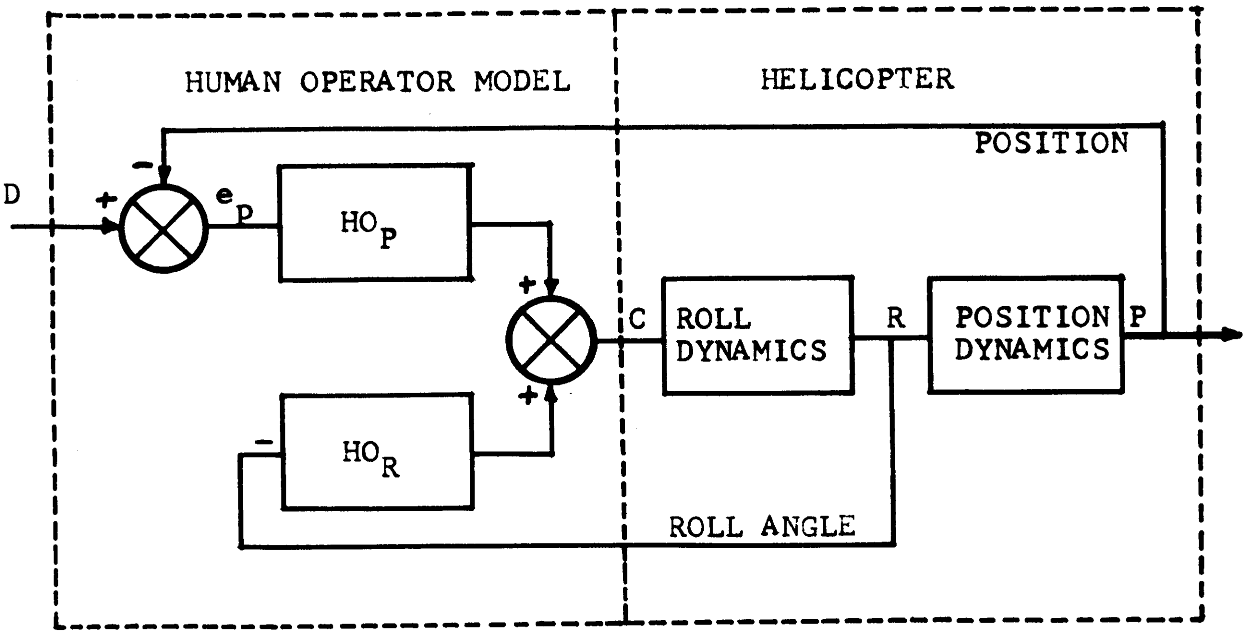
A typical input variable is sensed and given a value that has associated with it some error distribution. This distribution is dependent on the sensor's characteristics and the time available to make the measurement. From successive measurements, an estimate of the rate can be made and further a poor estimate of the acceleration can be developed. The error distributions of these inferred variables are successively wider to the point that usually the acceleration information significance is limited to polarity. It would appear that the attention given to the variable is dependent on its bandwidth and the wider the bandwidth the less time available to develop estimates of the rate and acceleration. In the compensatory task, the human operator has the additional problem of sorting out that part of the error rate and error acceleration due to the output of the system and that part due to the input. This difficulty increases the uncertainty of his measurement and decreases the reliability of his estimates of rate and acceleration.

For convenience, we usually model the human operator as having a single input, a single output, and one feedback loop. Since, at best, the human operator can generate a first order linear lead, and possibly a second order non-linear lead, higher order systems must provide additional information to the human operator if stable operation is to occur. In the case of the helicopter, this additional information is helicopter attitude. For modeling the human operator in the helicopter task, we need for each axis a single reference position input, a single control output, and two feedback loops. This implies that the model requires two single input-single output blocks plus a combinatorial box to result in one control stick movement.

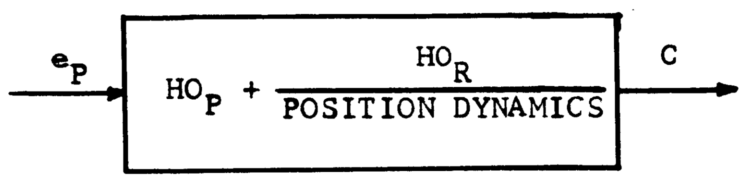
Using Stapleford, McRuer, and Magdaleno's classifications, the helicopter pilot, in regard to horizontal positional control, would be classified as a single point controller. In this configuration, the control variable is the sum of the outputs of two quasi-linear human operator describing functions, each operating on one of the feedback variables. The single point controller model suggests equal task difficulty in controlling each of the feedback loops. This model form always can be reduced to a single feedback loop and a single human operator block. This single human operator block has two terms, one of which has as a factor the dynamics separating the two variables that are fed back, as illustrated in figure 2.2.

An alternate form for a model is suggested if we consider a typical control sequence of a helicopter pilot. The pilot notices an error develop in his position and, using his measurement of position error along with inferred velocity and acceleration, estimates what the roll angle program should be to correct this error. He then proceeds to generate the roll angle response while continuing to monitor his position error. Sequential operation suggests a cascade model. In this model, roll error serves as an input to one human operator block. The output of this block directly controls the system. The roll error reference is provided by a second human operator block that has as input position error. The cascade model is illustrated in figure 2.3.

Since the operator must maintain his attitude more exactly than position (a small attitude error will quickly result in a larger position error), roll angle can be considered the controlled variable and position, the monitored variable. For this reason, it would be suspected that attitude control would be of higher frequency than positional control. If the roll reference is of low frequency and the positional portion of the model requires little of the human pilot's attention, the roll loop human operator block is probably very similar to that of the single loop problem.

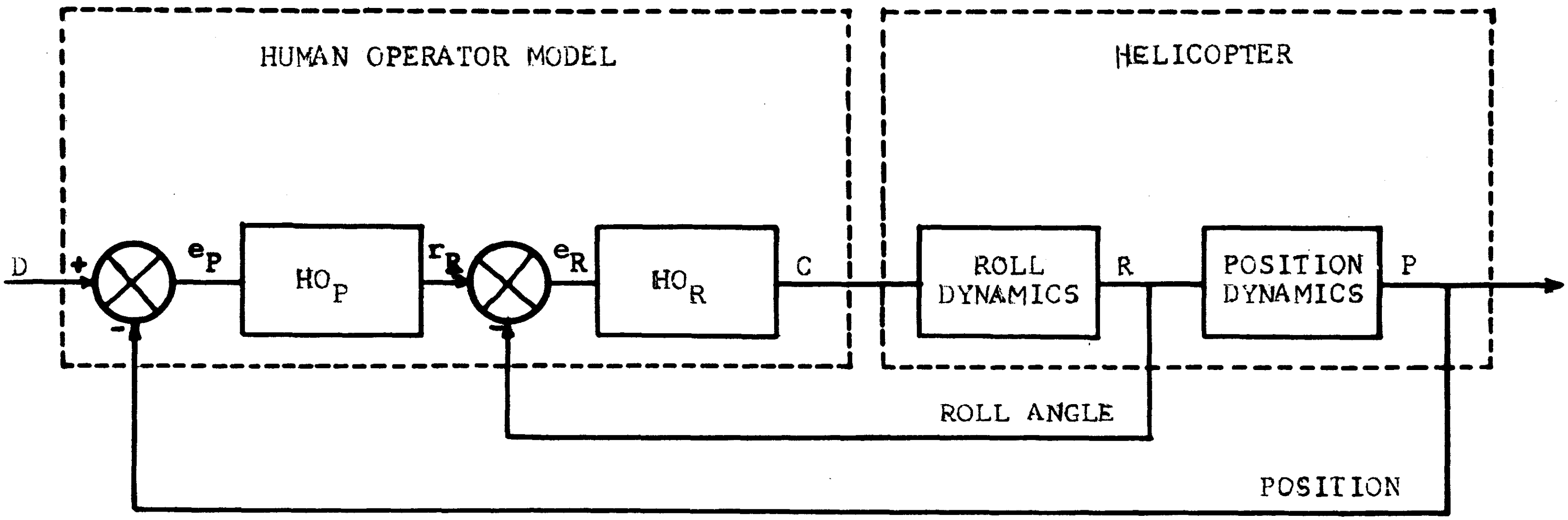


a, PARALLEL MODEL



b, EQUIVALENT SINGLE BLOCK MODEL

Figure 2.2



D, Desired Position
C, Manual Output
r_R, Roll Reference
e_P, Position Error
e_R, Roll Angle Error

Figure 2.3 Cascade Model

For purposes of this thesis, only lateral motion will be simulated. Display will consist of two points, one giving position error information and the other, roll angle. Fixed base simulation will be used. The task then is similar to one axis of a slow-moving helicopter under inclement weather with a display composed of two points on a CRT, one giving positional error information and the other, attitude.

CHAPTER 3

THE METHOD OF AVERAGE RESPONSES

The usual statistical identification techniques are impractical for this study. Although spectral analysis techniques are efficient, an evaluation of the assumptions inherent in this method leads to the following limitations.

The basic assumption in the spectral analysis method is that a linear system of some order with prechosen input and output variables can provide the best description of the system. One of the serious drawbacks of a linear model is that it cannot model responses to discontinuous inputs for which the subject temporarily ceases to follow the signal while trying to generate the required discontinuous response.

Stapleford, McRuer, and Magdaleno tried using statistical identification in a multi-loop task and ran into many problems. They first had to select a configuration for the human operator that would result in explicit describing functions. This problem is complicated by the fact that signals, associated with different parts of the model, pass through common dynamics. For this reason, it is necessary in certain configurations to use several random appearing inputs, each with different frequency components. For example, to identify the two human operator describing functions in this multi-loop task would require one forcing function in the roll loop and a second in the position loop.

The spectral analysis tools assume stationarity of statistics and ergodicity. The first requires that we consider only steady state responses and that the human operator be described as time invariant. Because of this restriction, the describing function can be found only in terms of random appearing, stationary inputs. In addition, the variability of performance and its statistics can be measured only in terms of mean squared error. The model developed will never be as bad as the human operator was momentarily during the run. Use of the model is restricted to those cases where we are primarily concerned with time averaged characteristics of the complete system. Ergodicity assumes that time averaging can replace ensemble averages. This has the effect of averaging out nonlinear effects and hiding the relationship of a specific stimulus to its responses.

These limitations still make the model good for such tasks as tracking, aircraft carrier landing, automobile driving, etc. When we want to study such effects as a sudden change in dynamics caused by a system failure or a suddenly noticed step error, we have to consider a nonstationary model. In the study of a multi-loop system, we will be interested in time synchronized events or time-shared or time alternating modes of control. This suggests that a time domain approach would be best.

The method of average response computation has been used by Young, et al., and by Elkind and Miller to investigate changes in dynamics and adaptation processes. This technique offers significant advantages over other methods for studying the multi-loop system.

The average response is obtained by first generating an ensemble of independent responses to some input after requiring that some conditions on the input, output, and control variables are met. In the experiments of this thesis, two inputs are used: a random appearing signal and a deterministic input, such as a step or ramp. Each sample is taken about the occurrence of the step. In order for the step to occur, certain conditions on the magnitudes of the display and control variables have to be met.

The advantages of this technique are many. The model form does not affect the procedure. Ergodicity and stationarity are not assumed. The study of small positional and rate errors results in a model for all inputs. The variance of the sample gives an indication of the variation in responses to be expected.

Step and ramp responses of second and fourth order systems were studied using this technique. A random appearing forcing function was inserted as an error in second order response or roll. Steps occurred in roll, roll rate, position, and velocity. As conditions for a step, roll error must be passing through zero, fourth order position error must be within 1 millimeter, and the control stick must be within 10 degrees of vertical. These conditions assure that the system is well under control and that the appearance of steps occurs under similar situations. Because no restrictions are placed on the random-appearing input, the part of the response due to the random input will average out as the number of samples increases. Young, et al., had to subtract a no transition response from the average response due to a change in plant, because they had placed restrictions on the input signal.

The human operator responds to deterministic inputs differently than he would respond to a random input. For the deterministic input, the operator has more information than can be predicted by a linear operation on the input. This permits him to improve his response. For example, in responding to a step or ramp, the subject knows that either the input or its derivative will remain constant. Similarly, a subject responding to a sinusoidal input first adjusts his frequency and then slowly synchronizes with the input, resulting in a much smaller phase shift than would be predicted by a random input describing function. To emphasize this limitation on their describing functions, McRuer, et al., expressed them in terms of the Fourier variable, $j\omega$, instead of the Laplace variable, s. Since the steps and ramps for the average response experiments have a random input superimposed on them, the subject is unable to take advantage of the discrete nature of these inputs. Therefore, the models developed from the average response results will hold for all inputs for which the subject is unable to profit from the future nature of the input.

McRuer's random-appearing input was used for the experiments. This input consists of 10 sines chosen without common low order multiples. The spectrum follows:

.157 rad/sec	1.49 rad/sec
.262 rad/sec	2.54 rad/sec
.393 rad/sec	4.03 rad/sec
.602 rad/sec	7.57 rad/sec
.969 rad/sec	13.80 rad/sec

The frequencies below the cutoff frequency are weighted the same, while those above are weighted one-tenth. For the experiments of this thesis, a cutoff frequency of 1.5 rad/sec was used. For the second order experiments, an rms value of .6 centimeter was used. Because of the greater difficulty in controlling the fourth order system, the rms value was decreased to a tenth of this value. McRuer, et al., indicate that this signal is Gaussian to the 5% level. The probable error for this signal is .09 cm. This means that the average of 20 independent segments of the input will exceed .09 cm for approximately half the segment. The one-third law of McRuer and Krendel states that the ratio of mean squared error to the variance of the input is approximately equal to one-third the ratio squared of input cutoff to bandwidth of the human operator. This means that the average error response due to this signal should have a probable error of about .03 cm. For this reason, twenty samples are sufficient to average out those characteristics in the average response due to the random input tracking.

The steps occur at random during an experimental run and are spaced far enough apart to insure their independence. As a first approximation, the responses can be expected to be distributed normally about the average response. The variance of the measured average response is equal to the variance of the sample divided by the number of responses. From consideration of early results, it was decided that twenty steps would suffice for average response calculation of the display variables but that for average responses of roll rate or control stick movement at least thirty steps were necessary.

Various size steps were used ranging from .25 to 2 centimeters for steps and from .5 to 1 centimeter/second for ramps. During a typical run, all steps were of constant magnitude but of random sign. Initially, the responses due to positive steps were averaged separately from responses due to negative steps in order to note any asymmetry in response. Later, negative responses were inverted and averaged with the positive responses. Asymmetry then tended to cancel, and the number of steps necessary was cut in half.

A typical sampling run included ten steps of random polarity. Steps occurred approximately at .5 minutes intervals, with the entire run taking about 5 minutes. To generate enough steps for an average response took two to four runs. The subjects rested between runs, but in all cases the responses averaged together were gathered within one hour. Before the day's runs were made, the subject was given sufficient practice to reacquaint himself with the tasks.

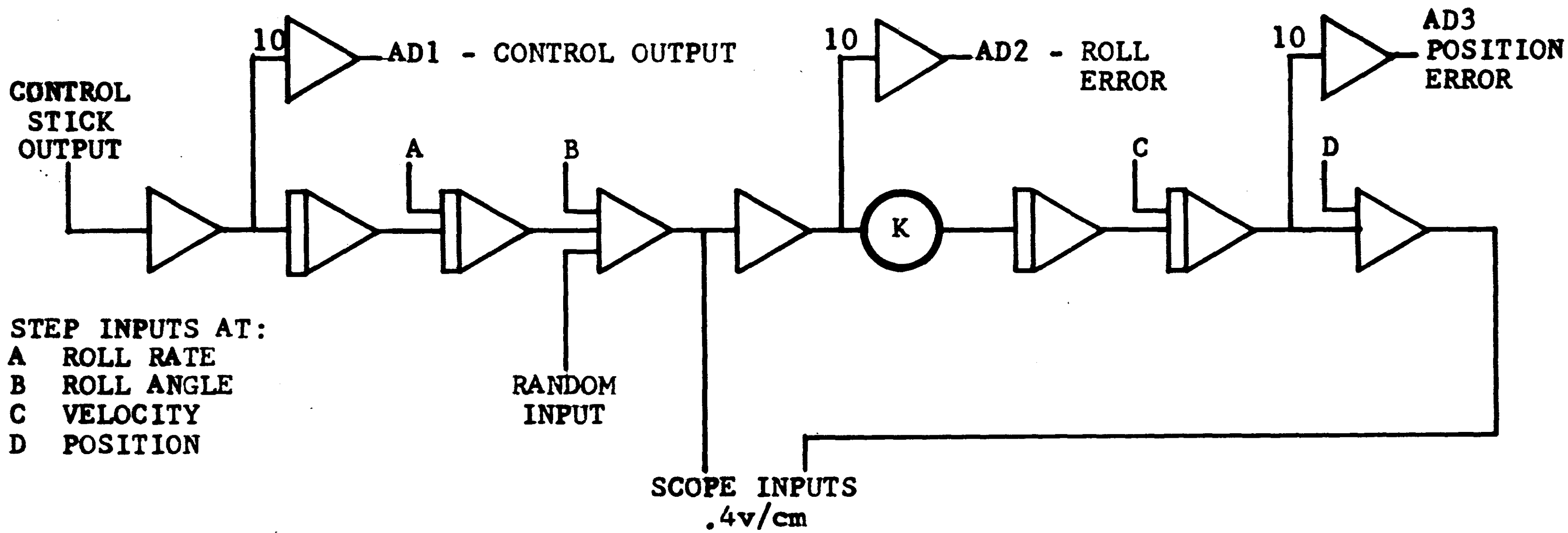
CHAPTER 4

PROCEDURE AND APPARATUS

The GPS 290T Hybrid Computer serves to simulate the dynamics, process the data, and control the sampling run for these experiments. Appendix A gives a description of this computer. Variables are displayed to the subject on an oscilloscope with a ten centimeter square grid. Each variable is displayed as a horizontally moving point. The grid lines aid in finding the true zero and in estimating error. Roll angle and position error are displayed 2 centimeters apart vertically. The subject is seated in a comfortable chair, with a light spring-restrained control stick mounted on the right arm.

The analog panel of the computer is programmed for both second and fourth order systems. Maximum stick output of 2.5 volts occurs at about 45 degrees. CRT gain was set at 2.5 centimeters/volt so that overall system gain was close to 1. Steps can be inserted so as to appear as steps in roll rate, roll angle, velocity, or position. Since roll rate and velocity are not displayed, the effect of steps in these variables appears as ramp inputs in roll and position respectively. All measured variables are amplified by a factor of ten. Figure 4.1 illustrates this arrangement.

As conditions for a step, control input, roll error, and position are required to remain within bounds. Control input is required to be within .5 volt or approximately 10 degrees.



ANALOG COMPUTER DIAGRAM
FIGURE 4.1

Position is required to be within 1 millimeter on the display or .04 v. Each of these conditions is implemented with two comparators, one biased to the positive limit and the other biased to the negative input. Because of the small tolerance on position, the signal is amplified by 10 and then required to be within .4 volt. Roll error is required to be zero. This is done using two comparators, one with roll error as input and the other with the negative. In this case, the pulse outputs of the comparators, signifying a negative-going zero crossing, are used.

Digital programs perform such tasks as providing a random input, magnetic tape storage, statistical processing, and sampling. These programs, along with a detailed discussion, are included in appendix B.

Sampling periods of .04 to .06 seconds were used. Samples consisted of 256 points or about 1 second before the step and 9 to 14 seconds afterwards. This sampling rate is fast enough to pick up all significant frequency components in the signal while permitting a reasonably long run. Although samples of twice the size can be handled by the programs, preliminary results showed that this sample length was satisfactory.

Roll angle and position errors, as well as control stick output, were sampled for each run. Roll rate and velocity were recorded also for some responses.

The subject was put into control of the dynamics and the random input program started. After a minimum period of

½ minute, the experimenter could initiate a sampling run by throwing a switch on the analog computer. From this point on, until the completion of the run, the computer was in control of the experiment, with the experimenter providing only manual override. The main program had been initialized with the sequence and magnitudes of the steps and would proceed then to test the subject. A test started with a variable length delay after which the sampling program would begin to fill the pre-transition part of the buffer. After this was filled, transition would be enabled. Now the program would continue to sample while waiting for the analog conditions of the comparators to be met. When these conditions are met, a digital to analog conversion is ordered from the control panel and the digital sampling program informed. The sampling program then fills the post-transition part of the buffer before exiting to the main program. At this time, the magnetic tape storage program was called to store the data until it was needed later for processing. After this test was made, the main program would recycle until all the steps, in this case ten, had occurred. At the conclusion of the run, results can be processed or particular responses printed or graphed on a real time recorder. Two or three runs were made, and twenty to thirty step responses stored before statistical processing. The statistics program retrieves responses from magnetic tape and forms the average response and its associated variance. The results then are printed out and graphed.

CHAPTER 5

SECOND ORDER RESPONSES

Initial experiments were performed using the second order roll dynamics only. Since the factorization of the helicopter dynamics into attitude and positional dynamics results in two second order systems, it appeared that the characteristics of the second order response would be found in the fourth order responses. Before considering the actual responses, it is desirable to examine the types of responses to be expected.

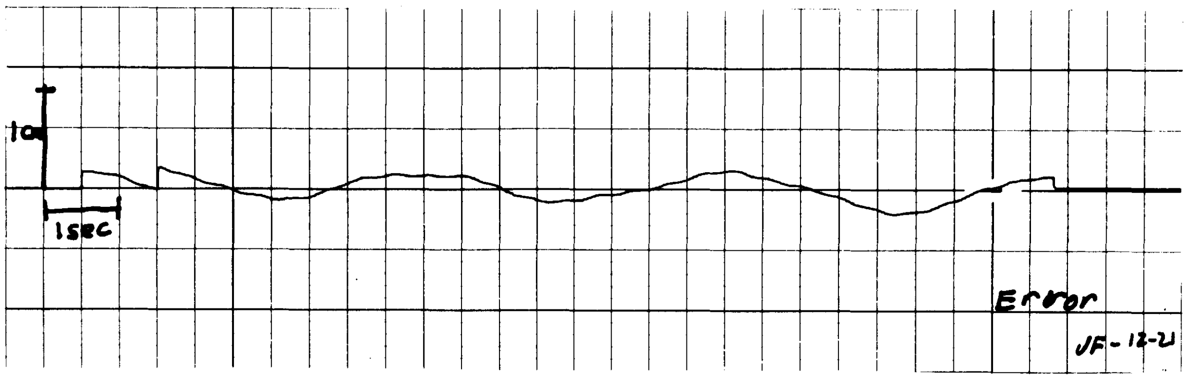
Error in roll angle only, as in any second order system, is brought back to zero most efficiently by first a pulse of polarity opposite that of the error followed by a pulse in the same direction as the error. This dipole should have the same width as the time it takes the error to return to zero. If the pulses in the dipole are symmetric so that the switch occurs when the error has decreased by half, the error rate is also zero when the error has been corrected. An error in rate only is corrected by a single pulse with area equal to the rate. Correction for both error and error rate results in an asymmetrical dipole. If the human operator could respond in this manner, he would be described completely by switch lines on a phase plane.

Human responses are limited by several factors. Various constraints, such as physiological motion limitations, saturation, and self-imposed constraints, act to shape his responses.

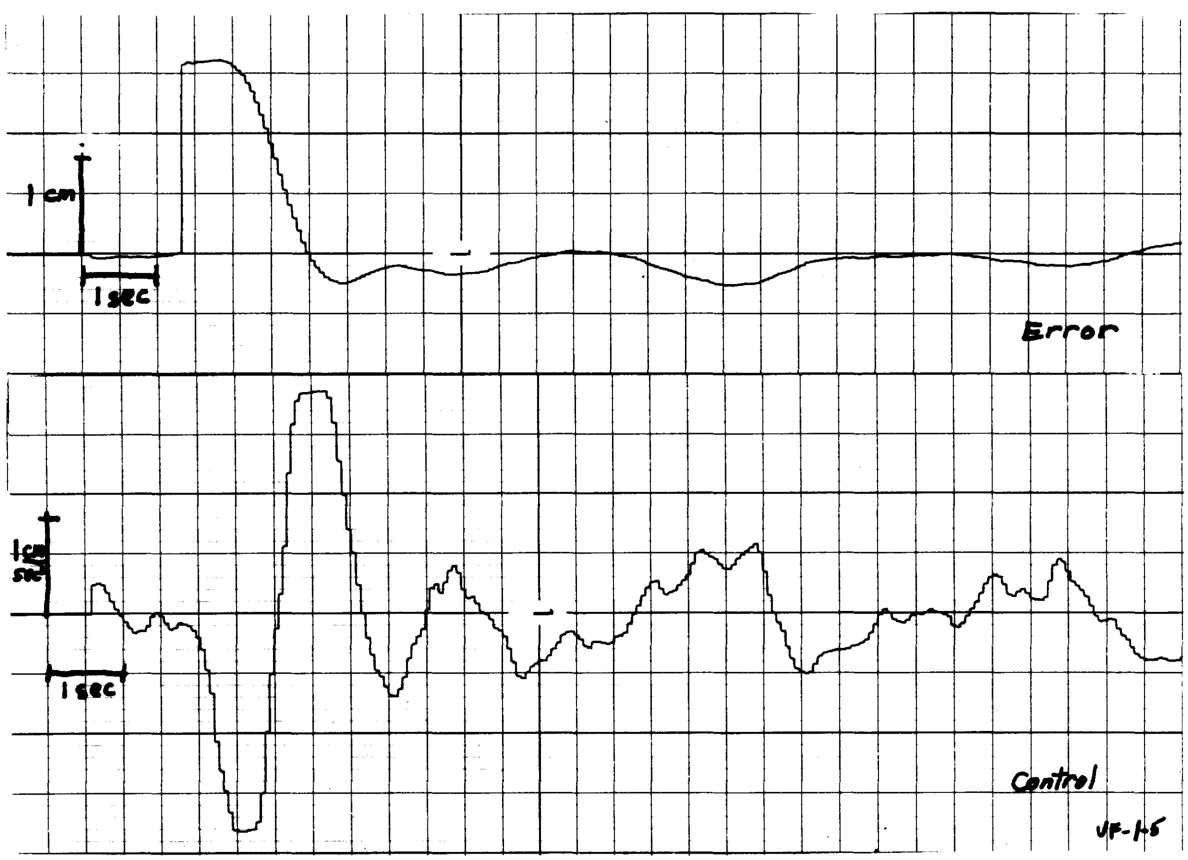
His inherent time delay prevents him from switching at the most opportune time. This time delay is partially compensated for by a first order lead. The dipole, in general, becomes a very difficult control movement since it requires the manual control output to occur at twice the frequency of the error.

The first series of second order experiments concerned step responses. Steps from .25 to 2 cm were tested to find the smallest step that could be used. It was expected that for large steps the human operator would respond differently than for small steps. It was found that steps that are small compared to the limit cycle of the human operator were essentially ignored and treated as a time shift in the limit cycle. A .25 cm response is illustrated in figure 5.1. A large response to a 2 cm step is illustrated in figure 5.2, showing nonlinear switching behavior between levels of saturation.

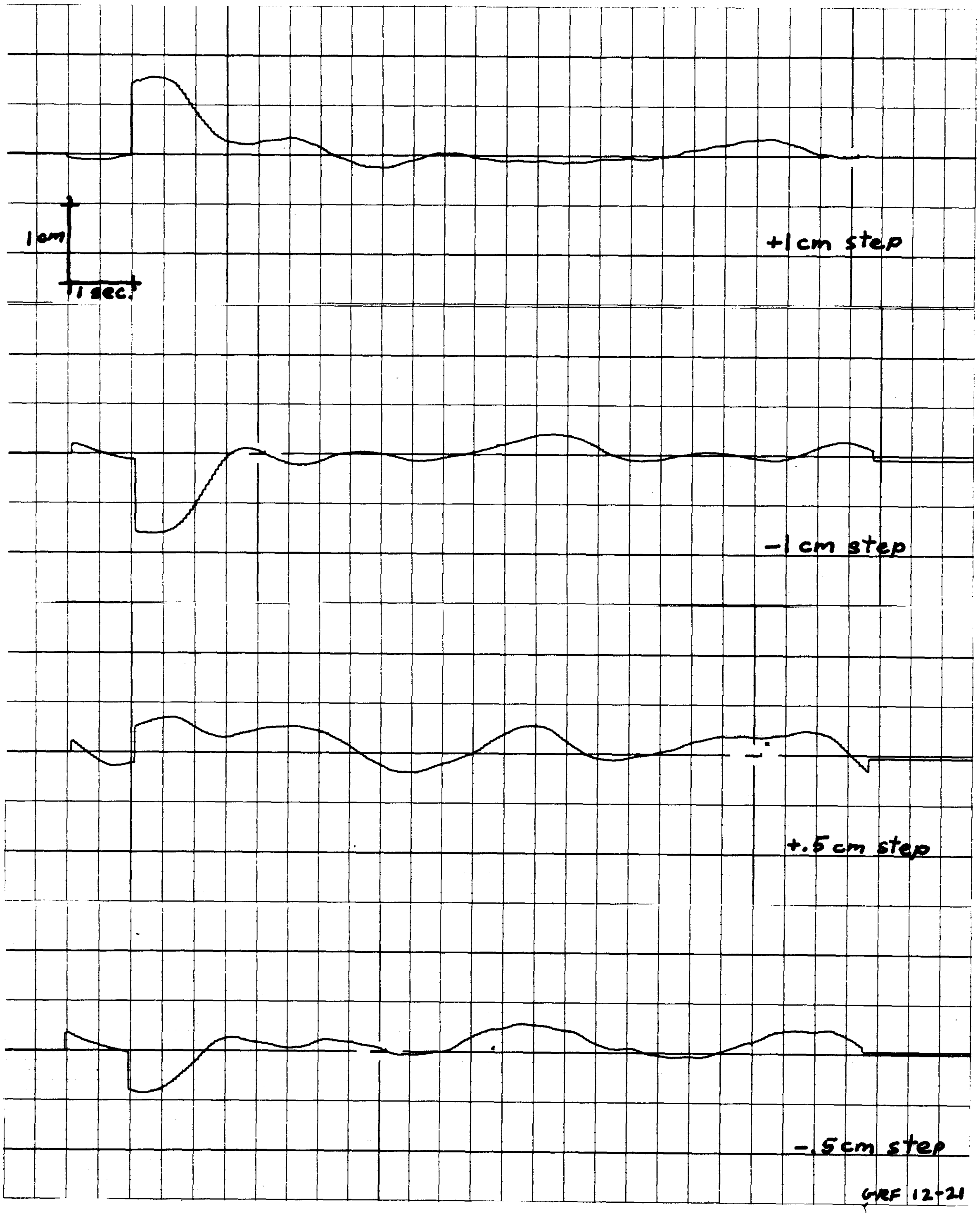
During early testing, negative-going steps were averaged separately from positive-going steps. These early responses, as illustrated in figure 5.3, showed asymmetric behavior. Slightly positive errors were tolerated more than slightly negative errors, resulting in a bias. Negative velocities were reduced to zero sooner than positive velocities, resulting in small errors that still had to be corrected. To eliminate this asymmetrical behavior, negative-going responses were inverted and averaged in with the positive-going responses.



.25 cm Step in Error - $1/s^2$ - Subject JF
Figure 5.1



2 cm Step in Error - $1/s^2$ - Subject JF
Figure 5.2



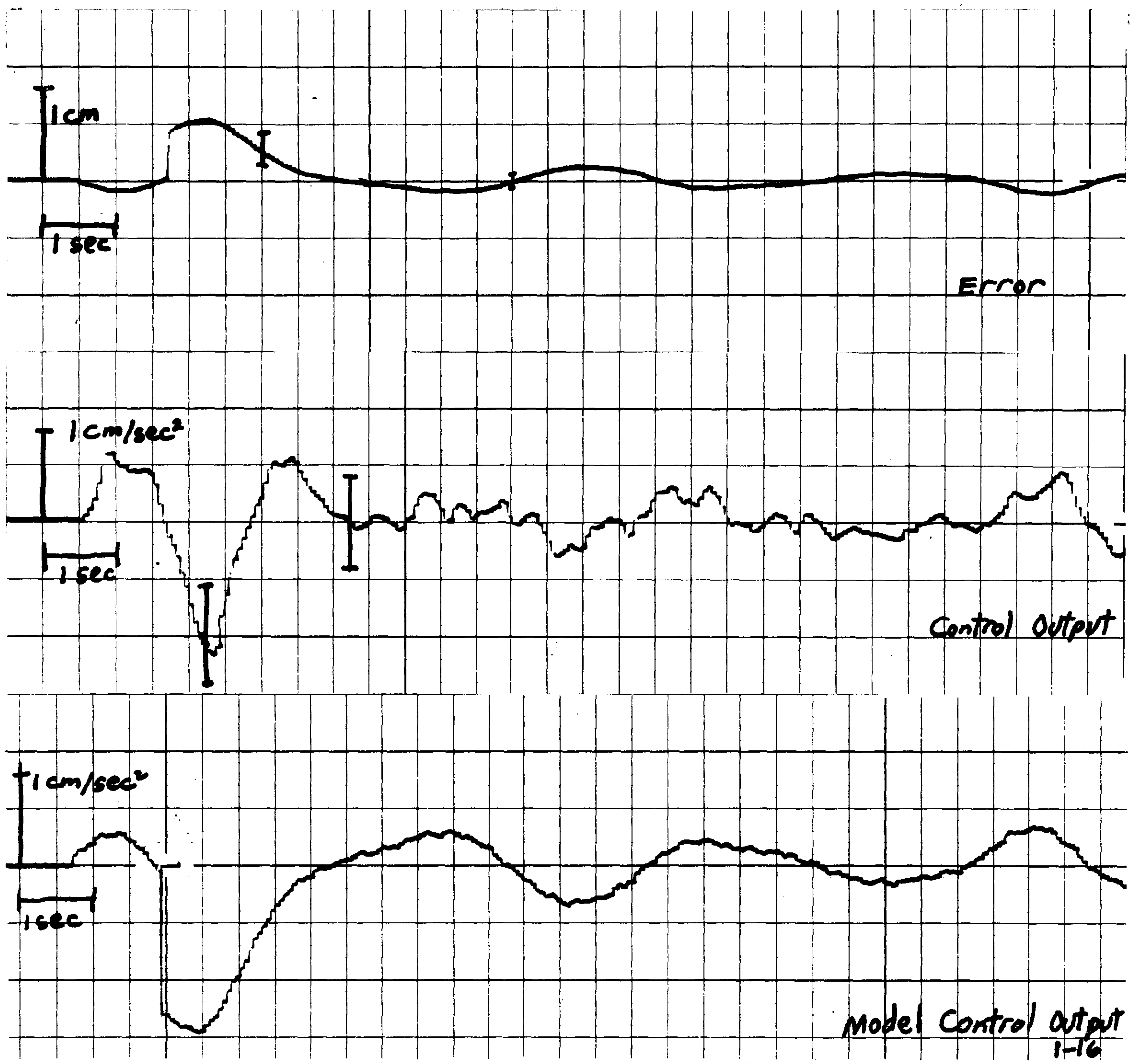
Asymmetry in Positive and Negative Step Error Responses - $1/s^2$
Figure 5.3

On the basis of these early tests, it was decided to use .5 cm steps. Typical responses are illustrated in figures 5.4, 5.5, and 5.6. In these responses, the typical control sequence included a negative-going pulse followed by a positive-going pulse to reduce the velocity to zero as well as the error. In figure 5.4, this resulted in a slow, but deadbeat response. Figure 5.6 illustrates a fast, but oscillatory response.

The behavior illustrated in these step responses was compared to a linear model of the human operator. The model consisted of a lead term of 5 seconds, a lag of .1 second, and a pure time delay.

$$Y_P = 34.6 \frac{s+.2}{s+10} e^{-.3s}$$

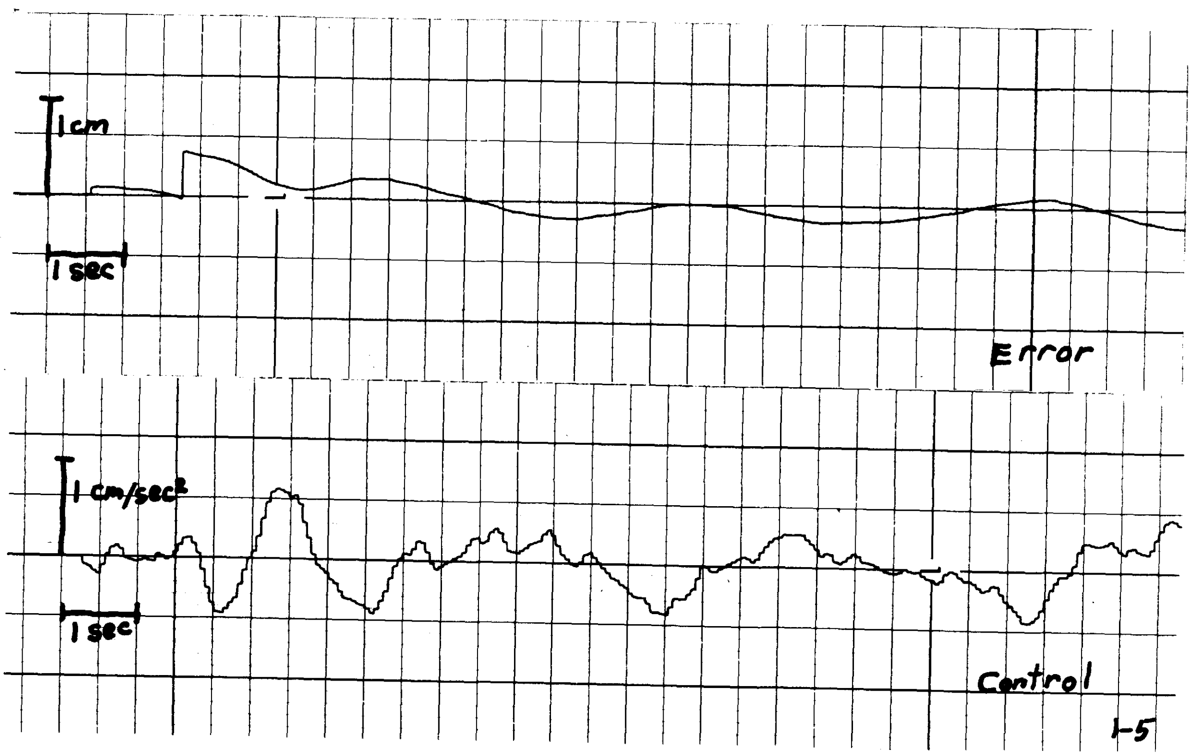
The error was provided as input to the model as well as presented on the display for the subject. The output of the model then was sampled and averaged in the same manner as the human responses. The results are illustrated in figure 5.4. Once the error has been returned to zero, the model predicts the frequency of the limit cycle very well, although the gain probably should be reduced. Initially, the fit is quite poor. The sudden step of the model response exists because the form of the model has an equal number of poles and zeros. A more precise model would add a second order lag so that the initial output and output rate would be zero. Even taking this into account, the model falls down since it cannot generate the deadbeat control that the human operator would use in the case of a sizable error.



Model, $Y_p = 34.6 \frac{s+.2}{s+10} e^{-.3s}$

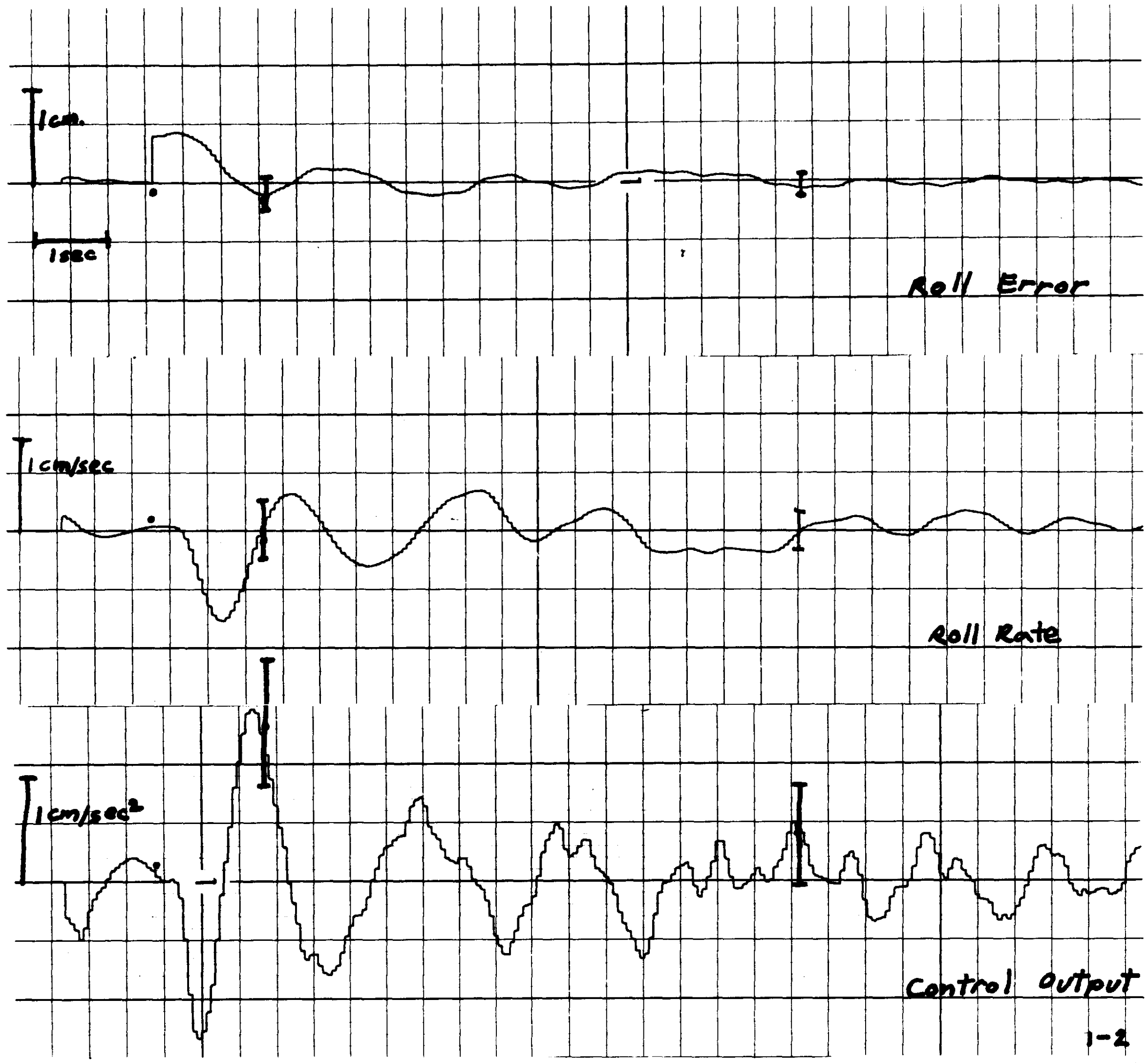
.5 cm Step Response - $1/s^2$ - Subject NVH - 40 Step Average

Figure 5.4



.5 cm Step in Error - $1/s^2$ - Subject JF

Figure 3.5

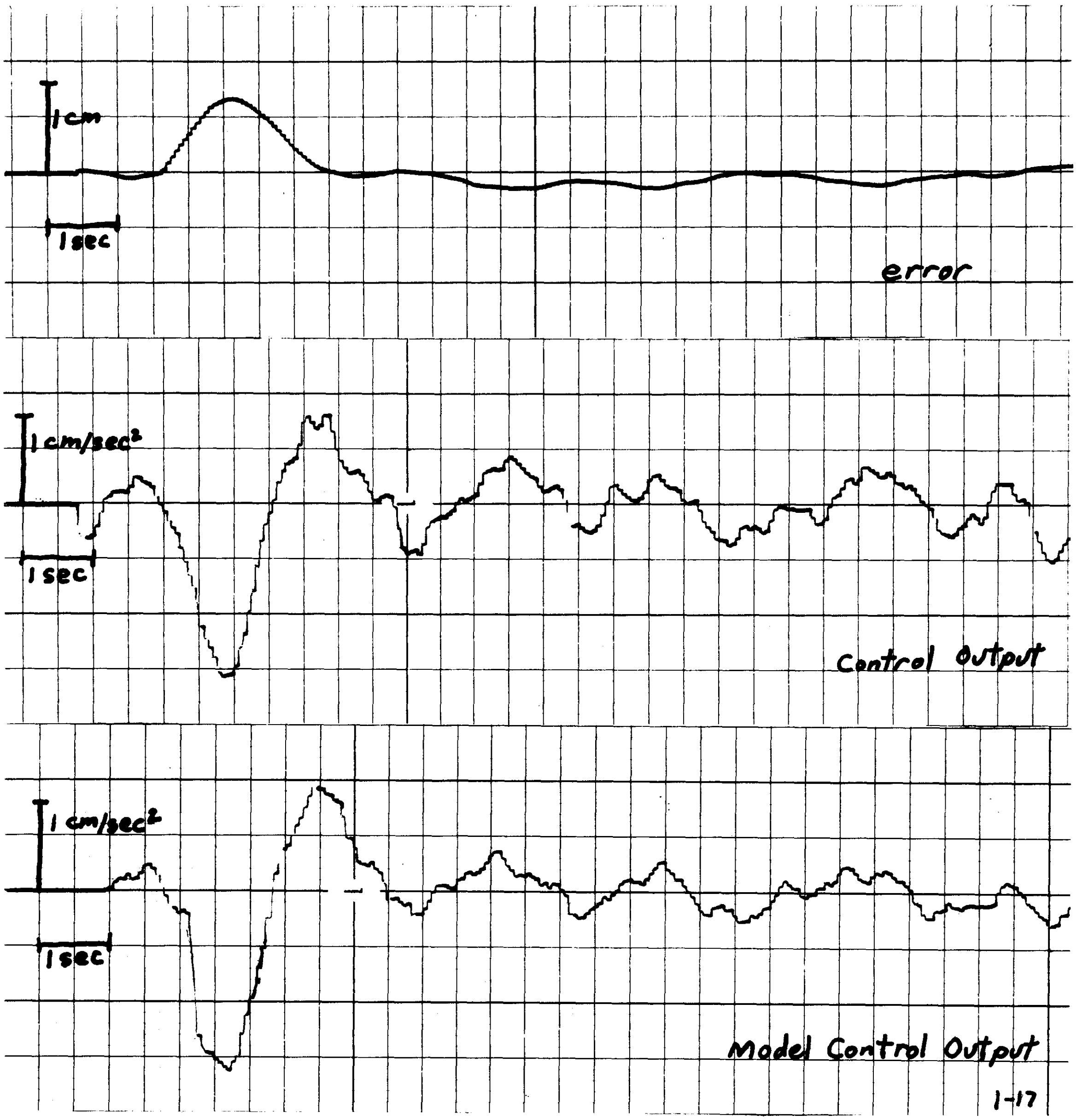


.5 cm Step in Error - $1/s^2$ - Subject GRF
Figure 5.6

Since step responses showed significant nonlinearity, ramp responses next were investigated. In the case of the ramp, there is no discontinuity of error to cue the subject. Initially, the ramp looks sinusoidal and should elicit a similar linear response. Ramps of both .5 cm/sec and 1 cm/sec were tested, with the larger selected for the remainder of the series. This value generates a maximum error comparable to the .5 cm step.

Typical ramp responses are illustrated in figures 5.7, 5.8, and 5.9. These responses tend to be very similar to the responses to steps. This can best be seen by comparing figures 5.4 and 5.7, figures 5.5 and 5.8, and figures 5.6 and 5.9. The initial rate error is brought under control by a negative-going pulse. By the time the rate has been reduced to zero, an error has developed. This error then is brought under control as in the case of the step response. Since the negative-going pulse now has to bring the rate to zero before it begins the error correction, the initial pulse is wider. In the case of the steps, the negative-going pulse tended to be narrower than the positive stopping pulse.

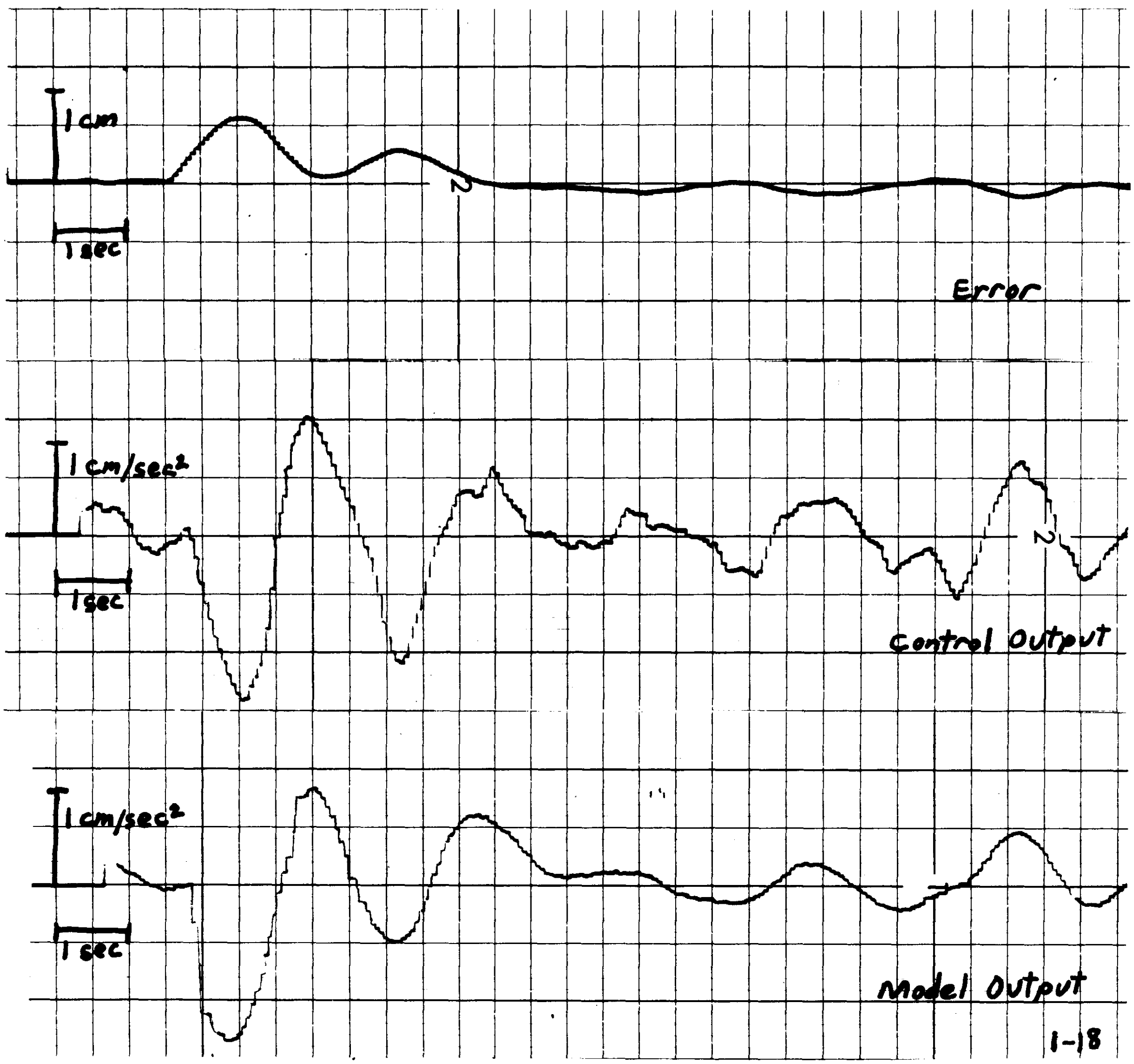
Fitting a linear model to the ramp responses was more successful than to the step responses. The model was the same as mentioned under step responses, with the gain cut in half. As can be seen in figures 5.7 and 5.8, the fit is very good. In figure 5.8, the only serious point of disagreement is the magnitude of the second negative pulse. It



Model, $Y_p = 17.3 \frac{s+.2}{s+10} e^{-.3s}$

1 cm/sec Ramp in Error - $1/s^2$ - Subject NVH - 40 Step Average

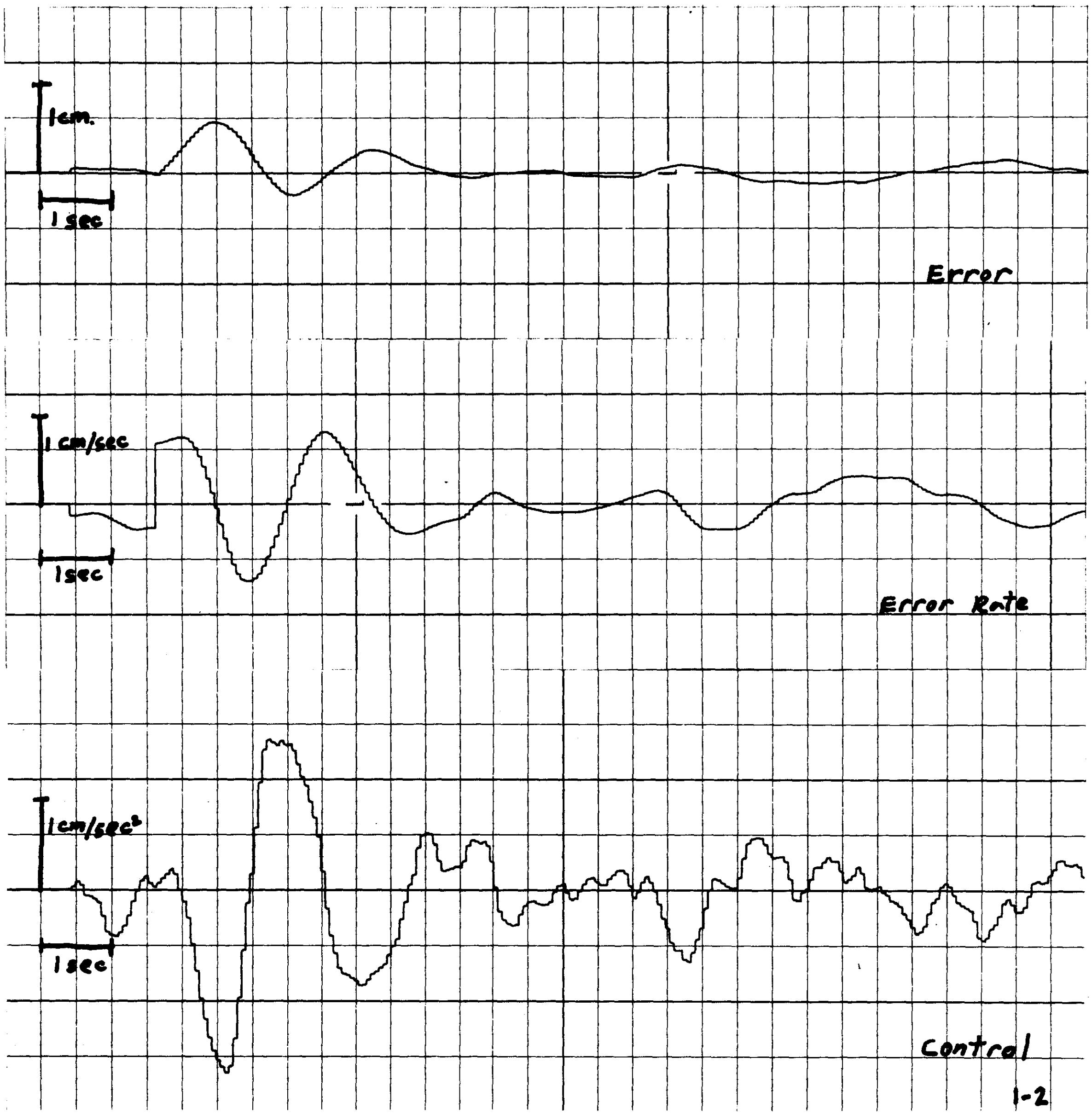
Figure 5.7



Model, $Y_p = 17.3 \frac{s+2}{s+10} e^{-.3s}$

1 cm/sec Ramp in Error - $1/s^2$ - Subject JF - 32 Step Average

Figure 5.8



1 cm/sec Ramp in Error - $1/s^2$ - Subject GRF
Figure 5.9

is interesting to note that if the human operator had used less control at that point, as the linear model suggests, the error response would have been deadbeat and would not have the second peak. A more precise model is treated in a later chapter on closed loop simulation.

Step responses are similar to ramp responses once the maximum error is reached. This seems to indicate that one linear model should describe the response to both inputs. The discontinuity in the step produces an impulse in velocity. The lead term in the human operator model can be interpreted as meaning that the subject responds to both the input and the first derivative of the input. The relative weighting of each is expressed by the lead time constant. Since the step input has a non-zero rate only for an infinitesimal period of time, it is reasonable to assume that the subject never recognizes the velocity impulse and only responds to the error in position. This is equivalent to saying that the human estimate of velocity ignores all discontinuities. Rather than simulating the rejection mechanism, the linear model will be tested only with ramps with the understanding that the portion of the response after the maximum error is reached also corresponds to step inputs.

The standard deviation of the average responses has been indicated at several points in figures 5.4 and 5.6. The vertical lines correspond to plus and minus one standard deviation. As can be seen, the average error responses are known with high confidence. The average control stick output shows a much larger standard deviation. Since the control stick responses are fast, only a small delay in executing the control movement will result in a large amplitude disagreement with the average. As a conceptual aid, if the slope of the control output in a given period of time is reasonably constant, then the variance at a particular time divided by the slope is a variance that expresses a slight phase difference between the average curve and a particular response. This would have the effect of exchanging the rather large amplitude standard deviation for a smaller standard deviation of phase. Part of the standard deviation of the average responses results from control responses due to the random input. Although the response to the random input averages out in time, the variances are increased by the random part of the signal. Average response experiments were performed with all the requirements on error and stick position but without the occurrence of a step or ramp. These experiments showed that most of the variance was due to the random input which was the sole source of the variance after the error induced by the step or ramp had been corrected.

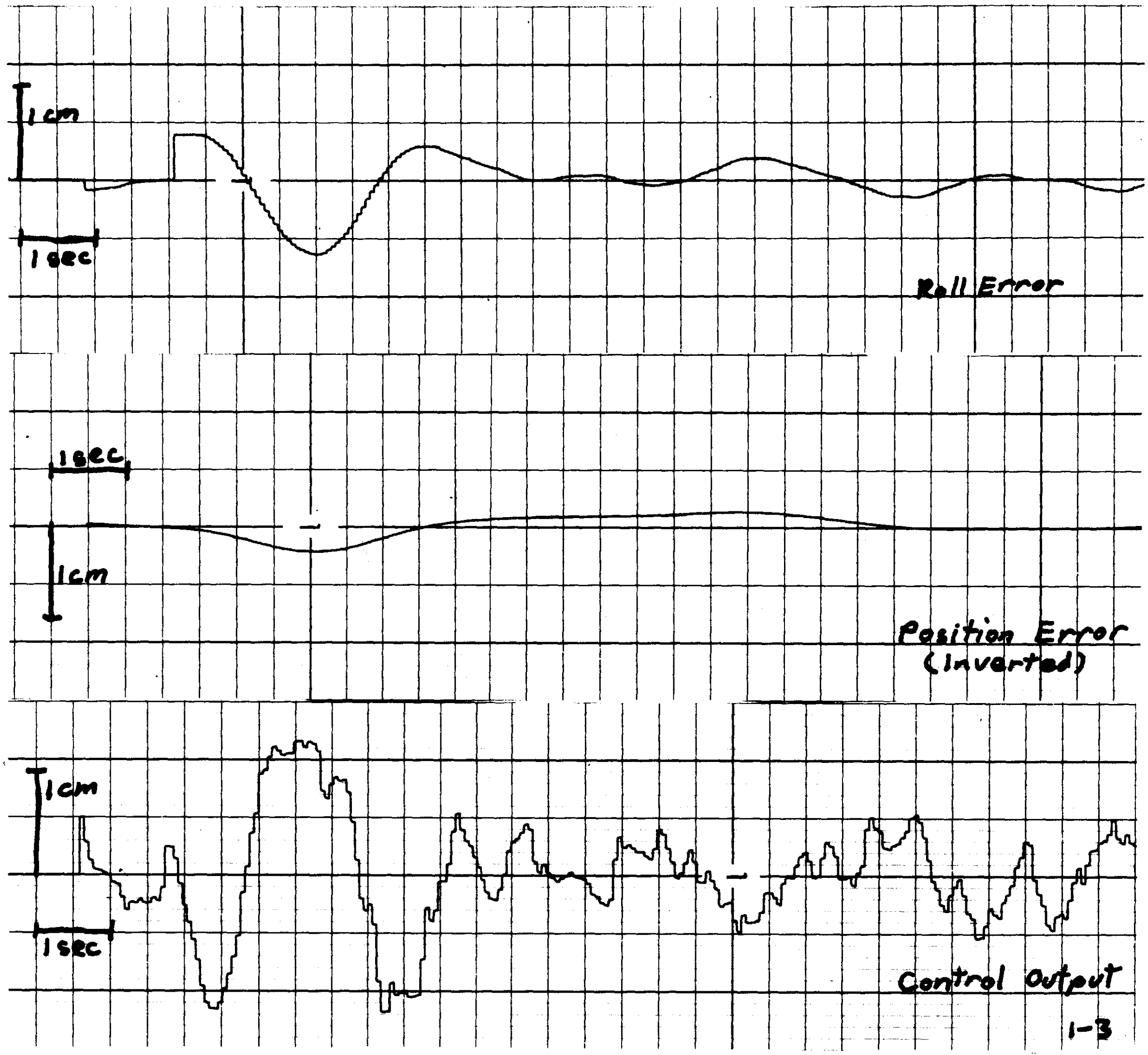
Closed loop modeling and simulation of the human operator controlling the second order system will be considered in Chapter 7.

CHAPTER 6

FOURTH ORDER RESPONSES

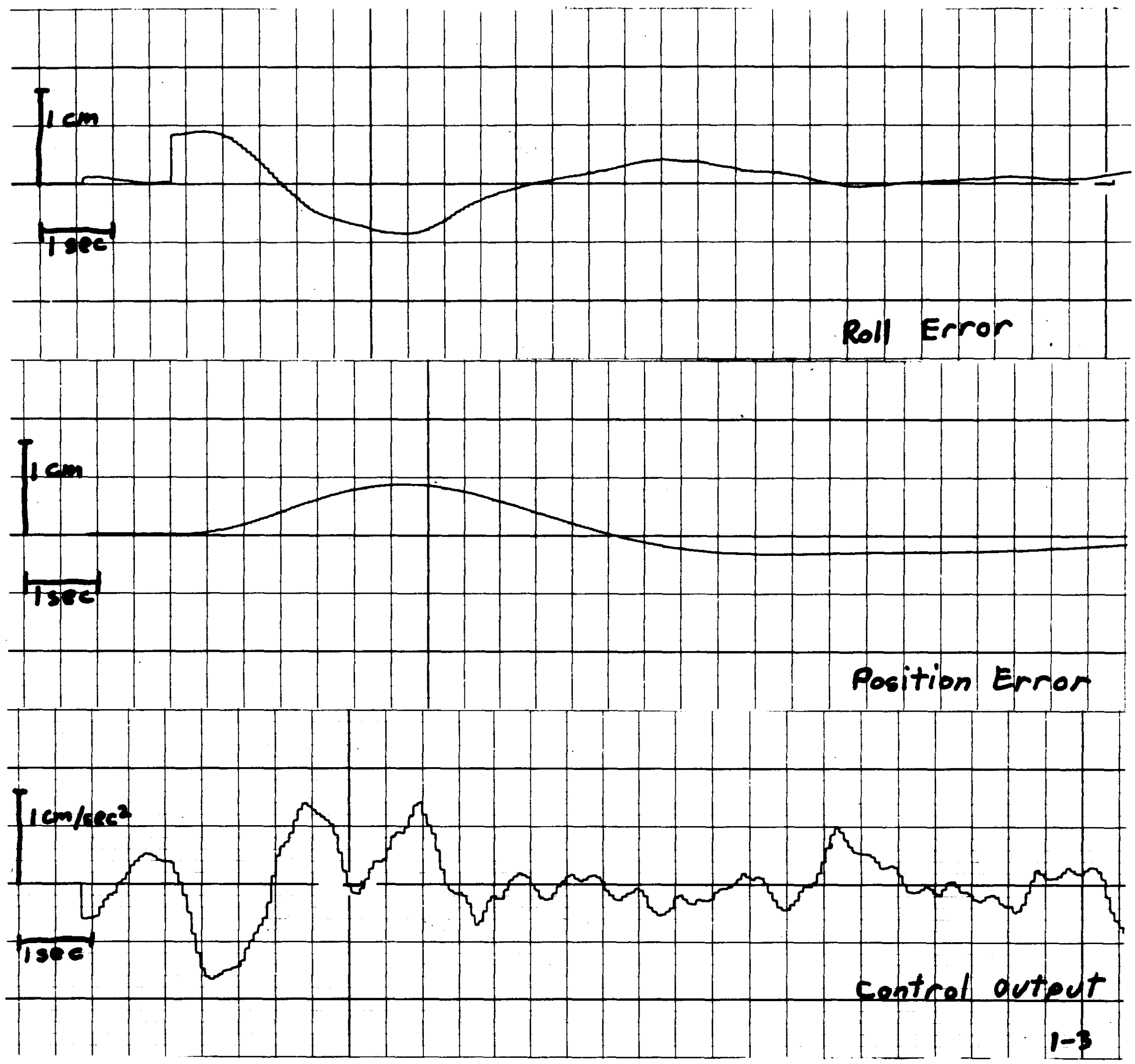
After the subjects became proficient in controlling the second order system, they were introduced to the complete fourth order system. Initially, a unity gain was placed in the dynamics relating roll angle to position. This was found to be too difficult a task. Although the subject could maintain control, responses were very lightly damped, making it difficult to get consistent results with a reasonable number of transitions. By reducing the gain to one-half, the responses became more consistent. Because of the inherent divergence of this system, the random forcing function was reduced to a tenth of its previous value. It now provided only a nuisance level that required continuous attention to the roll angle error.

The first series of experiments was performed with steps in roll angle error. Typical responses are indicated in figures 6.1 through 6.5. Each response consists of two phases. First, the roll angle error is reduced towards zero. Second, the accumulated position error is corrected by the execution of some roll angle program. In each response, the roll angle error took one to two seconds to be reduced to zero. This one-sided roll angle error imparts a velocity to the position error. Because of the increasing position error, a period of negative roll angle must be generated to decelerate the position error and return it to zero. The

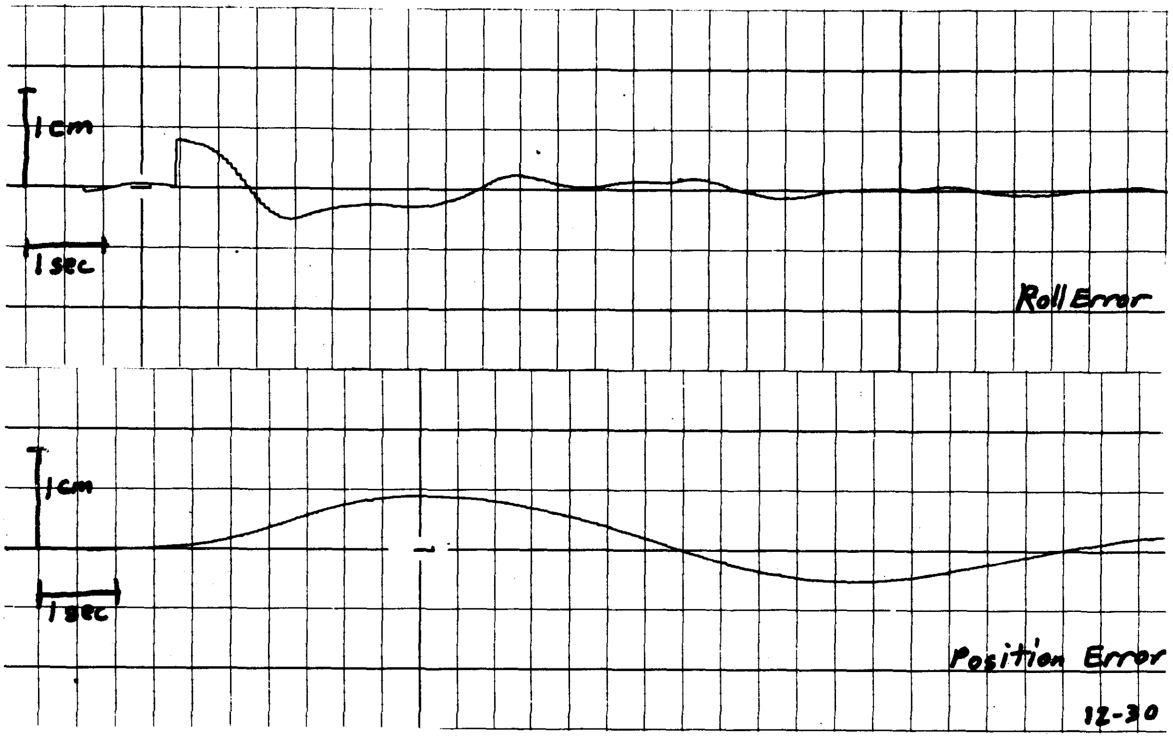


.5 cm Step in Roll Error - $1/(2s^4)$ - Subject NVH

Figure 6.1

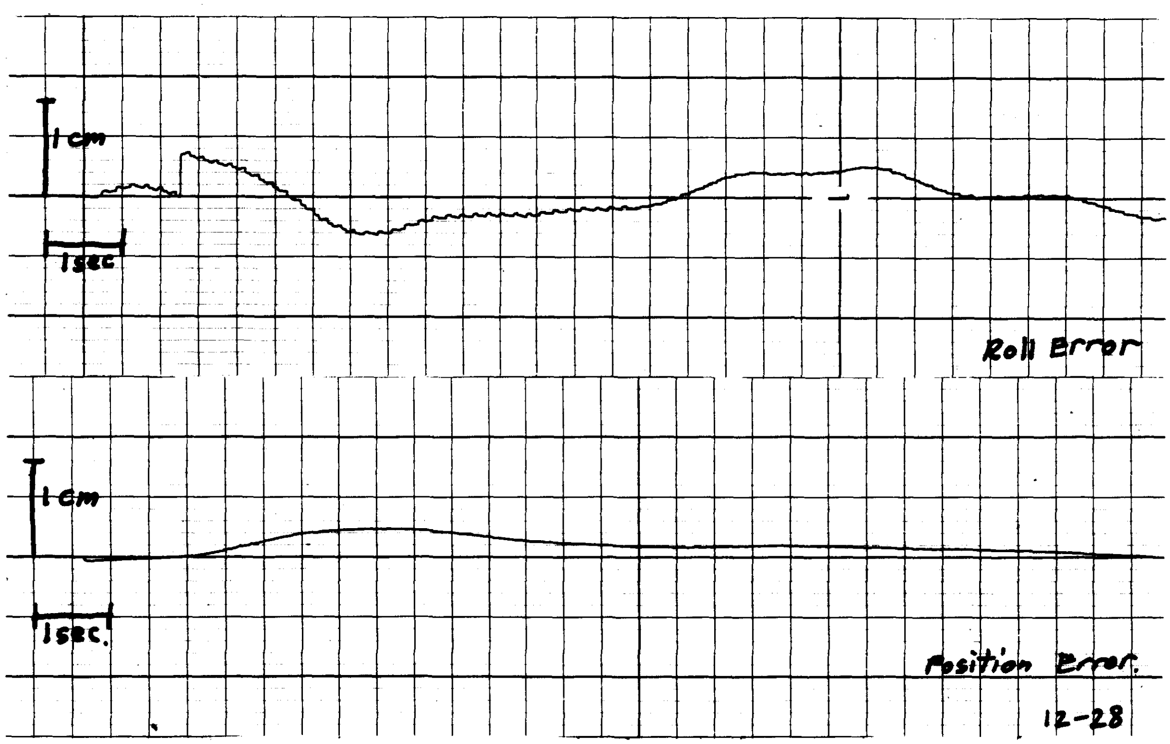


.5 cm Step in Roll Error - $1/(2s^4)$
Subject JF - 30 Step Average
Figure 6.2



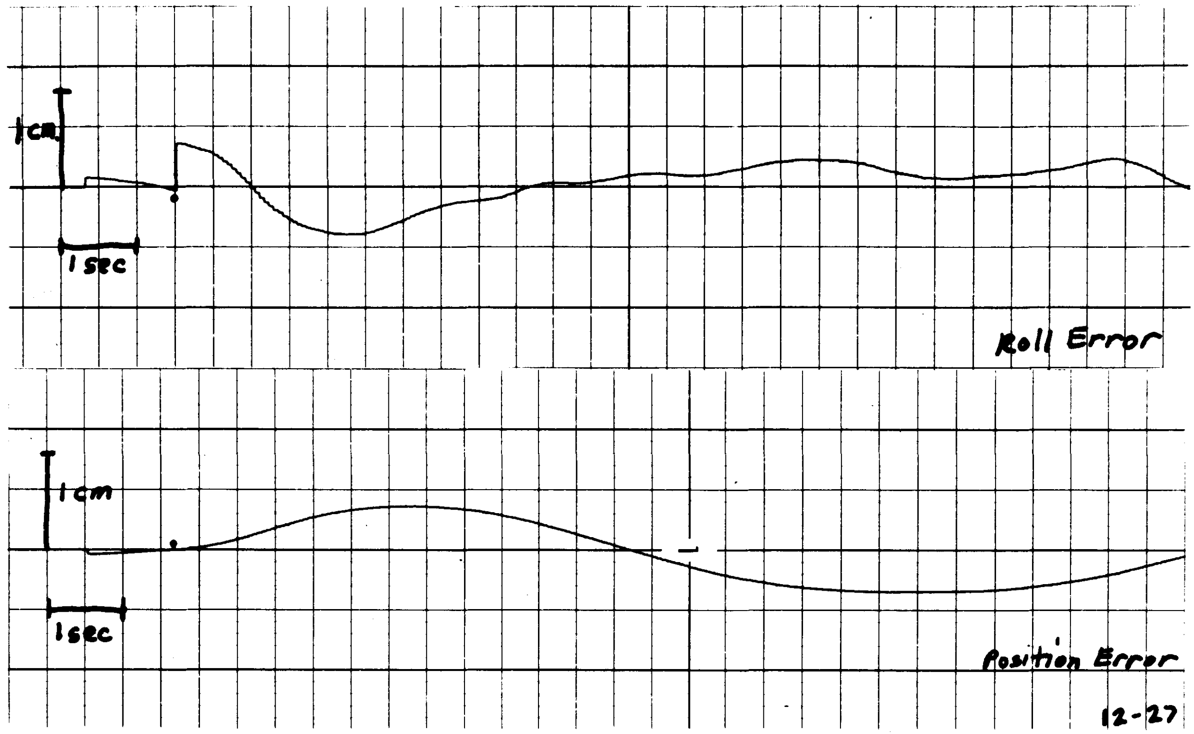
.5 cm Step in Roll Error - $1/(2s^4)$ - Subject CO

Figure 6.3



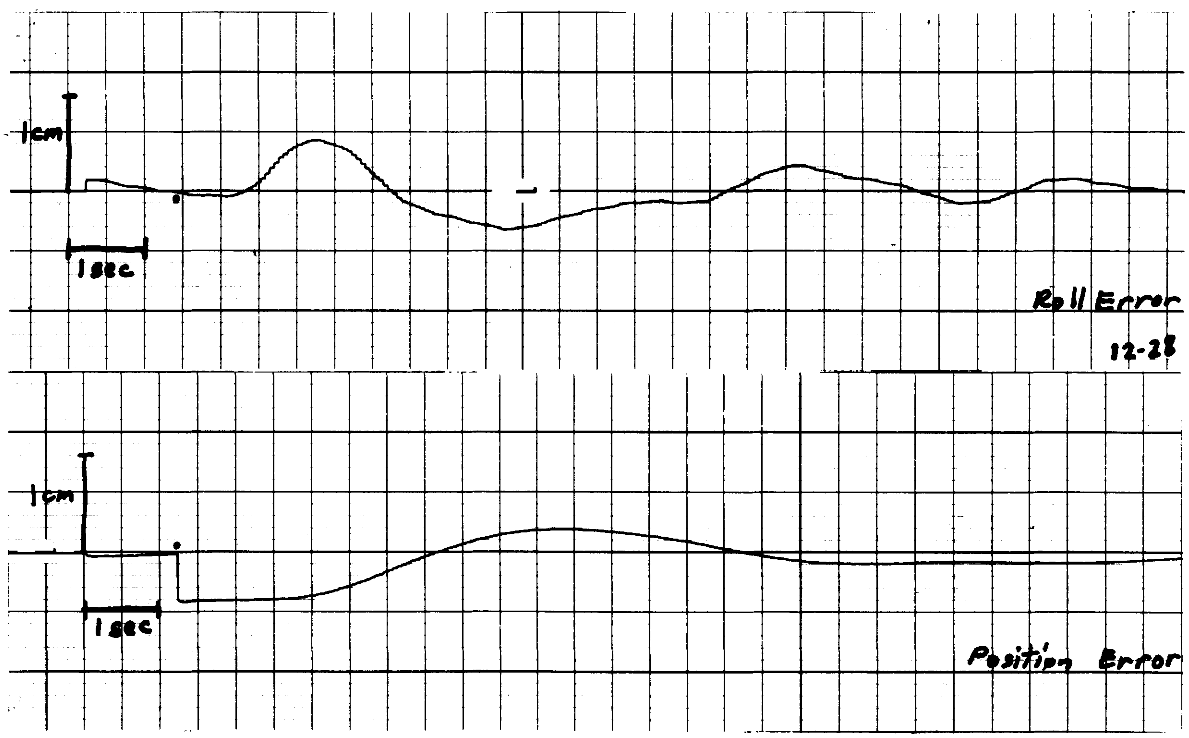
.5 cm Step in Roll Error - $1/(2s^4)$ - Subject RS

Figure 6.4



.5 cm Step in Roll Error - $1/(2s^4)$ - Subject GRF

Figure 6.5



.5 cm Step in Position Error - $1/(2s^4)$ - Subject GRF

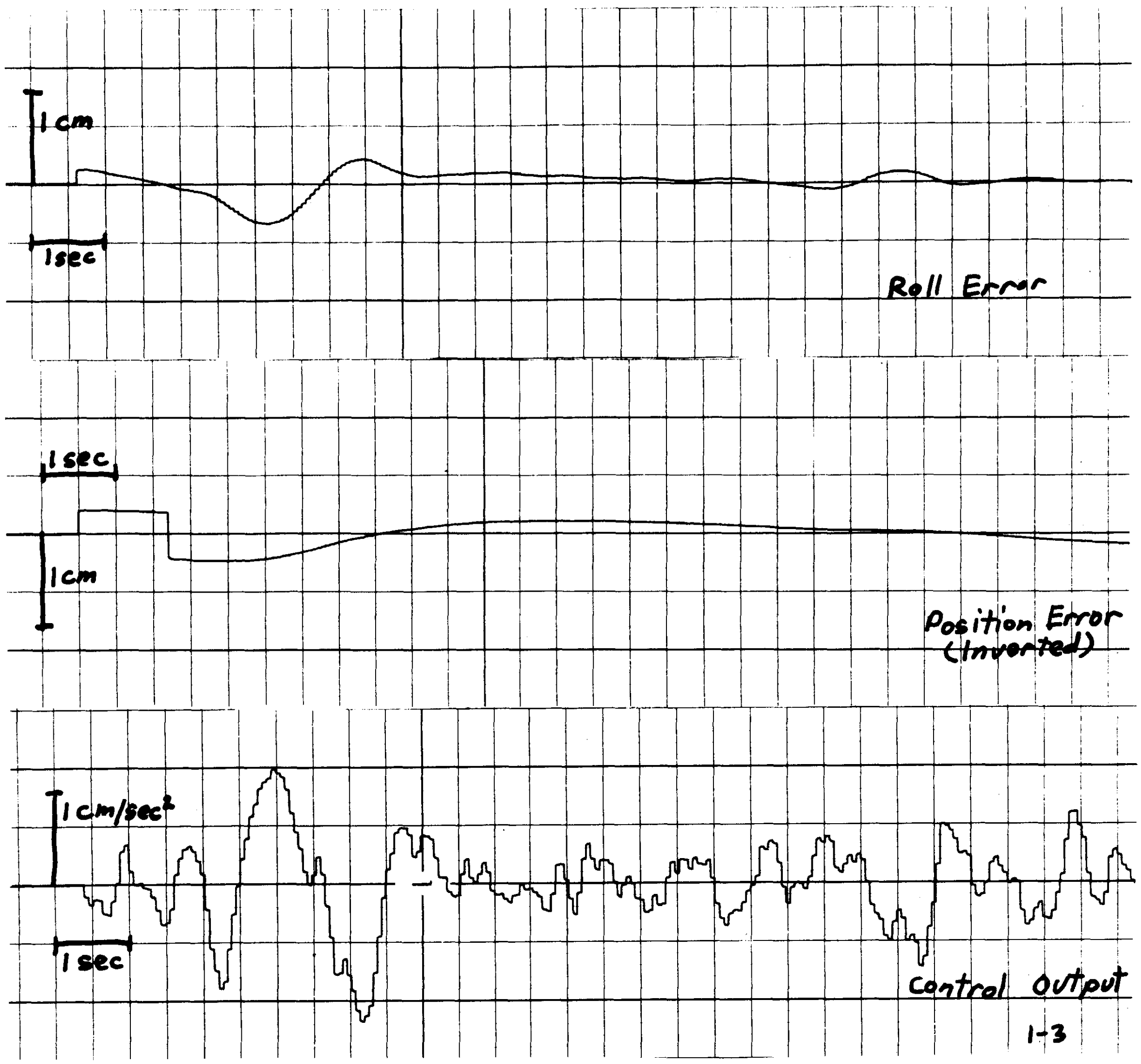
Figure 6.6

roll angle program that is necessary to correct the position error is similar to the control sequence needed to correct a rate error in the second order system. The major difference is the greater time lag in controlling the roll angle in contrast to the neuromuscular lags in controlling the stick output. Since it takes time to generate the roll angle, the general effect is that of a slower time scale.

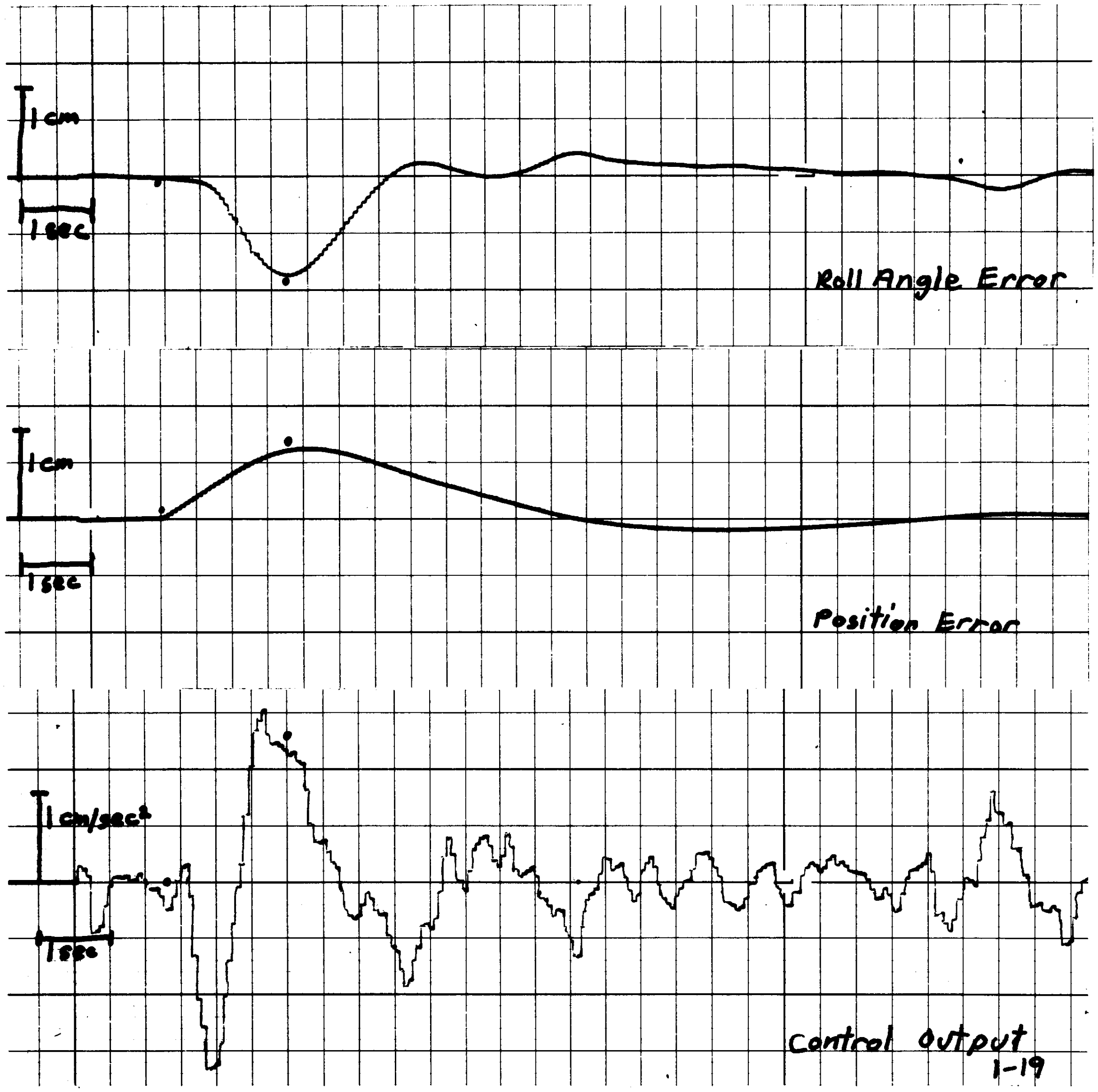
The roll angle correction program differs among subjects. Figures 6.1 illustrates an excellent response. Correction of the step in roll error takes approximately 1 second. During this time, a velocity error of .25 cm/sec has developed. The subject corrects for this velocity by a large pulse of negative roll angle. The subject then brings the velocity and position error to zero, as the stopping roll angle pulse is brought back to zero in a deadbeat fashion. As is typical, a small position error remains that takes a long period to correct. The roll and position average responses have standard deviations of the order .02 cm to .06 cm. The average control output has a typical standard deviation of .3 cm. The responses in figures 6.2 through 6.5 are similar to that of figures 6.1, although the responses show lower frequencies and less amplitude in the negative roll angle pulse used to reverse the velocity error. As can be seen in figures 6.2 and 6.4, as well as in figure 6.1, there is a tendency to permit small position errors to remain uncorrected for a significant period of time.

Responses to ramp errors in roll error can be predicted on the basis of these step responses and last chapter's second order system results. The previous chapter indicates that the portion of the ramp responses after maximum error is reached corresponds well to the step response. In this fourth order task, a ramp input in roll error would take twice as long to return to zero as a comparable step response. This would result in a velocity error twice as large. The position response then would have the same frequency and damping ratio as in the case of a step in roll but would have a greater initial amplitude.

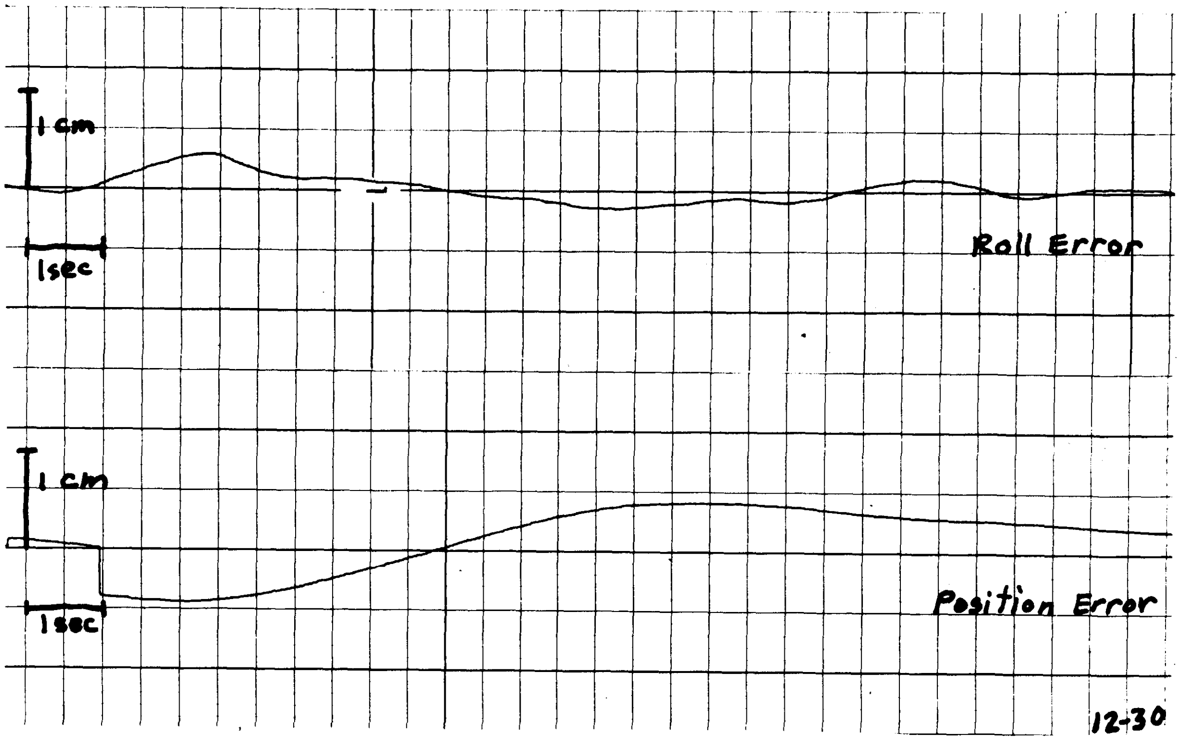
The second series of experiments was performed with steps and ramps in position error. These responses are illustrated in figures 6.6 through 6.10. All these responses are characterized by a delay of about 1.5 seconds before the position error is changed significantly. The roll angle response shows an initial delay of about .5 second, a little longer than that observed in the second order experiments. A step in position error requires the subject to generate a roll correction program similar to the control stick movements needed in controlling the second order system. First, a velocity must be induced by a roll angle pulse and then, as the position error decreases toward zero, the velocity must be reduced by a roll angle pulse in the opposite direction. This is illustrated in figures 6.6 and 6.7. Figure 6.8 shows the response to a ramp error in position. The initial velocity is reversed by a large negative roll angle pulse. The velocity is slowly decreased to zero, and the



.5 cm Step in Position Error - $1/(2s^4)$
Subject NVH - 30 Step Average
Figure 6.7

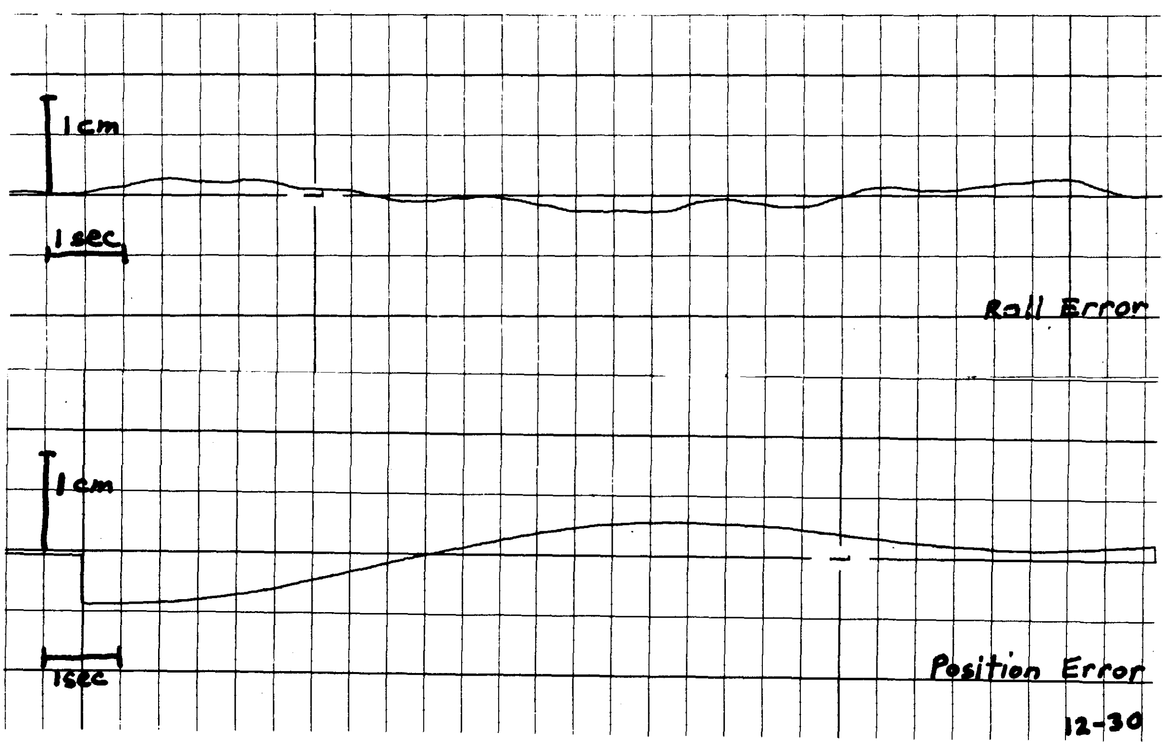


.5 cm/sec Ramp in Position Error - $1/(2s^4)$
Subject NVH - 40 Step Average
Figure 6.8



.5 cm Step in Position Error - $1/(2s^4)$ - Subject JF

Figure 6.9



.5 cm Step in Position Error - $1/(2s^4)$ - Subject CO

Figure 6.10

position error is brought to zero with negligible overshoot. Figures 6.9 and 6.10 illustrate poorer control of position error. In figure 6.9, the subject was generating a correct roll angle pulse when, after 2.5 seconds, he leveled off and maintained a slight roll angle. This resulted in a very lightly damped position error. In both figures, the subject used too small a gain.

Because of the time required to generate fourth order corrections, it is very likely that the human operator controls the roll angle in a manner similar to the second order system but switches to a preprogrammed form of response in correcting position errors.

CHAPTER 7

LINEAR MODELS

Experiments showed that the human operator, in controlling the second order system, could be described by the following describing function

$$Y_p = K \frac{s+.2}{s+10} e^{-sT}$$

This describing function differs from McRuer's model in the generalization from the Fourier variable, $j\omega$, to the Laplace variable, s. This is justified, since the subject is unable to take advantage of the future behavior of the deterministic portion of the input signal when the rms value of the random input is large compared to changes in the deterministic signal. The high frequency attenuation of the second order system permits the human operator to respond with high frequency movements, such as triangular pulses, while the linear approximation can respond only in a smoother fashion. The linear model response is synchronized with the time of application of the transient input, while the human operator becomes less synchronized as time goes on. For this reason, it is expected that the linear model will be accurate for only a few periods of oscillation.

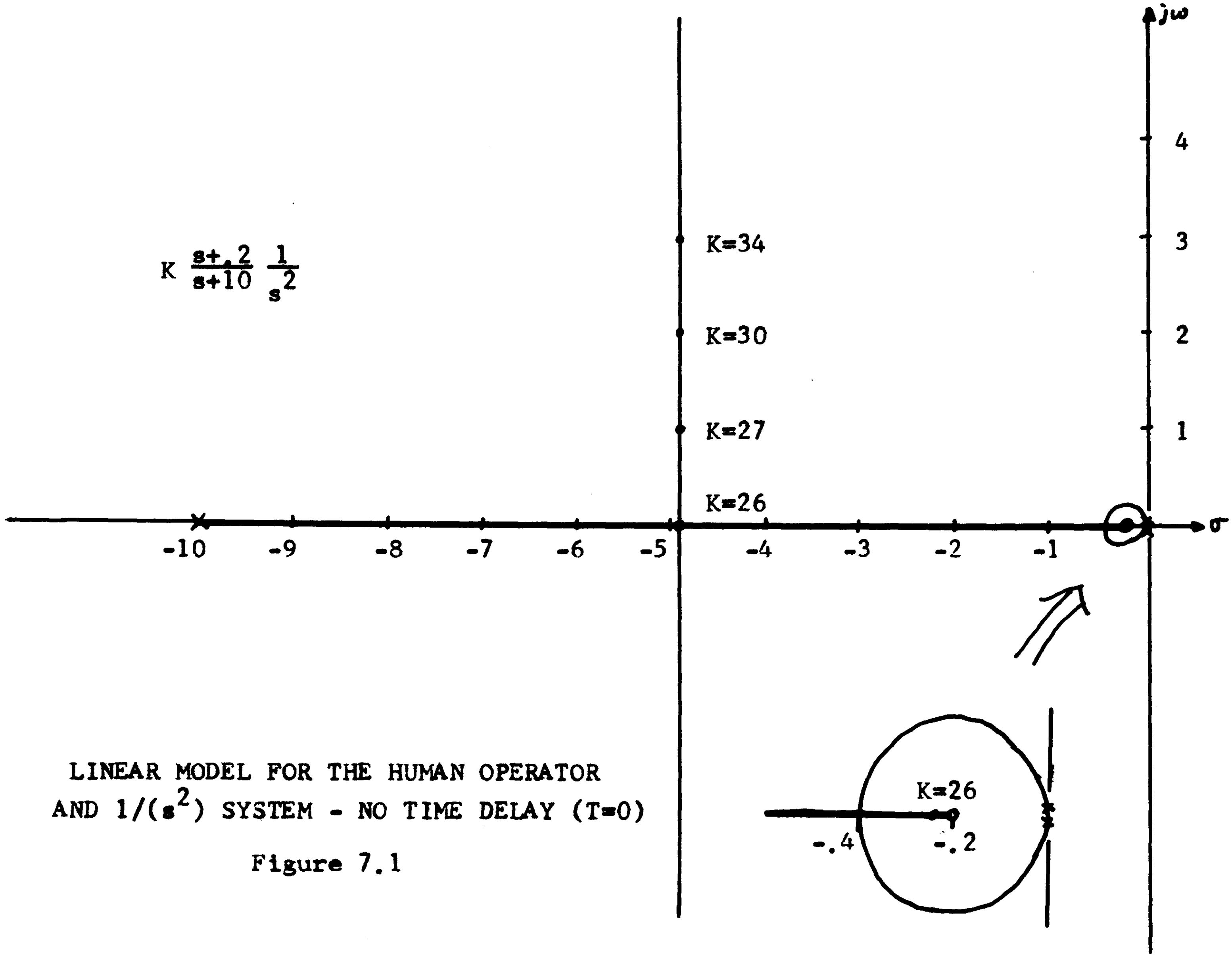
As indicated in earlier chapters, it is expected that this model will hold for step inputs as well as ramp inputs if the lead is modified so as to ignore the velocity impulse associated with the discontinuity. The actual simulation was performed only with ramp inputs with the understanding that the portion of the response starting from maximum error also corresponds to a step input.

The root locus of the human operator model controlling the second order system, without the time delay, is indicated in figure 7.1. The plant introduces two poles at the origin, while the human operator places a lead zero at s=-.2 and a neuromuscular lag pole at s=-10. As the locus leaves the pole at s=-10, other loci curve out from the origin around the zero. The characteristic equation is

$$s^2(s+10) + K(s+.2) = 0$$

Since the sum of the roots must always be equal to -10 (minus the coefficient of the s^2 term), corresponding closed loop poles can be found immediately. When the undamped closed loop poles approach the asymtote, the zero is cancelled by the third closed loop pole.

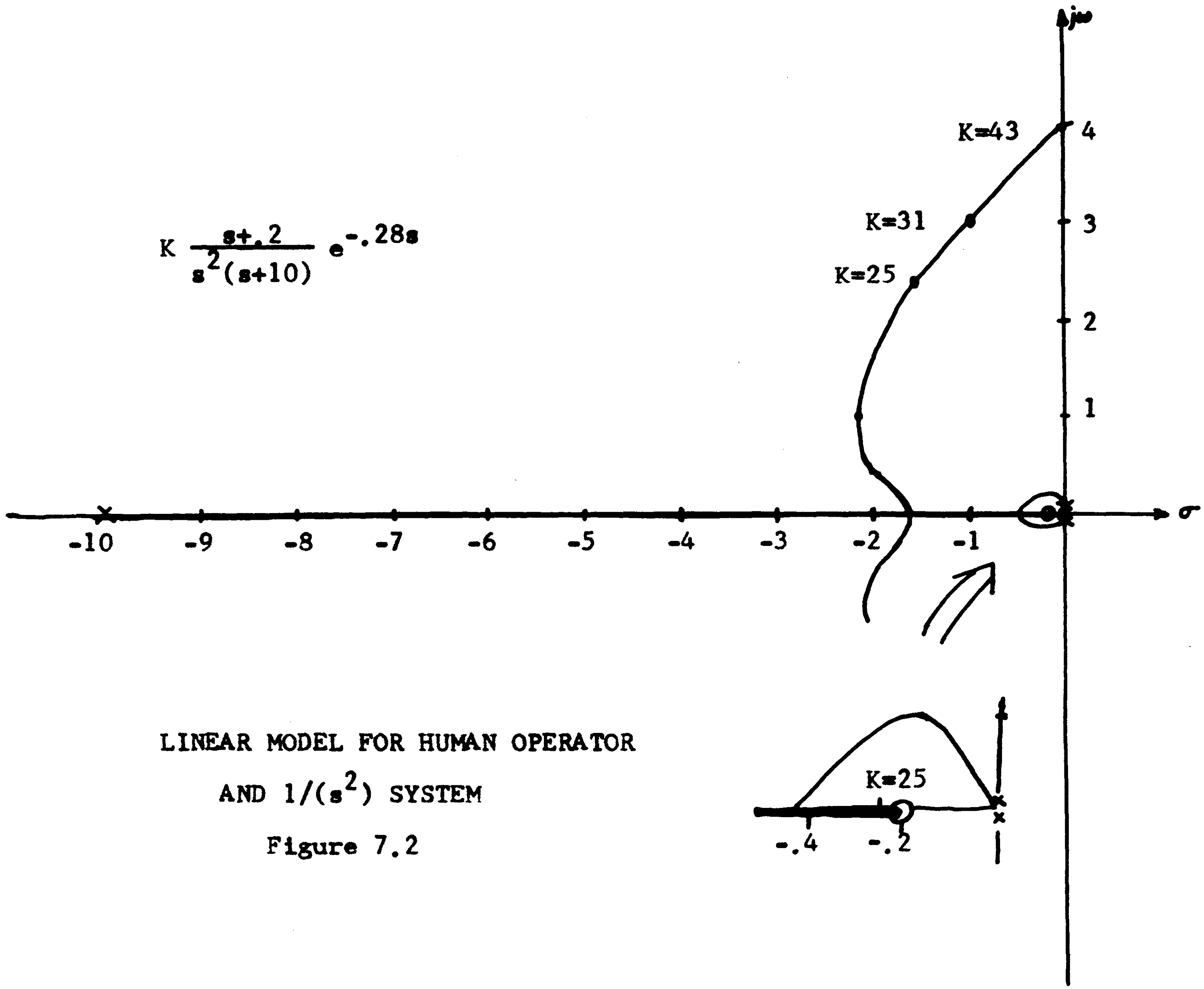
When a pure time delay is added to the human operator model, the root locus for the combined system is altered, as indicated in figure 7.2. The pure time delay affects the locus by introducing a phase lag equal to ωT and also modifies the closed loop system by adding a pure time delay. The breakaway point is shifted to the right. The exact locations of the breakaway and entry points can be found by taking the derivative of the expression for gain with respect to σ while holding ω equal to zero. This results in the condition



$K \frac{s+.2}{s+10} \frac{1}{s^2}$

LINEAR MODEL FOR THE HUMAN OPERATOR
AND $1/(s^2)$ SYSTEM - NO TIME DELAY (T=0)

Figure 7.1



LINEAR MODEL FOR HUMAN OPERATOR

AND $1/(s^2)$ SYSTEM

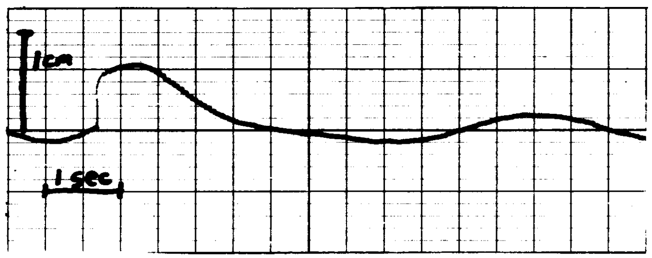
Figure 7.2

$$T\sigma^3 - (10.2T+2)\sigma^2 - (10.6+2T)\sigma - 4 = 0$$

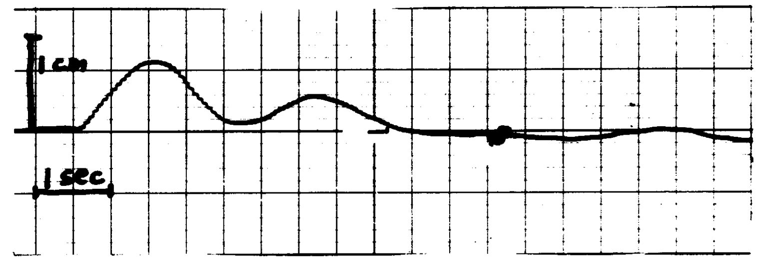
For T=.28, roots are found at σ=-.45, -1.6, and +19.4. The latter is extraneous since no locus exists at that point. The time delay also introduces harmonics because of the periodic behavior of the complex exponential. For this system, the harmonics are far from the origin.

The linear system was simulated on the hybrid computer, with the digital computer simulating a pure time delay. The digital computer sampled the signal every millisecond, stored the values in memory, and generated the delayed signal by digital to analog conversion. Responses for several gains are illustrated in figure 7.3. The model error response with a gain of 25 approximates the responses of figures 5.4 and 5.7. All are characterized as being very well damped. The exact placement of the zero dictates the nature of the exponential decay. These solutions would be approximated better by a faster decay caused by moving the zero further from the origin. The model with the gain of 30 approximates the responses in figures 5.5 and 5.8. The natural frequency of the model response is 3.5 rad/sec, while that of the response in figure 5.8 is 3 rad/sec. The natural frequency and amplitude are better matched if the pure time delay is increased.

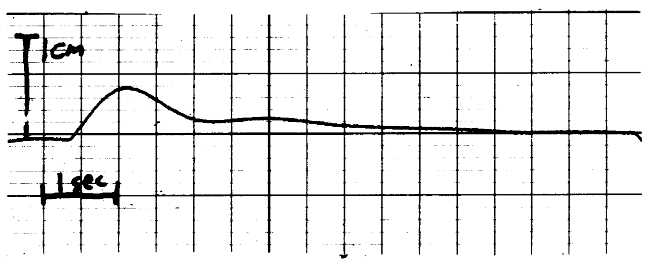
It was suggested in Chapter 6 that the human operator model controlling the roll dynamics was identical to the model for controlling a pure second order system. The justification of this assumption was the low frequency nature of



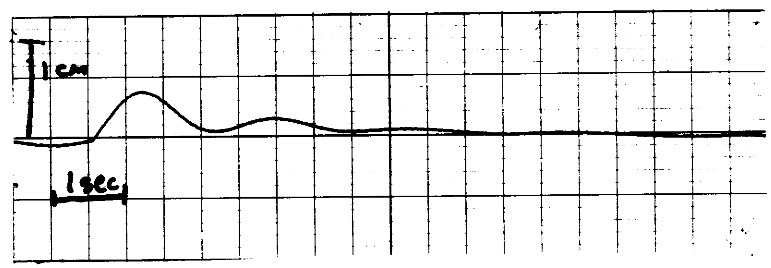
Response of Figure 5.4



Response of Figure 5.8



Model Response - Gain of 25



Model Response - Gain of 30

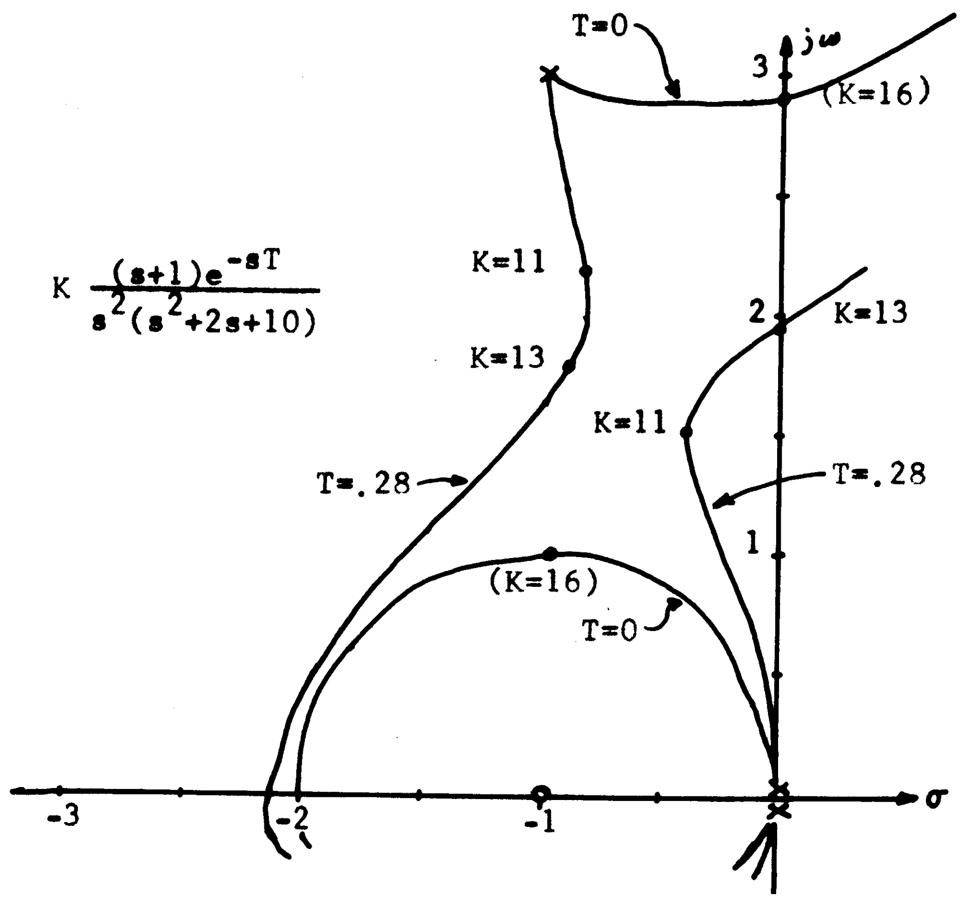
Simulation of Second Order System
Figure 7.3

position error compared to the roll error. For the fourth order simulation, the second order model was chosen with a gain of 30. The closed loop describing function for the roll dynamics is then, neglecting higher harmonics

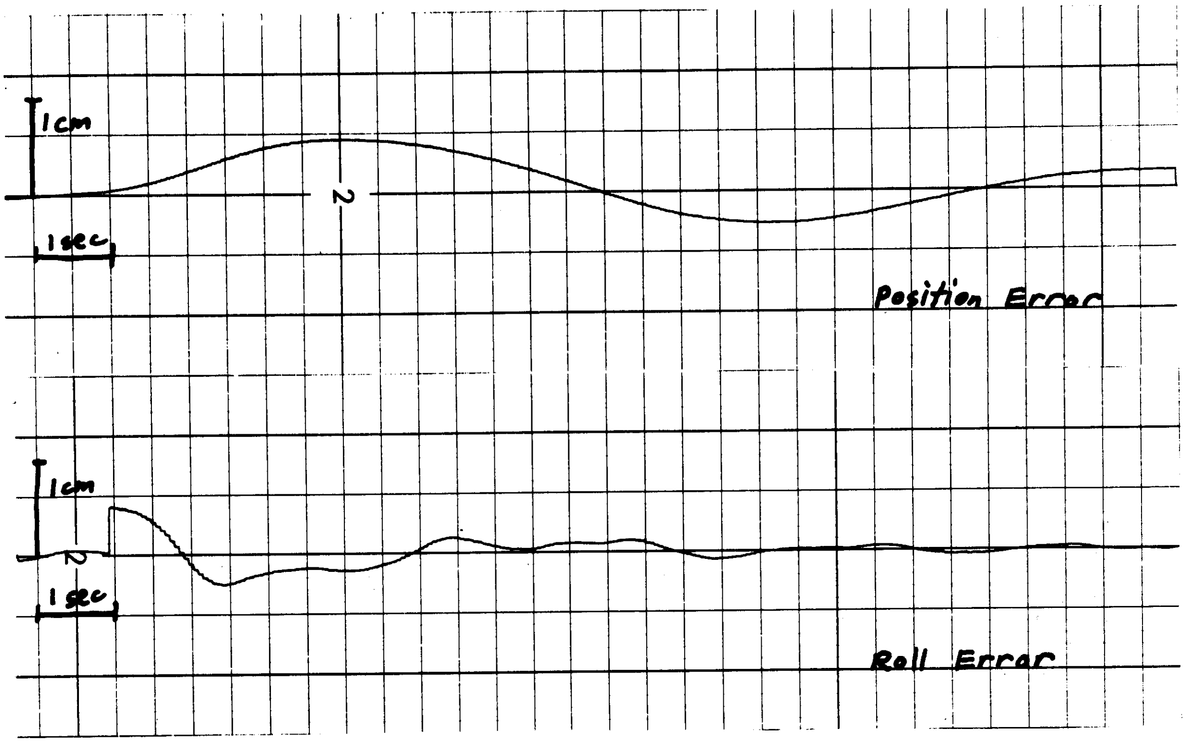
$$30 \frac{(s+.2)}{(s+.22)(s^2+2s+10)} e^{-.28s}$$

Consideration of the fourth order responses of Chapter 6 indicated a lead of .5 to 1 second. The lead was approximated by measuring the position error and velocity associated with the roll error at a given time. The root locus plot of the position loop, with a lead of 1 second, is illustrated in figure 7.4. For stability, the gain must be under 13. Since the closed loop roll dynamics introduce a gain of 30, the position loop must have a gain less than .43. The human operator generates the most damped solution consistent with the stability condition on the high frequency underdamped poles. As the zero is moved further from the origin, the response becomes more damped.

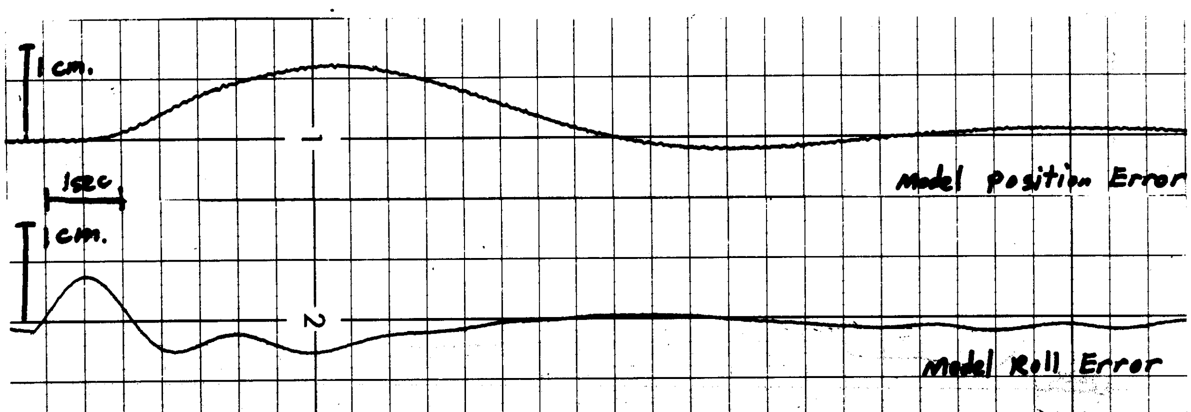
The fourth order model was simulated on the hybrid computer. In place of the approximate closed loop roll function, the actual system was simulated with the time delay. Model responses for lead zeros at both s=-1 and s=-2 in the position loop are illustrated in figures 7.5 and 7.6. The model response of figure 7.5 corresponds to the human operator response illustrated in figure 6.3. The damping ratio is high. This response can be matched better by a small increase in gain. As the root locus of figure 7.4 illus-



$$K \frac{(s+1)e^{-sT}}{s^2(s^2+2s+10)}$$



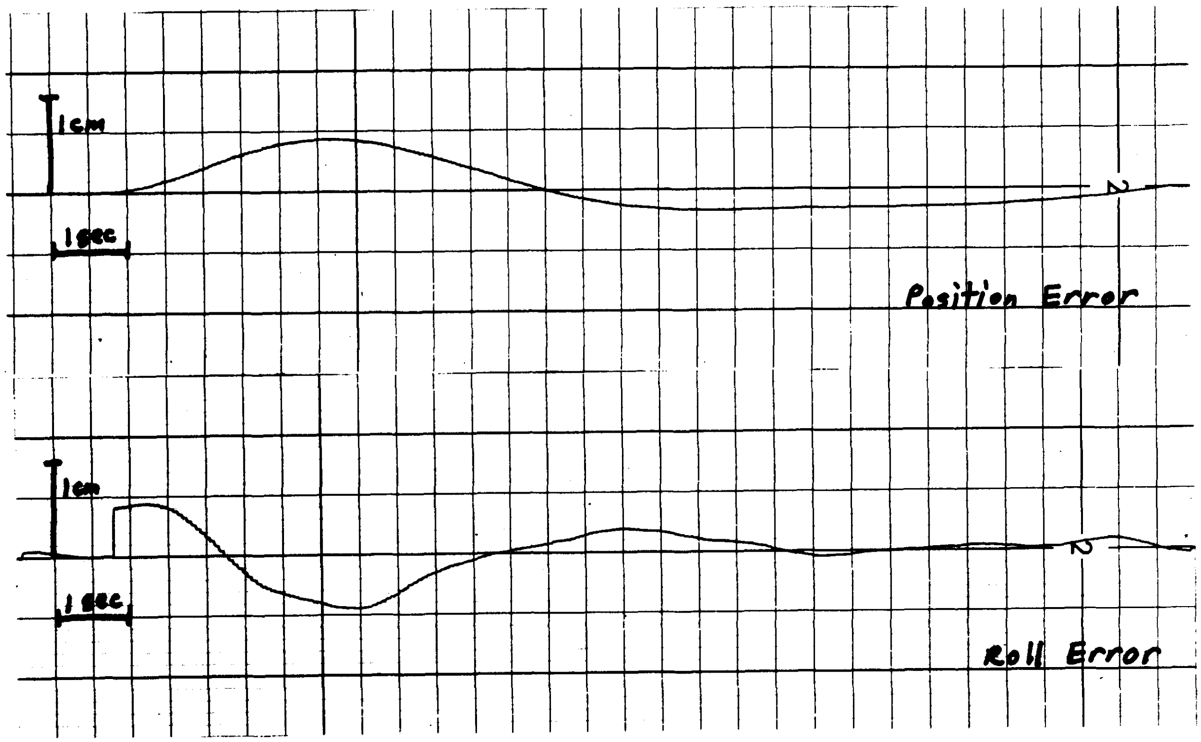
Response of Figure 6.3



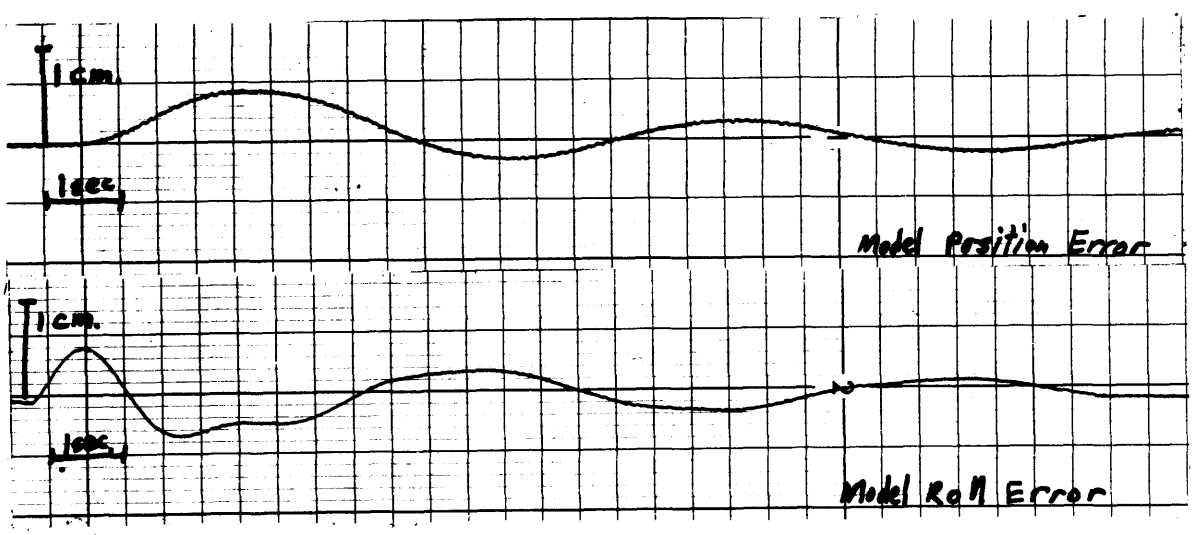
Model Response - HO_p = .4(s+1)

Simulation of Fourth Order System

Figure 7.5



Response of Figure 6.2



Model Response - $HO_p = .4(s+2)$

Simulation of Fourth Order System
Figure 7.6

trates, once the gain exceeds 11 (which corresponds to a gain of 30 in the roll loop and .37 in the position loop), the natural frequency remains almost constant. Figure 7.6 illustrates a model response similar to the human response of figure 6.2. The frequency is slightly high, which can be corrected by a decrease in position loop gain.

Summarizing these results, it is suggested that appropriate describing functions for the two human operator models in the cascade model for helicopter control, as illustrated in figure 2.3, are

$$HO_R = 30 \frac{s+.2}{s+10} e^{-.28s}$$

$$HO_P = .37 (s+1)$$

CHAPTER 8

CONCLUSIONS

The cascade model has been demonstrated to be a good model configuration for studying pilot control of the helicopter. The two simple human operator models are listed at the end of the previous chapter. The model form for the roll dynamics is the same as the single loop describing function for the same dynamics. This indicates that in a multi-loop system the high frequency loop which requires the most attention is controlled as if it were the sole task. The simple model for the position loop shows that this model configuration is the best for describing this task. Any other configuration would have resulted in more complicated models. The root loci show the desirability of the operating points. In the case of roll control, changes in gain result in changes in damping ratio with the natural frequency remaining constant. An increase in time delay changes the natural frequency near the operating point. In the position loop model, an increase in gain, from the operating point, results in a poorer damped response of the same frequency, while a decrease in gain results in a lower frequency. The position lead zero affects the damping ratio directly.

It has been shown that transient analysis by the average response techniques generates describing functions very similar to the spectral analysis describing functions. The spectral analysis results can be generalized to the entire complex plane, if the open loop describing function behaves properly for very small and very large frequency. (For low frequencies, the open loop describing function should be large compared to 1. For high frequencies, it should go to zero.) This technique permits the investigation of responses to signals outside the narrow band described by the spectral analysis results.

The average response method permits a fast identification of the time domain response of a manual control system. On-line identification permits constant evaluation of the partial results and the associated statistics. Since this method is particularly applicable to nonstationary responses, adaptive manual control tasks and transient tasks are open to investigation in a quantitative way.

The nature of the human operator response seems to indicate that the fundamental frequency of his response can be described by a linear describing function. The human operator generates less complicated control movements by taking advantage of the attenuation characteristics of the controlled system. In the second order task, this corresponds to using constant velocity control movements in contrast to linear sinusoidal movements. Finally, he uses past experience to modify his response as the error conditions change.

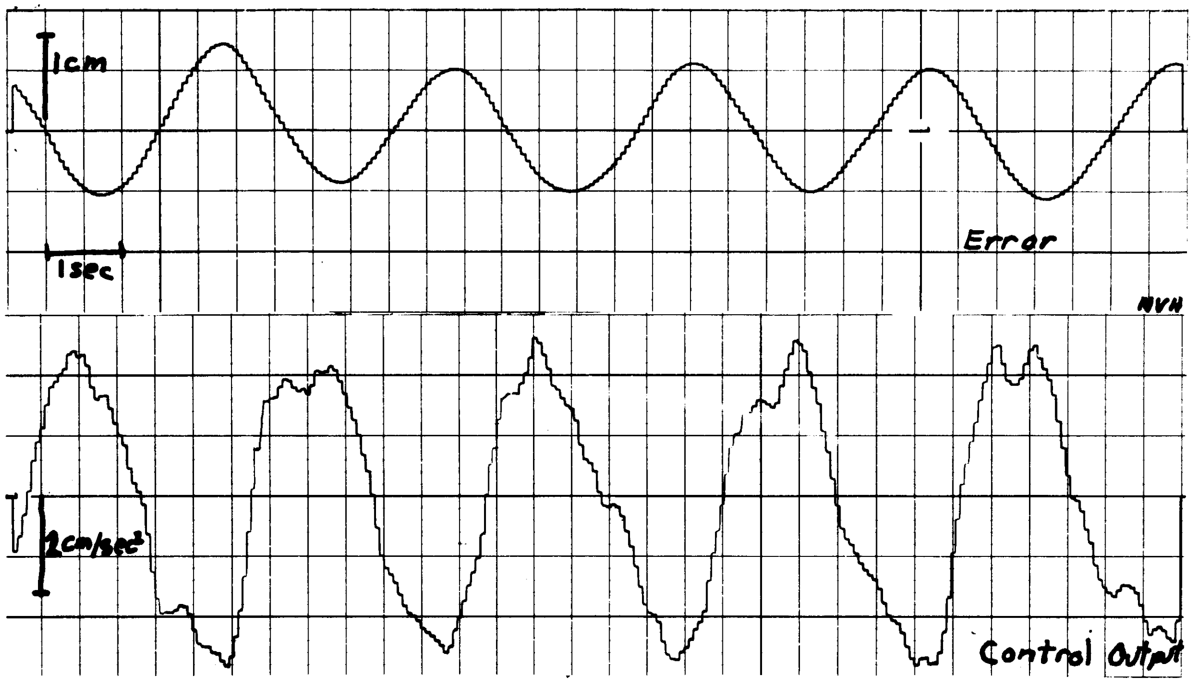
The actual helicopter equations are more complex than the fourth order integration used in the experiments. A pair of complex zeros corresponds to the fact that horizontal acceleration is proportional not only to roll angle, but also to the angle of the rotor plane with respect to the helicopter vertical. Another zero enters the equation, since most helicopters use some mechanical or aerodynamic method to reduce the roll dynamics to rate control. These zeros decrease the difficulty of the task.

Roll and position errors have been interpreted in terms of centimeters on the display. Although the hand control stick used in the experiments differs from the floor-mounted cyclic control stick, if it is assumed that the important control stick input variable is horizontal movement of the stick and not angular motion, performance of the human operator can be described in terms of roll angle degrees and position error feet. Each centimeter of roll error corresponds to 14.5 degrees, while each centimeter of position error corresponds to 16.5 feet. After sufficient practice, all subjects could maintain the simulated hover with position errors less than 3 feet while generating roll angles up to 10 degrees for control. The ramp errors in position corresponded to velocity errors of 16.5 ft/sec or 11 mph. This velocity error is equivalent to a sudden wind gust.

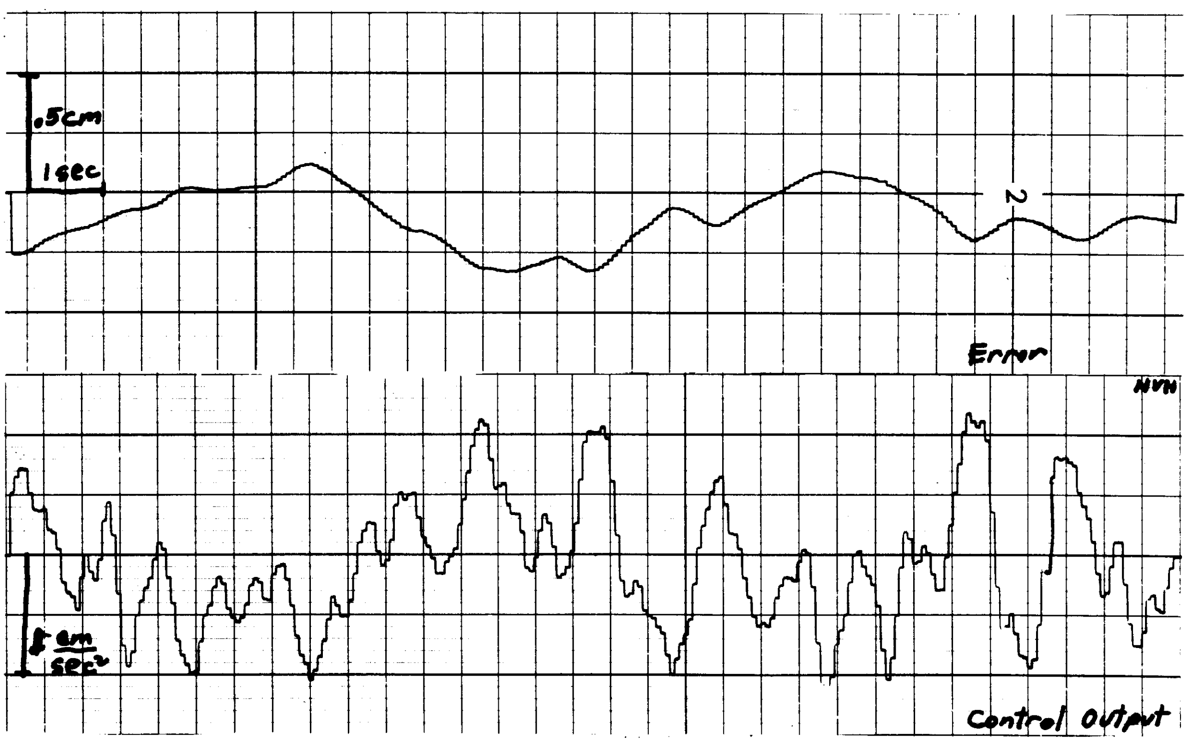
In the experiments of this thesis, the ensemble of responses for the average response was synchronized with the occurrence of a transient input, but there is no reason why the ensemble could not be synchronized with some other event. This event could be some particular error condition, such as a position error of a given magnitude. Synchronization with one of the sine waves in the random-appearing input is another possibility. This technique then makes it possible to examine the response to a single sine wave without having to be concerned with the possibility that the human operator will recognize the sine wave as deterministic. For a single sine wave averaged input, the power in the error and manual outputs could be measured at all frequencies. This permits evaluating at all frequencies the remnant associated with a particular input frequency.

A few experiments were run to evaluate this frequency response technique. Forty sine waves were averaged for each response. Figure 8.1 shows the response to a high frequency sine wave. As can be seen, the error is almost a perfect sine wave. For this frequency, the gain was measured to be 4.7 with a phase lag of 145 degrees. McRuer's results were a gain of 6.4 with a phase lag of 135 degrees. Figure 8.2 shows the results of synchronizing with a low frequency sine of .13 cps. It is obvious in this case that high frequency control manipulations are used with as much power as the low frequency part of the response.

In any case, a more efficient computer program could be written for this frequency response experiment. This would permit greatly increasing the number of sinusoids averaged and, consequently, would produce smoother results. It would be suggested to first perform the ensemble average and then to compute the cross correlation with various sinusoids.



Response to .32 cps Sine Wave - 40 Sample Average - $1/s^2$
Figure 8.1



Response to .13 cps Sine Wave - 40 Sample Average - $1/s^2$
Figure 8.2

The computer programs developed for this thesis are modified easily for use in any experiment. This includes adaptive control problems as well as transient and frequency response identification tasks.

The analysis in this thesis suggests that other multi-loop control problems can be handled in a similar manner. Whenever sequential operation is a good way to explain control technique, a cascade configuration may provide the simplest model for identification. If an analysis of the results of a multi-loop experiment shows different frequency ranges for different portions of the system, a first approximation might be to model the high frequency portion of the system as if that portion were an isolated system.

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APPENDIX A

THE GPS 290T HYBRID COMPUTER SYSTEM

This system was designed to permit real time solutions to complicated dynamic and control systems and to provide on-line computational facilities for the processing of experimental data while the experiment is in progress. The analog half of the system simulates the dynamics and performs the high speed calculations and integrations. The digital half provides overall control, performs the lengthy and high accuracy calculations, stores temporary results, and provides the analog simulation with time-varying and other changing parameters and forcing functions. There are many overlapping functions. The analog computer can perform certain simple digital functions and can instigate data transmission in the interface. The digital computer can control the individual analog components.

The digital computer is the PDP-8, built by the Digital Equipment Corporation. This computer is a one address, fixed word length, 12 bit machine employing two's complement arithmetic and a 4096 word core memory. Basic cycle time is 1.5 microseconds, with addition performed in two cycles. Multiplication and division are performed by the Extended Arithmetic Element option in 21 and 37 microseconds respectively. The input/output part of the computer is extremely flexible; additional instructions and input/output devices can be added easily. The interrupt feature permits utilizing time to the fullest by permitting several programs to overlap in operation.

A DECtape magnetic tape unit provides temporary data storage. Blocks of 128 words on the tape can be addressed directly with the actual data transfer occurring by cycle stealing and without disturbing the program in progress.

The analog half of the system is composed of the GPS 200T built by the GPS Instrument Company. Amplifiers, integrators, and multipliers are quite compatible with the digital computer since they have a megacycle bandwidth. Other analog components include comparators, electronic switches, and limiters. The control panel has the individual integrator controls. These may be controlled directly by mode push buttons on the front of the analog computer, by two different clock busses for repetitive operation, or by the digital logic on the control panel. This digital logic consists of nand and nor gates, flip-flops, JK or gated flip-flops, inverters, pulse generators, and one-shot delays. This logic can operate on the clock signals, control lines, and comparator outputs and provide outputs to the electronic switches, integrators, sense lines, D/A and A/D converters, and digital program interrupt.

The hybrid capabilities fall into three classes: data transmission, program control, and analog function control. The first is provided by an analog to digital converter multiplexed to 8 channels and 4 digital to analog converters. Twelve bit A/D conversion takes 35 microseconds, while D/A conversion time is of the order of a computer instruction. Program control consists of 8 logic level control lines to the analog control panel from the digital computer and 12 sense lines from the analog control panel back to the digital computer. The analog computer can cause a digital program interrupt. This is useful to permit two analog clocks to synchronize digital programs. A/D and D/A conversion along with multiplexer channel incrementing can be commanded by the analog computer as well as the digital computer. Function control includes the selection of the analog mode and the amplifier address from both computers. The output of the amplifier or potentiometer selected can be read from the digital voltmeter or through channel zero of the multiplexer.

The programming system developed for this thesis constitutes an example of almost all the capabilities of the hybrid computer.

APPENDIX B

COMPUTER PROGRAMMING SYSTEM FOR TIME DOMAIN STUDIES OF THE HUMAN OPERATOR

An extensive system of computer programs has been developed to perform this experiment. All programs are very general and can be adapted easily for other tasks. The programs are concerned with input generation, sampling, magnetic tape storage, input/output, and statistical processing.

Two random-appearing input generation programs are available. Both generate a sum of sines signal while the second also generates a second independent-appearing sum of cosines signal. Any number of sinusoids can be specified, each having an independent frequency, amplitude, and initial phase. The sum of sines signal and the sum of cosines signal provided by the second program have identical frequency spectra. A four bit flip-flop counter, driven by one of the analog clocks set at one millisecond, provides time information to the programs through the sense lines. The counter is reset by a control line after reading. The outputs of the two high order bits are gated together and, when enabled by a control line, provide an interrupt whenever the time increment exceeds 12 milliseconds. Normal operation is to permit the input routine to cycle continuously during the sampling run and then switch to interrupt operation when storing and processing the data.

Accuracy and speed were the requirements for these input programs. The time increment is measured only to the integer value, but the fractional time adds into the next time increment since clearing the time counter after reading does not affect the arrival of clock pulses. Occasionally time pulses are lost when they appear during the two microsecond interval between reading the counter and clearing it. This results in a time error less than .1%. The time increment in milliseconds is then multiplied by the double precision frequencies. This permits specifying each frequency component to plus or minus .12 deg/sec. The result of this double precision multiplication then is added into the accumulated angle. Series approximations to the sine proved to be too slow; the fastest still took about 2 milliseconds. The method selected involves table lookup and an average of only 30 microseconds per sine. A short program first corrects the accumulated angle to less than 360 degrees; then the angle (reduced now to the number of quarters of a degree) is reduced to first quadrant and an appropriate sign associated with the answer. The value of the sine is then looked up in a table. This consisted of 361 sines for angles from 0 to 90 degrees at .25 degree intervals. Each value in the table is accurate to .0002. Cosines are obtained by subtracting 90 degrees and changing the sign. The sine is then multiplied by an amplitude of 1 to 400 before being added into the accumulated sum of sines total. Before the point is converted to an analog voltage, it is scaled so that the signal is 20 volts peak-to-peak. Time to generate a single input point is .2 millisecond per sinusoid.

The sampling program can sample any number of available channels obtaining a specified number of pre-transition points and a specified number of post-transition points. Transition is enabled by a control line after the pre-transition number has been obtained. Logic on the analog control panel then waits for various conditions to be met, such as requiring certain variables to be within a specified bound or crossing through zero, before causing the transition. This may be the throwing of electronic switches to change some analog components or signals, or a digital to analog conversion after the step desired is preloaded into a D/A buffer. When the transition occurs, a sense line is set to inform the sampling program.

During the sampling run, it is desirable to spend as much of the available time as possible producing input. The first part of the sampling program, after initializing various registers and control lines, turns the interrupt on and sets the input program up to run continuously. An analog clock, enabled by a control line, provides an analog program interrupt at each sampling time. The input program then is temporarily suspended while the requisite number of channels is sampled. Each channel has associated with it a buffer of length equal to the number of samples. Samples are stored circularly. This means that after the highest position is filled, the next point goes into the lowest position. After the number of samples requested is obtained, the buffer is rotated so that the first point in the pre-transition buffer occupies the lowest position. This procedure is more efficient than using a pushdown list. In this latter method, only the specified number of pre-transition samples is retained. As each new point is sampled without the transition occurring, the oldest value is discarded and the list moved down one location. Storing the data circularly means less moving (which takes 13.5 microseconds per point per move) and, in any case, delays the moving until after the data is obtained. Time to sample is about 50 microseconds per channel sampled. After the data is complete, rotation of the buffers takes about 14 microseconds multiplied by the number of sample points and the number of channels. This is about 3.5 milliseconds per channel when 256 data points are collected. Before the sampling program returns to the main program, the input program is permitted to finish the point it was generating when interrupted for the final sample.

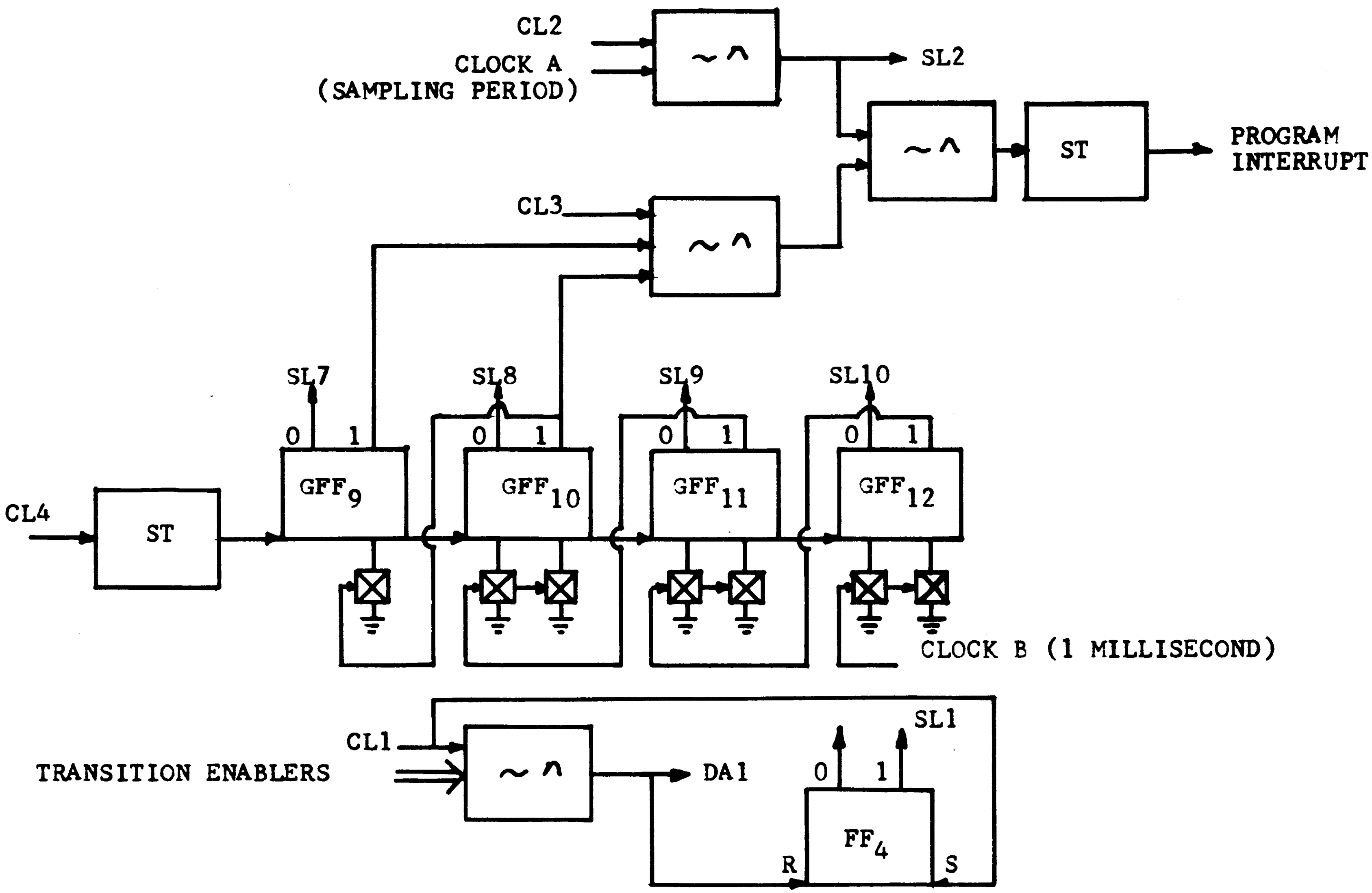
After each sample is made, it is stored on magnetic tape until the completion of the run. A store program assigns a sequence number and sets up a directory listing, as it stores the sample on tape. For retrieval, the sequence number alone has to be specified. In this manner, samples of any size can be stored conveniently without having to refer to tape locations. The actual reading, writing, and searching of the DECtape is done by a general purpose routine. This routine uses the interrupt feature so that once the tape function begins a minimal amount of time is used to keep track of tape operation and the maximum amount of time is available for program execution. This routine replaces the commercially available version that suspends operation of the program for as much as .25 second. This would be unsatisfactory since this would result in a .25 second delay in random input generation.

Various output options include the printing of the voltage or scaled interpretations of a sample or the plotting of the sample on a real time recorder. The print program prints ten values to the line with the transition point marked. That program calls other routines which print the voltage, scaled, or octal interpretation of a number, and provide carriage returns. All call a short routine that prints the actual character. This routine will operate with the interrupt on or off.

The statistical routine computes an ensemble averaged response along with the standard deviation or variance at every fifth point. The averaged wave form then can be graphed or printed out by the output routines. The sequence numbers of the samples to be averaged are given to the program through the switch register. Samples corresponding to negative-going steps can be negated and averaged with positive-going step samples. Double and triple precision arithmetic is used to obtain the greatest significance in the statistics.

All the above programs are written as subroutines so that they can be called conveniently by a short main program written for the given task. The main program written for this experiment first initializes the various control lines and clears the D/A buffers, then runs the experiment, and at the end provides a convenient interface with the output options and the statistical routine. The main loop of this program first provides a specified delay during which input is displayed to the subject, the D/A buffer is loaded with the size of the next step, the sampling routine is called, and finally the store routine saves the data on magnetic tape.

All these programs are listed in this appendix along with the analog control logic they require.



DIGITAL CONTROL LOGIC

figure B.1

```
/MAIN PROGRAM
*200
START,CCL03 SCL02      /ENABLE INPUT INT, DISABLE SAMPLE INT
SCL01                  /RESET TRANSITION INDICATER
SCL04                  /RESET TIMER
CCL04
ADRB                   /CLEAR FLAGS
KCC
TCF
MMCF
CLIF
DALB3                  /RESET STEP OUTPUT
DALC2
DCA STEP
TAD Z SEQNUM
DCA SEQST
TAD Z LENGTH
CIA
TAD Z BUFAD
DCA LO EST
ION
REPEAT,ION
TAD NUMBER
CIA
DCA CNTR
TAD TABLE
DCA Z 17
LOOP,TAD I Z 17        /DELAY
JMS DELAY
TAD I Z 17             /LOAD STEP
TAD STEP
DALB3
DCA STEP
JMS I PSAMP            /SAMPLE
CCL03
JMS I PSTORE           /STORE
ISZ CNTR
JMP LOOP
JMS I CRLF
TAD SEQST              /PRINT STORE AREA OF RUN
JMS I PROCT
CMA CLA
TAD Z SEQNUM
JMS I PROCT
JMS I CRLF
NEXT,LAS               /WHAT NEXT?
AND M1000
SNA
JMP REPEAT             /000, REPEAT
TAD M1000
SNA
JMP PRONE              /001, PRINT
```

```
TAD M1000
SNA
JMP G ONE               /010, GRAPH
JMS I STATS             /111, STATISTICS
RETURN,HLT
JMP NEXT
STEP,0
SEQST,0
CNTR,0
TABLE,NUMBER
PSAMP,1600
PSTORE,2400
RETREV,2505
CRLF,2050
PROCT,2163
STATS,200
M1000,7000
DELAY,0
CMA
DCA CNTR1
ISZ CNTR1
SKP
JMP I DELAY
TAD M55
DCA CNTR2
TAD M2892
DCA CNTR3
ISZ CNTR3
JMP .-1
ISZ CNTR2
JMP .-4
JMP DELAY+3
CNTR1,0
CNTR2,0
CNTR3,0
M55,7711
M2892,2264
PRONE,CLA
TAD PRSAMP
JMP OUTPUT-1
GRONE,CLA
TAD GRAPH
DCA POINT
OUTPUT,HLT
LAS
SNA
JMP RETURN
JMS I RETREV
JMP OUTPUT
DCA Z LENGTH
```

```
JMS I POINT
JMP OUTPUT
POINT=CNTR1
PRSAMP,2000
GRAPH,2200
SEGNUM=166
LENGTH=174
BUFAD=172
LOWEST=171
NUMBER,12
30                      /DELAY IN SECONDS
146                     /SIZE OF STEP
5                       /NEXT DELAY
7632                    /NEXT STEP
5                       /ETC.
146
5
7632
5
7632
5
146
5
146
5
7632
5
7632
5
146
$
```

```
/SUBROUTINE TO GENERATE RANDOM APPEARING INPUT.
/4 BIT COUNTER HOOKED TO SL7-1Ø INCREMENTS EVERY MILLISEC
/IF COUNTER REACHES 12 MILLISEC, INTERRUPT OCCURS.
/COUNTER CLEARED BY SETTING CLØ4 THROUGH SCHMIDT TRIGGER.
*4ØØ
INPUT,4Ø1               /GET TIME
SCLØ4
SLR CAC
CCLØ4
AND MSK
DCA TIME1
TAD TABLST              /INITIALIZE
DCA Z 11
TAD ANGL
DCA PANGL
TAD ANGH
DCA PANGH
TAD NUMSIN
CIA
DCA CNTR3
DCA HIGH
DCA LOW
LOOP,TAD I Z 11         /UPDATE ANGLE
MQL MUY
TIME1,Ø
TAD I PANGH
DCA I PANGH
MQA
CLL
TAD I PANGL
DCA I PANGL
SZL
IAC
TAD I PANGH
MQL DVI
264Ø
DCA I PANGH
TAD I PANGH
TAD DM18Ø
JMS I LSIN              /GET SINE
MQL
CLA CMA RAL             /SAVE SIGN INDICATOR
DCA LK
TAD I Z 11              /SCALE UP AND ADD TO SUM
DCA .+2
MUY
Ø
ISZ LK
CMA
TAD HIGH
DCA HIGH
MQA CLA
```

```
ISZ LK
JMP .+5
CIA CLL
SZL
ISZ HIGH
NOP
CLL
TAD LOW
DCA LOW
SZL CLA
ISZ HIGH
NOP
ISZ PANGL
ISZ PANGH
ISZ CNTR3
JMP LOOP
TAD HIGH                    /GET MAGNITUDE OF SUM
SMA
JMP .+12
CMA CLL
DCA HIGH
TAD LOW
CIA
MQL
DCA LK
SZL
IAC
JMP .+5
CLA CMA
DCA LK
TAD LOW
MQL
TAD HIGH
DVI
SCALE,2                     /SCALE=2*SUM OF MAGS
CLL RAL                     /ROUND OFF
CIA
TAD SCALE
CLA MQA
SNL
IAC
ISZ LK
CIA
DALB1                       /OUTPUT
DALC1
JMP I INPUT
/
/CONSTANTS & VARIABLES
LSIN,INPUT+400
LK,0
CNTR3,0
HIGH,0
```

```
LOW,0
NUMSIN,1
TABLST,INPUT+177
ANGL,INPUT+236
NGH,INPUT+274
PANGL,INPUT+236
PANGH,INPUT+274
DM180,6460
MSK,0074
$


*600
0045
12
0075
12
0134
12
0215
12
0343
12
0536
12
1124
1
1662
1
3360
1
6246
1
$
```

```
/TABLE LOOK-UP SINE ROUTINE
/ENTER WITH ANGLE IN DEGREES IN AC, BINARY POINT 2 BITS FROM THE RIGH
/EXIT WITH SINE IN AC, BINARY POINT AT FAR LEFT.
/IF SINE IS NEGATIVE LINK IS SET.
/
*1000
SINGRF,0
CLL                     /GET MAGNITUDE WITH SIGN IN LINK
SPA
CIA CML
JMP .+5
TAD DM90
CML
SPA
CIA
TAD DM90
SMA SZA
JMP .-6
TAD D90
CML
TAD SINES               /LOOK UP SINE IN TABLE
DCA SINAD
TAD I SINAD
JMP I SINGRF
D90,0550
DM90,7230
SINAD,0
SINES,.+1
$
```

```
/SAMPLING PROGRAM
/CLOCK B CAUSES AN INTERUPT AT EACH SAMPLING INSTANT,
/IF CLØ2 IS CLEAR.
/TRANSITION SETS SL1.
/CLØ1 MUST BE CLEAR FOR TRANSITION TO OCCUR.
/NUMBC=NUMBER OF SAMPLES BEFORE TRANSITION
/NUMAD=NUMBER OF SAMPLES AFTER TRANSITION
/NUMSAM=NUMBER OF CHANNELS SAMPLED
/LENGTH=NUMBC+NUMAD AND MUST BE A POWER OF 2
/
/INITIALIZATION FOR EACH TRANSITION
*16ØØ
SAMP,7747
IOF
CLA CMA
TAD BUFAD               /SET UP STORAGE POINTER.
DCA STPNTR
TAD NUMBC
CIA
DCA CNTRBC
TAD NUMAD
CMA
DCA CNTRAD              /=-(NUMAD+1)
TAD NUMBC
TAD NUMAD
DCA LENGTH
CMA
TAD LENGTH
DCA MASK
TAD SLRCAC
DCA TRTEST
SCLØ3                   /INPUT INT INHIBITED
TAD INPUT1
DCA I PINPUT
CCLØ2 SCLØ1             /PERMIT SAMPLING & INHIBIT TRANSITION.
ION
JMP I INPUT1
/ANALOG FLAG INTERUPT ROUTINE
ANFLG,Ø
IOF
ADCC ADIC               /START AD1 CONVERSION.
ADCV
CLA IAC
TAD STPNTR              /SET STORAGE POINTER
AND MASK
TAD BUFAD
DCA STPNTR
TAD NUMSAM
CIA
DCA CNTR1
TRTEST,SLR CAC          /HAS TRANSITION JUST OCCURRED?
SMA CLA
```

```
JMP BC                  /NO! NOT YET
TAD JMPAD               /YES! JUST NOW
DCA TRTEST
TAD NUMBC
CIA
TAD STPNTR
AND MASK
TAD BUFAD
DCA PNTR                /SET POINTER TO ZERO POINT
AD,ISZ CNTRAD           /COMPLETE?
JMP CONT                /NO!
SCL01                   /YES!
SCL02
TAD SAMP
DCA I PINPUT
JMP NTANGL
BC,ISZ CNTRBC           /IS BC BUFFER FULL?
SKP CLA                 /NO OR ALREADY FULL
CCL01                   /PERMIT TRANSITION
CONT,ADSF               /CONTINUE SAMPLING
JMP .-1
ADRB
DCA I STPNTR
ISZ CNTR1
SKP
JMP I ANFLG
ADIC
ADCV
TAD STPNTR
TAD LENGTH
DCA STPNTR
JMP CONT
/CONSTANTS & VARIABLES
CNTR1,0
CNTRAD,0
CNTRBC,0
JMPAD,JMP AD
SLRCAC,SLR CAC
STPNTR,0
PNTR,0
PINPUT,INPUT
INPUT1,INPUT+1
MASK,177                /LENGTH-1
INPUT=400
/ROUTINE TO UNTANGLE BUFFER
/BUFFER IS LOWERED LENGTH WORDS IN THE PROCESS
NTANGL,TAD PNTR
CIA
TAD BUFAD
DCA TEM1
TAD LENGTH
TAD TEM1
CIA
```

```
DCA TEM2
TAD BUFAD
DCA TEM3
TAD LENGTH
CMA
TAD BUFAD
DCA Z 10
TAD NUMSAM
CIA
DCA CNTR2
LOOP,TAD TEM2
DCA CNTR1
CMA
TAD PNTR
DCA Z 12
TAD I Z 12
DCA I Z 10
ISZ CNTR1
JMP .-3
CMA
TAD TEM1
DCA CNTR1
CMA
TAD TEM3
DCA Z 12
JMP .+3
TAD I Z 12
DCA I Z 10
ISZ CNTR1
JMP .-3
TAD LENGTH
TAD TEM3
DCA TEM3
TAD LENGTH
TAD PNTR
DCA PNTR
ISZ CNTR2
JMP LOOP
ADRB
JMP I ANFLG
TEM1=CNTRAD
TEM2=CNTRBC
TEM3=TRTEST
CNTR2=SAMP
*172
BUFAD,4600
NUMSAM,1
LENGTH,200
NUMAD,147
NUMBC,31
$
```

```
/MAGNETIC TAPE STORAGE SYSTEM

*2400
STORE,7747              /STORE RESULTS ON TAPE
CLA
TAD LENGTH
ASR
6
MQL
MQA
DCA LBLK
TAD NUMSAM
DCA .+2
MUY
0
MQA CLA
DCA WT1+4
TAD LENGTH
CIA
TAD BUFAD
DCA WT1+1
TAD NXTBLK
DCA WT1+5
SKP
HLT
WT1,JMS I PWRITE
0
.-3
0100
0
0
JMS WAIT
JMS GETDIR
TAD NUMSAM              /MAKE DIRECTORY LISTING
CIA
DCA CNTR10
TAD NXTDIR
TAD 07002
SMA CLA
HLT
TAD NXTDIR
TAD GETDIR+4
DCA Z 16
LOOP10,TAD SEQNUM
DCA I Z 16
TAD NXTBLK
DCA I Z 16
TAD LBLK
DCA I Z 16
ISZ SEQNUM
TAD NXTBLK
TAD LBLK
DCA NXTBLK
```

```
ISZ CNTR10
JMP LOOP10
TAD GETDIR+4
CIA
TAD Z 16
DCA NXTDIR
SKP
HLT
WT2,JMS I PWRITE
DSTART
.-3
0100
4
DRCTRY
JMS WAIT
JMP I STORE
PREAD,READ
PWRITE,WRITE
O7002,7002
RETREV,7747              /RETREVE SAMPLE, ENTER WITH SEQNUM IN AC
CIA
DCA BLOCKL
JMS GETDIR
CMA
TAD GETDIR+4
DCA Z 16
TAD DM170
DCA CNTR10
LOOKUP,TAD BLOCKL
TAD I Z 16
SNA CLA
JMP FOUND
ISZ Z 16
ISZ Z 16
ISZ CNTR10
JMP LOOKUP
JMP I RETREV             /ERROR RETURN
FOUND,TAD I Z 16
DCA BLOCK
TAD I Z 16
DCA BLOCKL
TAD Z LOWEST
DCA READIN+1
SKP
HLT
READIN,JMS I PREAD
0
.-3
0100
BLOCKL,0
BLOCK,0
JMS WAIT
```

```
TAD BLOCKL
SHL
6
ISZ RETREV
JMP I RETREV
DM170,7526
WAIT,0
CLA MQL
TAD I PDONE
SNA CLA
JMP .-2
JMP I WAIT
PDONE=PWRITE
GETDIR,0
SKP
HLT
JMS I PREAD
DSTART
.-3
0100
4
DRCTRY
JMS WAIT
JMP I GETDIR
LBLK=BLOCKL
CNTR10=BLOCK
*164
NXTBLK,100
NXTDIR,7777
SEQNUM,1
READ=3206
WRITE=3200
DRCTRY=74
LENGTH=174
BUFAD=172
NUMSAM=173
DSTART=6600
LOWEST=171
$
```

```
/GEORGE FRIEDMAN
/MAN VEHICLE CONTROL LABORATORY
/MASSACHUSETTS INSTITUTE OF TECHNOLOGY
/CAMBRIDGE, MASSACHUSETTS
/
/ONE PAGE SUBROUTINES FOR READ, WRITE & SEARCH OF DECTAPE
/WITH OR WITHOUT INTERUPT OPERATION
/FOR DECTAPE CONTROL TYPE 552 ONLY.
/
/CALL IS  JMS I X      /X CONTAINS READ OR WRITE
/         CORE         /ADDRESS FOR DATA
/         ERROR        /RETURN ADDRESS IN CASE OF ERROR
/         UNIT         /IN BITS 2-5,ZEROS ELSEWHERE
/         NUMBER       /OF BLOCKS, 0 FOR SEARCH ONLY
/         BLOCK        /INITIAL BLOCK ON TAPE
/
/NON-INTERUPT OPERATION, DEFINE DISM=NOP IN ASSEMBLY
/         PROGRAM IS HELD UP UNTIL OPERATION COMPLETE
/INTERUPT OPERATION, DEFINE DISM=JMP Z SCAT OR JMP I Z SCAT
/         AS EXPLAINED FOR DEC STANDARD SUBROUTINES
/         SET UP INTERUPT ROUTINE
/         INT,(SAVE AC, LK, CLEAR AC)
/              MMRS
/              RAL
/              SNL SMA (CLA)
/              SKP
/              JMP I Y
/              ...
/              ...
/         Y,   RETURN          /RETURN=WRITE+141
/         DONE (=READ) CAN BE TESTED FOR COMPLETION.
/
/TO SEARCH ONLY, REQUEST 0 BLOCKS, CORE IMMATERIAL
/THE 129TH WORD IS PROPERLY HANDLED.
/ALL BLOCKS (INCLUDING 0) CAN BE READ AND WRITTEN
/IN CASE OF ERROR RETURN, STATUS IS IN AC.
/
WRITE,0                /WRITE ENTRY
CLA
TAD WRITE              /GET ADDRESS OF LIST
JMS PICKUP             /GO PICKUP AND SEARCH
STL RTL                /SET AC=2,2+RDF=WRITE FORWARD BITS
JMP READ+4
READ,0                 /READ ENTRY
CLA
TAD READ
JMS PICKUP
TAD RDF                /GET READ FORWARD BITS
WORK,MMLF              /SET FUNCTION
TAD NBLOCK
SNA CLA
JMP EXIT               /0 BLOCKS REQUESTED, EXIT
```

```
RLP,TAD CORE            /SET CORE ADDRESS
MMML
TAD CORE
TAD K0200
DCA CORE
TAD I CORE              /SAVE 129TH WORD
DCA SAVE
JMS DELAY               /WAIT FOR END OF BLOCK
TAD SAVE                /RESTORE 129TH WORD
DCA I CORE
ISZ NBLOCK              /COMPLETE?
JMP RLP                 /NO!
EXIT,MMMF               /YES! STOP TAPE
JMS DELAY               /WAIT FOR TAPE TO STOP
CLA CMA                 /SET DONE=-1
DCA DONE
MMCF
DISM                    /EXIT
JMP I Z 0
PICKUP,0                /PICKUP LIST
IOF
DCA Z 0
DCA DONE                /DONE=0
TAD I Z 0
DCA CORE                /GET CORE ADDRESS
TAD I CORE              /SET UP SAVE IN CASE OF SEARCH ERROR
DCA SAVE
ISZ Z 0
TAD I Z 0               /GET ERROR RETURN ADDRESS
DCA ERROR
ISZ Z 0
TAD I Z 0               /GET UNIT NUMBER
AND MASK
DCA UNIT
ISZ Z 0
TAD I Z 0               /GET NUMBER OF BLOCKS
CIA
DCA NBLOCK
ISZ Z 0
TAD I Z 0               /GET INITIAL BLOCK
CIA
DCA MRBLK
ISZ Z 0                 /FIRST RETURN IS VIA Z 0
SEARCH,TAD ABLOCK       /SEARCH FOR BLOCK
MMML
TAD C8                  /SET UP REVERSAL ERROR COUNTER
DCA COUNT
SFWD,TAD SRCHF          /SEARCH FORWARD
TAD UNIT
MMMM
JMS DELAY               /WAIT FOR SET-UP DELAY
FSC,DCA DIREC           /SET DIRECTION SWITCH
```

```
SCONT,JMS DELAY         /WAIT FOR BLOCK NUMBER
TAD BLOCK               /ACTUAL BLOCK
TAD MRBLK               /-REQUESTED BLOCK
SNA                     /ARE WE THERE?
JMP FOUND               /YES!
ISZ DIREC               /NO, WHAT DIRECTION?
JMP .+4                 /FORWARD!
SMA CLA                 /REVERSE, IS REVERSE CORRECT?
JMP RSC                 /YES, LET SEARCH CONTINUE
JMP REVD                /NO, REVERSE DIRECTION
SPA CLA                 /IS FORWARD CORRECT?
JMP FSC                 /YES, LET SEARCH CONTINUE
REVD,ISZ COUNT          /REVERSE DIRECTION
SKP
JMP TILT+4              /ERROR, BLOCK CAN'T BE FOUND
TAD DIREC
SNA CLA                 /REV=0,FWD=1, AT THIS TIME
JMP SFWD
SREV,TAD SRCHR          /SEARCH REVERSE
MMMF
JMS DELAY               /WAIT FOR SET-UP FLAG
RSC,CLA CMA             /DIRECTION SWITCH=-1
JMP SCONT-1
FOUND,ISZ DIREC         /BLOCK FOUND, DIRECTION?
JMP I PICKUP            /FORWARD,RETURN
JMS DELAY               /REVERSE,WAIT TO PASS OVER IT
JMP SFWD                /GO SEARCH FORWARD
DELAY,0                 /WAIT FOR DT FLAG
MMCF                    /CLEAR FLAGS
DISM                    /NOP OR JUMP TO SCAT
RETURN,MMSF             /RETURN ON INTERUPT
JMP .-1
CLA CLL
MMSC
JMP I DELAY
TILT,MMRS               /END ZONE?
RTL
SPA CLA
JMP REVD                /YES, REVERSE DIRECTION
MMMF                    /NO, STOP TAPE
TAD SAVE                /RESTORE 129TH WORD
DCA I CORE
MMRS                    /GET STATUS
MMSF
JMP .-1
JMP I ERROR             /ERROR RETURN
/CONSTANTS AND VARIABLES
ABLOCK,BLOCK
SRCHF,21
SRCHR,31
RDF,22
K0200,200
C8,7770
```

```
BLOCK,0
CORE,0
UNIT,0
MRBLK,0
NBLOCK,0
DIREC,0
COUNT,0
SAVE,0
MASK,1700
ERROR=WRITE
DONE=READ
$
```

```
/PRINT ROUTINES
*2000
PRSAMP,7747                  /PRINT SAMPLE
CLA CMA
TAD LOWEST
DCA Z 10
TAD LENGTH
CIA
DCA CNTR12
TAD FRSTHF
CIA
DCA CNTR14
JMS CRLF
TAD DM10
DCA CNTR13
JMS CRLF
LOOP13,TAD I Z 10
JMS PRVOLT
ISZ CNTR14
JMP .+3
TAD LF
JMS PRCHAR
ISZ CNTR12
JMP .+4
JMS CRLF
JMS CRLF
JMP I PRSAMP
ISZ CNTR13
JMP LOOP13
JMP LOOP13-3
CNTR12,0
DM10,7766
M4,7774
SPACE,240
MINUS,255
NUM,0
LOW2,0
HIGH2,0
CNTR11=NUM
O260,260
POINT,256
CNTR13,0
CNTR14,0
CRLF,0                       /CARRIAGE RETURN - LINEFEED
TAD CR
JMS PRCHAR
TAD LF
JMS PRCHAR
JMP I CRLF
CR,215
LF,212
PRVOLT,0                     /PRINT VOLTAGE IN AC
```

```
CLL RAL
SNL
JMP POS
CIA
MQL
MQA
DCA NUM
TAD MINUS
JMP .+5
POS,MQL
MQA
DCA NUM
TAD SPACE
JMS PRCHAR
TAD SCALEH                /SCALE
DCA .+2
MUY
Ø
DCA HIGH2
MQA
DCA LOW2
TAD NUM
MQL
TAD SCALEL
DCA .+2
MUY
Ø
SHL                       /ROUND OFF
Ø
RAR CLL
SNL
SKP
CLL IAC
TAD LOW2
DCA LOW2
SZL
ISZ HIGH2
TAD M4
DCA CNTR11
TAD LOW2
MQL
TAD HIGH2
TAD 026Ø
JMS PRCHAR
TAD POINT
JMS PRCHAR
LOOP11,MUY
12
TAD 026Ø
JMS PRCHAR
ISZ CNTR11
JMP LOOP11
JMP I PRVOLT
```

```
PRCHAR,Ø                /PRINT CHARACTERS WITH OR WITHOUT INTERRUPT.
DCA SAVE
DCA Z PRFLG
TAD SAVE
TLS
CLA
TAD Z PRFLG
SZA CLA
JMP I PRCHAR
TSF
JMP .-4
JMP I PRCHAR
SAVE,Ø
PRFLG=123
PROCT,Ø                 /PRINT OCTAL FROM AC
MQL
TAD M4
DCA CNTR11
LOOP12,SHL
2
TAD 026Ø
JMS PRCHAR
ISZ CNTR11
JMP LOOP12
JMP I PROCT
*163
FRSTHF,31
*167
SCALEH,12
SCALEL,Ø
LOWEST,34ØØ
LENGTH=174
$
```

```
/GRAPH ON A REAL TIME RECORDER.
*2200
GRAPH,0                 /GRAPH THE DATA
CLA CMA
TAD Z LOWEST
DCA Z 17
IOF
HLT                     /TURN ON RECORDER,PRESS START
CCL02
SCL03
CLA CMA CLL RAR         /SET AC=+10 VOLTS
JMS LINE
CLA STL RAR             /SET AC=-10 VOLTS
JMS LINE
JMS LINE                /DRAW 0 LINE
TAD LENGTH
CIA
DCA CNTR
LOOP,TAD I Z 17
JMS POINT
ISZ CNTR
JMP LOOP
JMS LINE                /DRAW 0 LINE
SCL02
HLT
JMP I GRAPH
LINE,0
DALB2
DALC1
CLA
TAD M10
DCA CNTRL
SKIF
SKP
JMP .-2
CLIF
ISZ CNTRL
JMP .-5
JMP I LINE
M10,7766
POINT,0
DALB2
CLA
SKIF
SKP
JMP .-2
DALC1
CLIF
JMP I POINT
CNTR=LINE
CNTRL=POINT
LENGTH=174
LOWEST=171
$
```

```
/STATISTICAL PROCESSOR
*2600
STATS,7747
CLA IAC
TAD BUF3
DCA Z LOWEST
TAD BUF1
DCA Z 16
TAD BUF3
CIA
TAD BUF1
DCA CNTR30
DCA I Z 16
ISZ CNTR30
JMP .-2
DCA NUMBER
CLA CMA
GET,HLT
CLA
TAD BUF1
DCA Z 12
TAD Z 12
DCA Z 13
LAS
SNA
JMP FINISH
SPA
JMP I PINVRT          /GP INVERT RUNNING AVERAGE.
JMS I PRTREV
JMP GET-1             /SEGNUM NOT FOUND
DCA Z LENGTH
TAD Z LENGTH
CMA
DCA CNTR30
ISZ NUMBER
TAD BUF2
DCA Z 14
TAD Z 14
DCA Z 15
TAD BUF3
DCA Z 16
TAD M5
DCA CNTR31
END,ISZ CNTR30
SKP
JMP GET
ADDIN,CLA CLL
TAD I Z 16
MQL
MQA
TAD I Z 12
DCA I Z 13
MQA CLA
```

```
SPA CLA
CMA
SZL
IAC
TAD I Z 12
DCA I Z 13
ISZ CNTR31
JMP END
MQA
SPA
CIA
DCA .+3
TAD .+2
MQL MUY
SAVE,0
DCA SAVE
MQA
TAD I Z 14
DCA I Z 15
RAL
TAD SAVE
TAD I Z 14
DCA I Z 15
RAL
TAD I Z 14
DCA I Z 15
JMP END-2
/CONSTANTS
BUF1,3577
BUF2,5577
BUF3,6577
CNTR30,0
CNTR31,0
PRTREV,RETREV
MS,7773
OUTPUT,2300
PINVRT,INVERT
SIGN=CNTR31
/CONTINUE
FINISH,TAD BUF1
DCA Z 12
TAD BUF3
DCA Z 13
TAD Z LENGTH
CIA
DCA CNTR30
AVERAGE,TAD I Z 12
MQL
CMA
DCA SIGN
TAD I Z 12
SMA
JMP NUMBER-1
```

```
CMA
DCA SAVE
DCA SIGN
MQA
CIA CLL
MQL
RAL
TAD SAVE
DVI
NUMBER,Ø
CLL RAL
CIA
TAD .-3
CLA MQA
SNL
IAC
ISZ SIGN
CIA
DCA I Z 13
ISZ CNTR3Ø
JMP AVERAGE
JMS I OUTPUT
TAD BUF2                    /SET-UP FOR SD COMPUTATION
DCA Z 12
TAD BUF3
DCA Z 13
TAD NUMBER
*STATS +2ØØ                 /START OF PAGE 2
DCA NUMBR2
TAD NUMBR2
DCA NUMBR3
TAD Z 13
DCA MEAN
TAD Z LENGTH
MQL DVI
FIVE,5
CLA MQA
DCA Z LENGTH
MQA
CIA
DCA CNTR32
SD,TAD I Z 12
DCA SAVE2
TAD I Z 12
MQL
TAD I Z 12
DVI
NUMBR2,Ø
DCA SAVE3
MQA
DCA HIGH
TAD SAVE2
MQL
```

```
TAD SAVE3
DVI
NUMBR3,0
CLL RAL                 /ROUND
CIA
TAD .-3
CLA MQA
SNL
IAC
DCA LOW
TAD FIVE
TAD MEAN
DCA MEAN
TAD I MEAN
SPA
CIA
DCA .+3
TAD .+2
MQL MUY
SAVE3,0
CMA
TAD HIGH
DCA HIGH
MQA
CIA CLL
TAD LOW
DCA LOW
SZL
ISZ HIGH
TAD HIGH
SMA CLA
JMS DSQRT
DCA I Z 13
ISZ CNTR32
JMP SD
TAD Z FRSTHF
DCA SAVE2
DCA FRSTHF
JMS I PRSMP2
TAD SAVE2
DCA Z FRSTHF
TAD I PSTATS
DCA CNTR32
JMP I CNTR32
PRSMP2,PRSAMP
SAVE2,0
PSTATS,STATS
CNTR32,0
HIGH,0
LOW,0
MEAN,0
INVERT,CLA              /INVERT RUNNING AVERAGE
TAD Z LENGTH
```

```
CIA
DCA CNTR32
LOOPI,TAD I Z 12
CIA CLL
DCA I Z 13
TAD I Z 12
CMA
SZL
IAC
DCA I Z 13
ISZ CNTR32
JMP LOOPI
JMP I PGET
PGET,GET
DSQRT,0                    /RETURN WITH VARIANCE DIVIDED BY TEN
CLA CLL
TAD LOW
MQL
TAD HIGH
SHL
0
DCA HIGH
MQA
SMA CLA
IAC
TAD HIGH
JMP I DSQRT
RETREV=2505
LENGTH=174
LOWEST=171
PRSAMP=2000
FRSTHF=163
$
```

```
/INTERRUPT ROUTINES
*1
JMP INT
INTKEY,KCC
ION
JMP I PKYFLG
SCAT
RETURN,3341
*20
INT,SKIF
JMP INTAN
KSF
SKP
JMP INTKEY
TSF
SKP
JMP INTPR
DCA SAVAC1
RAL
DCA SAVLK1
MMRS
RAL
SMA SNL CLA
SKP
JMP I RETURN
ADNF
ADRB
HLT
SCAT,CLA CLL
TAD SAVLK1
RAR
TAD SAVAC1
ION
JMP I Z 0
INTAN,DCA SAVAC2                    /ANALOG INT
RAL
DCA SAVLK2
MQA
DCA SAVMQ2
TAD Z 0
DCA SAVRET
CLIF
CAC SLR
AND TWOBIT
SZA CLA
JMP SAMPLE
SCL03
ION
JMS I PINPUT
IOF
CCL03
SKP
SAMPLE,JMS I PSAMP
```

```
CLA CLL
TAD SAVLK2
RAR
TAD SAVMQ2
MQL
TAD SAVAC2
ION
JMP I Z SAVRET
INTPR,DCA SAVAC1
CLA CMA
DCA PRFLG
TCF
JMP SCAT+3
PKYFLG,SCAT-1
SAVAC1,0
SAVAC2,0
SAVLK1,0
SAVLK2,0
SAVMQ2,0
SAVRET,0
PINPUT,INPUT
PSAMP,ANFLG
TWOBIT,2000
PRFLG,0
INPUT=400
ANFLG=1631
$
```

```
*2300
OUTPUT,0
JMS GRAPH
JMS I PRSMP
JMP I OUTPUT
PRSMP,2000
GRAPH=2200
$
```

```
/PURE TIME DELAY FOR ANALOG SIMULATION
/REQUIRES ANALOG CLOCK THROUGH SCHMIDT TRIGGER TO INTERRUPT.
*20
START,LAS HLT  /AD CHANNEL IN AC
ADSC
CONT,LAS        /NUMBER OF MILLISECS IN AC
CIA
DCA CNTR
TAD BUF
DCA Z 10
TAD BUF
DCA Z 11
LOOP,TAD I Z 10
DALB1
SKIF
SKP CLA
JMP .-2
DALC1
ADCV
CLIF
ADSF
JMP .-1
ADRB
DCA I Z 11
ISZ CNTR
JMP LOOP
JMP CONT
CNTR,0
BUF,BUF
$
```