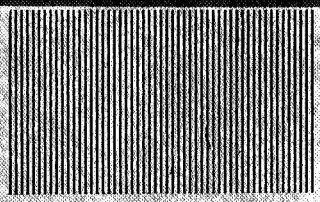


# MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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MANUAL CONTROL OF UNSTABLE VEHICLES  
USING KINESTHETIC CUES  
by  
Philip L. Noggle  
March 1969



E.A.A. Thesis

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**MAN-VEHICLE LABORATORY  
CENTER FOR SPACE RESEARCH  
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CAMBRIDGE, MASSACHUSETTS 02139**

MANUAL CONTROL OF UNSTABLE VEHICLES  
USING KINESTHETIC CUES

by

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by

Philip L. Noggle

Submitted to the Department of Aeronautics and  
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the requirements for the degree of Engineer of Aeronautics  
and Astronautics.

ABSTRACT

A control stick was constructed which sensed the operator's force but moved only in response to an external electrical signal, giving the operator kinesthetic cues. First and second order plants were used in experiments which compared human operators' ability to control instabilities with the force sensing stick fixed, driven by plant position, and driven by plant velocity. Great improvement in human control capability were found in controlling first order plants with the stick driven by plant position and in controlling second order plants with the stick driven by plant velocity. The large improvement was due to a reduction in lead required of the operator and a reduction in operator delay time. The necessity for lead was reduced by providing the operator with a signal, in the form of stick motion, with the proper phase for stabilization. The delay time was reduced by enabling the operator to transmit the stabilizing signal to the plant by stick reaction forces determined by muscle tensing instead of voluntary action.

Thesis Supervisor: Laurence R. Young

Title: Associate Professor of  
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TABLE OF SYMBOLS

a	Constant in muscle receptor model
b	Thickness of force sensing element
c	Position, plant output
d	Difference of two sample averages
D	Duty cycle of power regulator
e	Constant, 2.71. . .
E	Elastic modulus
E	Voltage output of power regulator
$E_b$	Battery voltage to strain gauge circuit
$F_m$	Force exerted by muscle
g.f.	Guage factor for strain gauges
I	Cross section moment of inertia
$I_m$	Imaginary part of expression that follows
$j\omega$	Imaginary part of LaPlace variable(s)
K	Arbitrary multiplicative constant
$K_1, K_2$	Constants in muscle receptor model
$K_{dc}$	Computer output gain, volts/volt
$K_{ds}$	Stick deflection gain, degrees/volt
$K_{dv}$	Visual display gain, inches/volt
$K_p$	Potentiometer gain, volts/degree
$K_R$	Power regulator gain, volts/volt
$K_s$	Display deflection per unit stick force, inches/lb.
$K_{sc}$	Force signal gain in computer input stage, volt/volt



TABLE OF SYMBOLS (CON'T)

$K_{sm}$	Force stick gain, volt/lb.
$K_{sp}$	Stick spring constant, inch lb./degree
$K_T$	Motor torque constant, inch lb./amp.
$K_\phi$	Motor armature reaction constant, volts/rad/sec.
$L$	Stick length
$M$	Bending moment
$N$	Pulley ratio in stick actuator
$n$	Sample size
$R$	Strain guage resistance
$R_A$	Motor armature resistance
$r$	Command position, input signal
$s$	LaPlace variable
$T_1, T_2$	Time constants in muscle receptor model
$T_L$	Operator lead time constant
$Y$	Transfer function
$Y_c$	Transfer function for controlled plant
$Y_p$	Transfer function for human operator
$Y_{p_{vis}}$	Transfer function for human operator using visual input
$Y_{p_{kin}}$	Transfer function for human operator using kinesthetic input
$X_1, X_2$	Inputs to power amplifier
$X_m$	Muscle length
$X$	Firing rate

TABLE OF SYMBOLS (CON'T)

$E$	Error signal
$\epsilon$	Strain
$\xi$	Damping constant
$\lambda$	Measure of task difficulty
$\bar{\lambda}$	Sample average, using maximum difficulty in each run
$\tau_e$	Operator delay time
$\sigma$	Deviation
$\sigma_{\bar{\lambda}}$	Deviation of $\bar{\lambda}$
$\omega$	Frequency in radians/sec.
$\omega_n$	Natural frequency

## CHAPTER I

### INTRODUCTION

#### 1.1 Background

In the late 1940's and early 1950's the increasing size and speed of aircraft required that power augmentation be used to enable pilots to control the aircraft. A serious degradation in controllability was found when the force amplification allowed the pilot to deflect control surfaces without sensing the reaction forces. It was evident that the pilots had been receiving necessary information in the form of kinesthetic cues from the control stick forces. Since that time, the necessary kinesthetic cues have been provided to the pilot in the form of a force on the stick which was achieved by using spring-centering and bob weights.

The use of automatic control in the form of an autopilot relieved the pilot of the need to be a continuous on-line controller throughout the flight. But the need remained for the pilot as a monitor to be able to enter the control loop either as a backup or to provide changes in characteristics when required by the flight environment.

New regimes of flight, both high and low speed, and the exploration of space and undersea regions present relatively unknown and changeable environments in which vehicles have

to be operated. At the same time, the vehicles designed for these environments are often, unavoidably, less stable. The need for stabilization with adaptability and reliability is being met in two ways: with adaptive automatic control systems having high redundancy, and with improved systems for manual control which increase the human operator's capability to enter the control loop. Research in this area has included improved cockpit layout, predictive and quickened displays, and some suggested improvements in the control stick.

In 1954, Gibbs<sup>1</sup> published results of experiments comparing two control sticks, an unrestrained stick and a highly restrained stick whose deflections could be sensed electrically, but were imperceptible to the operator. The unrestrained control stick is called a free stick or isotonic stick, referring to the constant muscle tone required for manipulation. The highly restrained stick is called a force stick, a pressure stick, a fixed stick, or an isometric stick, referring to the constant muscle fibre length in the controller's limbs. Gibbs found a significant improvement in controllers' performance with the fixed stick.

In 1966, McRuer and Magdaleno<sup>2,3</sup> compared controller tracking ability using three types of control sticks, free, spring-restrained, and fixed. Like Gibbs, they found that the RMS tracking error was lower for the force stick, primarily

due to smaller phase lag at high frequencies.

A further improvement in the control stick has been developed by Herzog and Pew<sup>4</sup> who duplicated the dynamics of the controlled element on the control stick to make it feel as though it were the actual dynamic plant being controlled. They reported a factor of three in improvement in controller performance with the "feel" stick over that obtained with a force stick.

A block diagram of this scheme is shown in Fig. 1.1. The output of  $Y_p$ , the operator force on the stick, is sensed and the signal is transmitted to the controlled plant. The control stick itself is a mechanical analog of the controlled plant, so its displacement, ideally, is proportional to plant displacement. The control loop is completed by the operator sensing the stick position with his hand and initiating corrective forces. The output of the actual plant is fed back visually to the pilot completing the outer loop. Considering only the inner loop around the pilot, the transfer function,  $Y_1$ , is given by

$$Y_1 = \frac{Y_p}{1 + Y_p Y_c}$$

if  $Y_p$  is a sufficiently high gain,

$$Y_1 \approx \frac{1}{Y_c}$$

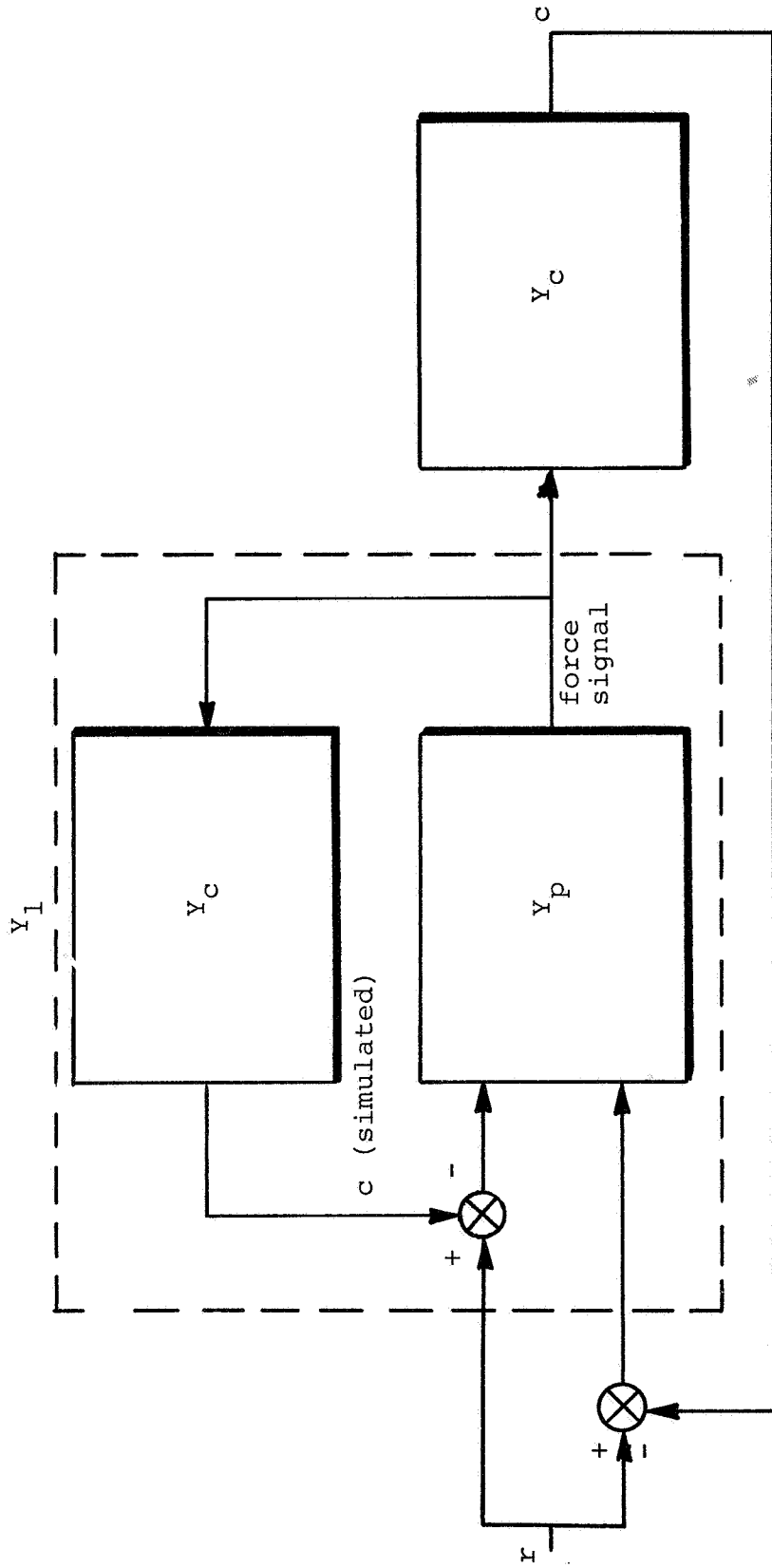


Figure 1.1. Block Diagram of Feel Stick Control

It would seem that any unstable root in  $Y_c$  could be cancelled by placing  $Y_1$  in cascade with the system to be controlled, making the forward path gain

$$Y = Y_1 Y_c \approx \frac{1}{Y_c} Y_c = \text{unity}$$

However, this scheme will be almost impossible to mechanize for unstable plants. The difficulty lies in precisely matching the initial condition and dynamics of the stick and the vehicle. If the slightest difference exists, in either the initial conditions or the dynamics, the situation will inevitably occur where the stick and the vehicle are displaced on opposite sides of the equilibrium point, accelerating in opposite directions. These difficulties can be overcome by feeding back information from the controlled plant to slave the simulated plant. This leads logically to the idea of feeding back the plant's output, or other state variables, to position a force stick, neglecting the simulated plant. The operator could then receive kinesthetic cues from the position of the stick while his response is sensed by sensing his reaction force.

## 1.2 Specific Intent of Thesis

This thesis investigates, by experiment, the possibility of significantly extending the limits of manual control of unstable vehicles by positioning a force control stick with feedback of the state variables of the system.

### 1.3 Results of the Experiment

The results of the experiment showed that positioning a force stick with feedback from the controlled plant greatly increased the controllability when displacement is fed back from a first order plant and velocity is fed back from a second order plant. Feeding back position of a second order plant did not greatly improve the second order plant's controllability.

### 1.4 Outline of Thesis

Chapter II of the thesis discusses the nature of kinesthetic cues that made possible the present improvements in the control sticks, the present limitation in human ability to control unstable plants and how kinesthetic cues from a control stick might overcome these limitations.

Chapter III of the thesis contains a description of the equipment used in the experiments to determine the benefit of feeding state variables back to position the control stick. Emphasis is placed on the equipment which had to be designed for the laboratory to accomplish the experiments. In addition, the other equipment used is described with particular details given in the appendices.

Chapter IV is a description of how the experiments were conducted and the reasons for using particular procedures.

Chapter V presents the results of the experiment with a discussion of the possible uses of the force stick positioned by state variables of the controlled plant.



Chapter VI summarizes the conclusions of the experiment. The appendices, in addition to equipment details, contains the run log of the experiment.

## CHAPTER II

### ROLE OF KINESTHETIC CUES IN MANUAL CONTROL

#### 2.1 Present Use of Kinesthetic Cues

Gibbs<sup>1</sup> explained the superiority of force over free sticks by stating that the feedback signal in the subject's nervous system, the muscle receptor's firing rate, was proportional to the log of the force, giving the force stick operator a continuous feedback of his control effort while the firing rate was proportional to the rate of change of position, requiring the signals to determine his present control level. Gibbs did not, however, explicitly state his model of the muscle receptors.

It is unlikely that pressure receptors in the skin are the primary transmitters of stick force information. Bliss<sup>5</sup> conducted tracking experiments using a moving air jet impinging on the subject's skin to transmit position information. The task was to move the hand or forehead to keep the air jet trained on a designated spot. He found that the tactile display was somewhat inferior to the usual visual display. Conversely, Gibbs<sup>1</sup> greatly reduced skin receptor cues by firmly strapping the subject's hand to an isometric stick and found no degradation in performance. Thus, the muscle

receptors are the most likely paths of stick force information.

Stark<sup>6</sup> has proposed a model of the muscle receptor which is compatible with Gibb's statement. The form of the model is as follows:

$$X = K_1 \frac{s + a}{\left(s + \frac{1}{T_1}\right) \left(s + \frac{1}{T_2}\right)} X_m + \frac{K_2}{\left(s + \frac{1}{T_1}\right) \left(s + \frac{1}{T_2}\right)} F_m \quad (2.1)$$

where X is firing rate,

$X_m$  is muscle length,

$F_m$  is muscle force,

a,  $K_1$  and  $K_2$  are constants,

$T_1$  and  $T_2$  are time constants.

Although firing rate in Stark's model is linearly related to force instead of logarithmically related, Gibb's hypothesis of continuous information of force transmitted through muscle receptors is still supported. The values Stark computed for the above constants provide the transfer function, relating muscle length to firing rate, with a substantial lead in the frequency range from .3 to 16 rad/second. This gives the differentiation of muscle length to which Gibbs referred. The subjects using the feel stick must have been able to use this stretch rate information to advantage, but in a manner that is not known. There is, as yet, no proven model of the human's transfer function predicting response to kinesthetic cues.

If one existed, the optimum input to the operator, in terms of stick position could be calculated to make a maximum increase in the operator's ability to control unstable vehicles. In the absence of such a transfer function, the closed loop stability of the human operator and controlled plant combination is examined in the next section to determine what the response to kinesthetic cues must be to make greater instabilities controllable.

## 2.2 Increasing Controllability with Kinesthetic Cues

A block diagram of the human operator using visual and kinesthetic cues in a compensatory tracking task is shown in Fig. 2.1a. Considering second order controlled elements with transfer function

$$Y_c = \frac{K}{s^2 + 2\xi\omega_n s + \omega_n^2} \quad (2.1a)$$

state variables are position and velocity are given by

$$\underline{C} = \begin{pmatrix} C \\ \dot{C} \end{pmatrix} \quad (2.2)$$

The error,

$$E = \begin{pmatrix} E \\ \dot{E} \end{pmatrix} \quad (2.3)$$

is sensed by the operator through both the visual display and the stick position. Although some visual displays are

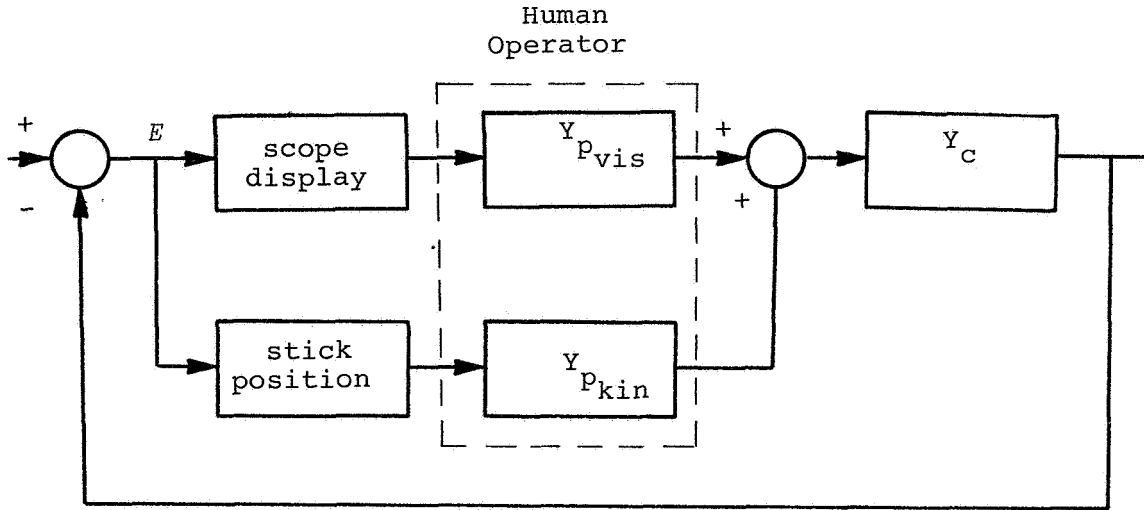


Figure 2.1a

Control Loop with Visual and Kinesthetic Error Signal to Controller

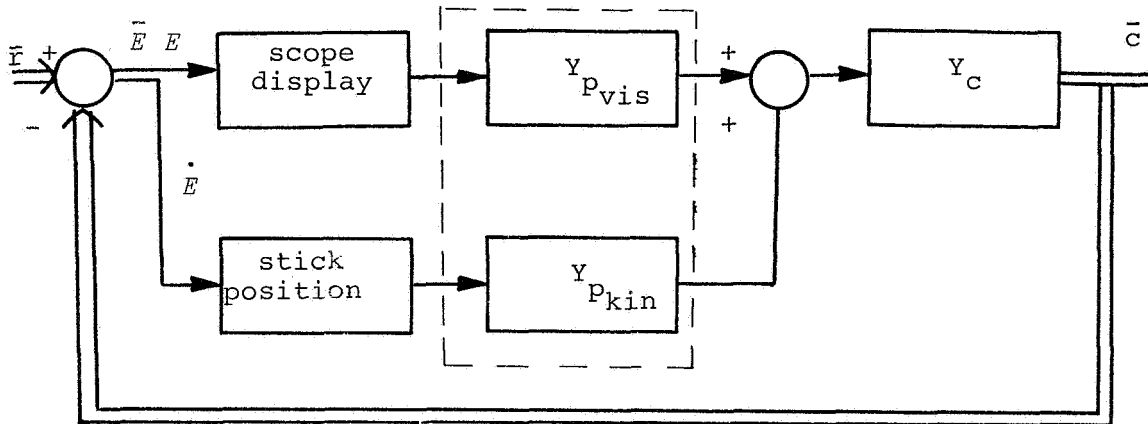


Figure 2.1b

Control Loop with Visual Error and Kinesthetic Error Rate Signal to Controller

"quickened" by adding velocity error to position error, only the usual visual cues of position are assumed here. The stick position is assumed to be driven by either position or velocity error. If the stick is driven by the position error, the closed loop transfer function, in LaPlace notation, is given by

$$\frac{c}{r} = \frac{K(Y_{P_{vis}} + Y_{P_{kin}})}{s^2 + 2\xi\omega_n s + \omega_n^2 + K(Y_{P_{vis}} + Y_{P_{kin}})} \quad (2.4)$$

For neutral stability, the roots of the characteristic equation will be on the  $j\omega$  axis and are found by substituting

$$s = j\omega \quad (2.5)$$

in  $Y_1$  and setting the denominator equal to zero.

$$-\omega^2 + \omega_n^2 + j\omega(2\xi\omega_n) + K(Y_{P_{vis}} + Y_{P_{kin}}) = 0 \quad (2.6)$$

Both real and imaginary parts must equal zero so

$$\omega_n^2 - \omega^2 + K \operatorname{Re} \left\{ Y_{P_{vis}}(j\omega) + Y_{P_{kin}}(j\omega) \right\} = 0 \quad (2.7)$$

$$2\xi\omega_n(\omega) + K \operatorname{Im} \left\{ Y_{P_{vis}}(j\omega) + Y_{P_{kin}}(j\omega) \right\} = 0 \quad (2.8)$$

To compensate for negative values of  $\omega_n$  the operator must increase the real part of his transfer function and to

compensate for negative values of  $2\xi\omega_n$  he must increase the imaginary part.

McRuer, et al<sup>7</sup>, have found that the compensation in visual tracking that a human is capable of producing can be described by the cross-over model of the human operator

$$Y_{p_{vis}} = K_{p_{vis}} e^{-\tau_e s} (T_L s + 1) \quad (2.9)$$

where  $T_L$  = operator lead  $\leq$  5 seconds

$\tau_e$  = operator delay time  $\approx$  .2 seconds

If the time delay,  $\tau_e$ , were not present, the operator could overcome the effects of either negative dynamic stability,  $2\xi\omega_n$ , or negative static stability,  $\omega_n^2$ , merely by increasing his gain. The effect of the time delay term,  $e^{-j\omega\tau_e}$ , is to rotate the phase of the operator's output as shown in Fig. 2.2. The operator's output which should be providing damping is rotated to a position where it contributes to the spring constant of the system, and the operator's output, which should increase static stability, is rotated to a position where it decreases the dynamic stability.

Kinesthetic cues could help the operator if they would reduce the delay time or place another lead term in the operator's transfer function. Presumably, this would be possible if the human operator were able to operate on the muscle receptor signal with the same transfer function used

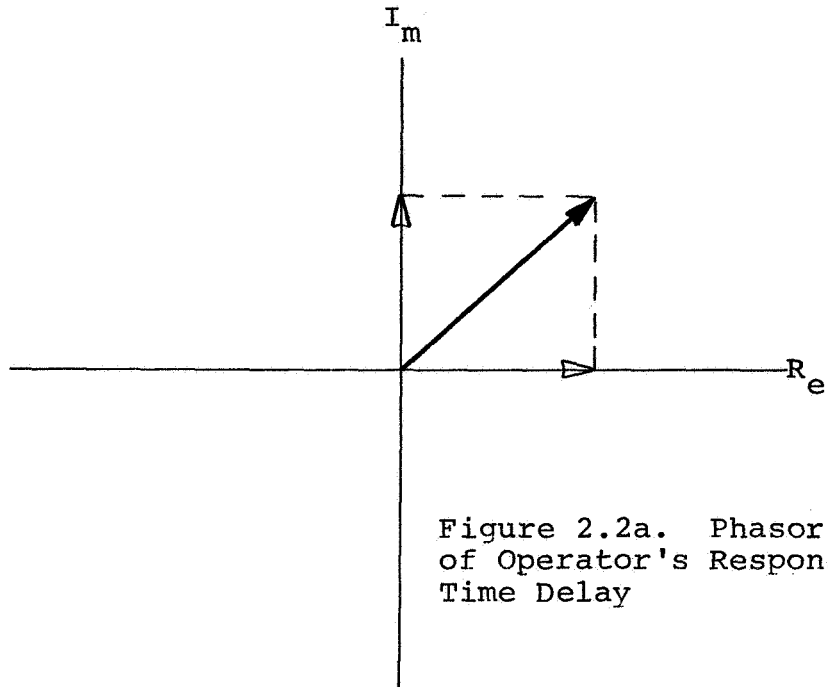


Figure 2.2a. Phasor Diagram of Operator's Response without Time Delay

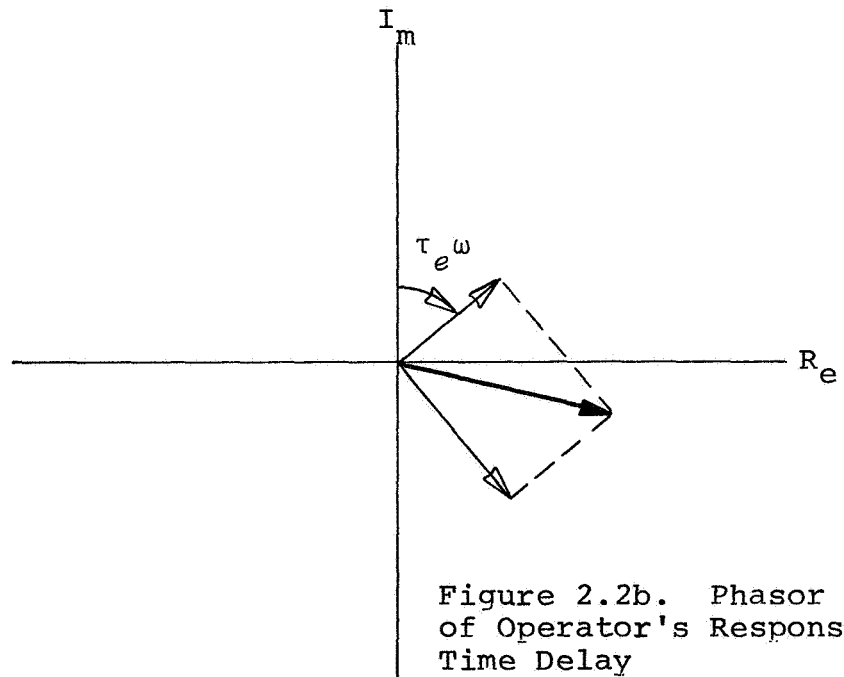


Figure 2.2b. Phasor Diagram of Operator's Response with Time Delay



for visual signals. In the frequency range, .3 to 16 rad/second, where the receptor's lead term predominates, the receptor's response to length can be approximated by

$$X = (T_1 s + 1) X_m \quad (2.10)$$

and the operator's transfer function could be modeled as

$$Y = (T_1 s + 1) \left\{ (T_L s + 1) e^{-\tau_e s} \right\} \quad (2.11)$$

If this hypothetical transfer function is valid, the muscle reception would provide the human operators with the necessary lead to control greater instabilities.

If the control stick were driven by error rate as shown in Fig. 2.1, another source of lead generation might be possible. In this case, equation 2.8 and 2.9 would take the form:

$$\omega_n^2 - \omega^2 + KR_e \left\{ Y_{p_{vis}}(j\omega) + j\omega Y_{p_{kin}}(j\omega) \right\} = 0 \quad (2.12)$$

$$2\xi\omega_n(\omega) + KI_m \left\{ Y_{p_{vis}}(j\omega) + j\omega Y_{p_{kin}}(j\omega) \right\} = 0 \quad (2.13)$$

The additional phase lead, provided by the error rate signal, would decrease the operator's requirement to generate  $T_1$  or  $T_L$ . If  $T_1$  can, in fact, be generated, the rate feedback to the control stick would give performance superior to the error feedback. In summary, to be beneficial in stabilizing

second order systems, kinesthetic cues would have to function in one of the following ways:

- 1) Reduce  $\tau_e$ , which would enable modest values of lead,  $T_L$ , to be more effective.
- 2) Place an additional lead term in the transfer function. This is presumably possible due to the differentiating nature of the muscle receptor transfer function described in equation 2.9.
- 3) Provide a separate input to the operator enabling him to sense a signal to which the required lead has already been provided.

## CHAPTER III

### EXPERIMENTAL EQUIPMENT

#### 3.1 Design Objectives for Specially Constructed Equipment

The equipment that had to be built to obtain experimental data on the usefulness of state variable feedback to position a force stick consisted of the stick with force sensing elements, the actuating mechanism and a suitable fixture to support the apparatus during the experiments. The primary objective was to build a control stick that had the advantage of an isometric stick, yet would move under command of an external signal. Accordingly, the stick's displacement under the controller's force was to be imperceptible, so a high gain position servo with no dead zone or backlash was required. In anticipation of extending the limits of manually controllable instabilities, the position servo was to have a natural frequency higher than previously recorded human operator bandwidth. The sensitivity of the force transducer was to be as high as possible to reduce the relative amount of noise introduced in amplification stages. A secondary consideration was that the control stick would be more useful if it could be mounted easily in other simulations such as the Ames two-axis simulator located in the M.I.T. Man-Vehicle

Laboratory.

### 3.2 Details of Design and Construction

This section describes the components of the feedback positioned control stick and relates how the selection was governed by the design objectives. The actuator, drive train, and force sensor are described, in that order.

Electric power was chosen instead of hydraulic power for operating the position servo to avoid the difficulties which may be encountered with dead zones of valves, and leaks in fittings. A D.C. torque motor was furnished by the M.I.T. Instrumentation Laboratory. The motor had been built under special contract by Kearfott. It is similar to the so-called "pancake" torque motor and has a permanent magnet field and a wave-wound armature.

The rotor and field were furnished unmounted and were incorporated in the structure and drive of the rest of the equipment. For high torque the motor had been designed to have an air gap of less than .005 inches. This required the support structure for the rotor bearing and field to be precisely machined and made of a material with low residual stress to prevent warpage. A one-inch thick piece of cast aluminum tooling plate was used and a recess was machined to receive the armature winding and rotor bearing as shown in Fig. 3.1. It was anticipated that the bearing support would have to be mounted in a movable pillow block to allow final

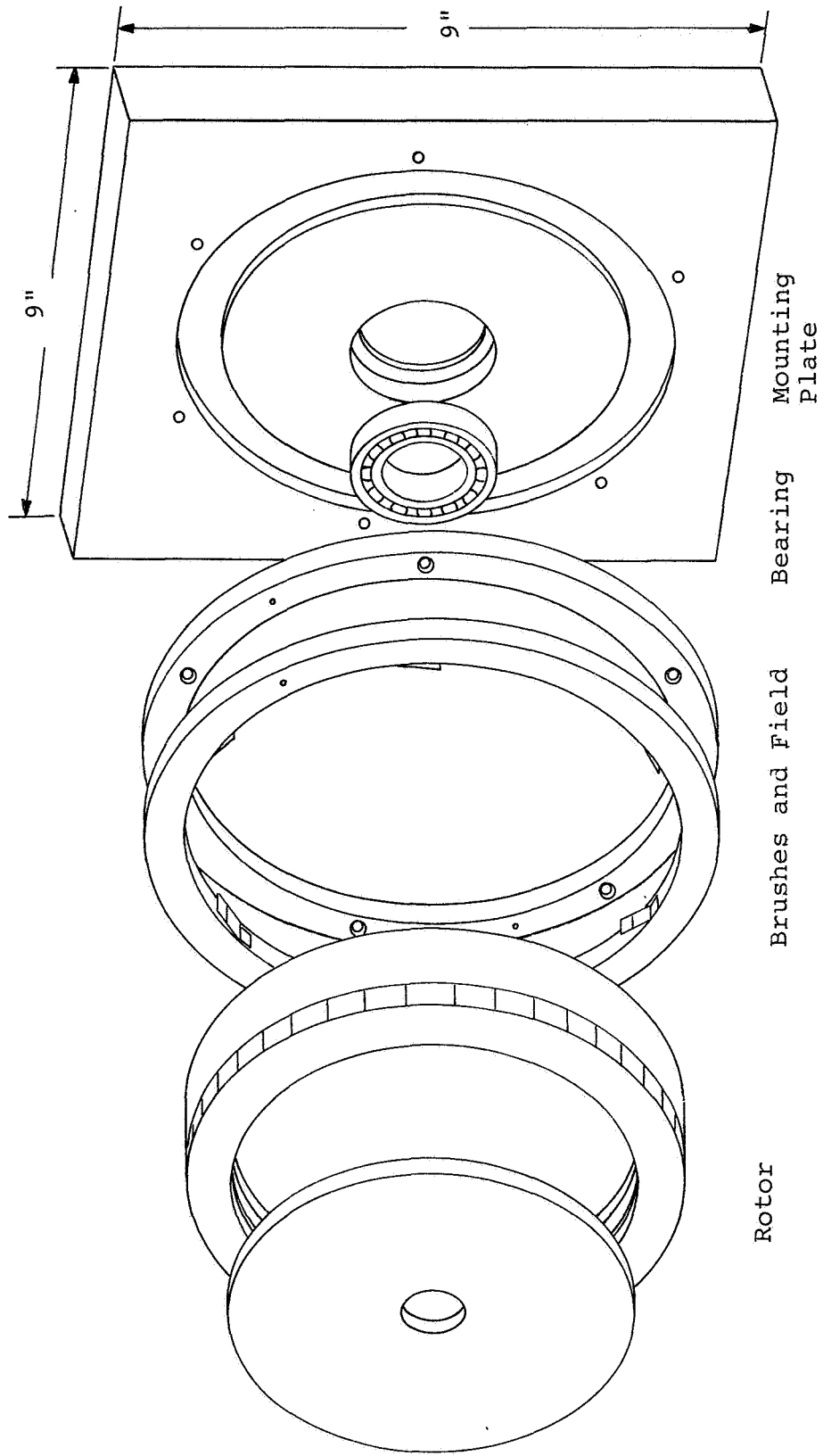


Figure 3.1

Torque Motor and Mounting

adjustments of the close air gap. However, by mounting the rotor first, and positioning the field with shims in the air gap, the field was mounted satisfactorily without further adjustment.

The stick was mounted on an axis parallel to the motor axis but displaced as shown in Fig. 3.2. This made possible the use of torque amplification as a means of increasing the effective spring constant of the stick and enabled the stick and actuator unit to be more compact, for possible use in other experiments. A disadvantage of not mounting the stick on the motor shaft was the requirement for a driving mechanism other than a straight shaft.

Gears could not be used in the driving mechanism because the backlash would give a dead zone in the control, limiting the controller's performance. One-sixteenth inch steel control cable was found to be difficult to use on the small diameter pulley. Double strands of dial cord were tried, but the strength was too low for the tension required. Steel tapes of 1/8 inch width by .006 inch thickness resulted in satisfactory operation. The steel, furnished by the Ward Steel Company, was SAE 1095 tempered spring steel. After cutting the tapes, the ends were annealed and the upper ends drilled to receive the tension adjusting screw as shown in Fig. 3.3. The lower ends were secured to the small brass double pulley by inserting them into the slots of spring pins

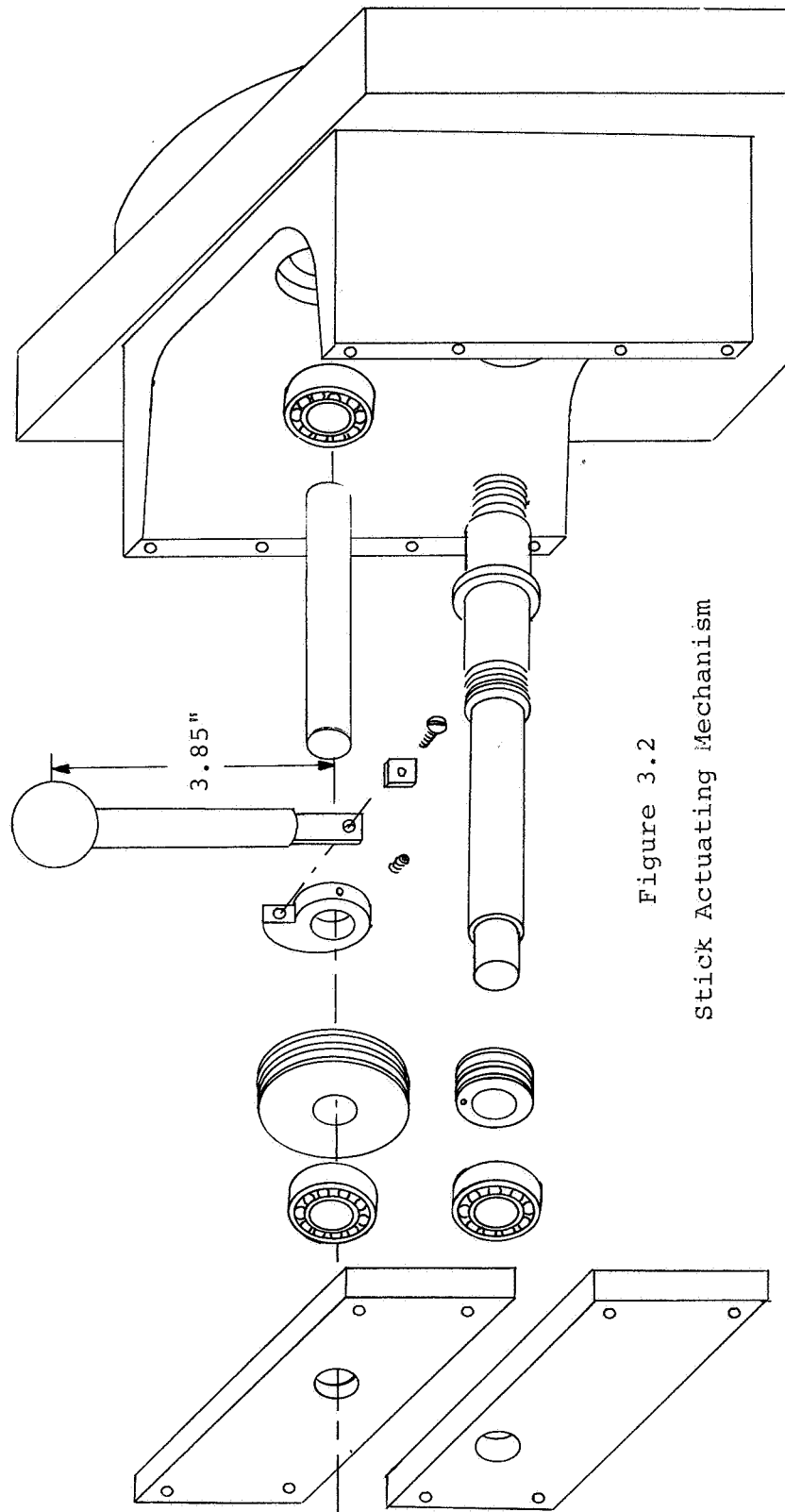


Figure 3.2  
Stick Actuating Mechanism

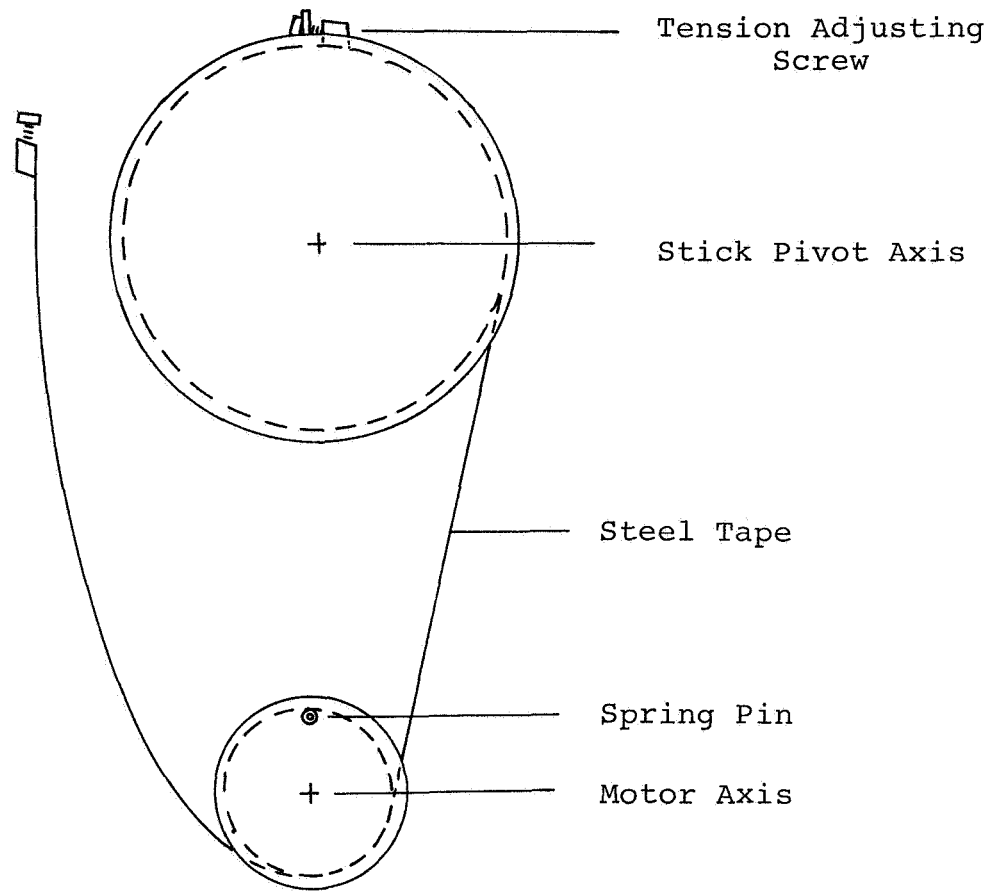


Figure 3.3  
Stick Actuating Pulleys

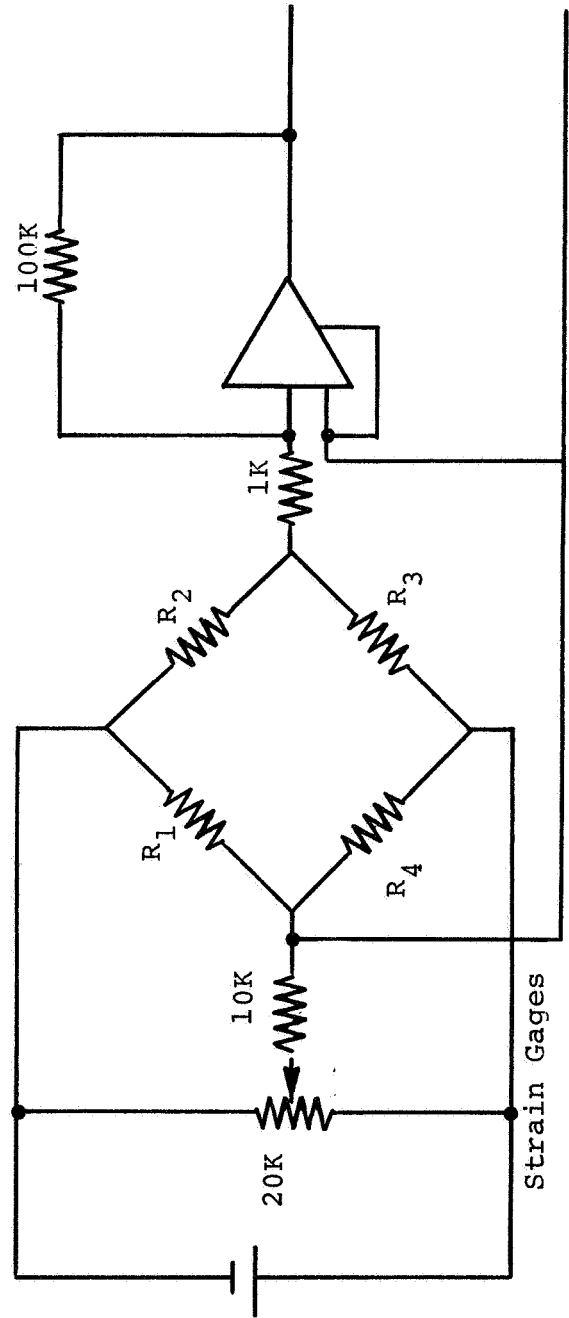


embedded in the bottom surface of the pulley tracks. The pins were twisted to cinch the steel tapes in place. The tapes were wrapped one around the lower pulley before being attached to the tension adjusting screws mounted on the large phenolic pulley on the control stick shaft.

For the force sensor, strain gauges were chosen instead of wafer type force transducers. In comparison, strain gauges are cheaper, have less hysteresis when mounted on any common structural material and occupy less space. Strain gauges are more fragile but, for this application, durability was not a factor. The strain gauges used were SR-4-M7 wound wire gauges made by Balwin Lima Hamilton Corporation.

The sensitivity of the force sensing system was maximized by choice of strain gauge circuit and design of the sensitive element, the portion of the control stick structure on which the gauges were mounted. A strain gauge bridge circuit with four active elements was used, which gives four times the sensitivity of a bridge with a single active element and provides temperature compensation. The circuit with zeroing adjustment and amplifier is shown in Fig. 3.4. The amplifier is a model SQ 10A made by Philbrick/Nexus Research Company.

Since the electrical signal from the sensor is proportional to strain, a material with a high yield strain was used and the cross-section of the sensitive element chosen to cause the strain under the anticipated maximum controller force to be about one-third of the yield strain.



$R_1$  through  $R_4 = 120 \pm \Delta R$

$R_1$  mounted beside  $R_3$

$R_2$  mounted beside  $R_4$ , opposite  $R_1$  &  $R_2$

Figure 3.4

Strain Gage Bridge and Amplifier Circuit

To determine a useful value for the controller's maximum force, a brief experiment was done using three subjects who were asked to exert what they believed to be a comfortable maximum control force on a control stick which was roughly the diameter of that anticipated for the final construction. Table 3.1 shows the results, with a comparison value derived from Ref. 9 which gives an optimum lateral stick force per unit display deflection of .615 pounds/cm. The maximum display deflection was four centimeters giving a force for maximum display deflection of 2.5 pounds. Three pounds was adopted as the maximum force for a lateral mode.

Table 3.1

ANTICIPATED MAXIMUM STICK FORCE

<u>DIRECTION OF FORCE</u>	<u>"COMFORTABLE" MAXIMUM FORCE</u>				<u>"OPTIMUM" MAXIMUM FORCE FROM REF. 9</u>
	<u>A</u>	<u>B</u>	<u>C</u>	<u>AVE</u>	
Lateral	2.5	3.0	3.5	3.0	
Fore & Aft	3.5	4.0	4.25	4.0	2.5

Table 3.2 gives yield strength and yield strain for several materials. Silicon manganese steel has the highest yield strain but aluminum alloy 7075-T6 has a yield strain almost as high and was chosen because it was readily available.

Table 3.2

YIELD POINT FOR STRUCTURAL MATERIALS

<u>Type</u>	<u>Elastic Modulus-Psi</u>	<u>Yield Strain, <math>\epsilon_y</math></u>
Structural	$30 \times 10^6$	$1.27 \times 10^{-3}$
Hi-Strength Structural	$30 \times 10^6$	$1.66 \times 10^{-3}$
Silicon-manganese	$30 \times 10^6$	$7.6 \times 10^{-3}$
7075-T6 Aluminum	$10^7$	$7.2 \times 10^{-3}$

The width of the sensitive element was chosen to accommodate two strain gauges side by side. The thickness was computed to give a surface strain of one-third of the yield point strain under maximum stick force. The two strain gauges require at least 3/8 inch wide surface so the thickness was calculated from

$$\epsilon_b = \frac{M b/2}{EI} = \frac{\epsilon_y}{3} \quad (3.1)$$

where  $b$  = thickness of rectangular section

and,  $I = 1/12 ab^3$  = cross section moment of inertia

which gives  $b = .1265$  or  $1/8$  inch. (3.2)

To protect the sensitive element from permanent damages, it was fastened to the shaft with a single brass screw which would fail in tension if the bending stress of the test section reached 80% of the yield point stress.

The support for the mechanism consists of a padded arm rest in which the stick can be mounted to move fore and

aft, simulating longitudinal control, or sideways, to simulate lateral or roll control. The height of the arm rest is adjustable.

### 3.3 Description of Additional Equipment

In addition to the equipment constructed for the experiment, a D.C. power supply, power regulator, analog computer, oscillograph and oscilloscope were used and are described in this section.

The D.C. power supply is a Technipower model L 80-12. It has a capacity of 12 amperes at 80 volts with lower, regulated, levels available by adjustment of control knobs.

The power regulator had previously been built in the M.I.T. Man-Vehicle Laboratory. It is capable of regulating up to 150 watts at a maximum voltage of 40 volts by pulse length modulation at 60 cps. Its duty cycle, determined by a linear combination of two inputs, is given by

$$D = .5 + \frac{X_1 - 4X_2}{20} \quad (3.3)$$

where D = fraction of cycle during which the output is positive

$$(0 \leq D \leq 1)$$

$X_1$  and  $X_2$  = input signals in volts.

The circuit for the regulator is in Appendix A.

The analog computer is a G.P.S. Instrument Company model 290 T. It operates with voltages between  $\pm 10$  with amplifier

saturation occurring at  $\pm 12$  volts.

Data was recorded on a four channel oscillograph, Mark 240, made by Brush Instrument Company.

For the visual display, a Dumont type 304 cathode ray oscilloscope was used. The maximum display deflection possible was 2.25 inches.

### 3.4 Performance of Servo-Positioned Force Stick

The stick positioning loop using the regulator, power supply, and stick mechanism described in the preceding section is shown in the block diagram of Fig. 3.5. The constants of the system are defined and their values given in Table 3.3. The effective spring constant of the control stick, given by

$$K_{sp} = \frac{4N^2 K_R K_T K_P}{R_A} \quad (3.4)$$

was maximized by making  $N$ , motor to stick pulley ratio, the highest practical value of 4. Higher values would have required overly large or inconveniently small pulleys or another stage of pulleys.  $K_T$  and  $R_A$ , the torque constant and armature resistance of the motor, are fixed and their values listed in Table 3.3. Increasing either  $K_P$  or  $K_R$  would increase  $K_{sp}$  but would have required the modification of existing hardware to do so. This was not necessary since a satisfactory value of  $K_{sp} = 440$  in. lb./rad was

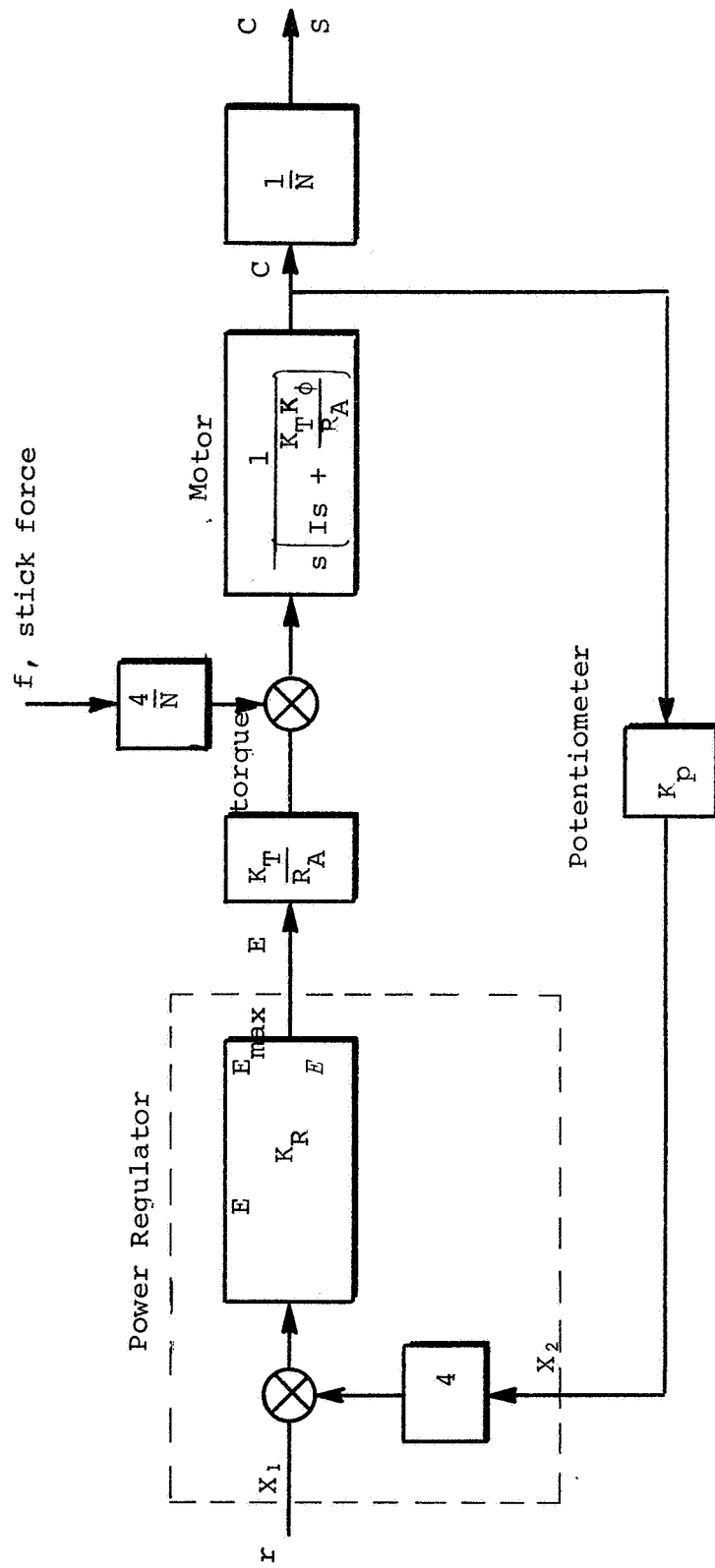


Figure 3.5. Stick Position Control Loop

Table 3.3

CONSTANTS IN STICK POSITION CONTROL LOOP

$K_T$	= Motor Torque Constant	= 13 $\frac{\text{in. lb.}}{\text{amp}}$
$K_\theta$	= Motor Armature Reaction Constant	= 1.6 $\frac{\text{volt}}{\text{rad/sec.}}$
$E_{\text{max}}$	= Maximum Regulator Output Voltage	= 40 volts
$R_A$	= Motor Armature Resistance	= 9 $\Omega$
$K_p$	= Potentiometer Gain	= 4.76 volt/rad
$K_R$	= Power Regulator Gain	= 2 volts/volt
$N$	= $\frac{\text{Stick Pulley Diameter}}{\text{Drive Pulley Diameter}}$	= 4
$K_{sp}$	= Stick Spring Constant	= $\frac{4N^2 K_R K_T K_p}{R_A} = \frac{440 \text{ in. lb.}}{\text{rad}}$
$\omega_n$	= Natural Frequency of Position Servo	= $\left( \frac{4K_R K_T K_p}{I R_A} \right)^{1/2} = \frac{25 \text{ rad}}{\text{sec}}$
$\xi$	= Damping Constant of Position Servo	= $\frac{K_\theta}{4} \left( \frac{K_T}{I R_A K_R K_p} \right)^{1/2} = .28$
$L$	= Stick Length	$\approx$ 4 inches



achieved. This value is approximately one-half the spring constant used by McRuer, et al<sup>3</sup>, for a fixed stick, but their manipulator was to be gripped in the palm of the hand. A pencil stick held by the fingers would not need as great a spring constant.

The natural frequency of the position servo is given by

$$\omega_n^2 = \frac{4K_R K_T K_P}{R_A I} \quad (3.5)$$

could have been increased by increasing  $K_R$  which would also increase  $K_{sp}$ , the spring constant, but the measured value,  $\omega_n = 25$  rad/second, is much higher than the 10 rad/second limit of operator ability found by Taylor and Day.<sup>10</sup>

The damping constant

$$\xi = \frac{K_\theta}{4} \left( \frac{K_T}{I R_A K_R K_P} \right)^{1/2} \quad (3.6)$$

was estimated from the frequency response to be = .28. Provided that no frequencies higher than  $\omega_n$  would be encountered, lowering the value of  $\xi$  would be desirable, since it would give less phase lag in the frequencies below  $\omega_n$ . If  $K_R$ , the power regulator gain, were increased to increase  $K_{sp}$  and  $\omega_n$ , equation 3.7 shows that  $\xi$  would be reduced. Thus, if improvement in overall system performance

had been necessary, it could have been accomplished by increasing  $K_R$ .

The sensitivity of the force sensing element is given by

$$K_{sm} = \frac{4X \text{ g.f. } X E_b X L X b/2}{EI} \quad (3.7)$$

where g.f. = gauge factor of strain gauges = 1.97

4 = number of active gauges

$E_b$  = battery voltage = 6 volts

L = length of stick = 3.85 inches

E = Elastic Modulus =  $10^7$

I = Moment of Inertia of cross-section =

$6.1 \times 10^{-5} \text{ in.}^4$  of sensitive element

which yields a computed value of

$$K_{sm} = 24.2 \text{ volts/lb.} \quad (3.8)$$

In comparison, the measured sensitivity was

$$K_{sm} = 25.0 \text{ volts/lb.} \quad (3.9)$$

## CHAPTER IV

### DESIGN OF EXPERIMENT

#### 4.1 Purpose

The purpose of the experiment was to determine if the limits of controllability of unstable systems can be increased by feeding back state variables to command the position of a force sensing control stick. This purpose had to be accomplished within a short time period and with untrained subjects. This was not a great limitation, for, if the method of extending the limits of controllability is truly beneficial, it should increase the performance of untrained subjects as well as trained controllers. The tests, however, had to be ones in which untrained subjects could achieve consistent scores to enable a small number of runs to be meaningful. Accordingly, the procedure described in the following section was used.

#### 4.2 Procedure

A comparison of the variable position force stick with the fixed stick was made by determining which stick enabled a human operator to control a greater instability in a single axis task. This was done by requiring several subjects to maintain first and second order unstable plants in a position of equilibrium using, alternately, the variable position

and fixed sticks. No disturbing inputs to the plants were used. The plants were simulated on an analog computer and the level of instability increased automatically according to the subject's performance, thereby forcing him to work at his maximum capability.

The control tasks used in the experiment can be described by the transfer functions

$$A. \quad Y_C = \frac{\lambda}{s - \lambda} \quad (4.1)$$

$$B. \quad Y_C = \frac{\lambda}{s(s - \lambda)} \quad (4.2)$$

$$C. \quad Y_C = \frac{\lambda}{s^2 + 2\omega_n s - \lambda^2} \quad (4.3)$$

$$D. \quad Y_C = \frac{\omega_n^2}{s^2 - \lambda s + \omega_n^2} \quad (4.4)$$

$\lambda$  is the measure of difficulty and was set by an adapter circuit in the analog computer. The computer circuits for the transfer functions and the adapter are shown in Appendix B. Plants A and B are similar to the first and second order critical tasks suggested by Jex, McDonnell, and Phatak<sup>9</sup> for measurement of human operator performance. Plants B, C and D are all particular cases of a general second order transfer function,

$$Y = \frac{K}{s^2 + 2\xi\omega_n s + \omega_n^2} \quad (4.5)$$

They are simulated by three separate circuits on the analog computer so that the static stability represented by the coefficient  $\omega_n^2$  and dynamic stability represented by  $2\xi\omega_n$  can be varied independently.

Varying the static and dynamic stability independently enables a comparison to be made with data of other investigators of human operator limits such as those of Smith<sup>11</sup>, and Taylor and Day.<sup>10</sup> These investigators showed their results in a stability plane as shown in Fig. 4.1. The axes are  $2\xi\omega_n$  and  $\omega_n^2$ , the coefficient of a general second order transfer function.

Within the first quadrant a set of points, whose general location is shown by the crosshatched area of Fig. 4.1, represents transfer functions of plants with desirable handling qualities. Points below and to the left of this region represent plants that are difficult to control

The plants used in the experiment can be represented by loci which traverse the arrows in Fig. 4.1 as the adapter circuit increases the difficulty. The difficulty,  $\lambda$ , is represented by the distance along the arrows, measured in units indicated on the axis. The adapter circuit on the analog computer which adjusted the value of  $\lambda$  according to the operator's performance is described below.

### 4.3 Equipment Set-Up

Two forms of adapters were tried to enable the subject's performance to pace the difficulty. The first was a first

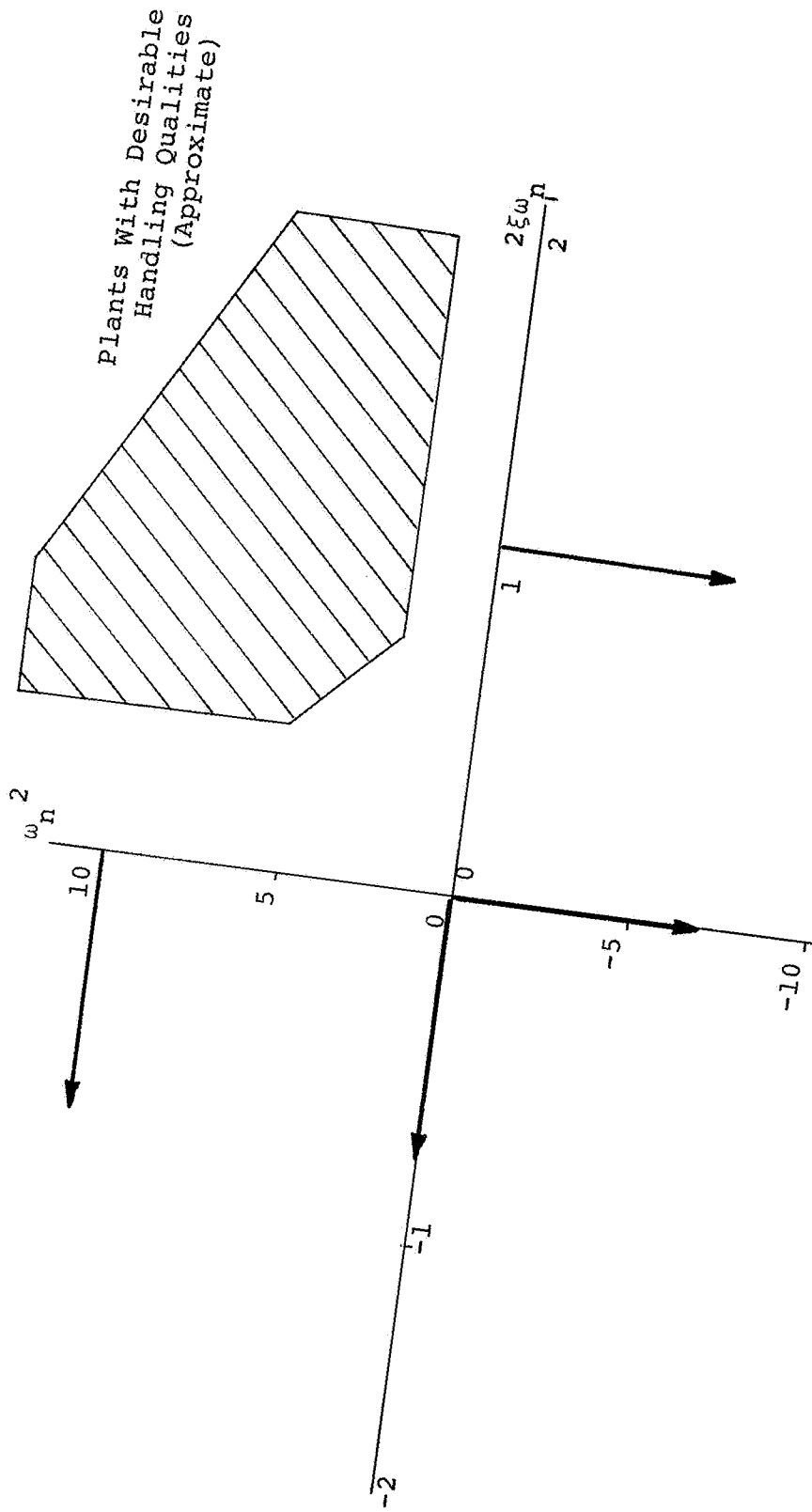


Figure 4.1  
 Stability Plane Showing Plants used in Experiment

order filter circuit which regulated the difficulty according to the relationship

$$\lambda = \frac{L - aE^2}{\tau s + 1} \quad (4.6)$$

Where L = upper limit of difficulty that adapter can set

L = factor which sets sensitivity of difficulty to performance

$\tau$  = Filter time constant = 4 seconds

At the beginning of each run, the filter output was set at zero and then increased exponentially toward the limit L which could be attained in the absence of any error. The effect that the squared error had on reducing the difficulty was set by the factor a and the smoothing effect of the filter was determined by the time constant,  $\tau$ .

This adapter was used for the first order task but displayed several disadvantages.

1. The factor, a, only set a relative effect of the limit L and the error in determining the value of  $\lambda$ , so a precise critical error could not be defined.
2. The limit L could not be changed without affecting the rate of increase of  $\lambda$  and affect the changing of limit L also changes the rate at which the difficulty increases and the relative effect of

the error so that comparison of data using two limits was not possible.

3. The value of  $\lambda$  fluctuated continually unless the limit was reached so that a good measure of the difficulty could only be obtained by taking the average over a number of fluctuations.

For experiments with the second order tasks, a second order adapter was used which was similar to one proposed by Jex, McDonnell and Phatak. In this adapter, the value of  $\lambda$  is determined from the following equation:

$$\dot{\lambda} = A \left[ \epsilon^2_{\text{crit}} - \frac{\epsilon^2}{\tau s + 1} \right] \quad (4.7)$$

where  $A\epsilon^2_{\text{crit}}$  = maximum rate of increase in difficulty

and  $\tau$  = filter time constant = four seconds

Limiters were used to establish the following constraints:

$$\dot{\lambda} \geq \frac{\epsilon^2_{\text{crit}}}{6} \quad (4.8)$$

$$\lambda \geq 0 \quad (4.9)$$

This is a mechanization of the idea that if a controller can maintain the average squared error,  $\epsilon^2$ , below a criterion value,  $\epsilon^2_{\text{crit}}$ , then the difficulty should be increasing. The squared error is filtered, compared with the criterion value, and the difference integrated to give the multiplier value. As the squared error increases, the rate of change of the multiplier becomes negative and the system becomes



easier to handle. The computer circuit for the adapter is in Appendix B.

Jex, et al,<sup>9</sup> discarded this scheme because of instabilities in the adapter-controller system. It is believed that these difficulties, since they were not encountered in this experiment, were overcome by the long time constant (four seconds) in the filter and by the use of limiters. The method used by Jex, et al,<sup>9</sup> called an "auto pacer" commanded the difficulty to increase at a constant rate until the error reached a specified level, then at a slower rate until control was lost.

The principal objection to using the autopacer for the stick positioned by feed back was that losing control of the plant meant large transient motions of the stick with associated structural stress on the mechanism. With an adapter circuit that sets the difficulty close to but not greater than the limit of the controller ability, damage would be avoided.

Another reason for allowing the subject to maintain control was that new runs would not have to be started whenever the controller faltered in his controlling technique. This should enable inexperienced controllers to achieve more nearly their maximum score at some time during each run, thereby eliminating some scatter in the data.

Although a different method of setting the task difficulty was used in the experiment, the reports of Jex, et al,<sup>9</sup> were helpful in determining the parameters used in the tests.

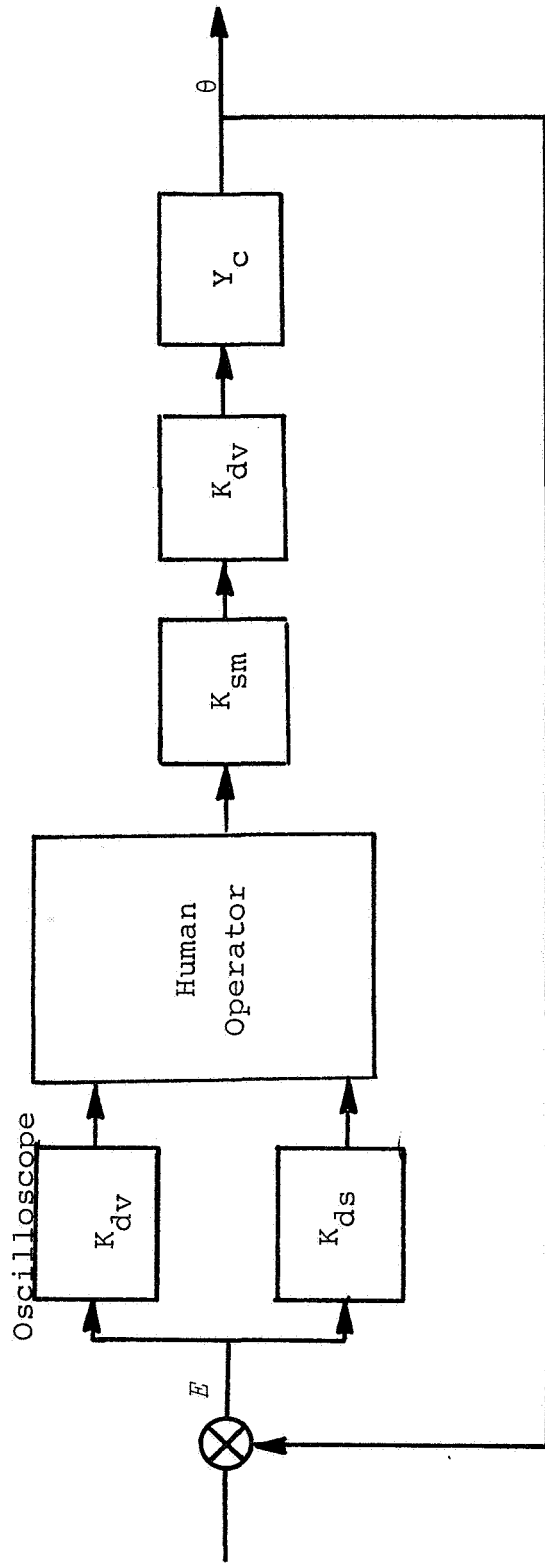


Figure 4.2  
Block Diagram of Test Set-Up

Table 4.1

CONSTANTS USED IN TEST CIRCUIT

$$K_s = K_{sm} K_{sc} K_{dc} K_{dv} = 9.8 \text{ in./lb.}$$

$$K_{ds} = \text{stick deflection gain} = 1.5 \text{ degree/volt}$$

$$K_{dv} = \text{visual display deflection gain} = 1 \text{ in./volt} = \\ .39 \text{ in./volt}$$

$$K_{sm} = \text{stick gain} = 25 \text{ volt/lb.}$$

$$K_{sc} = \text{computer input gain} = 1 \text{ volt/volt}$$

$$K_{dc} = \text{computer output gain} = 1 \text{ volt/volt}$$

$$K = \frac{\text{inches}}{\text{lb.}} \times .1$$

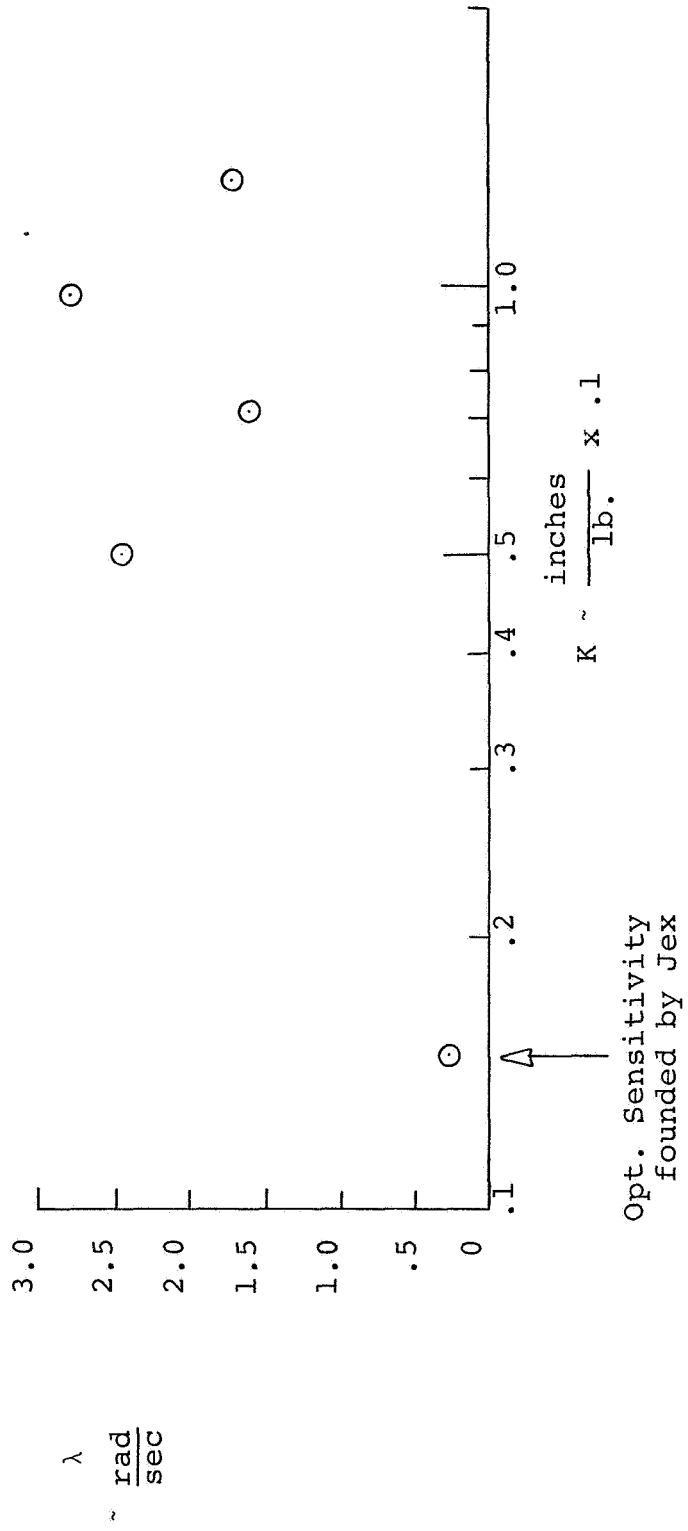


Figure 4.3

Optimization of Display Sensitivity to Stick Gain

Fig. 4.2 shows the block diagram of the test circuit. Table 4.1 lists the parameters of the circuit and the values that were used in the experiment. The critical error as recommended by Jex, et al, was 15% of the maximum display deflection. The rate of increase in  $\lambda$  was approximately that used for their auto paced task. It was adjusted by trial and error along with the filter time constant and the limiter setting for the rate of decrease in difficulty to achieve a system which allowed two subjects, who were helping to set up the experiment, to maintain control.

The display deflection per stick force expressed by the product

$$K_s = K_{sm} K_{sc} K_{dc} K_{dv} \quad (4.10)$$

was optimized by experiment. Fig. 4.3 shows the results of that experiment. The highest score was obtained using

$$K = 9.8 \text{ inches on CRT/lb. on stick} \quad (4.11)$$

and was the value chosen to use for the experiments. The data was scattered in this region so the results were only conclusive to the extent that the best sensitivity was shown to be much higher than the value of

$$K = 1.6 \text{ in./lb.} \quad (4.12)$$

found by Jex.

The difference could be due to two factors. Since the small, pencil type control stick used in this experiment was held by the fingers instead of being gripped in the palm of the hand, a small force may have been most desirable for the subject. Also, the "optimum" gain was the same as that used earlier to determine filter parameters so the subject had more practice with that gain. That may have been a factor in Jex's<sup>9</sup> experiments also, since only one subject was used. It is likely that determining optimum force stick gains by simulation will require close matching of manipulator feel in simulator and vehicle and close control of previous conditioning of subjects and operators.

To determine the best computer scaling, scaling was varied, keeping the  $K_s$  constant. Lower scale factors reduced the accuracy of the multiplier and potentiometer settings and higher settings resulted in saturation of the first stage of amplification of the controller's force signal. A convenient compromise resulted in a criterion level for  $\varepsilon^2_{crit}$  to be .08 volts giving  $K_{sc} = 1$  volt/volt, and  $K_{dc} = 1$  cm/volt. With this scaling some amplifier saturation occurred, particularly during a subject's first run.

#### 4.4 Determination of Sample Size

To determine the number of runs necessary to detect a difference in effectiveness of the control stick, an

estimate of the deviation in scores was required. The only data available was the results of Jex's<sup>9</sup> experiments with the auto paced critical task.

Jex found that a subject's scores on the critical task were normally distributed and the deviation was approximately  $.31 \text{ sec.}^{-1}$  for the first order task and about the same,  $.4 \text{ sec.}^{-1}$  for the second order task although the means were  $6.58 \text{ sec.}^{-1}$  and  $3.7 \text{ sec.}^{-1}$  respectively.

In applying these results to this experiment, the following assumptions were made:

1. The distribution of scores attained would be normal.
2. The deviation for the first order and negative damping task would be  $.35 \text{ sec.}^{-1}$  and  $.35 \text{ sec.}^{-2}$  for the second order static instability.

The assumption that the untrained subjects could attain scores as consistently, i.e., with as low a variance as those attained with the Jex's trained subjects, is in accordance with the assumption that the self pacer would reduce the scatter in the data. The assumption that the deviation would be the same for both controlling methods was based on the fact that the variance changed very little in Jex's experiments even though different tasks were used and a large difference in averages was obtained. Under these assumptions, a subject's scores using one of the



two control sticks and considered to be random samples drawn from one of two normal populations of equal variances. Conditions for detecting, with 95% confidence, a difference in the means, for this case, are derived in the following paragraph.

The deviation of an average of  $n$  samples, when the samples are drawn from a population of deviation,  $\sigma$ , is given by<sup>12,13</sup>

$$\sigma_{\bar{\lambda}} = \frac{\sigma}{\sqrt{n}} \quad (4.13)$$

Let  $d = \bar{\lambda}_1 - \bar{\lambda}_2$ , the difference between the means of samples drawn from two populations. If the two populations have normal distributions,  $d$  will be normally distributed with a deviation given by

$$\sigma_d = \sqrt{\frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_2}} \quad (4.14)$$

If the two populations have the same deviation, as assumed for this experiment and the same number of samples are drawn from each, the deviation of  $d$  is given by

$$\sigma_d = \sigma \sqrt{\frac{2}{n}} \quad (4.15)$$

Using a table of normal distribution, it can be seen that the condition

$$d \geq 1.8 \sigma_d \quad (4.16)$$

will assure, with 95% confidence, that  $\bar{d}$ , the observed value of  $d$ , will be greater than zero.

Substituting 4.15 into 4.16 gives the explicit relationship of minimum detectable difference and required number of runs.

$$d \geq 1.8 \sigma \sqrt{\frac{2}{n}} \quad (4.17)$$

After the data has been taken, the assumed value of deviation can be checked by the sample deviation given by

$$\bar{\sigma} = \sqrt{\frac{\sum_{n=1}^n (\bar{\lambda} - \lambda_n)^2}{n - 1}} \quad (4.18)$$

The sample deviation and observed value of  $d$  can then be used in the inequality

$$\bar{d} \geq 1.8 \bar{\sigma} \sqrt{\frac{2}{n}} \quad (4.19)$$

to obtain the condition for  $\bar{d}$  to be significant.

The minimum difference to be detected was arbitrarily set at  $0.4 \text{ sec.}^{-1}$  for the first order task and second

order dynamic instability and  $0.4 \text{ sec.}^{-2}$  for the second order static instability.

These rather high values were chosen because it was felt that a small improvement obtained by making a force stick movable would not compensate for the loss of simplicity and reliability. Substituting

$$d = 0.4 \tag{4.20}$$

into equation gives  $n \geq 5$  as the required number of runs. (4.21)

#### 4.5 Conduct of Tests

The subjects were seated, as in Fig. 4.1, with their eyes approximately 28 inches from an oscilloscope with a vertical bar display which moved laterally representing the position of the controlled plant. The side-arm controller was located on the right side of the subject with the stick positioned to be used in a lateral or roll mode. The polarity of the control was such that the display bar would move in the direction of the force on the control stick.

In all cases there was no external input to the system. Initial conditions for all runs were zero displacement and zero velocity. Each run was begun with a short count-down. The runs were to be continued until the subject either lost control or had attained two peaks in difficulty. The run length varied from 10 seconds to two minutes with at least a minute rest period between runs. The score

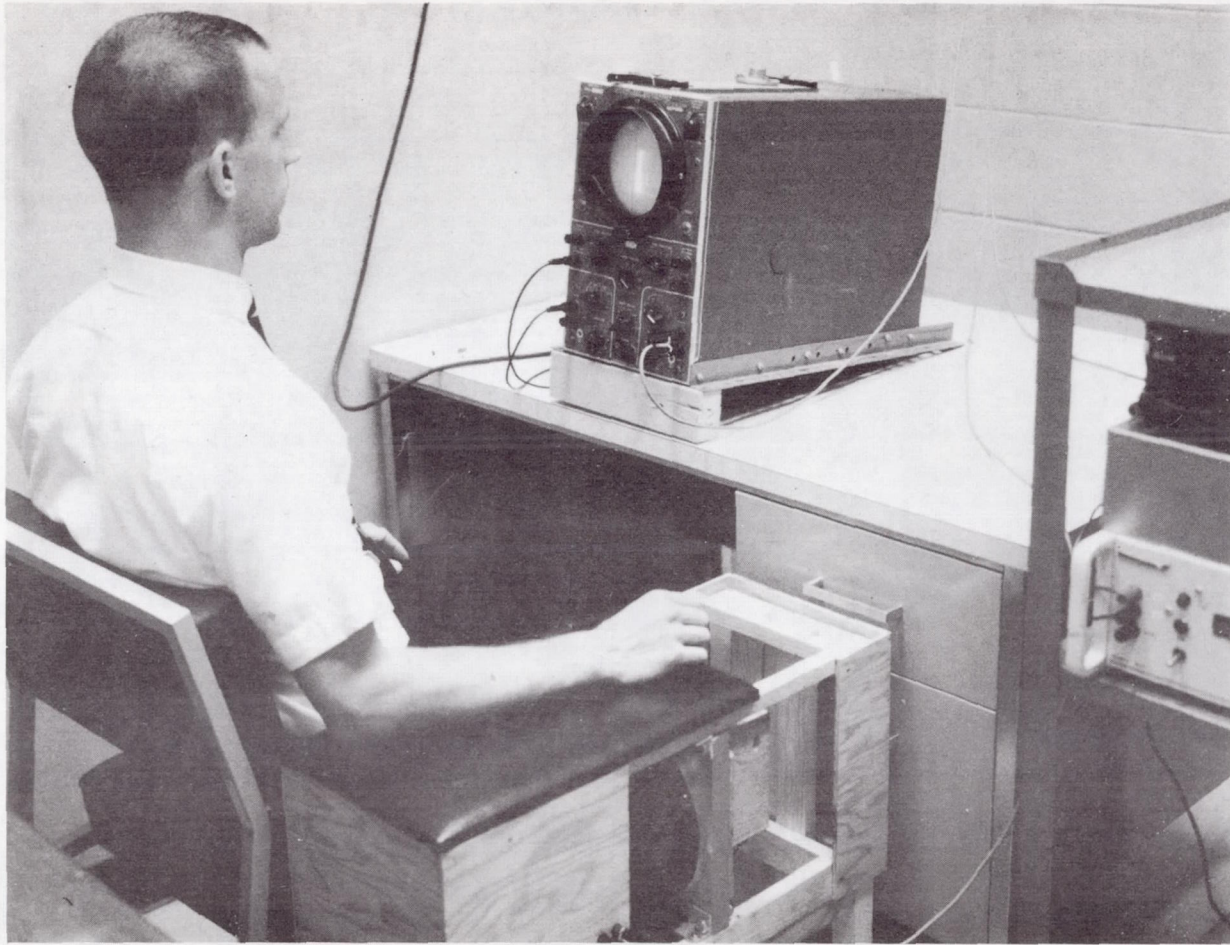


Figure 4.4. Position of Subject and Equipment during Experiment.

for a run was the maximum difficulty attained. With the first order task, the following three modes of control were to be compared:

1. Fixed stick; with the servo-positioned force stick commanded to zero deflection, the subject using visual cues for control.
2. Position feedback; with the stick commanded to move with the displacement of the plant and the subject receiving visual cues for control.
3. Blind; with the stick commanded to move with the displacement of the plant and the subject receiving no visual cues.

With the second order task, the following four modes of operation were to be compared:

1. Fixed stick
2. Position feedback
3. Blind
4. Velocity feedback; with the stick positioned by plant velocity and the subject receiving visual cues.

No separation of the data was to be made according to time of day of the test nor the date of the test.

#### 4.6 Instructions to Subjects

Several of the subjects were quite familiar with the procedures by the time the equipment was ready for runs to be

made, therefore, the instructions were not read to them verbatim. With these subjects, the nature of the tasks were usually discussed in more detail than was contained in the written instructions. All subjects were given, at least, the information contained in the following instructions:

"The stick in the arm rest on your right controls the position of the vertical line on the oscilloscope before you. The line will move either right or left and the control task is to attempt to keep it centered. To move the line to the left, push to the left on the stick, to move the line to the right, push to the right. The line will be centered at the beginning of the run but will start to drift left or right. It will become increasingly difficult to hold the line in the center until the errors become too large and the difficulty will be automatically decreased by the computer. When you are able to keep the line nearer the center, the difficulty will automatically increase again. Your performance is measured by the highest level of difficulty you achieve before the errors signal the computer to decrease the difficulty."

"On some of the runs with the moving stick, the visual display will be turned off and your task will then be to keep the stick centered. You will be informed before each run whether the stick will be moving or stationary and whether the visual display will be on or off."

#### 4.7 Subjects

The subjects were all male graduate students at M.I.T.

with the exception of one, a female college graduate. One subject had private pilot experience, but was not an instrument-rated pilot. Four subjects had had no previous experience in simulator tracking tasks. The task of controlling an unstable system was sufficiently different from previous experience for all subjects that grouping the subjects by prior experience did not seem necessary.

Training of subjects to a high level of competency was not possible, since none could afford to spend the required time away from his own studies.

The subjects cannot, however, be considered completely naive. All male subjects were familiar with control theory and several carefully computed their required control law for each plant. The subjects were all highly motivated to improve their scores. Many were impatient to try again after losing control so rest periods were not always taken between runs.

The scores attained and some of the controller's subjective opinions are included in the following chapter.

## CHAPTER V

### RESULTS OF EXPERIMENT

#### 5.1 Presentation of the Data

A total of 90 runs were completed by seven subjects during the experiment. Three subjects completed 13 runs using the first order critical task

$$Y = \frac{\lambda}{s - \lambda} \quad (5.1)$$

paced by the first order adapter described in Chapter IV. The results are plotted on horizontal scales in Fig. 5.1 and listed in Table 5.1. One set of runs was conducted using a slightly different transfer function

$$Y = \frac{1}{s - \lambda} \quad (5.2)$$

These results are plotted and listed with the rest of the first order data. Results are arranged vertically in Fig. 5.1 by subject and by mode of control with the results of Jex's<sup>9</sup> experiment included for comparison.

The three modes of control used for the first order tasks are as follows:

1. Fixed stick
2. Position feedback



### 3. Blind (position feedback without visual cues)

For one subject L.D., a subgroup is included for runs made with higher adapter limit making possible higher values of the measure of difficulty.

The results of the second order tasks, which were paced by the second order adapter are shown individually for each subject in Fig. 5.2 through Fig. 5.8. A fourth mode of control, velocity feedback was compared with the other three modes using the second order tasks.

The mode of control is denoted by the data point markers. A breakdown of all subjects' scores by control task is given in tables 5.1 through 5.4. These tables list the averages, deviation and number of runs for each subject using the various modes.

Fig. 5.9 shows the average scores attained by the most proficient controller of the subjects tested with results of Smith, Taylor and Day shown for comparison. Fig. 5.10 and Fig. 5.11 are chronological plots of the scores attained on typical sequences of runs. Fig. 5.12 shows the recorded output for a typical run using the position feedback mode. The signals recorded on the four channels are as follows:

1. Force on control stick
2. Error
3. Error rate
4. Difficulty

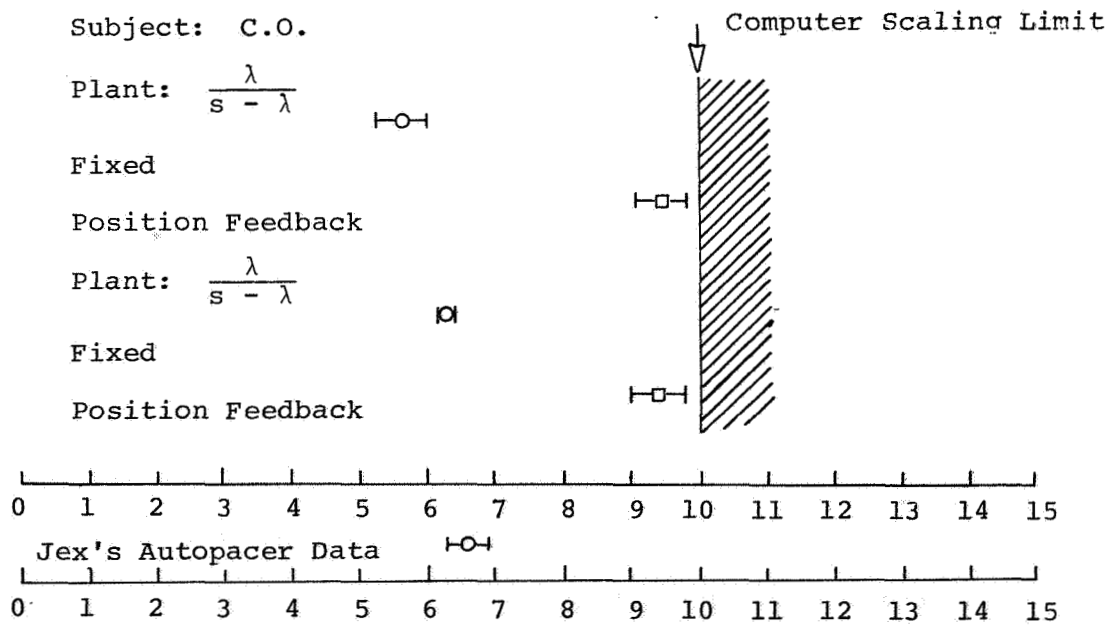
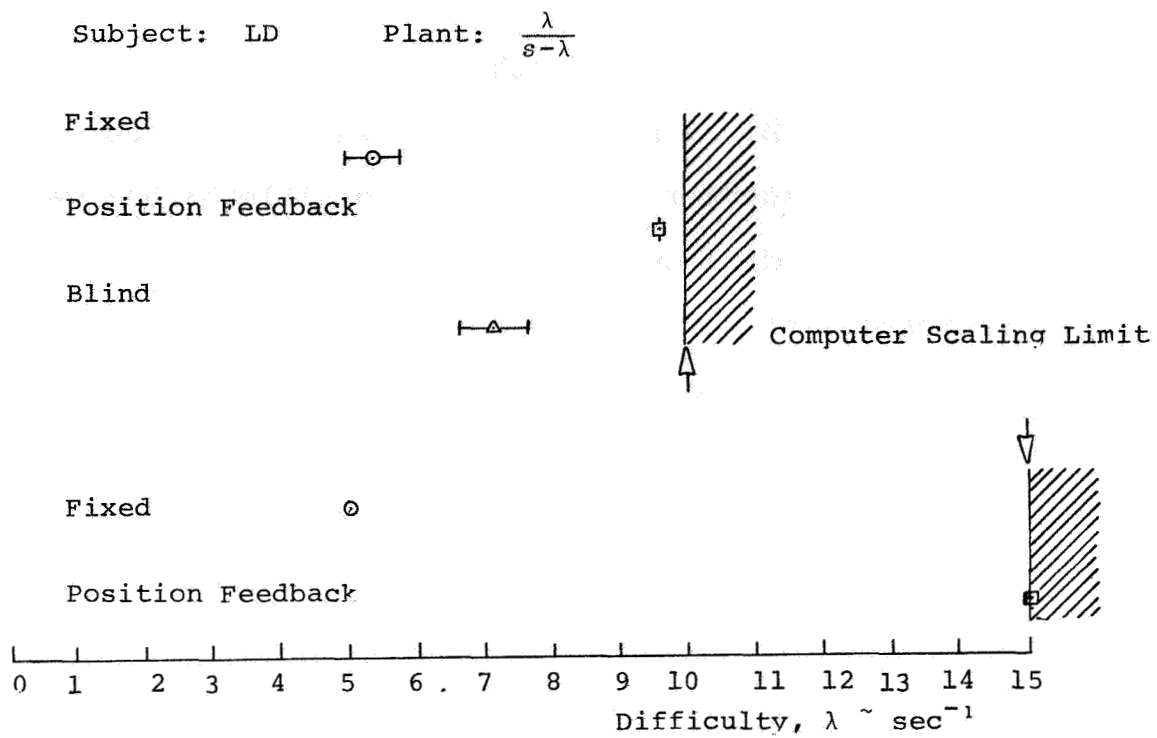
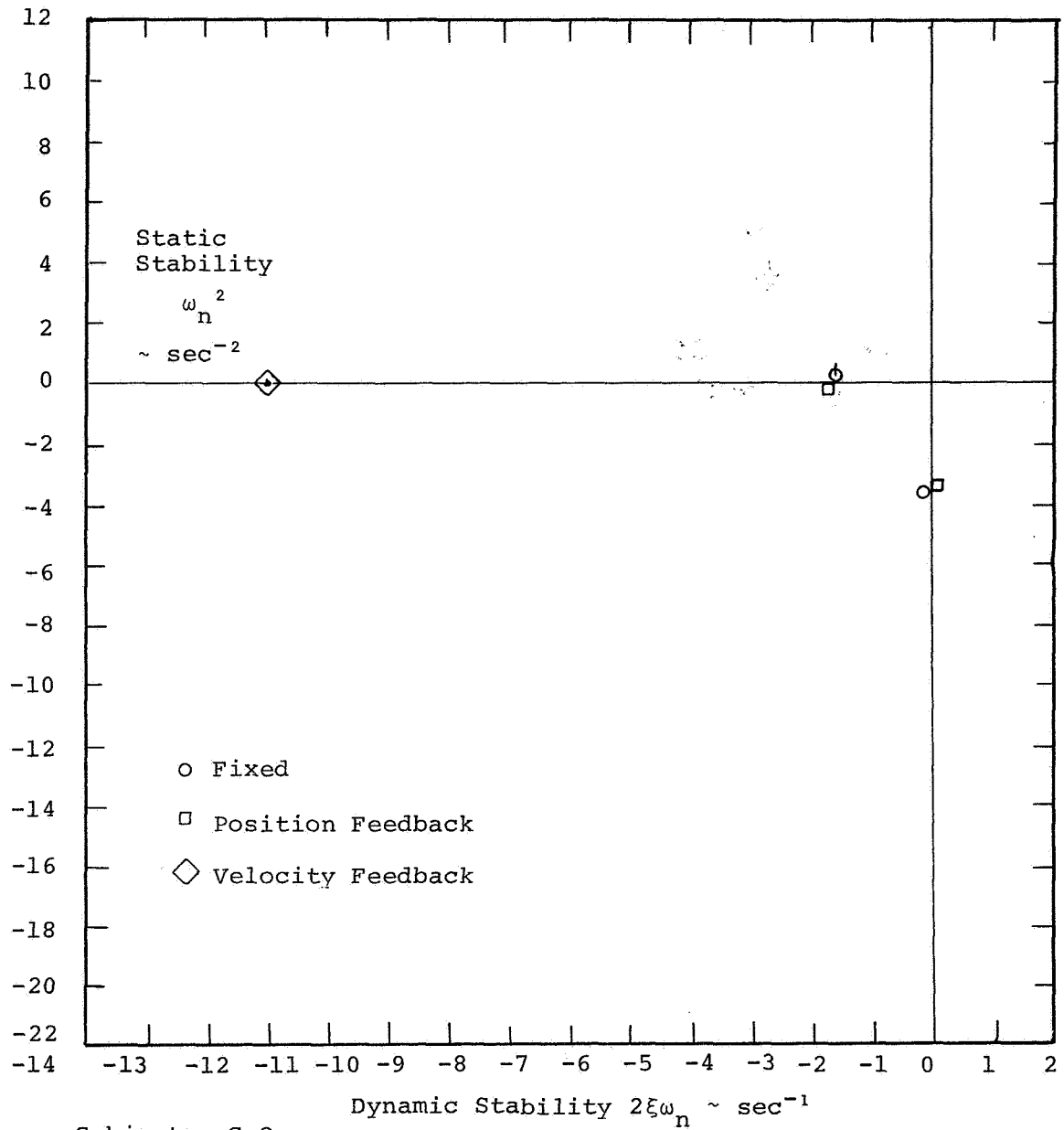


Figure 5.1. Results of Runs Using First Order Tasks

Subject and Task		Fixed Stick	Position Feedback	Blind
L.D. $Y = \frac{\lambda}{s - \lambda}$	$\bar{\lambda}$ $\bar{\sigma}$ n	5.25 .25 2	9.51 .31 3	7.1 .5 2
L.D. $Y = \frac{\lambda}{s - \lambda}$ with L = 15	$\bar{\lambda}$ $\bar{\sigma}$ n	5.0 --- 1	15 ----- 1	
C.O. $Y = \frac{\lambda}{s - \lambda}$	$\bar{\lambda}$ $\bar{\sigma}$ n			
C.O. $Y = \frac{\lambda}{s - \lambda}$	$\bar{\lambda}$ $\bar{\sigma}$ n	6.33 .154 3	9.4 .3 2	

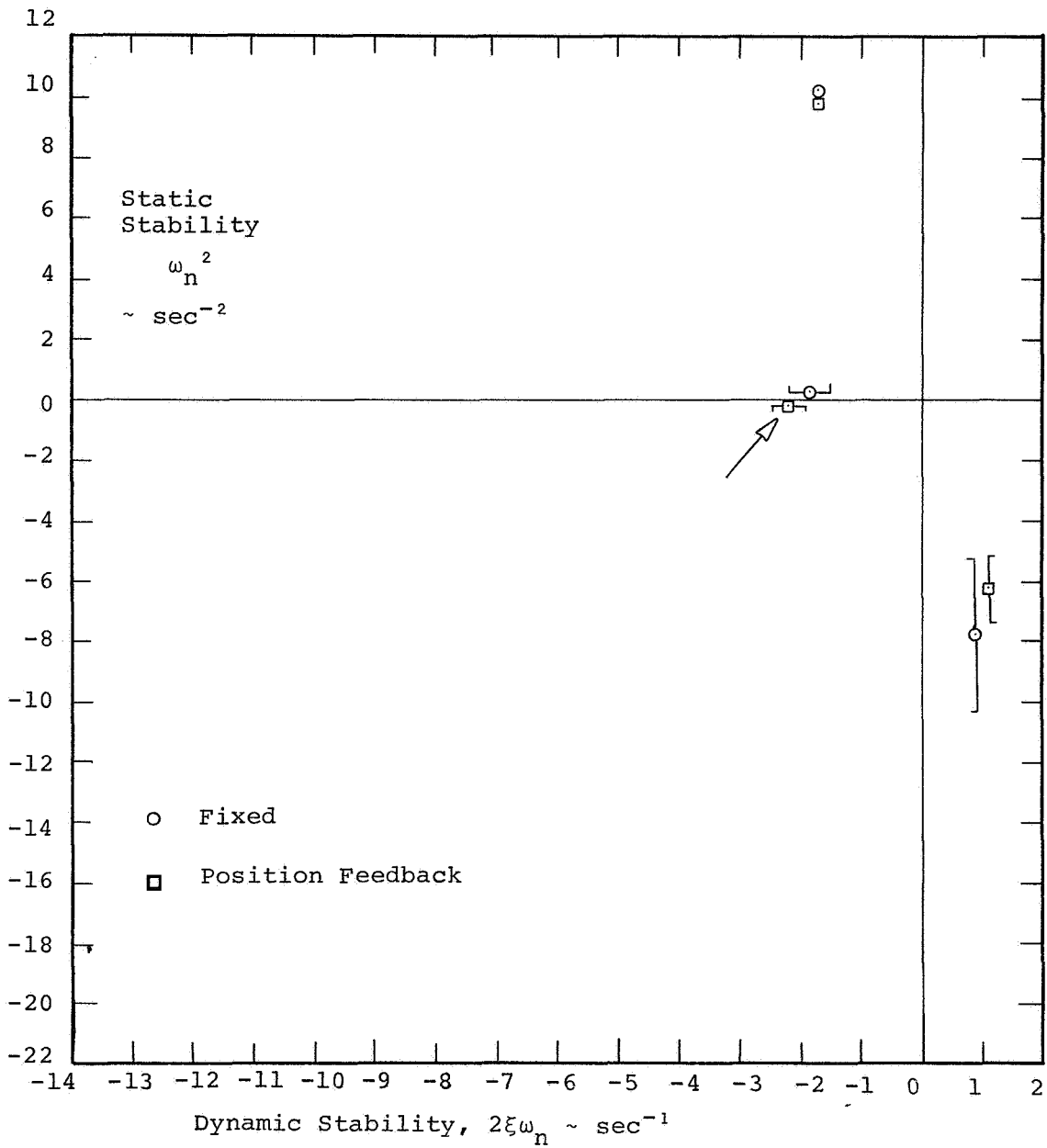
Table 5.1

First Order Task Data



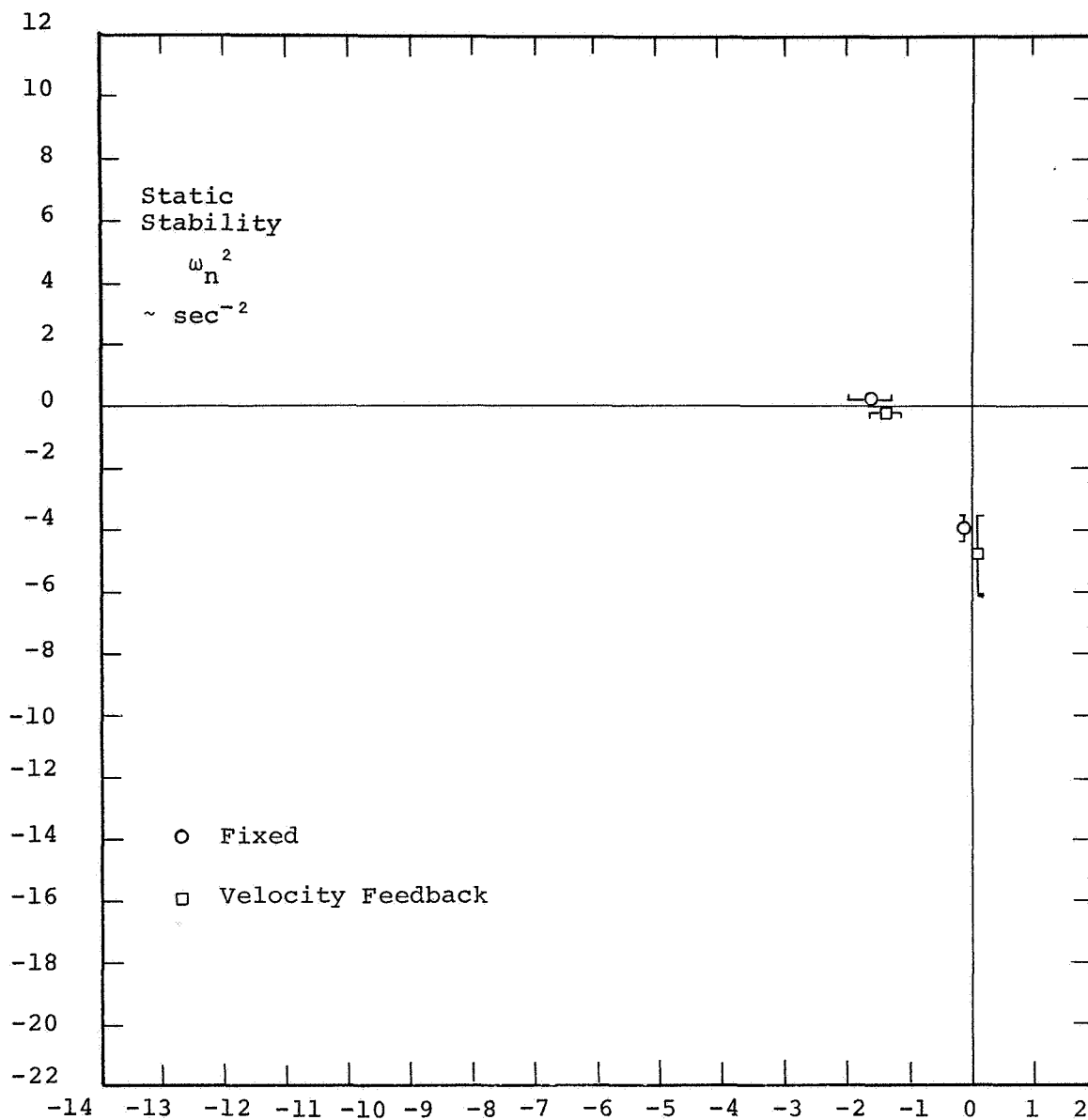
Subject: C.O.

Figure 5.2. Self Pacer Scores for Second Order Task



Subject: J.S.

Figure 5.3. Self Pacer Scores for Second Order Task



Dynamic Stability,  $2\xi\omega_n \sim \text{sec}^{-1}$   
 Subject: D.H.

Figure 5.4. Self Pacer Scores for Second Order Task

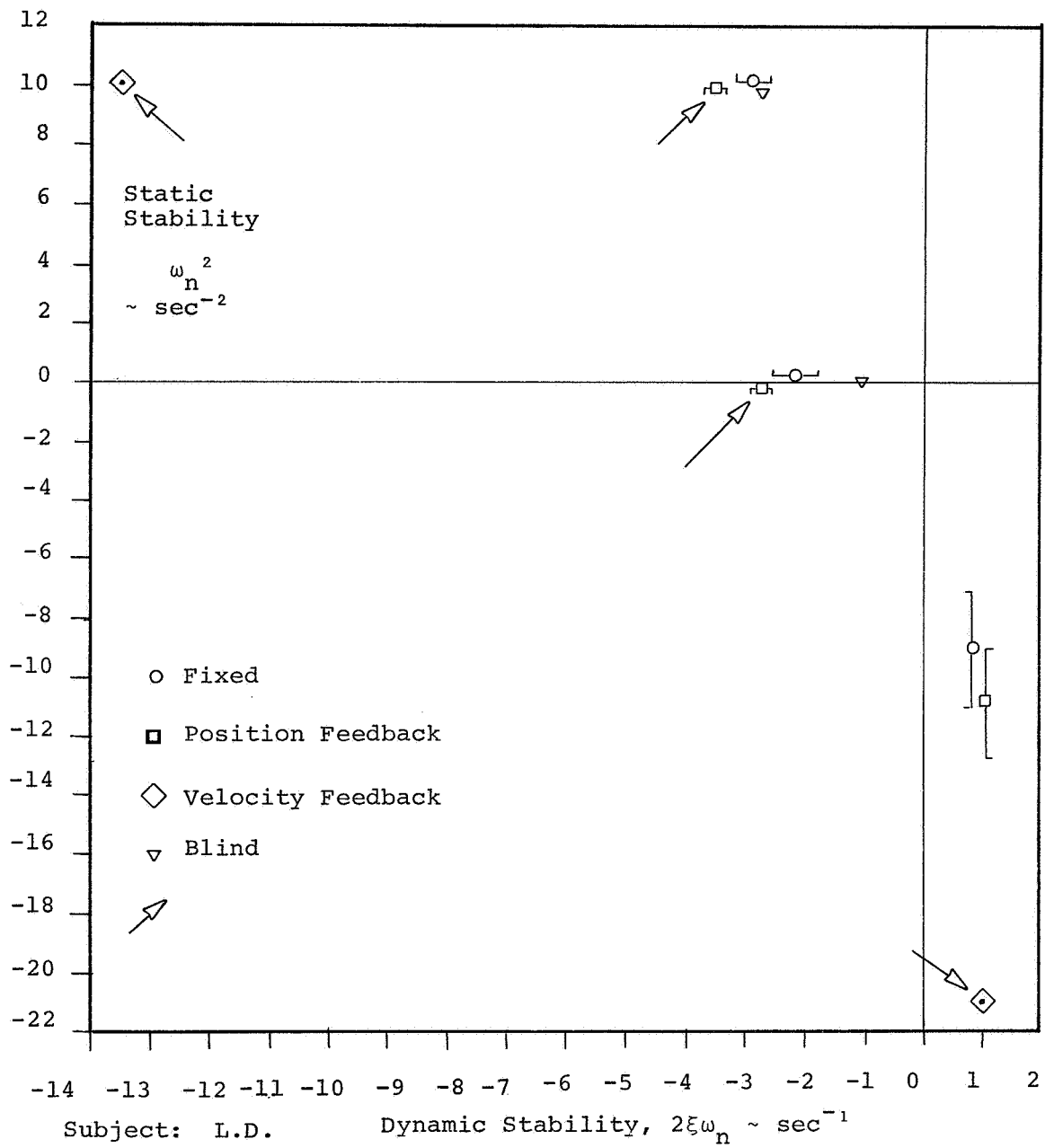


Figure 5.5. Self Pacer Scores for Second Order Tasks

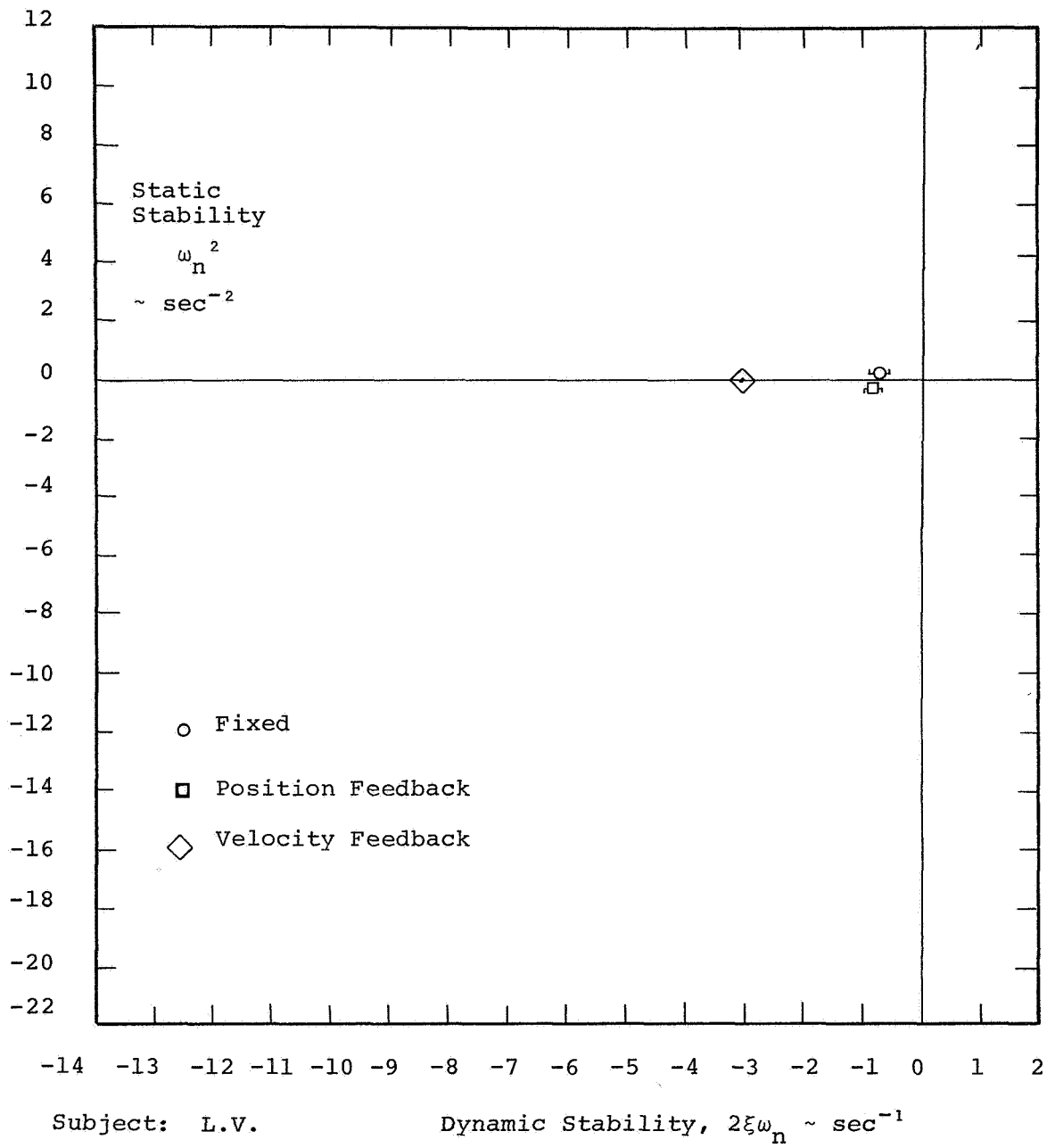
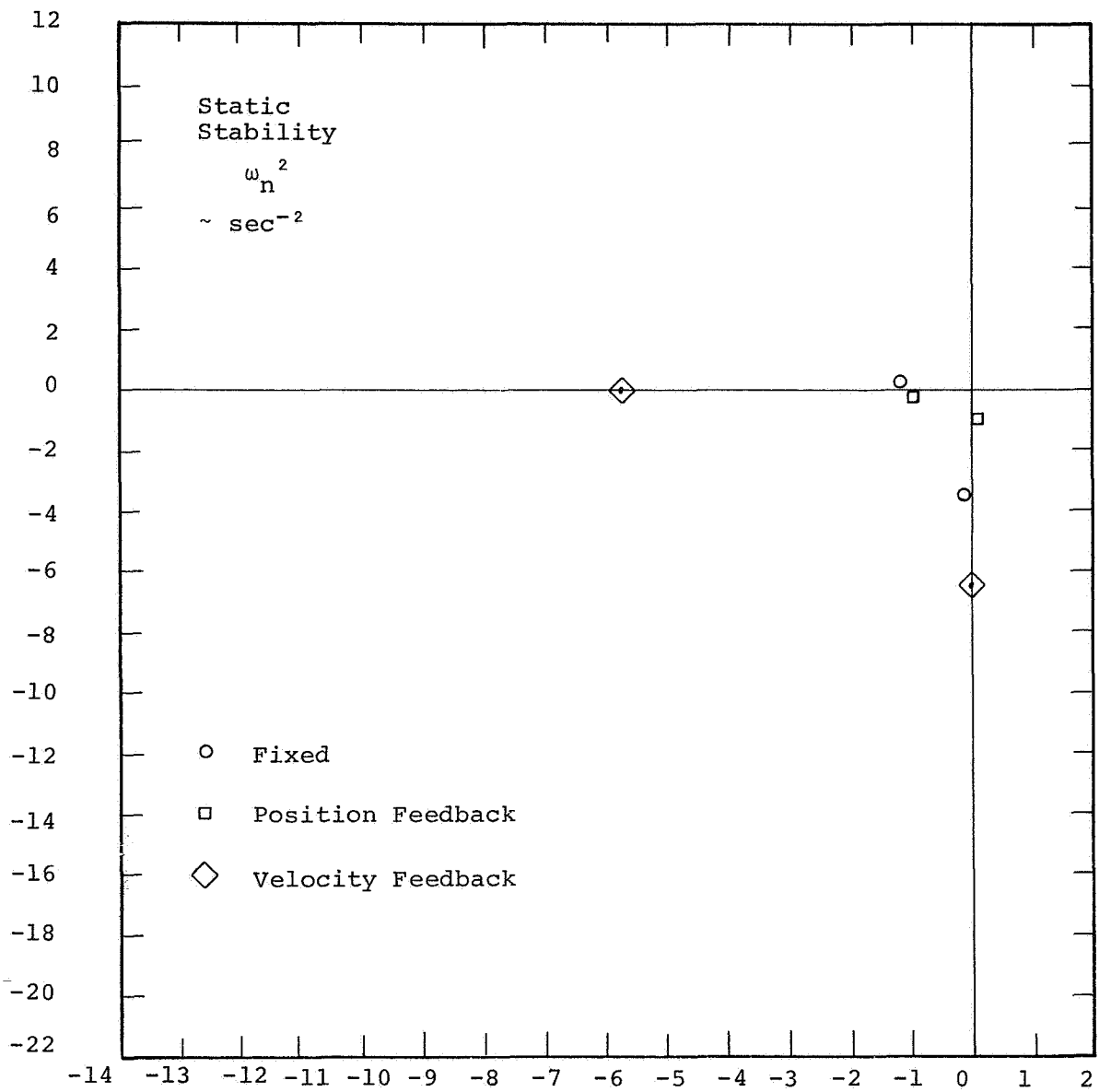


Figure 5.6. Self Pacer Scores for Second Order Task





Subject: J. D.      Dynamic Stability,  $2\xi\omega_n \sim \text{sec}^{-1}$

Figure 5.7. Self Pacer Scores for Second Order Task

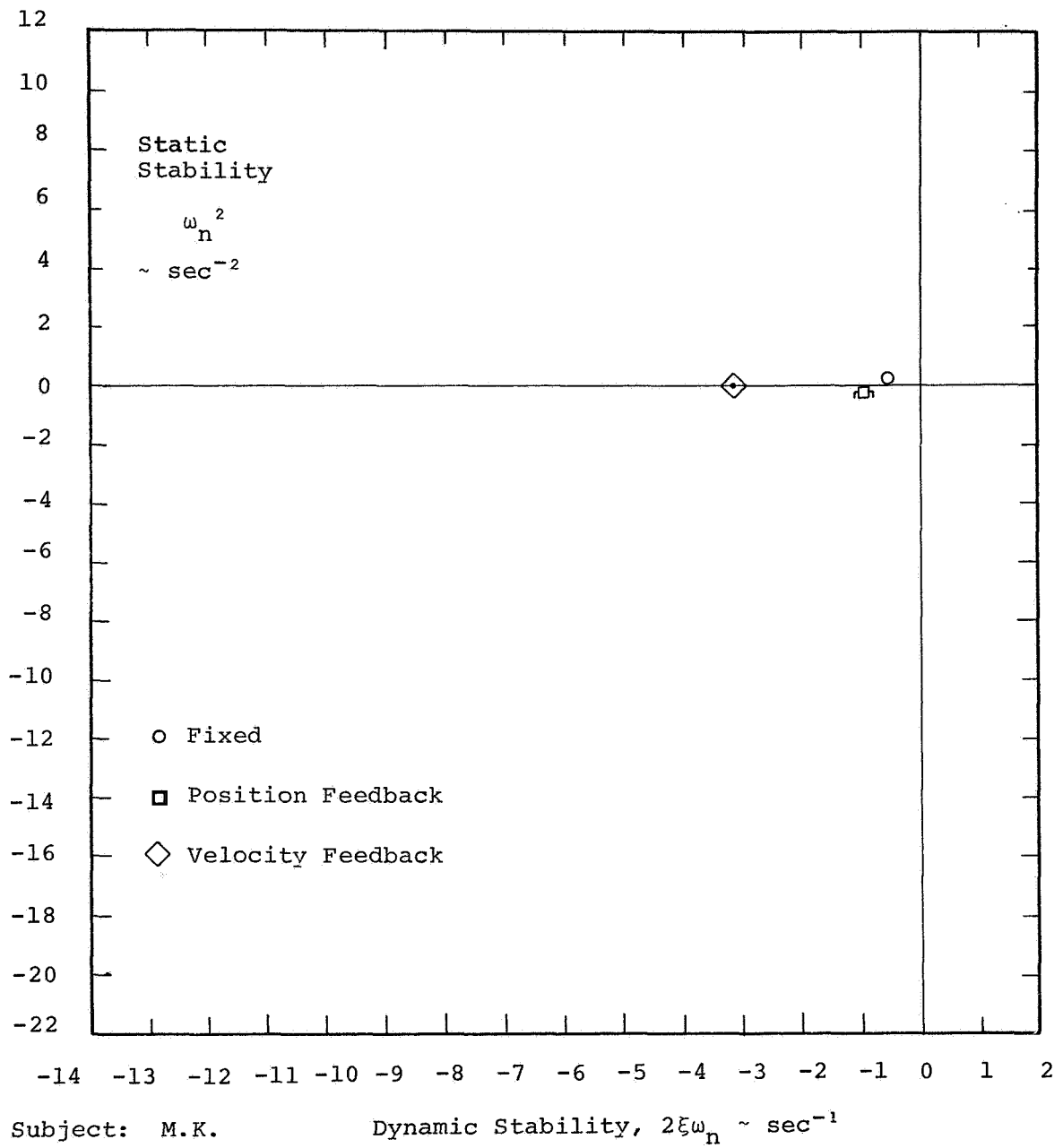


Figure 5.8. Self Pacer Scores for Second Order Task

Subject		Fixed Stick	Position Feedback	Velocity Feedback	Blind
C.O.	$\bar{\lambda}$ $\bar{\sigma}$ n	1.06 0. 2	1.7 - 1	10.5 .7 2	
C.O.	$Y = \frac{1}{s(s-\lambda)}$ $\bar{\lambda}$ $\bar{\sigma}$ n	2.25 .31 2	2.88 .13 3		
J.S.	$\bar{\lambda}$ $\bar{\sigma}$ n	1.85 .34 6	↘ 2.2 .27 5	3.0 0. 2	.75 - 1
D.H.	$\bar{\lambda}$ $\bar{\sigma}$ n	1.62 .38 4	1.4 .10 2		1.0 - 1
L.D.	$\bar{\lambda}$ $\bar{\sigma}$ n	2.1 .43 6	↘ 2.65 .21 2		1.0 - 1
L.V.	$\bar{\lambda}$ $\bar{\sigma}$ n	.66 .05 3	.8 0. 2		
L.V.	$Y = \frac{1}{s(s-\lambda)}$ $\bar{\lambda}$ $\bar{\sigma}$ n	3.6 - 1	3.3 - 1		.6 - 1
J.D.	$\bar{\lambda}$ $\bar{\sigma}$ n	1.12 .17 2	.90 .14 2	5.7 0. 2	
M.K.	$\bar{\lambda}$ $\bar{\sigma}$ n				

Denotes statistically significant improvement over fixed stick

Plant:  $Y = \frac{\lambda}{s(s - \lambda)}$

Table 5.2  
Second Order Task Data

Subject	Fixed Stick	Position Feedback	Velocity Feedback	Blind
J.S.	1.7 - 1	1.7 - 1		
L.D.	2.8 .3 3	3.4 .13 3	13.5 - 1	2.8 - 1

Plant:  $Y = \frac{10}{s^2 - \lambda s + 10}$

Table 5.3

Second Order Task Data

Subject	Fixed Stick	Position Feedback	Velocity Feedback	Blind
J.S.	7.7 2.6 3	6.3 1.1 3		
L.D.	9.0 2.1 6	10.7 1.5 4	21.0 - 1	
C.O.	3.8 - 1	3.7 - 1	16.0 - 1	.5 - 1

Plant:  $Y = \frac{\lambda}{s^2 + s - \lambda}$

Table 5.4

Second Order Task Data

↖ Denotes statistically significant improvement over fixed stick

J.D.	3.5 - 1	1.1 - 1	6.5 - 1	
D.H.	4.0 .49 3	4.8 1.3 2		

Plant:  $Y = \frac{\lambda}{s^2 - \lambda}$

Table 5.5  
Second Order Task Data

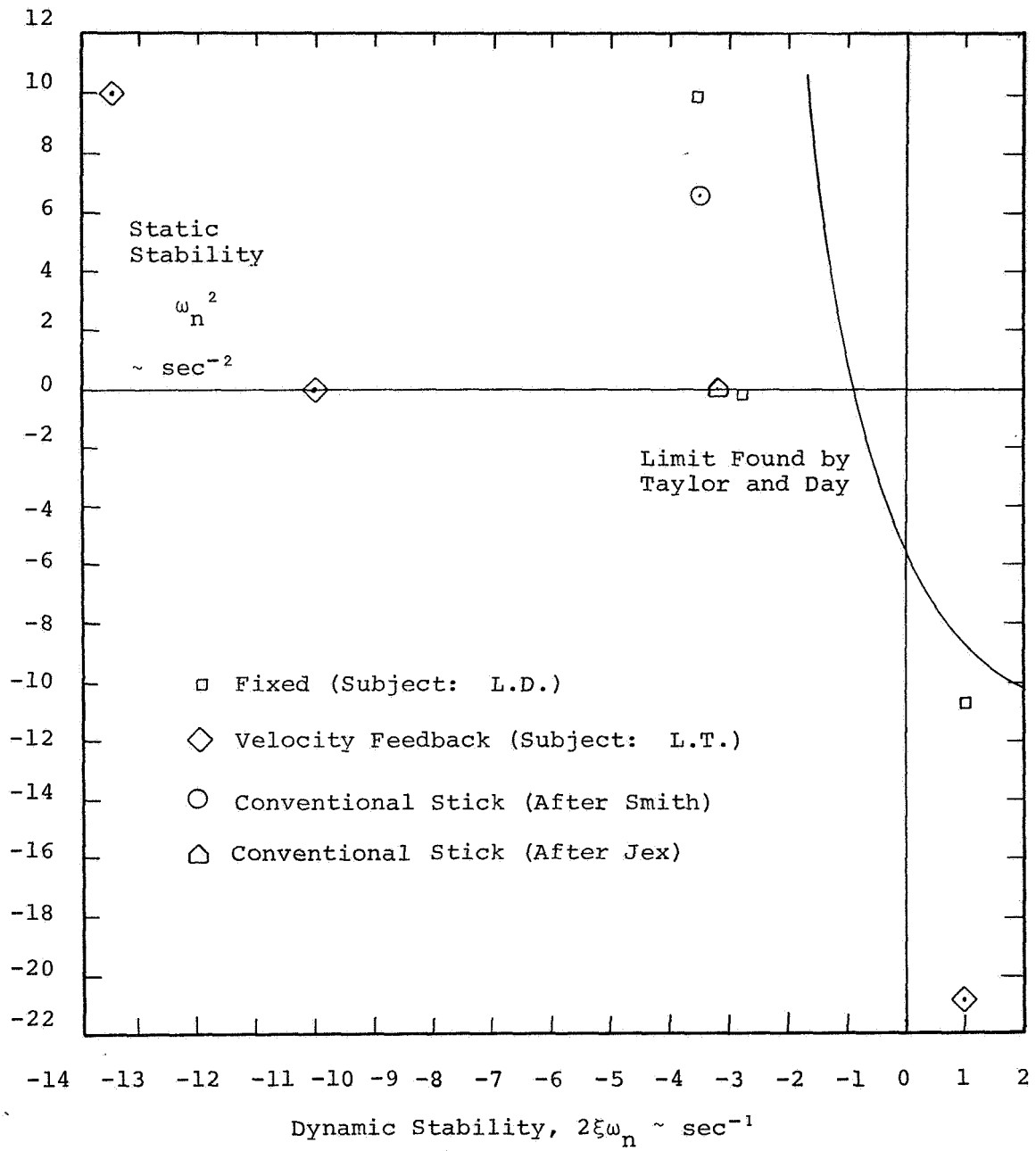
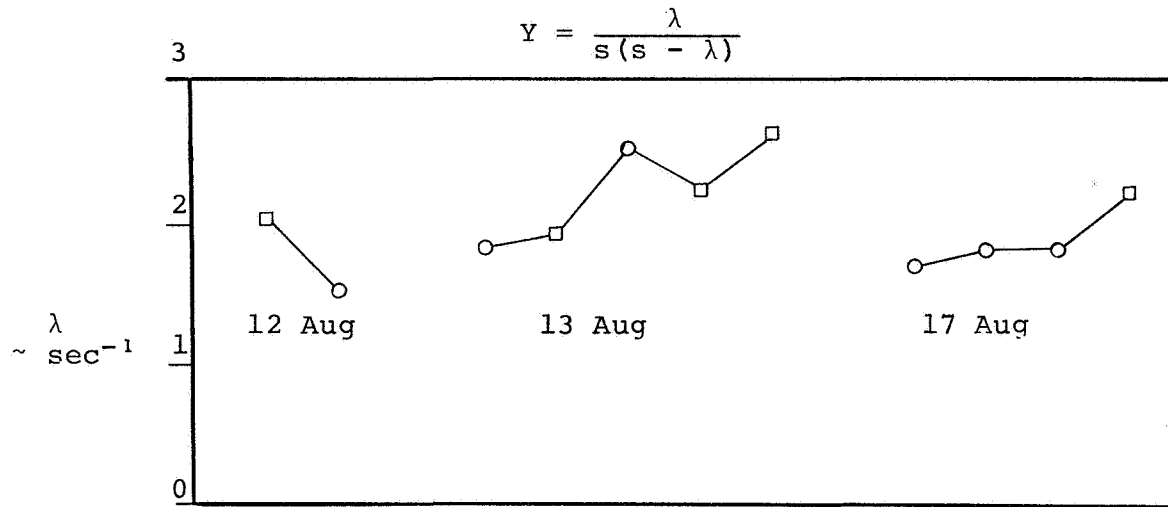
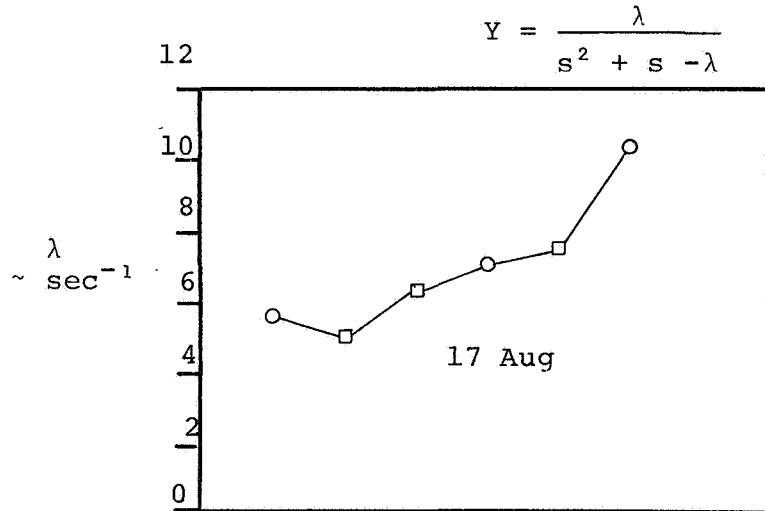


Figure 5.9. Comparison of Self Pacer Scores with Other Experiments



Subject: J.S.

Figure 5.10. Self Pacer Scores for Chronological Sequence of Runs



Subject: J.S.

Figure 5.11. Self Pacer Scores for Chronological Sequence of Runs

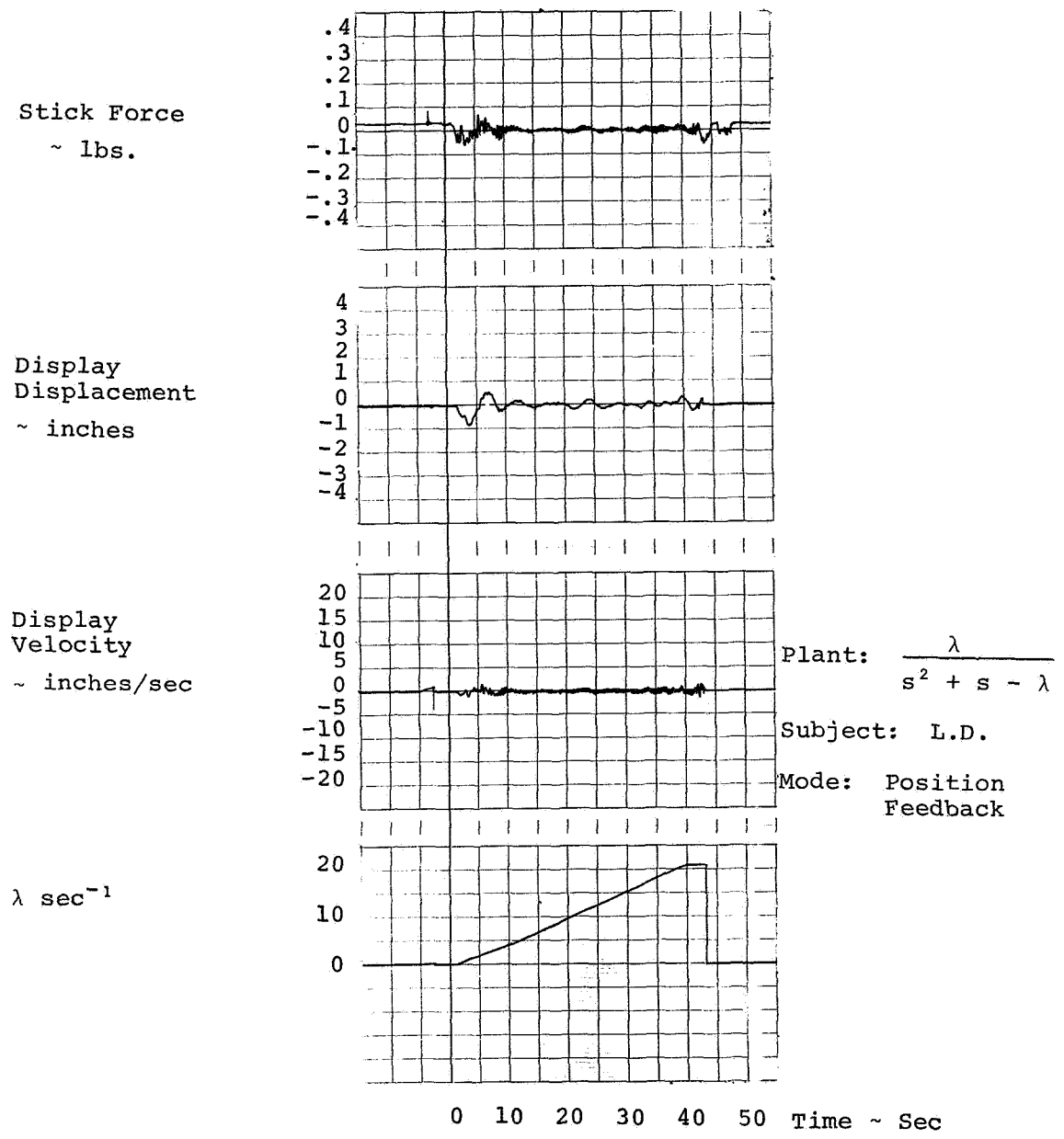


Figure 5.12. Oscillograph Recording of Typical Run



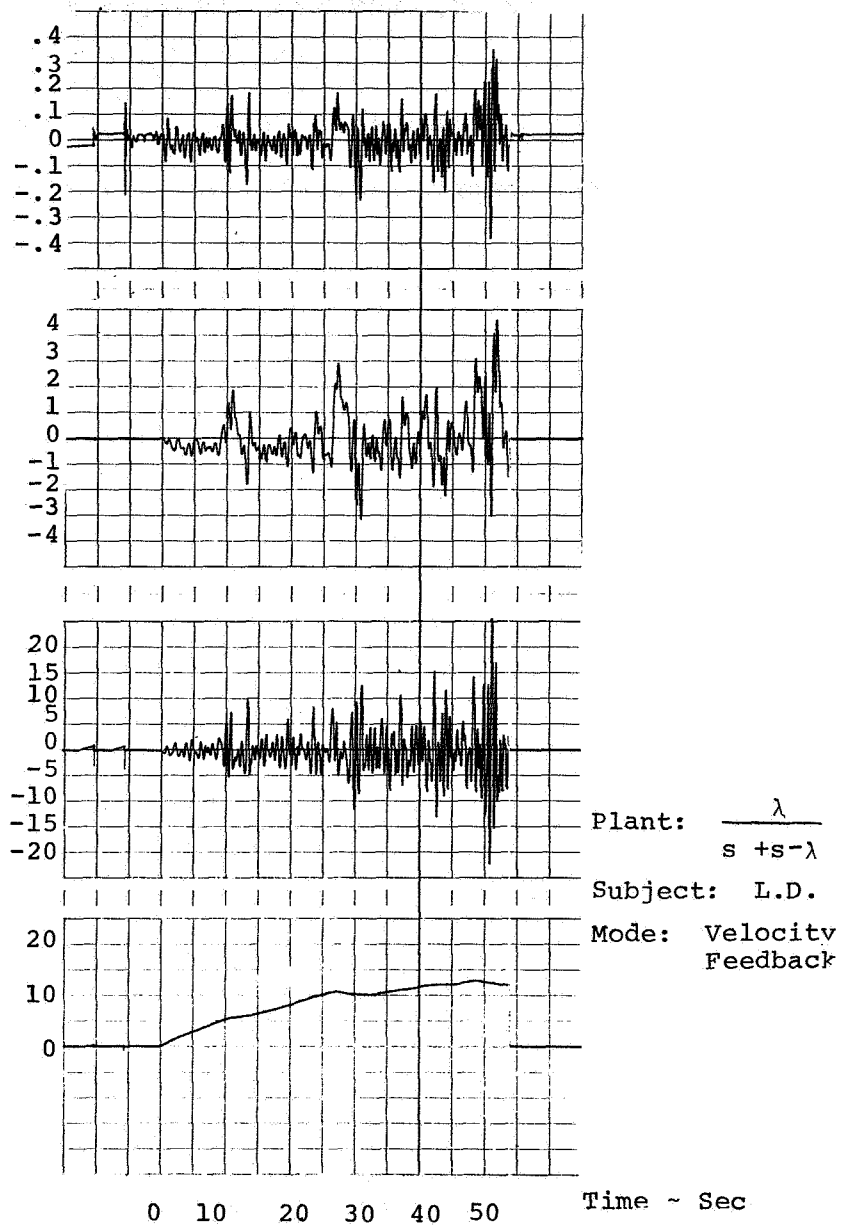


Figure 5.13. Oscillograph Recording of Typical Run

Fig. 5.13 is a recording of a run by the same subject using the same task, but with velocity feedback. A significant fact not expressed in the data is that in every trial using velocity feedback, the difficulty was limited by the scaling of the computer or the scaling of the recorder and not the ability of the controller. In each task, the difficulty steadily increased until the run was terminated. The deviation for these runs was computed but has no real meaning because it depends on how soon the run was stopped. When the recorder was set for high enough values of  $\lambda$ , the runs were allowed to go until the output amplifier of the adapter was saturated, otherwise the run was stopped when it was apparent that the pen recording values of  $\lambda$  would go off scale.

## 5.2 Discussion of First Order Data

Time did not allow a complete set of runs for all subjects with all the proposed tasks. The first and second order critical tasks were considered to be primary tasks for the investigation. The other transfer functions were used when time permitted. Runs in which the equipment malfunctioned or was found to be out of adjustment are not included in the data so that some of the tests sometimes yielded less than the desired number of runs. However, significant results were obtained which showed that the force stick positioned by feeding back position of a first order plant

or velocity of a second order plant had a definite superiority over the fixed stick.

The superiority of the position feedback stick for controlling the first order plant is shown in Fig. 5.1 by the high scores that all subjects were able to attain. All scores obtained with position feedback were over  $9 \text{ sec.}^{-1}$ , much higher than their fixed stick scores and higher than the average of 6.2 found by Jex.<sup>9</sup> In addition, the scores for the variable position stick were limited by the computer scaling in that the maximum multiplier value would yield a value of  $\lambda = 10 \text{ sec.}^{-1}$ . After the scaling was altered to allow a maximum of  $\lambda = 15$ , one subject, L.D., attained a score of  $\lambda = 15$ , indicating that his score with position feedback mode was limited by computer scaling and not by proficiency. To check that the change in scaling would not affect the performance with the fixed stick, another run was made by L.D. and the score was  $\lambda = 5$ , somewhat lower than the previous score of  $\lambda = 5.5$  obtained with the lower scaling. The subjective comment by L.D. was that he could increase his score merely by gripping the stick more firmly instead of attempting to react to stick motion. The fact that the score was limited only by the scaling of the test equipment contributed to the early realization that the variable position stick was superior for the first order task so the principal effort was directed to the second order tasks.

As shown in Fig. 5.1, a difference was noted in the scores using the plants

$$Y = \frac{1}{s - \lambda} \quad (5.1)$$

and

$$Y = \frac{\lambda}{s - \lambda} \quad (5.2)$$

This had not been expected since McRuer, et al, have shown that a human operator can compensate for a wide range of gain. The reason for the higher scores with the plant was that the lower forward path gain reduced the scaling of the position error,  $\epsilon$ , relative to the critical error,  $\epsilon_{crit}$ . This allowed  $\lambda$  to increase to higher values before the smoothed error exceeded  $\epsilon_{crit}$ . A discussion of the scores for the position feedback mode and the blind mode is included in the discussion of second order data.

### 5.3 Discussion of Second Order Data

For determining statistical significance, the deviation of scores was assumed to be equal for all subjects but to vary with control task. All subjects had less deviation in their scores using the position feedback stick than they did using the fixed stick. The reason for this is unknown. To make conservative estimates of the deviations, numbers were selected that were slightly smaller than the highest deviations observed. These estimates are given

in Table 5.6.

Table 5.6

ESTIMATE OF DEVIATION FOR SELF-PACER SCORES

	<u>Static Instabilities</u>	<u>Dynamic Instabilities</u>
Fixed Stick	2.2	.38 sec. <sup>-1</sup>
Position Feedback	1.3	.24 sec. <sup>-1</sup>

These figures were used in equation 4.14 to determine the statistical significance of observed difference in averaging scores.

A comparison of the four modes of controlling, fixed stick, position feedback, velocity feedback and blind can best be seen by examining Table 5.2 through Table 5.5. Comparing position feedback to the fixed stick, five of seven subjects obtained higher average scores with the position feedback and two of these can be claimed, with 95% confidence, to represent a significant difference. Two subjects attained higher scores using the fixed stick, though the differences were not statistically significant.

Fig. 5.1 shows the typical trend of scores for sets of runs comparing fixed stick with position feedback. Except for the two runs on the first day, the scores show

marked improvement as the subject acquires proficiency. A day to day difference in proficiency can be seen to contribute to the variance of the data. This day to day variance was also observed by Jex.

Fig. 5.11 shows a set of runs performed on a single day. Again, the subject's second run was not as good as his first, but his proficiency steadily increased thereafter. In future experiments, it would be desirable to allow several practice runs and take all data for a subject on the same day.

The position feedback mode appears to be superior to the fixed stick but there are factors which may have distorted the data somewhat. For one subject the runs yielding useful data did not occur in a strictly alternating sequence. The average indicated a significant superiority of the position feedback mode over the fixed mode, but Fig. 5.10 shows that the position feedback trials were located higher on the learning curve.

Another factor was the awareness most subjects had that better performance on the position feedback would imply a "successful experiment" and may have, unintentionally, increased their efforts with the position feedback. Further experiments would have to include more disinterested subjects.

Finally, most of the subjects felt that the moving stick did not really help them, and in the case of two of the subjects, it did hinder them to the extent of giving them

slightly lower scores. More experimentation is necessary to determine if a position feedback stick is generally superior to a fixed stick, but the position feedback stick can aid some controllers.

The effect of using position feedback without visual cues cannot be measured with a self pacer so very little data was taken for this mode. In both the first and second order experiments, the subjects low frequency drift due to lack of precise knowledge of the center point caused the adapter to reduce the difficulty even though the subject had stabilized the plant to the extent that the velocity was near zero. The center point can be sensed without visual cues for tasks with negative static stability but in searching for the center, the subject allows the error signal to integrate and the self pacer reduces the difficulty, making the center point more difficult to detect. When the plant has been reduced to neutral stability, the center can no longer be detected and, as in the case of pure dynamic instability, the subject must depend on his memory to locate the center point. Either a task of preset difficulty or an autopacer are needed to determine the value of position feedback without visual cues.

The stability limits found in this experiment with the fixed stick mode are compared with limits found by other investigators in Fig. 5.9. A limit point found by Smith<sup>11</sup> is closely aligned with the limits found in this

experiment. The controllability limit found by Jex<sup>9</sup> indicates a higher limit and the limit line found by Taylor and Day<sup>10</sup> indicates a lower limit. The difference is primarily due to the difference in criteria used by the different investigators. Jex used the difficulty at which control was lost, this experiment used a difficulty at which the operator could maintain control with an average of the error below a specified criterion. Taylor and Day used, as the limit, the difficulty at which the peak errors could be maintained within a small margin, thus obtaining a lower limit.

The most important result in the second order data was the very high scores attained by all subjects who made runs using the velocity feedback. The diamond shaped data point markers in Figures 5.2 through 5.8 represent the points at which the runs were stopped, not the controllers limitations. The recording of the controller force in Fig. 5.13 shows that the effort required to control with this mode is very small and the recording of error and error rate show much smaller values than those for the positions feedback in Fig. 5.12. The chart recordings for fixed stick were indistinguishable from those for position feedback so Fig. 5.12 can be considered a typical recording of both position feedback and fixed stick modes.

At the higher difficulties, the force signal appears to be oscillatory at about 20 cycles per second or more.



This is in excess of the fastest recorded finger movement in skilled piano playing which is quoted by Gibbs<sup>1</sup> as 15 cycles per second. It must be concluded that the force signal from the control stick is not a result of conscious decisions or reflexes by the controller.

The most likely explanation is that the controller's hand is merely providing the reaction force for a stabilizing signal travelling through the mechanical link of the servo positioned stick. The velocity feedback signal provides the necessary lead for second order plant and the operator need only grip the stick tightly to direct the signal to the plant. For the first order plant, the velocity and displacement are proportional and the signal through the tightly held stick is, again, of the proper phase for stabilization.

A question remains, however, as to why the second order static instabilities are not easily stabilized by the position feedback mode. Transmission of this signal with sufficient gain through the stick should stabilize the plant. A possible explanation is that whatever time delay is incurred in moving the stick, compressing the flesh of the controller's hand and bending the force sensing element, causes a phase lag in the signal to the plant. If the original signal is of the proper phase to oppose displacement, as it is in the case of position feedback, the lag will yield a negative damping component of the signal and

the system remains unstable. In contrast, if the original signal is in phase to oppose velocity as it was with velocity feedback, the lag will yield a component of the signal that contributes to static stability and the gain can be increased until the system reaches critical damping.

To verify the nature of the stabilization with the variable position stick, the stick was blocked in place for runs with both first and second order critical tasks. The position feedback mode for the first order task gave essentially the same results as holding the stick by hand without visual cues. The only difference observed was that the frequency of the small oscillations of the plant and stick combination was higher, since the blocks gave the stick more rigid positioning and reduced the delay in transmitting the signal to the plant. Drift occurred, as it did in the blind mode, because the blocks did not exactly center the stick. As the plant drifted, the adapter reduced the instability to zero.

Blocking the stick to control the second order critical task gave a similarly fast but much more intense oscillation. Blocking the stick in place was not attempted with the static instabilities.

It appears that the neuromuscular system is not able to derive usable velocity cues from the motion of the position feedback stick. Any improvement of the position feedback mode over the fixed stick mode is, most likely,

due to the reduction in time delay caused by the stick moving toward the side of the controller's hand that should, correctly, be pushing on the stick. Thus the operator does not derive a cue from each motion of the stick, but, in the case of velocity feedback, he can determine from stick motions the amount of reaction force necessary to provide sufficient damping for stability.

#### 5.4 Discussion of Self Pacer

The self pacer proved to be an adequate testing device; it gave as low a variance for most of the experimental results as had been assumed. Since the effect of learning appeared to be the major contributor to the variance, the self pacer might yield more precise results than an auto-pacer.

The first order mechanization of the pacer described in Chapter 4 was not satisfactory. The second order pacer worked quite well, although some subjects lost control of the plant, occasionally, when operating with the stick driven by the plant position. This caused damage to the stick's actuating mechanism but the loss of control might have been avoided by allowing the difficulty to decrease at a higher rate when errors were large.

Compared with the autopacer used by Jex, the self pacer yielded scores with the same variance and afforded the subjects more training time during each run. Thus, the self pacer could also be used as a training device

to acquaint subjects with the control task for further testing with either the self pacer or auto pacer.

### 5.5 Applications

As discussed in section 5.3, the effect of the velocity feedback positioning of a force sensing stick is to place the operator in series with a rate stabilization signal. While the operator maintains his grip on the stick, the circuit is completed. Rate stabilization is normally done by completing the circuit without the operator. This is highly desirable for vehicles that have little or no stability. However, there are several situations in which a force stick positioned by a rate signal could enhance a human operator's ability to monitor and control vehicles which have already been stabilized.

Such a situation is a rapid or unexpected change in vehicle dynamics, which would require a change in the rate feedback. Docking and undocking maneuvers by space and underwater craft, changes from coasting to thrusting flight and jettisoning of external stores can change the required amount of damping. With a rate positioned force stick, the operator would automatically provide the change, maintain control and could adjust a gain setting in the stability augmentation as time permitted.

Improper fuel transfer, a shift of cargo or failure of some external stores to jettison can render an aircraft unexpectedly unstable. A roll rate and pitch rate feedback

positioned force stick would enable the pilot to maintain control. Pilot induced oscillations would be eliminated. Also, the added source of motion cues could aid in spin recovery or in instrument flying.

The "hard over" type of failure giving asymmetrical thrust in a hovercraft or a VTOL aircraft is another critical situation in which the velocity feedback to the stick would enable the operator to initiate quickly the correct compensation. The pilot's reflex to hold the stick in position would command the correct control action.

It does not appear that the control stick positioned by plant displacement would be useful in as many situations as the stick positioned by velocity. The difference in scores showed a possible small improvement over an isometric stick but the results were not conclusive. Also, the displacement signal is difficult to obtain in a vehicle, requiring an inertial coordinate system to be maintained, on board, with very low drift. Another disadvantage is the limitation of the vehicle displacement by the allowable displacement of the control stick. A full 360° roll would not be possible unless a control wheel form of manipulator were used.

In contrast, a velocity signal is easily obtained from rate gyros, which are inexpensive and reliable. With the velocity feedback mode, the customary stick type manipulator can be used without limiting the rotation

of the vehicle and, in fact, the customary feel of conventional aircraft control with roll rate and pitch rate proportional to stick displacement is retained.

Both the velocity and displacement feedback systems would have less reliability than a force stick but would probably be comparable in reliability to present control sticks that have force sensors for an auto-pilot disconnect function.

From the results of this experiment, it appears that the rate positioned force stick can be a useful controlling device and further investigation should be pursued. Experiments in which the controlled element receives step inputs or undergoes step changes in transfer functions would test the stick's performance in situations of sudden changes in the vehicle's configuration. The use of this control stick for control of moving base simulators and incorporation into multitask simulators would test its merit as an additional information path, supplementing the visual and vestibular inputs to the controller.

## CHAPTER VI

### CONCLUSION

#### 6.1 Conclusion

It was found that the first order critical task can be stabilized by positioning a force stick with plant displacement. For the second order instabilities, the stick positioned by plant displacement gave only marginal improvement due, most likely, to a reduction in effective delay time.

It appears that the derivative information from the muscle stretch is not useful to the central nervous system in determining the velocity of the controlled plant. The results of feeding back velocity, however, show that highly unstable second order plants can be controlled quite easily by the human operator using the variable position force stick. The large improvement is obtained by a combination of two effects. The necessary lead is produced in the mechanization so the operator needs only to act as a gain and the delay time is reduced to almost zero since the mass of the controller's hand and the rigidity of his arm will cause a reaction force on the stick without requiring a reflex action or a decision by the operator. It is concluded that the most beneficial way found to use state

variable feedback for kinesthetic cues to aid the operator in controlling a second order instability is to position the stick in proportion to position rate. In vehicular control, an angular rate signal can be readily obtained from rate gyros which are inexpensive and reliable. Using angular rate to position the control stick does not, in any way, decrease the desirability of feeding the rate information directly into an automatic stabilization unit. This should be done whenever possible. However, this experiment has shown that if the rate signal is also used to position a force stick, the human operator can act as a back-up in controlling vehicles which are otherwise impossible to control manually. Since this is made possible by placing the operator at a point in the control loop where the change in gain caused by increasing his grip can stabilize the vehicle, an opportunity is presented to make effective use of the adaptability of the human operator. As a nearly instantaneous gain changer, he can exchange stability and maneuverability at will.



## APPENDIX A

### Power Regulator

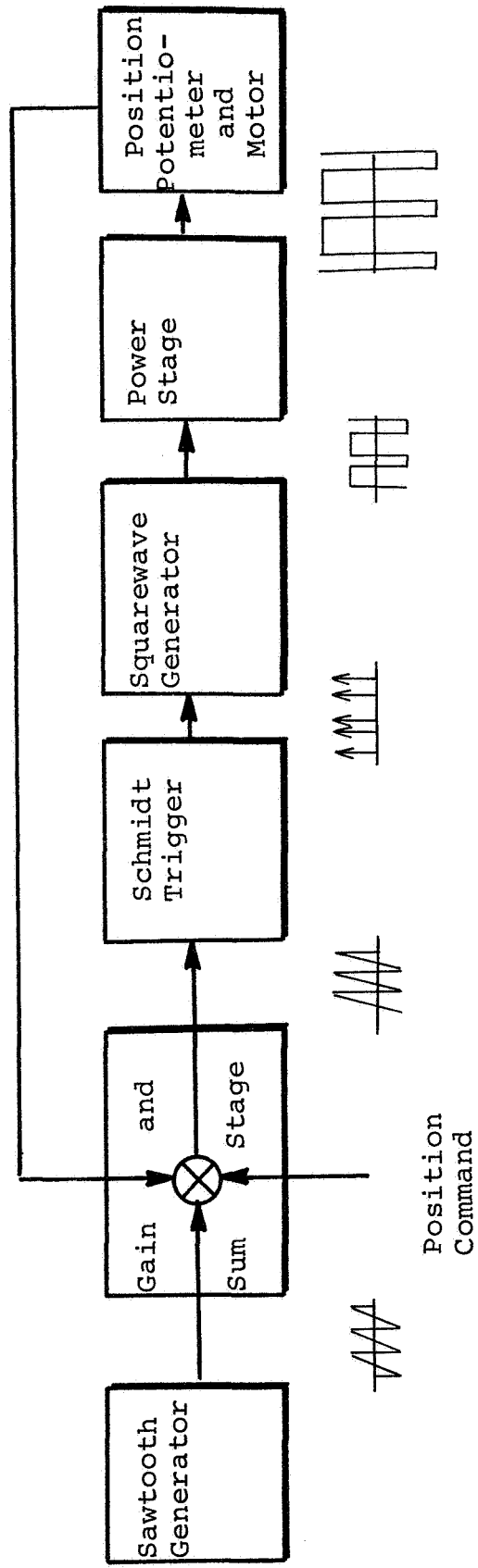


Figure A1. Block Diagram of Position Servo with Pulse Length Modulated Power Regulator



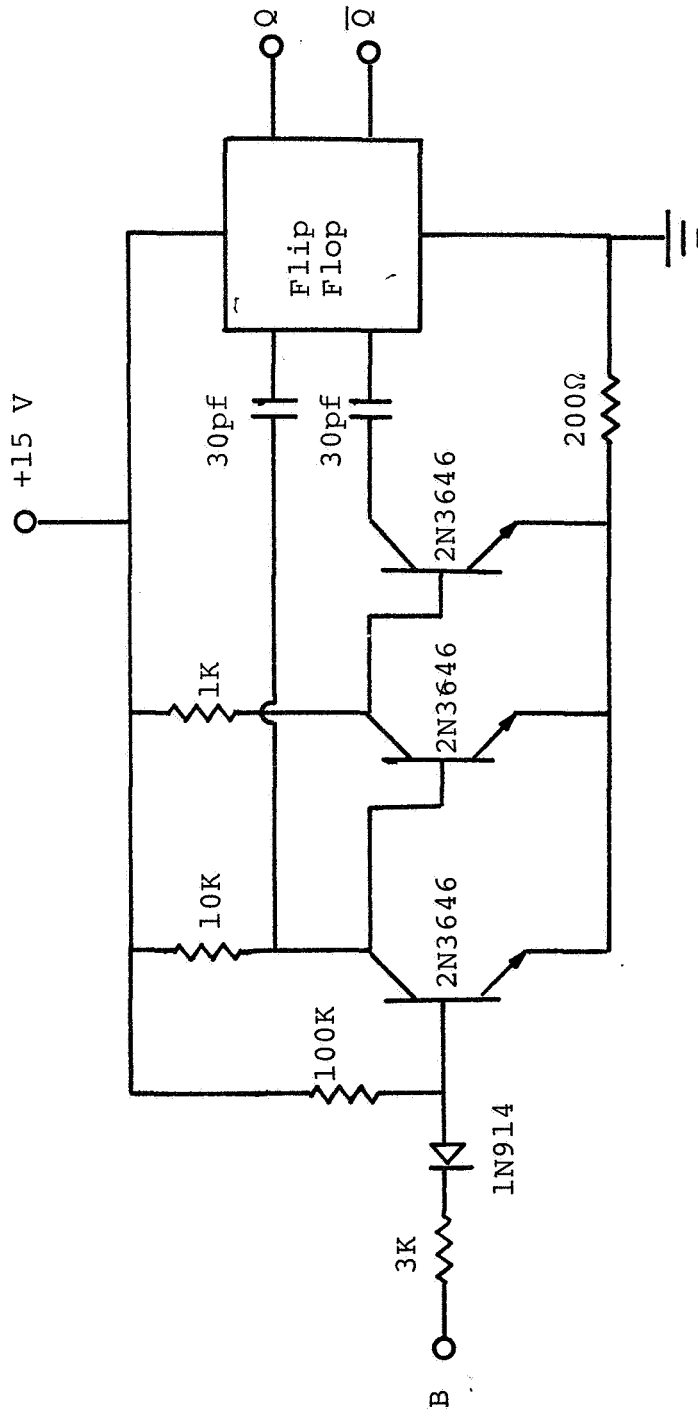


Figure A3. Square Wave Generator

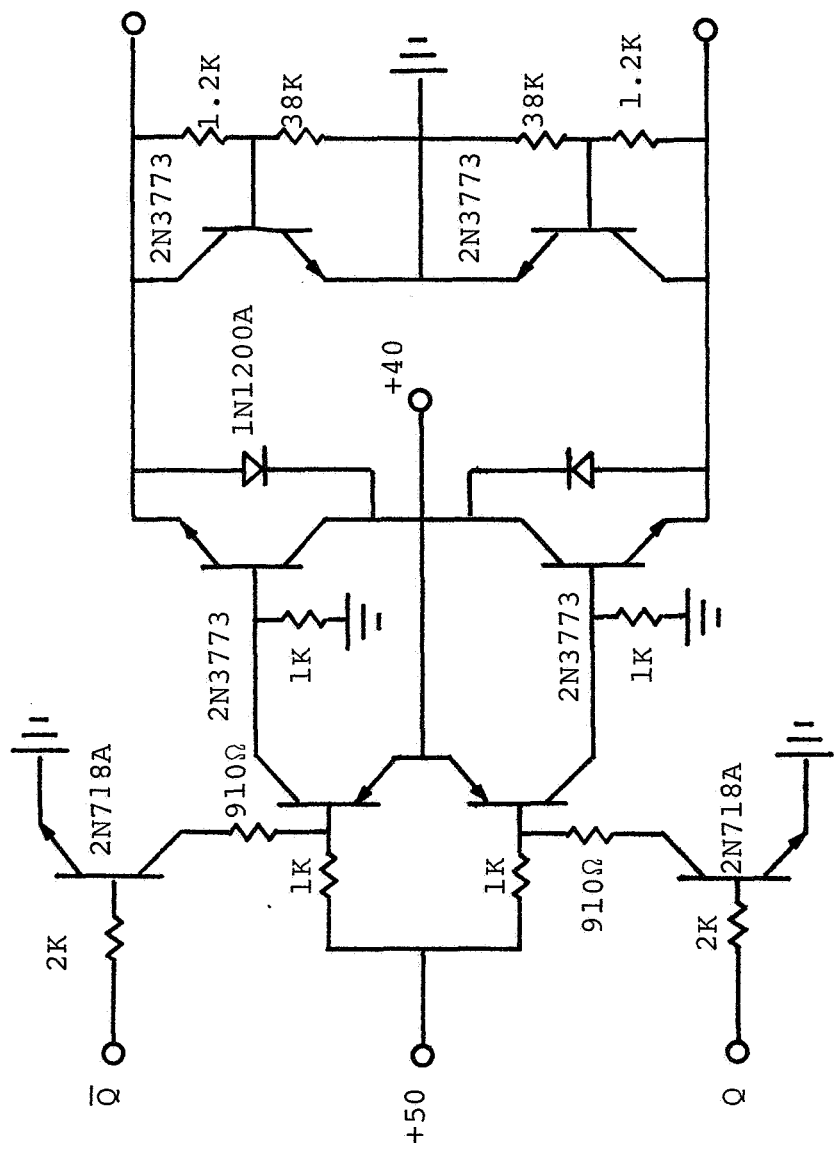


Figure A.4. Power Stage

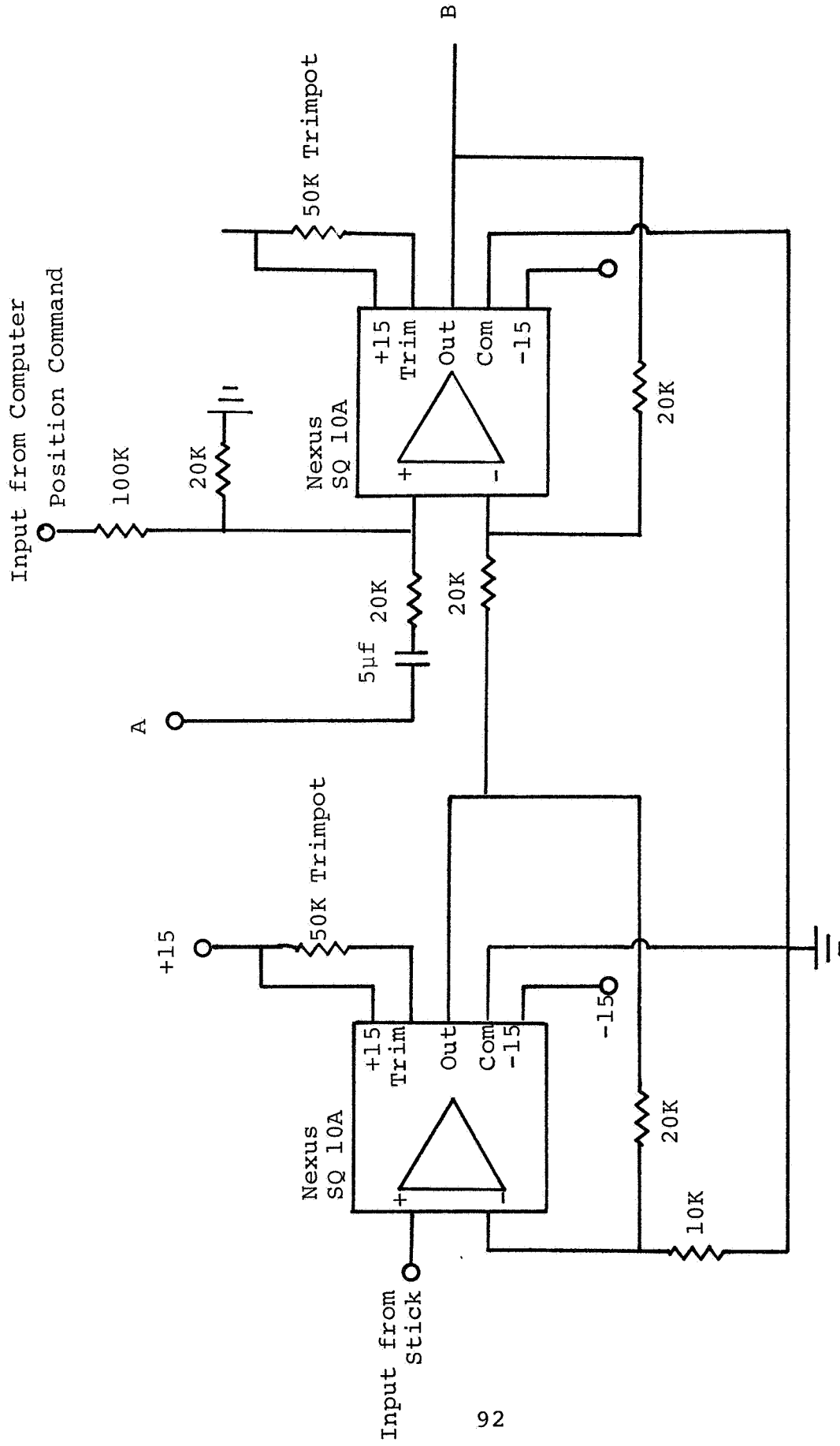


Figure A.5. Gain and Summary Stages

APPENDIX B

Computer Circuits

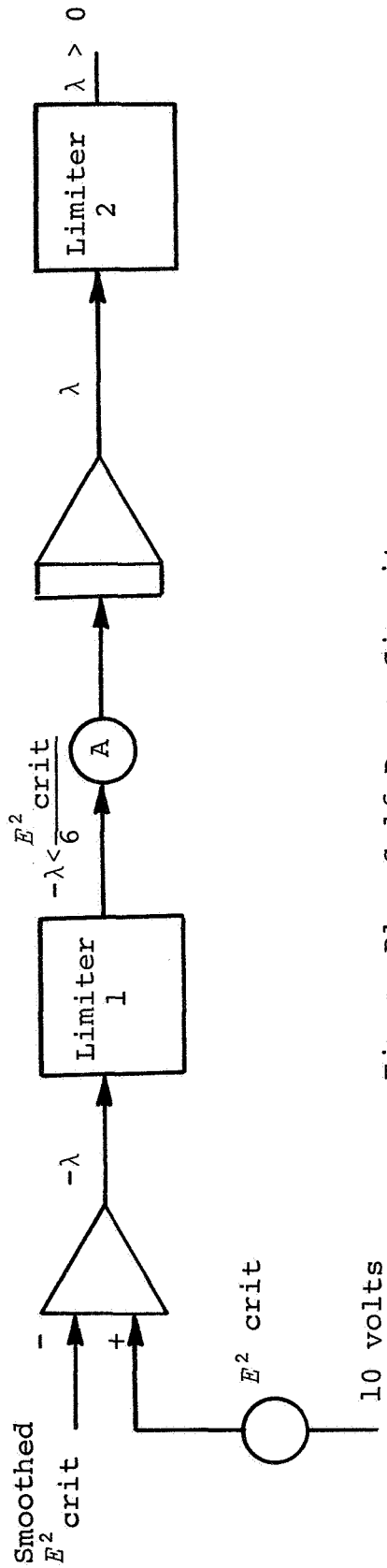
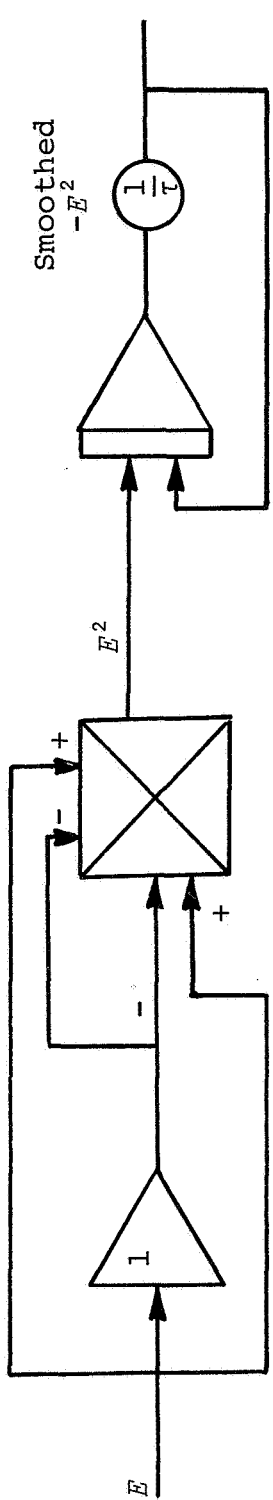


Figure B1. Self Pacer Circuit



- Switch Positions
1.  $Y = \frac{\lambda}{s(s - \lambda)}$
  2.  $Y = \frac{\lambda}{s^2 - 2\xi\omega_n s - \lambda}$
  3.  $Y = \frac{\lambda}{s^2 - \lambda s + \omega_n^2}$

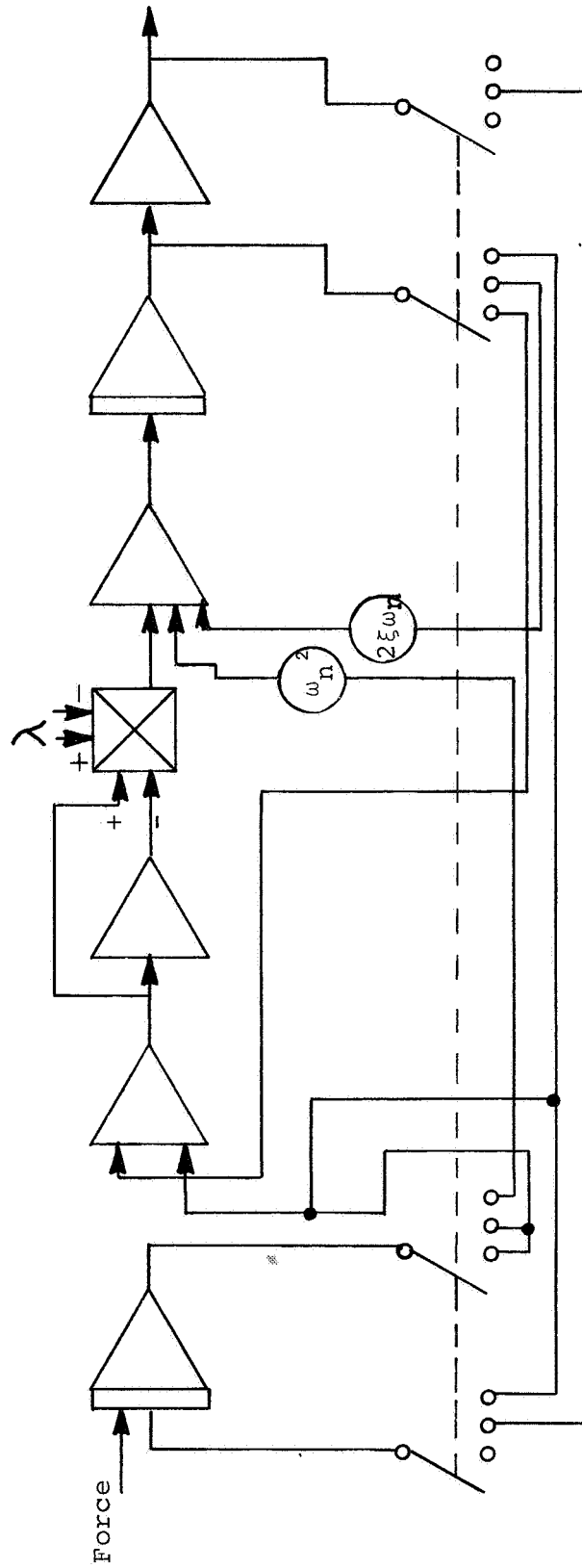


Figure B2. Computer Simulation of Unstable Plants

## APPENDIX C

### Run Logs

RUN LOG

Subject: C. O.

<u>Run</u>	<u>Plant</u>	<u><math>\lambda_{\max}</math></u>	<u>Mode/Comment</u>
1	$\frac{1}{s - \lambda}$	6.3	Fixed
2	$\frac{1}{s - \lambda}$	6.5	Fixed
3	$\frac{1}{s - \lambda}$	6.2	Fixed
4	$\frac{1}{s - \lambda}$	9.1	Pos Feedback
5	$\frac{1}{s - \lambda}$	9.7	Pos Feedback
6	$\frac{\lambda}{s - \lambda}$	5.5	Fixed
7	$\frac{\lambda}{s - \lambda}$	5.5	Fixed
8	$\frac{\lambda}{s - \lambda}$	6.0	Fixed
9	$\frac{1}{s(s - \lambda)}$	2.5	Fixed
10	$\frac{1}{s(s - \lambda)}$	3.0	Pos Feedback
11	$\frac{1}{s(s - \lambda)}$	2.0	Fixed

Run Log C. O. (Cont.)

12	$\frac{\lambda}{s(s - \lambda)}$	1.6	Fixed
13	$\frac{\lambda}{s(s - \lambda)}$	1.7	Pos Feedback
14	$\frac{\lambda}{s(s - \lambda)}$	10.0	Vel Feedback/Scale Limited
15	$\frac{\lambda}{s(s - \lambda)}$	1.6	Fixed
16	$\frac{\lambda}{s(s - \lambda)}$	11	Vel Feedback/Scale Limited
17	$\frac{\lambda}{s^2 + 2\xi\omega_n s - \lambda}$	3.8	Fixed
18	$\frac{\lambda}{s^2 + 2\xi\omega_n s - \lambda}$	3.7	Pos Feedback
19	$\frac{\lambda}{s^2 + 2\xi\omega_n s - \lambda}$	16	Vel Feedback/Scale Limited
20	$\frac{\lambda}{s^2 + 2\xi\omega_n s - \lambda}$	.5	Blind

RUN LOG

Subject: D. H.

<u>Run</u>	<u>Plant</u>	<u><math>\lambda_{\max}</math></u>	<u>Mode/Comment</u>
1	$\frac{\lambda}{s(s - \lambda)}$	1.2	Fixed
2	$\frac{\lambda}{s(s - \lambda)}$	1.4	Fixed
3	$\frac{\lambda}{s(s - \lambda)}$	1.3	Pos Feedback
4	$\frac{\lambda}{s(s - \lambda)}$	1.5	Pos Feedback
5	$\frac{\lambda}{s(s - \lambda)}$	1.9	Fixed
6	$\frac{\lambda}{s(s - \lambda)}$	2.0	Fixed
7	$\frac{\lambda}{s(s - \lambda)}$	1.0	Blind
8	$\frac{\lambda}{s(s - \lambda)}$	1.0	Blind

Run Log D. H. (Cont.)

9	$\frac{\lambda}{s^2 - \lambda}$	3.5	Fixed
10	$\frac{\lambda}{s^2 - \lambda}$	4.0	Fixed
11	$\frac{\lambda}{s^2 - \lambda}$	3.9	Pos Feedback
12	$\frac{\lambda}{s^2 - \lambda}$	5.8	Pos Feedback
13	$\frac{\lambda}{s^2 - \lambda}$	4.4	Fixed

RUN LOG

Subject: J. D.

<u>Run</u>	<u>Plant</u>	<u><math>\lambda_{\max}</math></u>	<u>Mode/Comment</u>
1	$\frac{\lambda}{s(s - \lambda)}$	1	Fixed
2	$\frac{\lambda}{s(s - \lambda)}$	1.25	Fixed
3	$\frac{\lambda}{s(s - \lambda)}$	.8	Pos Feedback
4	$\frac{\lambda}{s(s - \lambda)}$	1.0	Pos Feedback
5	$\frac{\lambda}{s(s - \lambda)}$	5.7	Vel Feedback Scale Limit
6	$\frac{\lambda}{s(s - \lambda)}$	5.7	Vel Feedback Scale Limit

RUN LOG

Subject: J. S.

<u>Run</u>	<u>Plant</u>	<u><math>\lambda_{\max}</math></u>	<u>Mode/Comment</u>
1	$\frac{\lambda}{s(s - \lambda)}$	2.0	Pos Feedback
2	$\frac{\lambda}{s(s - \lambda)}$	1.5	Fixed
3	$\frac{\lambda}{s(s - \lambda)}$	.75	Blind
4	$\frac{\lambda}{s(s - \lambda)}$		Fixed
5	$\frac{\lambda}{s(s - \lambda)}$		Pos Feedback
6	$\frac{\lambda}{s(s - \lambda)}$		Fixed
7	$\frac{\lambda}{s(s - \lambda)}$		Pos Feedback
8	$\frac{\lambda}{s(s - \lambda)}$		Pos Feedback
9	$\frac{\lambda}{s(s - \lambda)}$		Fixed



Run Log S. J. (cont.)

10	$\frac{\lambda}{s(s - \lambda)}$		Fixed
11	$\frac{\lambda}{s(s - \lambda)}$		Fixed
12	$\frac{\lambda}{s(s - \lambda)}$		Pos Feedback
13	$\frac{\lambda}{s^2 + 2\xi\omega_n s - \lambda}$	5.5	Fixed $2\xi\omega_n = 1$
14	$\frac{\lambda}{s^2 + 2\xi\omega_n s - \lambda}$	5.0	Pos Feedback
15	$\frac{\lambda}{s^2 + 2\xi\omega_n s - \lambda}$	6.3	Pos Feedback
16	$\frac{\lambda}{s^2 + 2\xi\omega_n s - \lambda}$	7.0	Fixed
17	$\frac{\lambda}{s^2 + 2\xi\omega_n s - \lambda}$	7.5	Pos Feedback
18	$\frac{\lambda}{s^2 + 2\xi\omega_n s - \lambda}$	10.5	Fixed
19	$\frac{\lambda_n^2}{s^2 - \lambda s + \omega_n^2}$	1.7	Fixed $\omega_n^2 = 10$
20	$\frac{\lambda_n^2}{s^2 - \lambda s + \omega_n^2}$	1.7	Pos Feedback

## Run Log

Subject: L.D.

<u>Run</u>	<u>Plant</u>	<u><math>\lambda_{\max}</math></u>	<u>Mode</u>	<u>Comment</u>
1	$\frac{\lambda}{s - \lambda}$	5.5	Fixed	
2	$\frac{\lambda}{s - \lambda}$	9.2	Pos Feedback	
3	$\frac{\lambda}{s - \lambda}$	7.6	Blind	
4	$\frac{\lambda}{s - \lambda}$	6.6	Blind	
5	$\frac{\lambda}{s - \lambda}$	9.6	Pos Feedback	
6	$\frac{\lambda}{s - \lambda}$	9.8	Pos Feedback	
7	$\frac{\lambda}{s - \lambda}$	15	Pos Feedback	Limit = 15
8	$\frac{\lambda}{s - \lambda}$	5	Fixed	Limit = 15
9	$\frac{\lambda}{s(s - \lambda)}$	1.7	Fixed	$K_{sc} = .75$
10	$\frac{\lambda}{s(s - \lambda)}$	2.0	Fixed	$K_{sc} = .5$
11	$\frac{\lambda}{s(s - \lambda)}$	1.8	Fixed	$K_{sc} = 1.25$

Run Log Subject L.D. (Cont.)

12	$\frac{\lambda}{s(s - \lambda)}$	2.8	Fixed	$K_{sc} = 1.0$
13	$\frac{\lambda}{s(s - \lambda)}$	2.0	Fixed	$K_{sc} = .5$ Above runs for optimum $K_{sc}$
14	$\frac{\lambda}{s(s - \lambda)}$	1.5	Fixed	
15	$\frac{\lambda}{s(s - \lambda)}$	1.75	Fixed	
16	$\frac{\lambda}{s(s - \lambda)}$	2.25	Fixed	
17	$\frac{\lambda}{s(s - \lambda)}$	2.6	Fixed	
18	$\frac{\lambda}{s(s - \lambda)}$	2.0	Fixed	
19	$\frac{\lambda}{s(s - \lambda)}$	2.5	Pos Feedback	
20	$\frac{\lambda}{s(s - \lambda)}$	2.8	Pos Feedback	
21	$\frac{\lambda}{s(s - \lambda)}$	1.0	Blind	
22	$\frac{\lambda}{s^2 - \lambda}$	7.0	Fixed	

Run Log Subject L.D. (Cont.)

23	$\frac{\lambda}{s^2 - \lambda}$	7.5	Pos Feedback	
24	$\frac{\lambda}{s^2 - \lambda}$	8.5	Fixed	
25	$\frac{\lambda}{s(s - \lambda)}$	2.5	Fixed	
26	$\frac{\lambda}{s^2 + 2\xi\omega_n s - \lambda}$	7.0	Fixed	$2\xi\omega_n = 1$
27	$\frac{\lambda}{s^2 + 2\xi\omega_n s - \lambda}$	7.0	Fixed	
28	$\frac{\lambda}{s^2 + 2\xi\omega_n s - \lambda}$	10.0	Pos Feedback	
29	$\frac{\lambda}{s^2 + 2\xi\omega_n s - \lambda}$	10.0	Fixed	
30	$\frac{\lambda}{s^2 + 2\xi\omega_n s - \lambda}$	8.0	Fixed	
31	$\frac{\lambda}{s^2 + 2\xi\omega_n s - \lambda}$	10.5	Fixed	
32	$\frac{\lambda}{s^2 + 2\xi\omega_n s - \lambda}$	10.5	Pos Feedback	

Run Log Subject L.D. (Cont.)

33	$\frac{\lambda}{s^2 + 2\xi\omega_n s - \lambda}$	12.	Pos Feedback	
34	$\frac{\lambda}{s^2 + 2\xi\omega_n s - \lambda}$	10.	Fixed	
35	$\frac{\lambda}{s^2 + 2\xi\omega_n s - \lambda}$	13.	Pos Feedback	
36	$\frac{\lambda}{s^2 + 2\xi\omega_n s - \lambda}$	21.	Vel Feedback	
37	$\frac{\omega_n^2}{s^2 - \lambda s - \omega_n^2}$	2.5	Fixed	$\omega_n^2 = 10,$
38	$\frac{\omega_n^2}{s^2 - \lambda s - \omega_n^2}$	3.25	Pos Feedback	
39	$\frac{\omega_n^2}{s^2 - \lambda s - \omega_n^2}$	2.75	Fixed	
40	$\frac{\omega_n^2}{s^2 - \lambda s - \omega_n^2}$	3.1	Fixed	
41	$\frac{\omega_n^2}{s^2 - \lambda s - \omega_n^2}$	3.5	Pos Feedback	
42	$\frac{\omega_n^2}{s^2 - \lambda s - \omega_n^2}$	2.8	Blind	

Run Log Subject L.D. (Cont.)

43	$\frac{\omega_n^2}{s^2 - \lambda s - \omega_n^2}$	3.4	Pos Feedback
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44	$\frac{\omega_n^2}{s^2 - \lambda s - \omega_n^2}$	13.5	Vel Feedback
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RUN LOG

Subject: M. K.

<u>Run</u>	<u>Plant</u>	<u><math>\lambda_{\max}</math></u>	<u>Mode/Comment</u>
1	$\frac{\lambda}{s(s - \lambda)}$	.5	Fixed
2	$\frac{\lambda}{s(s - \lambda)}$	1.0	Pos Feedback
3	$\frac{\lambda}{s(s - \lambda)}$	1.0	Pos Feedback
4	$\frac{\lambda}{s(s - \lambda)}$	.75	Fixed
5	$\frac{\lambda}{s(s - \lambda)}$	3.1	Vel Feedback

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