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PROPRIOCEPTIVE CUES AND THEIR INFLUENCE ON OPERATOR PERFORMANCE IN MANUAL CONTROL

by James Herman Herzog

Prepared by
UNIVERSITY OF MICHIGAN
Ann Arbor, Mich.
for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JANUARY 1969

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Control engineers and psychologists have jointly participated in research intended to investigate the unique characteristics of control systems which contain a human operator. A class of tracking problems known as compensatory tracking is of special interest due to its similarity to manual control problems such as flying an aircraft.

In this research the neuromuscular control system of the human upper limb was investigated as an auxiliary source of sensory information. Analysis of a functional block diagram of the human operator indicated that a control system with interesting characteristics could be devised if the control stick were constructed to be a mechanical analog of the plant being controlled. This is called the matched manipulator control technique. The torque applied by the operator to the control stick was sensed and used as the control input to the plant. For stable plants the plant output and the control stick position were placed in correspondence. This correspondence allowed the physiological force and position feedback paths of the upper limb to furnish information to the operator concerning the state of the plant.

When the matched manipulator technique is used, the control force applied to the plant is a scalar multiple of the reaction force experienced by the operator. The operator is in a particularly advantageous position to formulate control strategies to emphasize either accurate control performance or minimum use of control effort.

In order to investigate the matched manipulator technique and other questions associated with the relationship of control stick "feel" to performance in manual control a special control stick was constructed. Known as the Variable Dynamics Control Stick, this device utilized a torque motor to provide operator reaction forces as specified by functions generated on an analog computer. Using voltage signals related to the control stick position, velocity and acceleration, the analog computer formed functions of these variables. A closed loop control system allowed these functions to be accurately converted to torque by a torque motor. By simulating mechanical reaction forces with this apparatus it was possible to produce a wide range of control stick characteristics including time variations, instabilities, and nonlinearities.

Experimentation conducted utilizing the matched manipulator technique with several human operators indicated that performance with the matched manipulator technique was consistently superior to control of the same plants with position type control sticks. The experimentation included linear plants, nonlinear plants, time varying plants, unstable plants, and linear plants with time delay. Describing function representations of the combined open loop characteristics of the operator and the plant indicated a uniformity of performance when using the matched manipulator technique.

The matched manipulator technique seems to offer an interesting and useful means of altering the interface between the human operator and his electro-mechanical surroundings in order to improve the system performance. This technique when properly applied can result in extremely high compatibility between the human and the plant with corresponding improvements in control performance.

ACKNOWLEDGMENTS

The author wishes to express his sincere thanks for the suggestions and encouragement offered by his doctoral committee. Professor Louis F. Kazda, chairman of the committee, provided counselling throughout the author's graduate program. His open mindedness and interest in this interdisciplinary work enabled this research to be started. Professor Robert M. Howe of the Information and Control Engineering Department and Associate Professor Richard W. Pew of the Department of Psychology provided suggestions and periodic review of the author's research as co-principal investigators for the NASA contract which sponsored this work. In Professor A.D. Moore of the Department of Electrical Engineering and Assistant Professor Josephine C. Moore of the Department of Anatomy of the University of South Dakota, the author had the unique distinction of having a father and daughter serving on the same doctoral committee. The former provided an invaluable research philosophy for investigating the human. The latter provided the consultation needed in the study and interpretation of the neuromuscular control system of the human. Assistant Professor Richard A. Volz provided constructive criticism and suggestions concerning the technical aspects of this research.

Both the initial and final copies of the manuscript were typed by Mrs. Christine Long.

The author is particularly indebted to the faith and understanding of his wife, who made the sacrifices that can only be understood by one who has participated in a Ph.D. program.

This research was sponsored in part by the National Aeronautics and Space Administration under contract NASr 54(06).

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LIST OF SYMBOLS

a_1, a_2, a_3	Coefficients of a differential equation
a_h	Lag parameter associated with the combined operator and plant
A_C	Coefficient of a term in a linear plant
A_M	Coefficient of a term in a linear control stick
B	Viscous friction coefficient
B_1, B_2, B_3	Values of viscous friction used in Experiment 2
B_C	Coefficient of a term in a linear plant
B_M	Coefficient of a term in a linear control stick
B_S	Control stick viscous friction
c	Plant output
C	Electrical capacitance
C_1	Filter gain coefficient
D_C	Coefficient of a term in a linear plant
E	Laplace transform of system error
E_C	Coefficient of a term in a linear plant
E_i	Input voltage to an electrical circuit
E_o	Output voltage from an electrical circuit
f	A general function
f_C	Clock frequency
f_L	Muscular force applied to the limb
f_M	Net force applied to the manipulator

F	Fourier transform operator
F^{-1}	Inverse Fourier transform operator
F_L	Laplace transform of muscular force applied to limb
F_M	Laplace transform of net force applied to manipulator
F_S	Control stick coulomb friction
G_A	Transfer characteristics of the alpha motoneuron
G_C	Forward loop compensation
G_E	Compensation provided by operator
G_K	Transfer characteristics of limb force feedback path
G_L	Transfer characteristics of the coupled limb and manipulator
G_M	Transfer characteristics of the manipulator
G_N	Transfer characteristics of a nonlinear element
G_P	Transfer characteristics of the limb position feedback path
$H(j\omega)$	Transfer function of a filter
i	Input signal
J	Moment of inertia
J_S	Control stick moment of inertia
k	Scaling constant
K, K_1, K_2, K_3	Spring constants
K_C	Gain associated with the plant
K_h	Gain associated with the combined operator and plant
K_M	Gain associated with the manipulator

K_T	Variable dynamics control stick torque constant
K_{TM}	Motor torque constant
K_θ	Position transducer calibration constant
$K_{\dot{\theta}}$	Velocity transducer calibration constant
$K_{\ddot{\theta}}$	Acceleration transducer calibration constant
L	Electrical inductance
n	An integer
n(t)	Noise signal
N	Describing function for a nonlinear element
q	Electrical charge
R	Electrical resistance
R_{xx}	Autocorrelation of x(t)
R_{xy}	Cross-correlation of x(t) and y(t)
T	Time interval
T_h	Torque applied by human operator
Y_C	Transfer characteristics of the plant
$\hat{Y}_C$	Apparent plant using matched manipulator control
Y_P	Transfer characteristics of human operator
Z	Sequence length for a shift register generator
$\overline{\alpha}$	Command signal to alpha motoneuron
δ	Mismatch parameter
ϵ	System error
ϵ_A ϵ_B	Mismatch coefficients used in error analysis

θ	Mechanical rotation
θ_C	Plant output
θ_M	Manipulator position
Θ_C	Laplace transform of plant output
Θ_M	Laplace transform of manipulator position
ξ	Damping coefficient
ρ	Correlation coefficient
τ	Time delay
τ_h	Time delay associated with human operator
Φ_{xx}	Power spectral density of x(t)
Φ_{xy}	Cross-spectral density of x(t) and y(t)
ω	A sinusoidal frequency
ω_C	Gain crossover frequency of $Y_P Y_C$
ω_n	Undamped natural frequency of a second order system

CHAPTER I

INTRODUCTION

1.0 Abstract

The purpose of this chapter is to introduce the basic manual control problem which will be extensively studied in this research. Background material from the areas of psychology and physiology is presented to provide a basis for this investigation. This chapter concludes with a listing of research objectives.

1.1 Introduction to Manual Control

Manual control is a branch of control engineering which is concerned with the unique problems that arise when human operators are embedded in larger control systems. Classical control engineering, when complemented by the areas of experimental psychology and physiology, provides a basis for analyzing the problems which exist in this area. Researchers in each of these disciplines have made significant contributions. Some of this research is reviewed in Sections 1.2 and 1.3.

There is a large range of interesting problems which have been formally studied in the area of manual control. One such class, known as tracking tasks, is of particular interest because of its wide applicability and its similarity to control systems composed of only electromechanical elements. In this class of problems, the operator is required to take appropriate action to cause a controlled element, known as the plant, to agree with an input quantity known as a system forcing function. The plant is a fixed part of a control system that may be described by differential equations. Since output information is made available at the input of the system, this is known as a closed loop control system. If only the instantaneous error existing between the plant output and the forcing function is displayed to the operator, the situation is known as a compensatory tracking task. If plant output and input forcing function are displayed individually, the situation is known as a pursuit tracking task.

The order of a plant is an integer which indicates the highest order derivative present in the differential equation describing the plant. A linear plant is describably by a differential equation which is linear in the dependent variable and its derivatives. If a plant is not linear it is nonlinear. The ratio of the Laplace transform of an isolated linear element's output to the Laplace transform of its driving function when all initial conditions are zero is called a transfer function. Compensation refers to additional linear elements, described by transfer functions, which are included in a control system to modify the overall transfer function with the intent of improving system performance.

Several types of control systems that normally incorporate the human operator may be represented diagramatically as shown in Fig. 1.1.1.

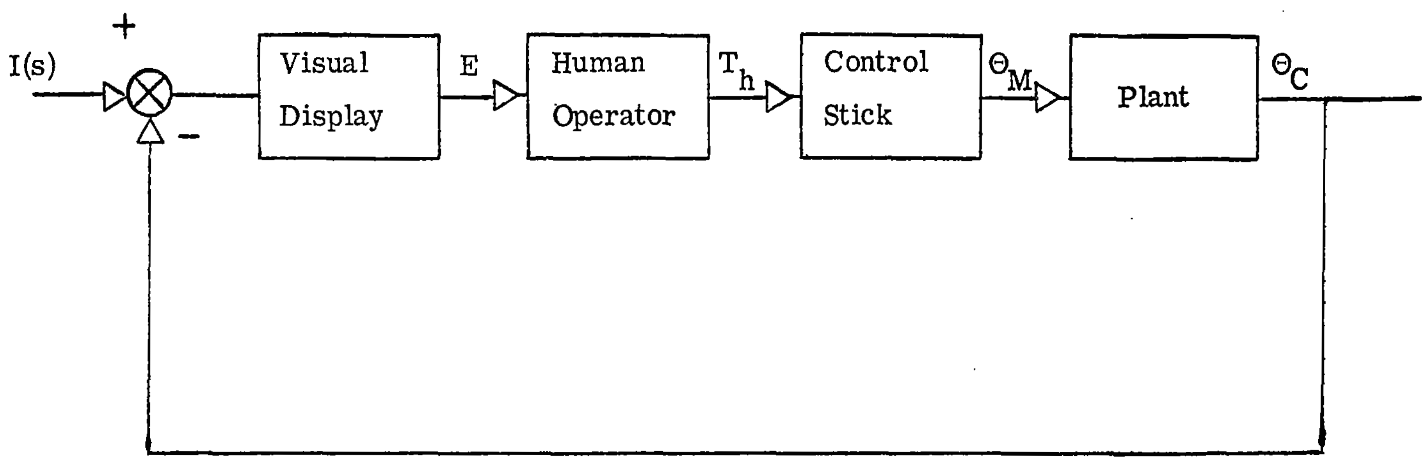

Figure 1.1.1 Compensatory Tracking Task

As an example consider an aircraft pilot using an ILS glide slope indicator during an instrument landing. The visual display indicates the position error of the aircraft as referenced to the prescribed landing trajectory.

There are several basic requirements imposed on the operator in all control situations characterized by Fig. 1.1.1. The operator must first perceive the system error. The display is usually visual, such as a meter, but auditory or tactile displays are also possible. Problems in the analysis of human perception are especially suited to the techniques and methods of experimental psychology.

Following the perception of the system error, the operator is required to specify a corrective action. From the control theory point of view, the operator is required to provide compensation for the control of the plant. The form of the compensation provided by the operator is related to the characteristics of the plant.

After determining his course of action the operator must communicate his control decision to the plant. For this purpose a control stick, sometimes referred to as a manipulator, is used as an intermediary device. The process of applying forces to a manipulator to produce a control action for control of a plant requires the skilled coordination of the operator's muscular system and limbs. This portion of the manual control problem is best suited for analysis by methods of physiology.

To perform well in a manual control situation, the human operator must exercise proficiency in all of the above mentioned tasks. In order to analyze overall performance, the systems engineer would like to describe the control characteristics of the operator in the same form as those of the electrical and mechanical members of the control system, a transfer function. An accurate mathematical representation of the human operator allows simulation of all the elements in the system and is an extremely valuable system design tool.

Formulation of a mathematical model to represent the human operator is not a trivial task. The operator has very few characteristics in common with the remainder of the control system. In many circumstances the operator tends to function in a nonlinear, time varying, and adaptive manner.

Despite the difficulties involved, the advantages to be gained by representing the control characteristics of the human operator in mathematical terms are quite significant. Modeling of the human operator has been attempted by many investigators. The reader is referred to the NASA Contractor report by Young and Stark [55] where many of these efforts are reviewed. Particularly noteworthy accomplishments have been made by McRuer and Krendel [37] in analyzing the characteristics of the human pilot.

One area in which much work remains to be done is the study of the interfaces which exist between the operator and the remainder of the control system. The input interface usually consists of the display apparatus. A great deal of effort has been expended by aircraft designers to improve the methods of information transfer to pilots with cockpit displays. Recent trends have been concerned with reducing the number of interpretive steps between display and desired information. In many cases simple meters have been replaced by more sophisticated displays which result in improved operator performance.

The output interface also represents an area in which large improvements in performance are possible if control techniques can be developed for improving the compatibility between the operator and the remainder of the system. A large portion of the material in this document is devoted to understanding and improving the characteristics of this interface.

The possibility of modifying the interface between the operator and the control stick to improve system performance opens a research area of great potential. The study of this interface requires an understanding of the characteristics of the mechanical control stick and the voluntary control system of the human limb. Section 1.2 presents a brief introduction into some of the characteristics of the physiological control system used in motion of the upper limb.

1.2 Proprioceptive Feedback System and Control of Voluntary Motion

An appreciation of the physiology involved in the control of voluntary motion is important to manual control for two reasons. First, the limitations of the muscular control system impose restrictions concerning the information which may be conveyed from the operator to the plant via the control stick. Second, there are elements in this control system which are capable of supplying information to the operator which may be useful in improving control performance.

The actuator mechanism of the human consists of muscles, tendons, bones, and motoneurons. The most elementary unit of the muscular system is the muscle fiber. Each muscle fiber is said to be innervated by a single terminal process of only one motoneuron. Upon stimulation by an electro-chemical pulse from a motoneuron, tension tending to shorten the fiber is developed as shown in Fig. 1.2.1.

A functional combination of all of the muscle fibers which are activated by the same motoneuron is known as motor unit. In the larger muscles of the body there are usually 50-200 muscle fibers in a motor unit. These motor units share a common source of excitation and contract as a group when stimulated. In large muscles, such as those of the human upper limb, there are hundreds of individual motor units. Variations in the strength of muscle contraction is possible through control of the number of stimuli entering the motor units through the motoneurons and through varying the number of motor units participating in a given action.

Muscles are unidirectional force generators whose output is

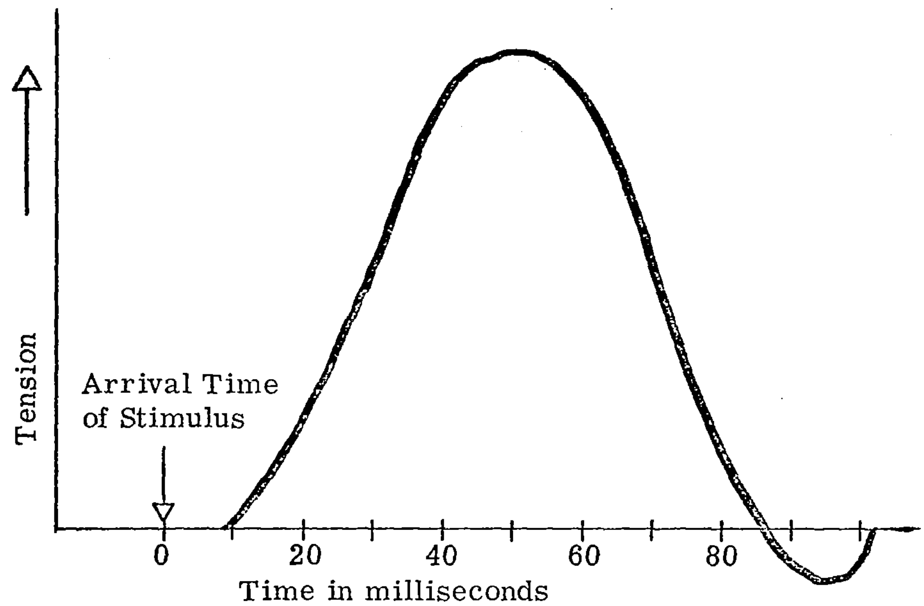

Figure 1.2.1 Isometric Response of a Typical Muscle Fiber to a Single Stimulus. Data obtained From Bowen [12]

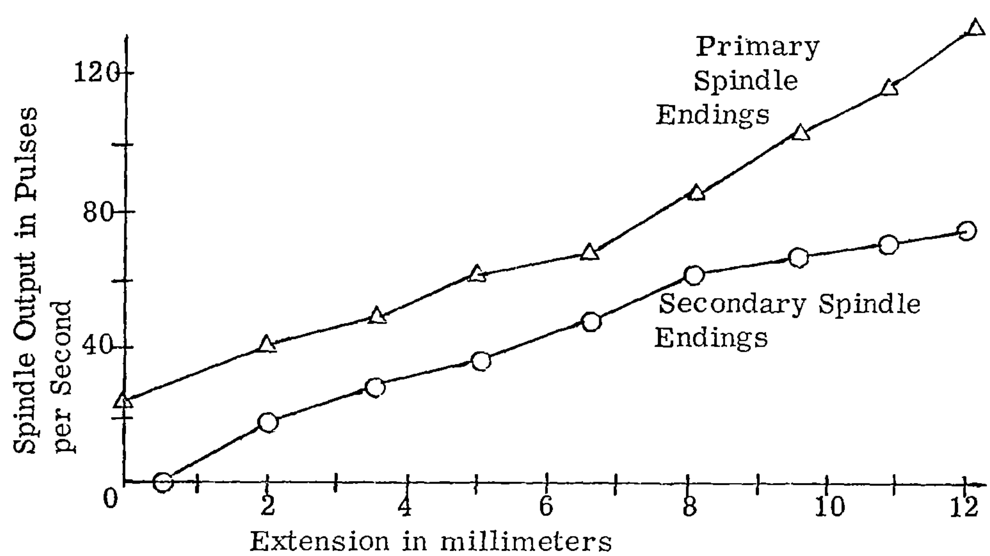

Figure 1.2.2 Experimental Relationship Between Frequency of Discharge and Extension for a Muscle Spindle. Data Obtained From Matthews [35]

controlled by signals stimulating them through the motoneuron. For bi-directional movement muscles must be paired.

It should be obvious that control of voluntary motion is not a trivial task. The actuators are distributed throughout the body requiring the presence of a highly efficient and reliable communications link. Conscious visual monitoring of all skilled movement is neither possible nor necessary. The human body contains a highly developed control, communication, and feedback system which coordinates voluntary motion.

Sensors, called proprioceptors, are located in the muscles, tendons, and joints of the body and furnish information to the central nervous system. There are several different elements which furnish information concerning the activity of areas of the body. The Pacinian corpuscles are pressure transducers and are found in tendons, joints, connective tissue, and other locations. Tension in the tendons and joints is perceived by the neurotendinous spindle (Golgi tendon organ). Joint receptors have been found to furnish information to the central nervous system regarding the extent of joint rotation.

The neuromuscular spindle, embedded within the muscle tissue is primarily a transducer. There are two types of neural outputs from the spindle. These are known as the primary and secondary endings and are often referred to as Group I-A and Group II fibers. The output of the primary and secondary endings of the spindle is in the form of pulses as shown in Fig. 1.2.2. The secondary endings have pulse output rates proportional to the stretch of the muscle tissue. This is directly related to the rotation of a body member. The primary endings have pulse output rates proportional to a weighted sum of the stretch of the muscle tissue plus the rate of stretch.

Figure 1.2.3 is a functional block diagram of a limb position servo system. Two muscle groups, a flexor and an extensor, are included to allow bi-directional rotation. Each of the control loops indicated in Fig. 1.2.3 will be examined individually.

Consider the control loop containing the spindle, the alpha motoneuron and the extensor. As the muscle tissue is stretched by the addition of a mechanical load to the joint, the pulse output rate of the spindle increases. This increased output is fed back to the muscle by means of the alpha motoneuron. This feedback mechanism increases the contraction force of the muscle and thus decreases the effect of the disturbance torque. This negative feedback phenomenon is known as the stretch reflex.

The propagation velocity of signals in neural networks is about 100 meters per second. This contributes to a transport delay in the feedback controlling the stretch reflex. The presence of rate feedback from the primary endings of the muscle spindle tends to make this loop more stable.

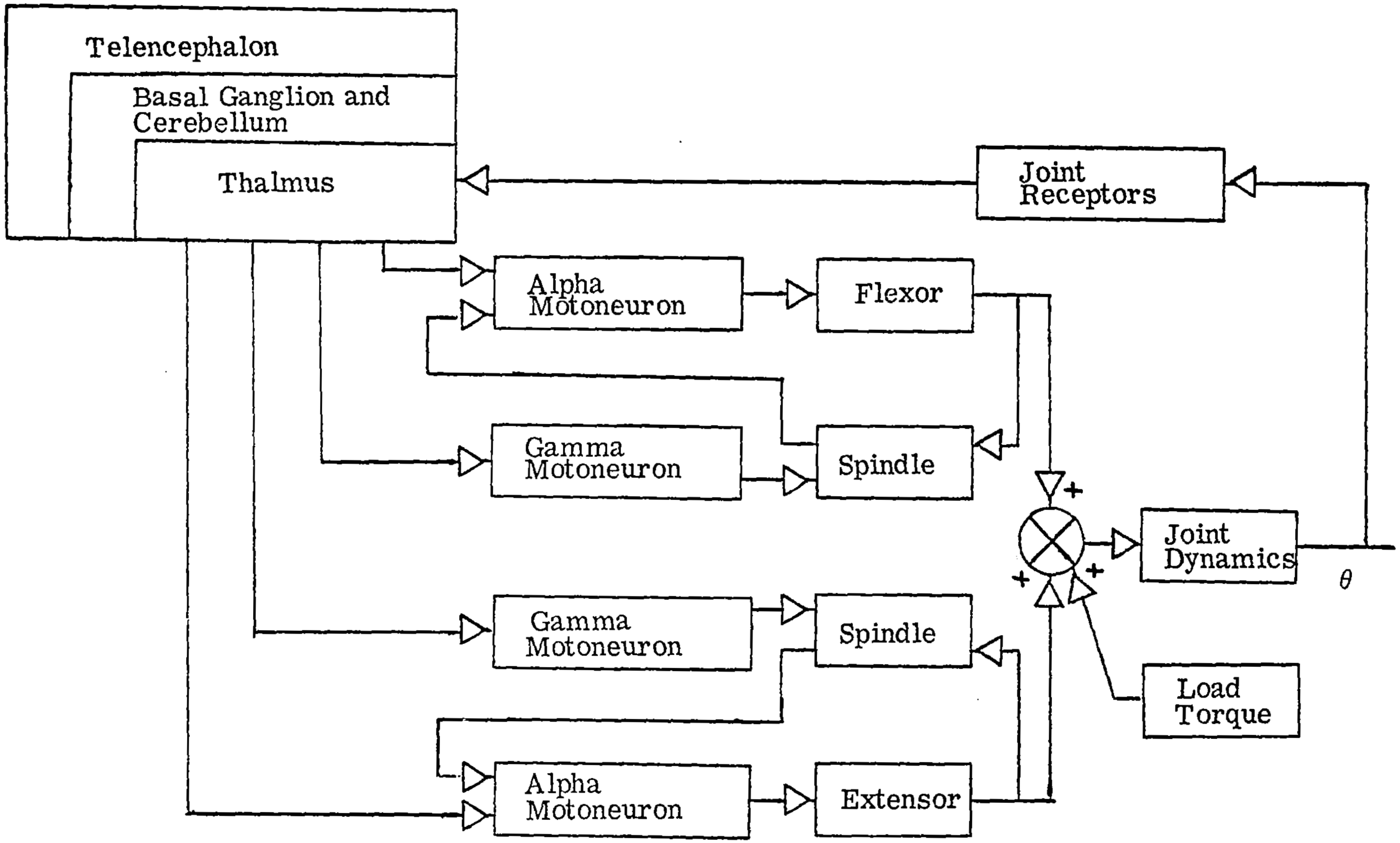

Figure 1.2.3 Simplified Joint Position Control System Functional Block Diagram

The higher centers of the central nervous system control and coordinate the various channels of sensory information. In particular the thalmus and the cerebellum are areas of the central nervous system which are believed to act as a switchboard for information received from the joint receptors and the neuromuscular spindles.

One possible way of controlling skilled movement is by transmitting direct command signals down the alpha motoneuron from the higher centers. This path is direct and fairly fast but almost useless since it would require continuous control by the higher centers and extensive monitoring via visual, vestibular, reticular and proprioceptive feedback. Also introspection suggests that the human thinks in terms of movements and not in terms of generating specific force programs for complementary muscle groups.

The gamma motoneuron acts as a pathway between the higher centers of the central nervous system and the muscle spindles. Information coming down this pathway is capable of modifying the characteristics of the muscle spindle. The gamma system as shown in Fig. 1.2.3, seems to have the effect of transferring control action to "positions" rather than "forces". Figure 1.2.4 shows some experimental results obtained by Mathews [35] and indicates the effect of gamma motor fiber activity. The gamma motoneuron controls the response of both the primary and secondary endings of the muscle spindles. Consider the effect resulting from the conditions shown in

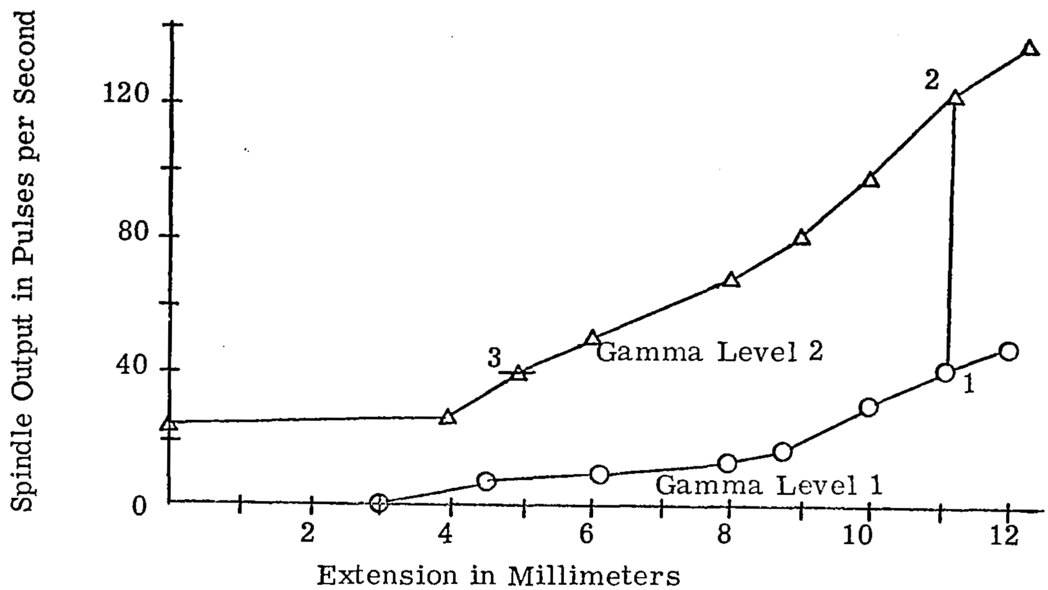

Figure 1.2.4 Spindle Secondary Ending Response for Two Levels of Gamma System Activity. Based on Data by Matthews [35]

Fig. 1.2.4 when the muscle is under a constant load. Originally we are operating on the curve at point 1. If there is activity on the gamma system we shift to point 2 on the second curve. Here spindle secondary ending activity is greater than that required to maintain the load. The unbalance of forces results in contraction of the muscle. At point 3 equilibrium is established at a new position. Through the use of the gamma system the human is able to specify voluntary motion from the higher centers of the central nervous system and have the process controlled locally by spindle feedback.

This brief introduction to voluntary motion indicates that the human limb is well instrumented to perform the accurate positioning tasks which are required in normal activity. Of particular interest is the amount of information concerning the state of the limb which is continuously supplied to the higher centers of the operator. When the human operator grasps a mechanical manipulator, information concerning the characteristics of the manipulator is likewise available through the proprioceptive feedback paths. In Chapter II a method for exploiting this natural feedback apparatus of the human limb will be suggested.

For a more complete discussion of physiological control systems, the reader is referred to the book by Ruch and Patton [44] in the list of references.

1.3 Review of Psychology Literature Relevant to the Role of Proprioceptive Cues in Manual Control

Several investigators have contributed results to the growing body of knowledge concerning the role of the proprioceptive feedback system in manual control. All agree that feedback information is available to the operator concerning displacement and reaction force of the manipulator. There is considerable disagreement concerning the pertinance of this information to manual control.

Bahrick, et al. [4] investigated the role of proprioceptive cues in positioning tasks. Springs were added to the manipulator to produce force information proportional to position. Therefore both position and force cues provided information relative to the positioning task. It was found that positioning errors were smallest when the ratio of relative torque change to displacement was the largest.

In a related experiment Bahrick, et al. [5], investigated manipulators having viscous friction and inertia. The tasks tested required uniformity of velocity. It was found that increasing the viscosity and inertia of a manipulator resulted in greater uniformity of velocity. The conclusion was reached that the human can indeed make use of available proprioceptive cues to improve his performance in control tasks.

Howland and Noble [30] investigated the effect of manipulator parameters in tracking sinusoidal input signals. They hypothesized that increased spring restoring torque would aid positioning, increased viscous friction would aid velocity control, and increased inertia would aid acceleration control. On the basis of their data they concluded that operator performance was best for a set of control stick characteristics that maximized the proprioceptive cues most relevant to the task. For tracking sawtooth signals, for example, a control stick should contain a significant amount of viscous friction.

The three previous investigations suggest that the operator reacts to changes in the characteristics of his control stick and is able to use information derived from them. Application of these principles is limited since ordinarily the nature of the input signal is only statistically known.

In cases in which the control stick is not mechanically coupled to the plant dynamics it is possible to select any of several signals for use in controlling the plant. Two common choices are a signal proportional to the rotation of the control stick and a signal proportional to the torque applied by the operator to the control stick. Gibbs [24] has conducted experiments in which he has concluded that forces applied to an immovable control stick result in better control performance than methods which utilize control stick rotation. He attributes the better performance to the unabiguous information concerning control force that is supplied by the muscle spindles. Weiss [51] has conducted experiments in which he has shown that a control signal proportional to control stick position is superior to a signal proportional to force applied by the operator. Contradictory results such as these demonstrate the lack of understanding of the pertinent variables which affect operator performance.

Birmingham and Taylor [10] take the fundamental control output of the human operator to be force. As a consequence of this assumption, it is implied that operator tracking performance remains unchanged providing that the combined transfer functions of the manipulator and plant remain constant.

Notterman and Page [41] have experimentally determined the beneficial effects of force and position cues. In the primary control stick they studied, it was possible to vary the spring force, viscous friction and inertia by coupling the control stick to devices having these characteristics. Control comparisons were provided by an isometric control stick having a transducer that provided an output voltage proportional to force and by a third control stick that was constructed to have minimum inertia and to move very freely.

Using this apparatus they investigated Birmingham and Taylor's assertion that the combined transfer functions of the manipulator and the external plant determine the performance level of the human operator. This statement was tested by comparing performances for the case in which all of the system dynamics were associated with the manipulator and the case in which the manipulator dynamics were negligible and the system dynamics were simulated on an analog computer. Thus it was possible to compare two systems with the same output / force transfer function. Although both systems had the same transfer function, the feedback information available to the operator was not identical. Both systems provided visual feedback but only in the first did the operator experience force and position cues relevant to the system dynamics.

Notterman and Page concluded that the presence in a control system of the dynamics investigated tends to degrade performance. If the dynamics must be included, it is better to represent them in the manipulator rather than in analog form.

The effect of nonlinear control system dynamics on operator performance has not been thoroughly investigated. Orlansky [42] studying stick and rudder controls in aircraft concluded that nonlinear torque-rotation relationships can be desirable features of control devices.

Wasicko and Magdaleno [50] reviewed the experimental literature concerning nonlinearities and human operator tracking performance. Their investigation showed that in most situations, performance deteriorates with friction, nonlinear feedback gains, and strong interaction among components but the effects are surprisingly small.

1.4 Research Objectives

The research objectives of this document are related to obtaining a better understanding of the role of the proprioceptive feedback system as it relates to manual control. Possible ways of using proprioceptive cues to improve operator performance will be studied. The specific research objectives are as follows:

1. Design and construct a manipulator capable of electrically providing a wide range of force-feel characteristics. The manipulator characteristics should be controllable from an electronic analog computer.
2. Attempt to show the presence of proprioceptive feedback in the human operator. Show that the presence of proprioceptive cues may improve manual control performance.
3. Develop a manual control technique which will make use of proprioceptive cues. Evaluate the usefulness of such a technique in a wide variety of situations.
4. Obtain a quantitative description of the operator representing his control activity under the conditions studied in 3.

1.5 Contents of the Following Chapters

Chapter I has served as an introductory chapter to present a background in the areas of psychology, physiology, and control engineering as they apply to manual control. With this groundwork, Chapter II investigates the specific problem of how proprioceptive cues relate to manual control. Based on the analysis of a functional block diagram of the human operator, a technique is formulated for maximizing the effectiveness of these cues in manual control situations.

Chapter III contains the experimental validation for the conjectures of Chapter II. The techniques of Chapter II are experimentally implemented and tested on several subjects in a controlled environment.

Chapter IV extends the technique developed in Chapter II to include a wider variety of plants. Supporting experimental evidence is presented for the control of plants higher than second order, unstable plants, and nonlinear plants.

Chapter V contains documentation of the major apparatus constructed for this investigation, the variable dynamics control stick. Operating characteristics and performance limits for the device are presented.

In Chapter VI the overall conclusions, summary of contributions, and suggestions for future work are presented.

Appendix A contains a discussion of the shift register generator which was used as a source of low frequency random noise. Appendix B investigates some possible areas of computational difficulty when using digital techniques to compute the describing function representation of some of the data from this research. Appendix C develops the mathematics for a representation of the operator as a random input describing function.

CHAPTER II

RELATIONSHIP OF FORCE-FEEL CUES TO PERFORMANCE IN MANUAL CONTROL

2.0 Abstract

This chapter is concerned with a compensation technique for use with the human operator in manual control tasks. Analysis of a functional block diagram of the human operator indicates that a judicious choice of manipulator characteristics may enable the human operator to generate control torques especially suitable for highly accurate control of a known plant. Use of the technique as a performance aid for several types of plants is discussed.

2.1 Introduction to Control Stick Compensation

Section 1.1 introduced the form of the manual control problem which will be considered in this research. In this type of manual control some unique characteristics exist at the interface between the operator and the remainder of the control system. At this interface a bond is established between the operator and the manipulator. It is at this point that the operator is exposed to reaction forces originating from the control stick.

In some circumstances the control stick is an integral part of the plant. Many of the characteristics of the control sticks of small aircraft are directly determined by the mechanical characteristics of the connecting cables and the reaction forces generated on the deflecting surfaces. This relationship, which exists between aircraft response and the reaction forces experienced by the pilot, is known as control "feel".

With modern high performance aircraft it is no longer possible or desirable for the pilot to be exposed to reaction forces from the control surfaces. In aircraft with auxiliary powered control surfaces it is possible to divorce the characteristics of the control stick from those of the controlled element. It has long been recognized that even when not mechanically linked to the airframe dynamics, the control stick should have an "appropriate" feel. This "feel" is considered so important that specifications regarding the allowed values of control stick characteristics are included in procurement contracts for military aircraft [52]. The characteristics specified are determined largely from pilot opinion and are not necessarily related to any specific characteristic of the aircraft or its control system.

When the control stick is not an integral mechanical member of the plant, a degree of freedom exists for the designer. He is free to choose any variable associated with the control stick as a control variable for presentation to the plant. Choices include the deflection of the control stick from its center position and the torque applied by the operator to the control stick. He may also specify the mechanical characteristics of the control stick.

Ordinarily the interface between the operator and the control stick is used only to transmit control information from the operator to the plant. Under suitable circumstances, however, it is possible for information to be transmitted from the plant to the operator across this interface for use by the operator in modifying his control activity. In the following sections a method will be developed which enhances this flow of information from the plant through the manipulator interface to the operator.

2.2 Formulation of the Problem

Section 1.2 has presented physiological evidence concerning the presence of proprioceptive force and position feedback paths in the human operator. Figure 2.2.1 suggests a possible functional block diagram of the manual control process in which these limb feedback paths are included. This form is similar to that selected by McRuer [34] and will be considered for further analysis. In Fig. 2.2.1:

$I(s)$ = Input signal

$E(s)$ = Visual error information provided by the display

$A(s)$ = Command signal presented to the alpha motoneuron

$F_L(s)$ = Muscular force applied to the limb

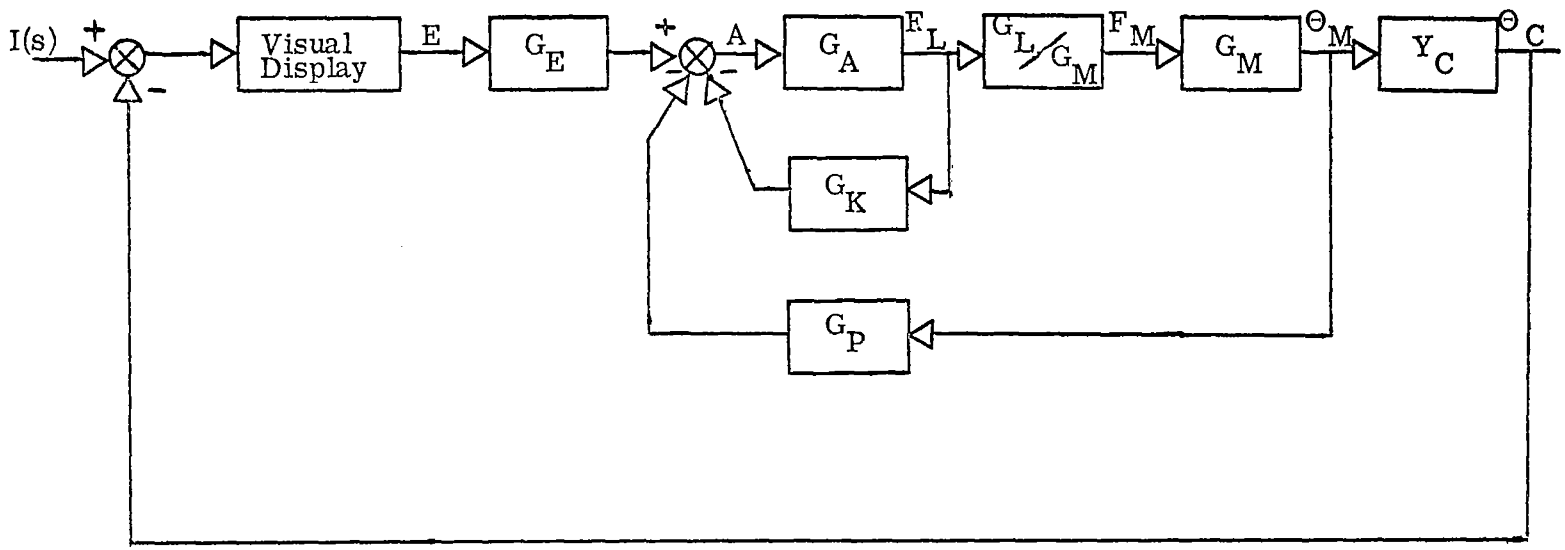

Figure 2.2.1 Functional Block Diagram of the Human Operator in a Compensatory Tracking Task Using Control Stick Position as the Control Variable

$F_M(s)$ = net force applied to the manipulator

$\Theta_M(s)$ = manipulator output position

$\Theta_C(s)$ = plant output

$G_E(s)$ = compensation provided by the operator

$G_A(s)$ = transfer characteristics of the alpha motoneuron

$G_L(s)$ = transfer characteristics of the coupled human limb and manipulator

$G_M(s)$ = transfer characteristics of the manipulator

$Y_C(s)$ = transfer characteristics of the plant

$G_P(s)$ = transfer characteristics of the limb position feedback path

$G_K(s)$ = transfer characteristics of the limb force feedback path

To facilitate analysis let us assume linearity of the components in Fig. 2.2.1 so that the functional block diagram may be represented by a transfer function.

$$\frac{\Theta_C}{E}(s) = \frac{G_E\, G_A\, \frac{G_L}{G_M}\, G_M\, Y_C}{1 + G_A\left(G_K + \frac{G_L}{G_M}\, G_M\, G_P\right)}$$

$$= \frac{G_E\, G_A\, G_L\, Y_C}{1 + G_A\,(G_K + G_L\, G_P)} \qquad (2.2.1)$$

If it is assumed that the human operator makes extensive use of either force or position information to formulate control signals for his muscular system, then:

$$G_A \left(G_K + G_L\, G_P\right) >> 1 \qquad (2.2.2)$$

This allows Eq. (2.2.1) to be simplified.

$$\frac{\Theta_C}{E}(s) \cong \frac{G_E\, G_A\, G_L\, Y_C}{G_A \left(G_K + G_L\, G_P\right)} \cong \frac{G_E\, G_L\, Y_C}{G_K + G_L\, G_P} \qquad (2.2.3)$$

McRuer has formulated rules which describe operator frequency response characteristics. These are essentially the same as the "rules of thumb" used by many in the design of control systems. McRuer's characteristics of a "good" control system, such as in Fig. 2.2.2, are repeated in the Table 2.2.1. For manual control, $Y_C(j\omega)$ refers to characteristics of the plant and $Y_P(j\omega)$ to the linear transfer characteristics of the operator. In Table 2.2.1 ω_C, the gain crossover frequency of $Y_P(j\omega)\, Y_C(j\omega)$, is the frequency at which the magnitude of $Y_P(j\omega)\, Y_C(j\omega)$ is unity. For good control characteristics ω_C must exceed the highest frequency present in the input forcing function.

The experimental data of McRuer [37] suggests that the human operator attempts to conform to the conditions of this table whenever possible. It is assumed that to agree with the frequency response characteristics of Table 2.2.1 the human operator has the ability to adjust the characteristics of $G_E(s)$, $G_K(s)$, and $G_P(s)$.

$G_E(s)$ represents the compensation the operator is capable of providing to the input error signal. When forced sinusoidally, a lag ele-

Frequency	Open Loop Transfer Function	Closed Loop Transfer Function
$\frac{\omega}{\omega_C} << 1$	$Y_P Y_C >> 1$	$\frac{Y_P Y_C}{1 + Y_P Y_C} \cong 1$
$\frac{\omega}{\omega_C} \approx 1$	$Y_P Y_C \cong \frac{1}{j\left(\frac{\omega}{\omega_C}\right)}$	$\frac{Y_P Y_C}{1 + Y_P Y_C} \cong \frac{1}{1 + j\frac{\omega}{\omega_C}}$
$\frac{\omega}{\omega_C} >> 1$	$Y_P Y_C << 1$	$\frac{Y_P Y_C}{1 + Y_P Y_C} \cong Y_P Y_C$

Table 2.2.1 Desirable Characteristics of a Closed Loop Control System

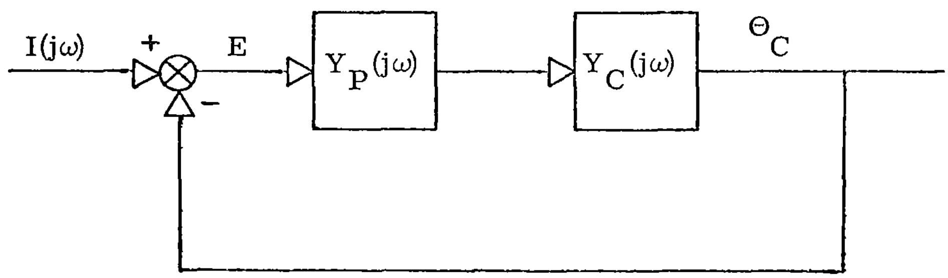

Figure 2.2.2 Generalized Control System as Used in Table 2.2.1.

ment is defined as one whose magnitude decreases with frequency and whose phase angle lags behind its input forcing function. A lead element has characteristics such that its magnitude increases with frequency and whose phase angle leads that of its sinusoidal forcing function.

Under many control situations $Y_C(s)$ is such that the operator is required to add lead compensation through $G_E(s)$ in order to make the open loop transfer function conform to the characteristics of Table 2.2.1. This means that the operator must extract derivative information from the visual error signal. Experimental evidence obtained in Chapter IV and from other sources [10] indicates that control performance is degraded as a function of the amount of lead compensation required of the operator. If $Y_C(s)$ has the especially simple form of a pure gain element, the operator must provide only lag compensation. Since the operator has intrinsic lag properties, this latter requirement is easily fulfilled.

$G_K(s)$ and $G_P(s)$ represent the characteristics of the proprioceptive force and position feedback paths respectively. Physiologically they are related to the neuromuscular spindles, Golgi tendon organs, and joint receptors. Because of the diffuse nature of the neuromuscular transducers it is not possible to establish a direct one-to-one correspondence between the transducers and their representation in the functional block diagram. $G_K(s)$ and $G_P(s)$ represent the overall characteristics of these systems.

It is assumed that the operator is capable of operating solely on the basis of one of the feedback information channels. That is, he is capable of operating solely on the basis of position information, ignoring force, or solely on the basis of force information, ignoring position. In the following two manual control situations the advantage to be obtained from operation in these modes will be considered.

Case 1 considers a manual control task in which the position output of the control stick is used to generate a signal for control of the plant. In case 2 the torque applied by the operator to the control stick is sensed and used as a control signal for the plant. These two cases are studied individually since they lead to different interpretations of the control task.

Case 1 Compensatory tracking using manipulator output, $\Theta_M(s)$ as the control input to the plant

In the compensatory tracking task of Fig. 2.2.1, the output position, Θ_M, of the manipulator is used as the control input to the plant. If Eq. (2.2.2), regarding the gain of the proprioceptive feedback paths, is valid, then Eq. (2.2.1) is simplified in form to Eq. (2.2.3).

If, in Eq. (2.2.3), the operator utilizes only force information in his physiological control loop and position information is rejected, i.e.,

$$G_P(s) = 0 \qquad (2.2.6)$$

then Θ_C/E becomes

$$\frac{\Theta_C}{E}(s) = \frac{G_E\, G_L\, Y_C}{G_K} \tag{2.2.7}$$

From Eq. (2.2.7) we may identify Y_P in Fig. 2.2.2 as

$$Y_P\,(s) = \frac{G_E\, G_L}{G_K} \tag{2.2.8}$$

The operator is now required to adjust $G_E\,(s)$ so that $Y_P(j\omega)\; Y_C(j\omega)$ will take the appropriate form in Table 2.2.1. On the other hand, if the operator utilizes only position information through $G_P\,(s)$ and rejects force information obtained through $G_K\,(s)$, i.e.,

$$G_K\,(s) = 0 \tag{2.2.9}$$

then

$$\frac{\Theta_C}{E}(s) = \frac{G_E\, G_L\, Y_C}{G_L\, G_P} = \frac{G_E\, Y_C}{G_P} \tag{2.2.10}$$

In this case we may identify $Y_P(s)$ in Fig. 2.2.2 as

$$Y_P\,(s) = \frac{G_E}{G_P} \tag{2.2.11}$$

Examination of Eq. (2.2.10) indicates that the use of position information greatly reduces the contribution of $G_L\,(s)$ in the open loop transfer function. This is a desirable situation since the presence of $G_L\,(s)$ requires the operator to provide additional lead compensation with G_E (s) in order to attain the form specified in Table 2.2.1. In the tracking situation described by Eq. (2.2.10), performance would be expected to be degraded as the order of the plant increased but be relatively independent of the manipulator characteristics. In this case, it would seem to be to the benefit of the operator to make extensive use of position cues and to ignore the force cues. As shown above this condition requires G_E (s) to furnish the least amount of lead compensation.

Case 2 Compensatory tracking using operator applied force as the control input to the plant.

Consider the method of control shown in Fig. 2.2.3 in which the force applied by the operator to the manipulator may be used as the control input to the plant. Figure 2.2.3 is a functional block diagram for this condition. In this case:

$$\frac{\Theta_C}{E}(s) = \frac{G_E\, G_A\, \frac{G_L}{G_M}\, Y_C}{1 + G_A\left(G_K + \frac{G_L}{G_M}\, G_M\, G_P\right)} \tag{2.2.12}$$

Assuming that Eq. (2.2.2) involving the magnitude of the proprioceptive feedback cues is valid, Eq. (2.2.12) simplifies to:

$$\frac{\Theta_C}{E}(s) = \frac{G_E\, G_L\, Y_C}{\left(G_K + G_L\, G_P\right) G_M} \tag{2.2.13}$$

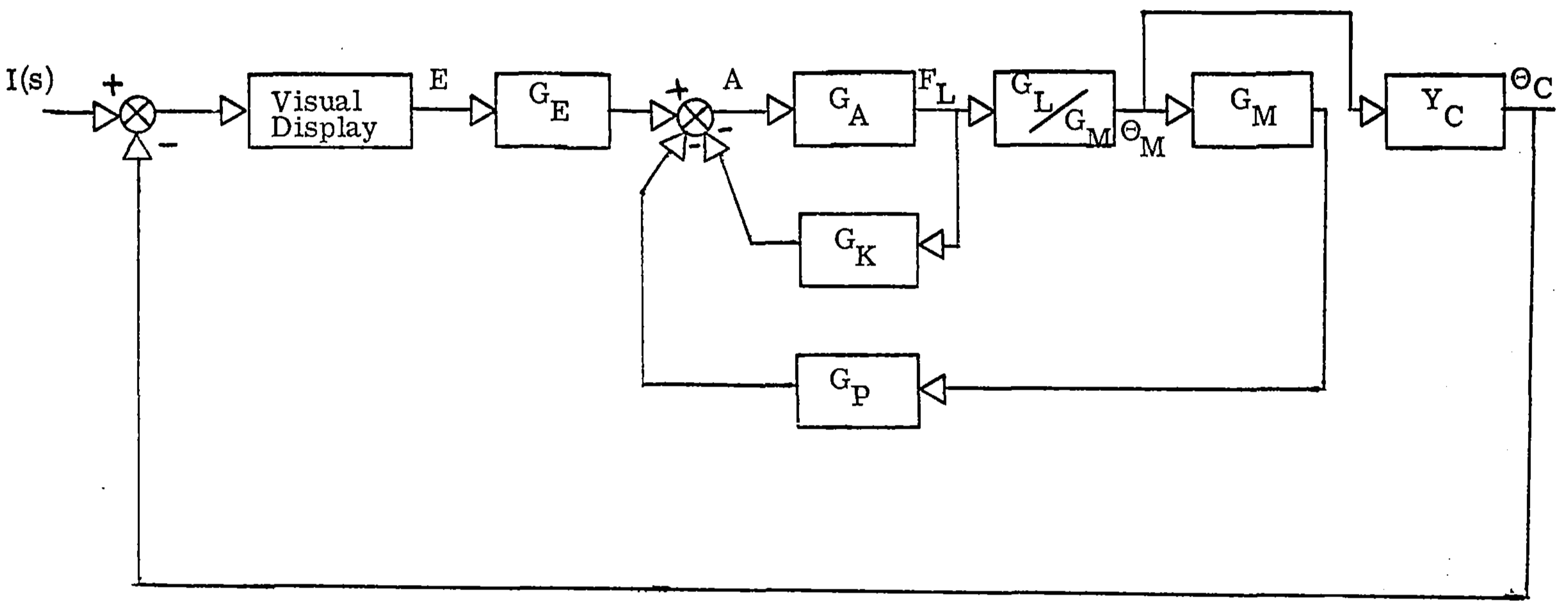

Figure 2.2.3 Functional Block Diagram of the Human Operator in a Compensatory Tracking Task Using Force Applied to the Control Stick as the Control Variable

As in the previous case, exclusive use of proprioceptive position information results in a simpler form of Eq. (2.2.13); i.e., if

$$G_K(s) = 0 \qquad (2.2.14)$$

then

$$\frac{\Theta_C}{E}(s) = \frac{G_E\, G_L\, Y_C}{G_L\, G_P\, G_M} = \frac{G_E\, Y_C}{G_P\, G_M} \qquad (2.2.15)$$

Equation (2.2.15) is of the same form as Eq. (2.2.10) if an apparent plant $\hat{Y}_C$ (s) is defined as

$$\hat{Y}_C(s) = \frac{Y_C}{G_M} \qquad (2.2.16)$$

This means that the manual control situation of Fig. 2.2.1, in which manipulator position is used as the control variable, and that of Fig. 2.2.3, in which force applied to the manipulator is used as the control variable, appear identical to the operator if $\hat{Y}_C$ (s) is the plant used in the first control situation and $Y_C(s)$ is the plant used in the second. Equation (2.2.16) suggests that the apparent plant, $\hat{Y}_C$ (s), can be made to appear in a less complex form than $Y_C(s)$, the actual plant, if $G_M(s)$ is selected in the appropriate manner.

A particularly interesting form of the open loop transfer function of Eq. (2.2.15) results if

$$G_M(s) = Y_C(s) \qquad (2.2.17)$$

Equation (2.2.15) then becomes:

$$\frac{\Theta_C}{E}(s) = \frac{G_E}{G_P}(s) \qquad (2.2.18)$$

G_E / G_P need only provide lag compensation to agree with Table 2.2.1. Since Eq. (2.2.18) is of the same form as Eq. (2.2.10) for $Y_C = 1$, the plant output is a scalar multiple of the control stick position. Another interesting result is that the open loop transfer function is independent of the plant dynamics.

Equation (2.2.15) implies that proper selection of $G_M(s)$ may result in a reduction of the complexity of the control task presented to the human operator. This is achieved by presenting the plant dynamics to the operator in the form of mechanical characteristics of the manipulator. The extensive proprioceptive feedback of the human limb makes control of the manipulator position a rather trivial problem. Since the manipulator and plant are analogs, the application of control inputs which are equal to the torque applied by the human operator to his manipulator, results in a correspondence of output states of the plant and the manipulator.

As another way of looking at this technique, consider the common method used to generate inverse transfer functions with a feedback amplifier. The function whose inverse is desired is placed in the feedback loop of a high-gain amplifier. Providing that the closed loop transfer function has no poles in the right half of the complex s-plane, the output of the amplifier will closely approximate the inverse function over the range of frequencies in which the open loop gain is much greater than unity.

A similar situation occurs when the operator is presented a model of the plant on his control stick. The extensive proprioceptive feedback associated with the human limb has the effect of including the mechanical analog of the plant in the feedback loop of the operator. This allows the operator to assume characteristics similar to those of the inverse plant. When the operator has inverse plant characteristics, the overall dynamics of the open loop system are simplified considerably. This simplification results in improved performance.

When this method of control is used, the control force applied to the plant is a scalar multiple of the reaction force experienced by the operator from the control stick. Proprioceptive force information is of particular value to the operator if the performance criterion involves control effort as well as tracking error. The operator is in a particularly advantageous position to formulate and change control strategies to emphasize either highly accurate tracking performance or minimum use of control effort.

A decision plan must be formulated to determine which of the two previously discussed control methods will give the better performance.

The manipulator position control method of case 1 and the manipulator force control method of case 2 may be compared by using Eq. (2.2.16) to compute an apparent plant for case 2. $Y_C(s)$ and $\hat{Y}_C(s)$ may then be compared. The one which results in the best control performance of the operator should then be selected. In most cases the most desirable plant is the one which requires lag compensation from the operator, a gain element. In some cases experimental evidence may have to be collected in order to make a decision.

If freedom exists in the selection of the manipulator dynamics, $\hat{Y}_C(s)$ may be made to assume the particularly simple form of a pure gain element. Since under this condition the plant requires no lead compensation from the operator, it would seem to provide a promising technique for use in manual control.

There are obviously some control situations in which there is not complete freedom in the selection of the manipulator characteristics. The possibility exists, however, that the $\hat{Y}_C(s)$ obtained using the force control method may be of a more desirable form than $Y_C(s)$. This condition will be examined in the next section.

2.3 Effect of Manipulator Mismatch

One of the questions of importance in the analysis of the matched manipulator technique, which was introduced in the previous section, is the effect of errors which may exist between the parameters of the plant and those of the mechanical analog of the plant. This situation will be called a mismatch and may arise due to restrictions on the manipulator, time variation of the plant, or nonlinearities of the plant. This section will analyze the effect of such mismatches on the control problem presented to the operator.

As an example consider the case of a linear second order plant with transfer function given by

$$Y_C(s) = \frac{K_C}{A_C s^2 + B_C s + 1} \tag{2.3.1}$$

Let the manipulator have the following form:

$$G_M(s) = \frac{K_M}{A_M s^2 + B_M s + 1} \tag{2.3.2}$$

The corresponding pairs of normalized coefficients A_C, A_M and B_C, B_M may not be equal. ϵ_A and ϵ_B are defined in Eq. (2.3.3) and (2.3.4) and represent the difference existing between the corresponding parameters.

$$\epsilon_A = A_M - A_C \tag{2.3.3}$$

$$\epsilon_B = B_M - B_C \tag{2.3.4}$$

The interpretation of the force control as an equivalent position control requires that:

$$\hat{Y}_C(s) = \frac{Y_C}{G_M} \qquad (2.3.5)$$

$\hat{Y}_C$ (s) is the apparent plant when using force as the control variable when Y_C(s) is the true plant, and G_M(s) is the manipulator dynamics. Using Eqs. (2.3.1) through (2.3.4)

$$\hat{Y}_C(s) = \frac{Y_C}{G_M} = \frac{\dfrac{K_C}{A_C s^2 + B_C s + 1}}{\dfrac{K_M}{A_M s^2 + B_M s + 1}} = \frac{A_M s^2 + B_M s + 1}{A_C s^2 + B_C s + 1} \frac{K_C}{K_M} \qquad (2.3.6)$$

$$\hat{Y}_C(s) = \frac{K_C}{K_M}\left[\frac{A_C s^2 + B_C s + 1 + \epsilon_A s^2 + \epsilon_B s}{A_C s^2 + B_C s + 1}\right] \qquad (2.3.7)$$

$$\hat{Y}_C(s) = \frac{K_C}{K_M}\left[1 + \left(\epsilon_A s^2 + \epsilon_B s\right)\frac{Y_C}{K_C}\right] \qquad (2.3.8)$$

The new equivalent $\hat{Y}_C$ (s) is shown in Fig. 2.3.1. The effect of manipulator inaccuracies is to alter the form of the equivalent plant. The result is a more complex apparent plant. The plant output and the manipulator position are no longer related by a scalar multiplier.

$$\frac{\Theta_C}{\Theta_M}(s) = \frac{K_C}{K_M}\left[1 + \left(\epsilon_A s^2 + \epsilon_B s\right)\frac{Y_C}{K_C}\right] \qquad (2.3.9)$$

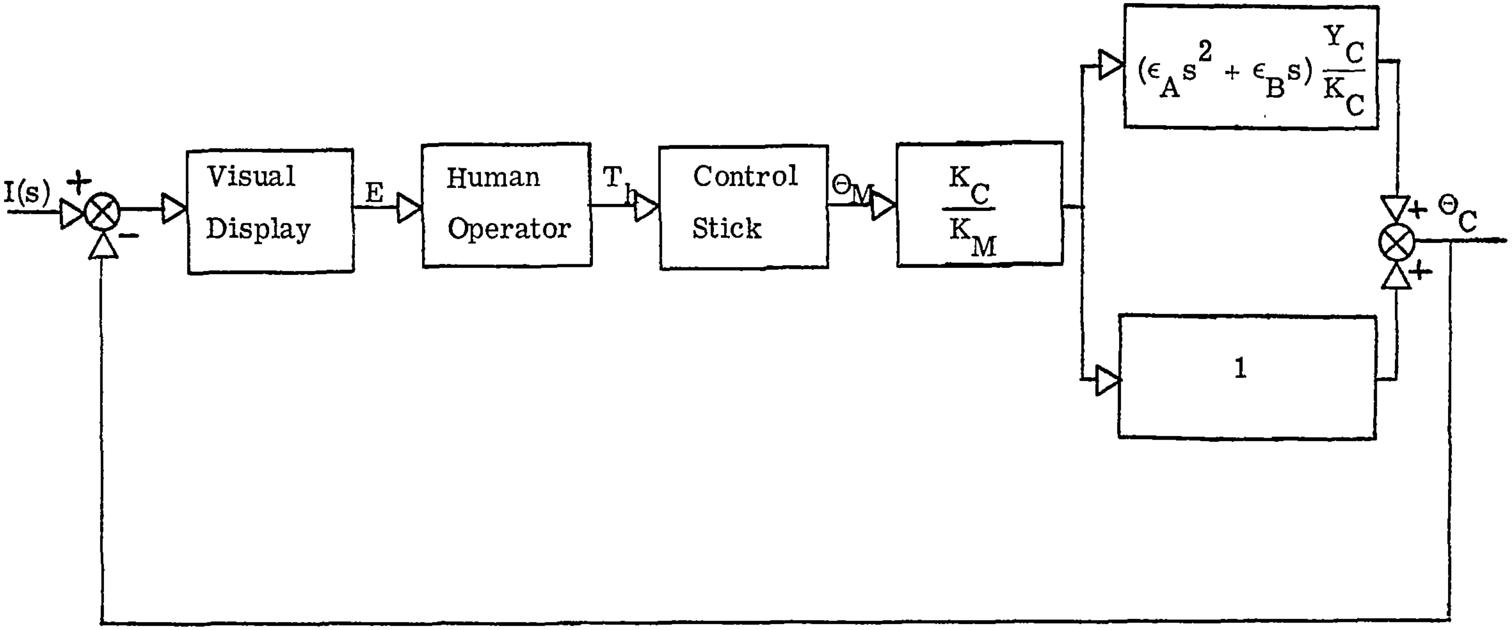

Figure 2.3.1 Effect of Control Stick Parameter Mismatch Interpreted as an Equivalent Plant.

$$\Theta_C(s) = \frac{K_C}{K_M}\left[\Theta_M + \left(\epsilon_A s^2 + \epsilon_B s\right)\frac{\Theta_M Y_C}{K_C}\right] \tag{2.3.10}$$

The error between the control stick position and the plant output is:

$$\Theta_C - \frac{K_C}{K_M}\Theta_M = \left(\epsilon_A s^2 + \epsilon_B s\right)\Theta_M \frac{K_C}{K_M} \tag{2.3.11}$$

K_C/K_M is a scaling factor relating the manipulator output to the plant output.

To maintain the advantage of having $\hat{Y}_C(s)$, the apparent plant, take the form of a gain element, the error term of Eq. (2.3.11) should be kept as small as possible. This error may be interpreted from Eq. (2.3.11) as the output of the actual plant with a forcing function of the first and second time derivatives of the manipulator output position.

For best results $Y_C(s)$ should be stable and not have poles on the $j\omega$ axis of the complex plane. This assures that the error will tend to zero in the steady state.

2.4 Limitations of the Use of the Matched Manipulator Technique

In this section the limitations on the use of the matched manipulator control technique will be considered. Elementary set theory will be used as a basis of the presentation.

A function consists of three objects: two non-empty sets X and Y (which may be equal, but need not be) and a rule, f, which assigns to each element x in X a single fully determined element y in Y. The y which corresponds in this way to a given x is usually written f(x) and is called the image of x under the rule f. The set X is called the domain of the function, and the set of all f(x)'s for all x in X is called the range. This type of relationship may be shown pictorially as in Fig. 2.4.1.

Let us consider a function f which maps elements of X into Y. By "into" it is meant that as x assumes all values in X, f(x) need not assume all possible values of Y. If f(x) does assume all possible values of Y the function is said to be a mapping of X onto Y. If any two unique elements in X always have unique images in Y, the function is said to be one-to-one. If f is such that it is both one-to-one and onto then an inverse function of f may be defined. For each value y in Y there exists a unique value x in X. We can then define $x = f^{-1}(y)$. Figure 2.4.2 illustrates the concept of an inverse function.

Figure 2.4.3 is a representation of a manual control scheme which uses the position output of the manipulator as the control input to the plant. $T_h(s)$ represents the set of operator applied torques. $G_M(s)$, the manipulator dynamics, relates these applied torques to a deflection of the control stick, which is represented by the set $\Theta_M(s)$. $Y_C(s)$ is the function which relates the manipulator deflection to $\Theta_C(s)$ which is the set of all possible plant outputs.

Figure 2.4.4 is a similar representation for the control technique of Section 2.2. Since $G_M(s)$ is selected to agree with $Y_C(s)$, there is a correspondence of elements in the sets $\Theta_M(s)$ and $\Theta_C(s)$. Under this

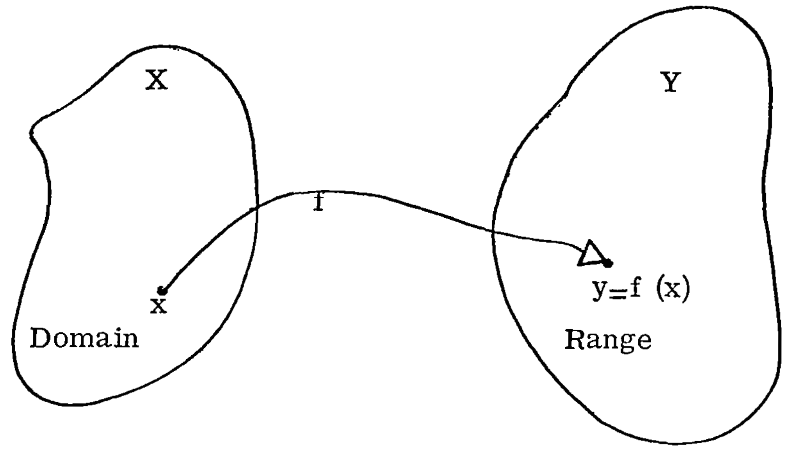

Figure 2.4.1 Graphical Representation of a Function.

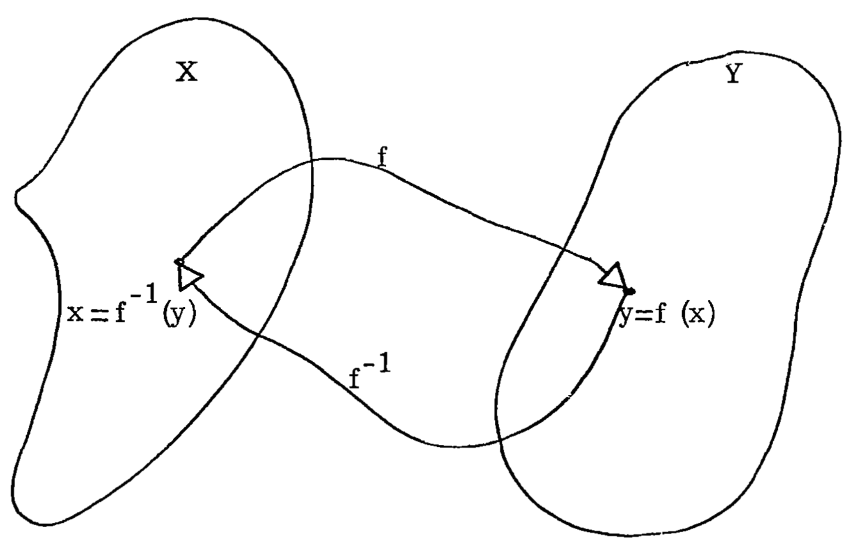

Figure 2.4.2 Graphical Representation of a Function and its inverse.

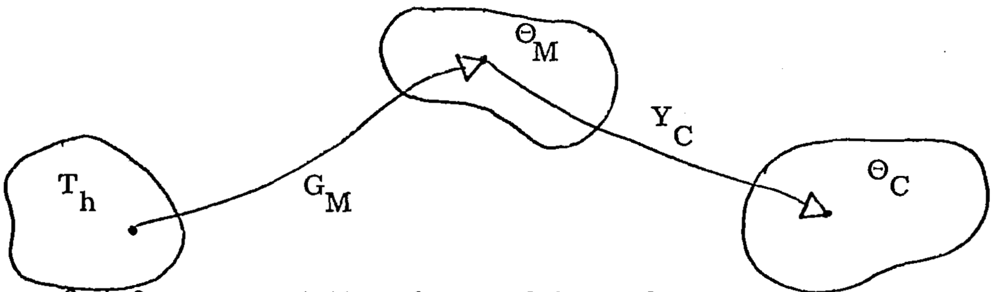

Figure 2.4.3 Representation of Manual Control Using a Position Control Stick.

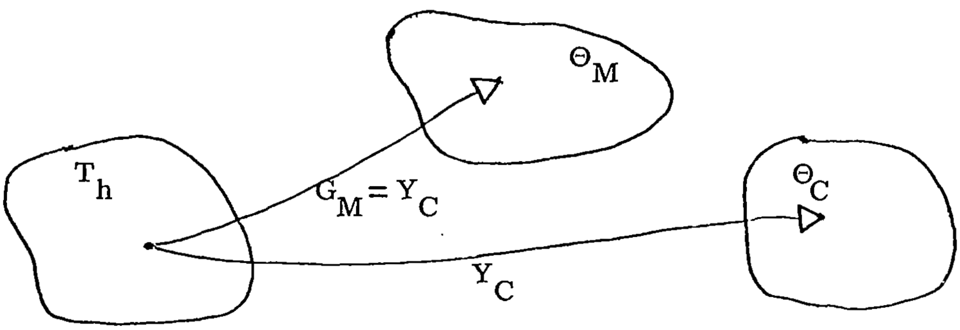

Figure 2.4.4 Representation of Manual Control Technique in which The Control Stick is a Mechanical Analog of the Plant.

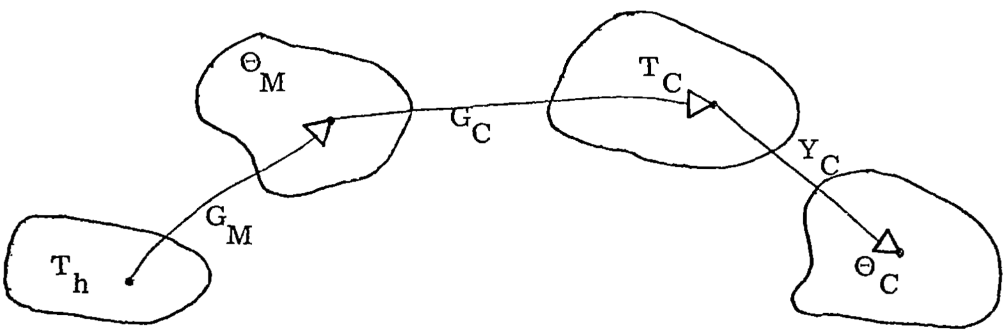

Figure 2.4.5 Effect of Adding Forward Loop Compensation, G_C, in Manual Control Task Using a Position Control Stick

condition when two sets are identical except for their designations, they are called isomorphic. Under the conditions of this control technique the set of manipulator outputs and the set of plant outputs are isomorphic. In order to retain this isomorphic relationship, $Y_C(s)$ must have characteristics of a function as defined above. In particular $Y_C(s)$ must be stable so that there is a fully determined plant output for every plant input.

Figure 2.4.5 shows the result of adding additional compensation between the control stick and the plant when using position control. To retain an association between the manipulator output position and the plant output, $G_C(s)$, must be a well defined function.

If $G_C(s)$ is selected to be of the form of the inverse of $Y_C(s)$, the combination of the plant, the inverse appears to the operator as a unity gain element. This is the same form in which the apparent plant $\hat{Y}_C(s)$ appears to the operator when using the matched manipulator technique. There are several limitations to the use of such compensation. Since such an inverse will usually require derivatives of the manipulator output position, this function will be difficult to formulate and will be extremely sensitive to noise present in the system. Making $G_M = Y_C^{-1}$ has the same problem.

Another limitation arises if the inverse of the plant is not uniquely defined over the entire domain of the plant output. Such a situation would occur if the function describing the plant were not one-to-one. Under such circumstances more than one input could result in the same plant output

As an example of such a situation, consider the case of a plant whose output is velocity limited. An increase in the control effort would have no effect in increasing the plant velocity. The function is well defined but its inverse is not. Also, an unstable plant has the same problem.

In considering the applicability of the matched manipulator control technique, there are several limitations. The plant to be controlled must be stable over some finite domain of output states. The coefficients of the differential equation describing the plant must be scaled such that they may be interpreted as physical characteristics of the control stick. For plants of higher than second order, either reasonably complex systems must be used to construct the manipulator characteristics or only a partial implementation of the control technique, as considered in Section 4.2, must be used.

The presence of plant nonlinearities may somewhat affect the performance of the operator using the technique. Gain changing nonlinearities may be handled in a straightforward manner. Characteristics such as limiting will result in a corresponding characteristic being experienced on the control stick. Product nonlinearities, which would involve an interaction among the stste variables of the plant output, are difficult to interpret in a mechanical manner but present no limitation to the usefulness of the technique. Nonlinearities involving the time history of the plant such as hysterisis are difficult to simulate. With nonlinearities of this type there is also no assurance that small errors in correspondence between the control stick and the plant output will tend to correct themselves.

This discussion indicates that the restrictions involved inthe application of the technique of Section 2.2 are not as severe as those resulting from the introduction of the plant inverse as an additional compensation between manipulator output and plant input. The experimentation os Section 4.4 will further consider the difficulties which are encountered when the function representing the plant does not have an inverse.

2.5 Implementation of the Technique

To implement the technique introduced in Section 2.2, a manipulator is constructed to have physical characteristics analogous to those of the plant. Both are described by the same ordinary differential equations. The control situation is then as shown in Fig. 2.5.1.

As an example of an application of this technique, consider the situation shown in Fig. 2.5.3. The voltage source, $e_i(t)$, is adjustable. The manual control problem is to adjust the voltage, $e_i(t)$, such that the voltage on the capacitor, $e_o(t)$, corresponds to a value indicated by an input signal. The relationship between $e_i(t)$ and $e_o(t)$ is a liner differential equation as indicated in Eq. (2.5.1).

$$e_i(t) = L\ddot{q} + R\dot{q} + \frac{q}{C} \qquad (2.5.1)$$

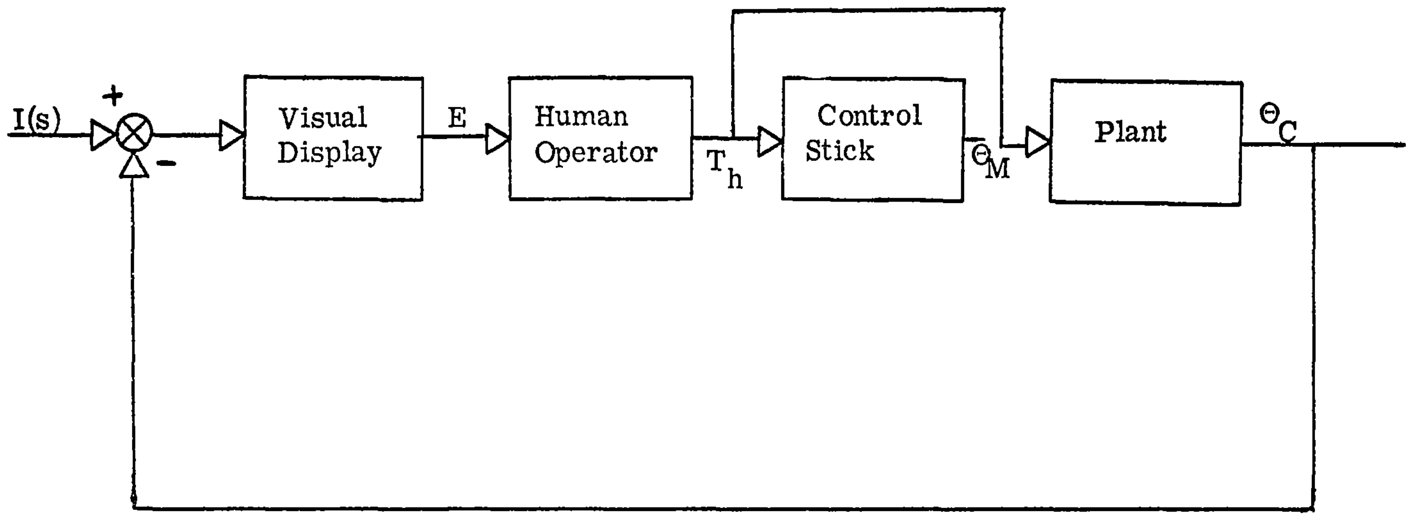

Figure 2. 5. 1 Manual Control Technique in which the Control Stick is a Mechanical Analog of the Plant

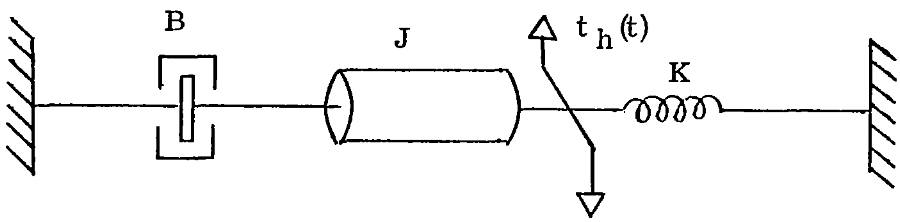

Figure 2.5.2 Mass, Spring, Damper Mechanical System

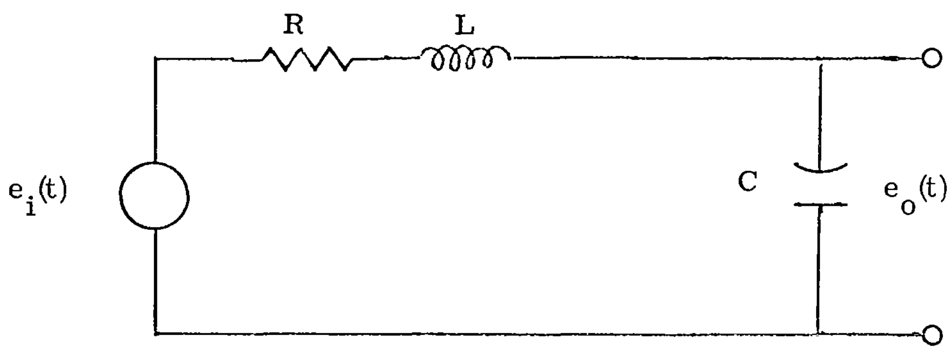

Figure 2.5.3 Electrical Analog of a Mass, Spring, Damper Mechanical System.

In this equation L is the inductance of the circuit, R is the resistance, and C is the capacitance. The variable q represents the electrical charge in the circuit. Equation (2.5.1) may be stated in terms of the output voltage, $e_o(t)$ as follows:

$$e_o(t) = \frac{q(t)}{C}$$

$$\dot{e}_o(t) = \frac{\dot{q}(t)}{C}$$

$$\ddot{e}_o(t) = \frac{\ddot{q}(t)}{C}$$

$$e_i(t) = LC\ddot{e}_o + RC\dot{e}_o + e_o \qquad (2.5.2)$$

The differential equation describing the angular displacement of the mechanical control stick of Fig. 2.5.2 is:

$$t_h(t) = J\ddot{\theta} + B\dot{\theta} + K\theta \qquad (2.5.3)$$

t_h is the applied torque, J the moment of inertia, B the coefficient of viscous friction, and K the spring constant of the system shown in Fig. 2.5.2. The electrical circuit of Fig. 2.5.3 and the mechanical circuit of Fig. 2.5.2 are analogs if they are represented by the same differential equation. That is

$$J = kLC \qquad (2.5.4)$$

$$B = k\,RC \tag{2.5.5}$$

$$K = k \tag{2.5.6}$$

$$t_h(t) = k\ e_i \tag{2.5.7}$$

The coefficient k in the above equations is a scaling constant and is selected such that the torque required of the operator is not excessive.

If the manipulator is constructed to have the characteristics specified by Eqs. (2.5.4), (2.5.5), (2.5.6), the manipulator and plant are analogs. Torque applied by the operator to the manipulator must be sensed and scaled according to Eq. (2.5.7) to provide the proper input for control of the plant.

The manual control problem is abstracted from the domain in which it is presented, converted to an analogous mechanical control problem, and presented to the human operator in mechanical form. The control action of the operator is then converted back to the original variables of the problem. The original form of the problem is immaterial to the operator.

In Chapter III experimental evidence is presented which verifies many of the ideas presented in this chapter. The experiments conducted indicate the performance improvement that is possible with the technique of Section 2.2. In Chapter IV the technique developed in this chapter is extended to include linear systems with time delay, linear systems of higher than second order, unstable linear systems, and nonlinear systems. Experimental results for each of these cases are also included.

CHAPTER III

EXPERIMENTAL VERIFICATION

3.0 Abstract

This chapter contains experimental evidence which supports many of the statements made in conjunction with the functional block diagram of the human operator. The technique for artificially providing force and position cues to the operator is evaluated experimentally for a linear plant. The technique resulted in improved performance when compared with standard manual control methods.

3.1 Introduction

This chapter is concerned with experimentally verifying many of the statements and analytic conclusions presented in Chapter 2. The main objectives were to validate the human operator functional block diagram and to establish that the control technique developed from an analysis of the block diagram is capable of improving operator control performance.

It is felt that the matched manipulator control technique has many possible applications. The experimental portion of this research will try to include a wide representative sample of these applications. Most of the experiments are exploratory in nature and are performed with only one or two operators. In these studies only large performance variations will be considered significant.

Experiment 1 in Section 3.2 examined two manual control situations for the purpose of verifying the presence of G_P, proprioceptive position feedback information. In the first condition a linear constant coefficient plant was presented in the form of manipulator characteristics. In the second the dynamics were computer simulated and controlled by an immovable force stick. In the first case the subject received full force and position proprioceptive cues. In the second only force cues were available.

In Experiment 2 in Section 3.3 the operator was presented with the task of controlling separately several linear manipulator characteristics. These ranged from fairly common configurations, such as springs and viscous friction, and also included such unusual sensations as negative friction, negative spring, and time varying parameters. This experiment examined the ability of the operator to make use of proprioceptive position feedback to minimize the effects of the manipulator characteristics.

In Experiment 3 of Section 3.4 the matched manipulator technique was applied to an underdamped second order linear system. Performance of the operator was then compared to that resulting from control of the same plant with a position control stick.

The variable dynamics control stick which was used extensively in this experimentation is discussed in detail in Chapter V. This device allowed a wide range of manipulator characteristics to be easily and accurately presented to the operator. Since the characteristics are formulated electronically on the analog computer, it was easy to provide time variation of the parameters, instabilities, and nonlinearities.

3.2 Experiment 1, Verification of the Presence of Proprioceptive Position Cues

The purpose of this experiment was twofold. First it was desired to establish experimentally the presence of proprioceptive position cues. The second goal was to show that the presence of these cues resulted in impro performance in a compensatory tracking task.

In Chapter II it was hypothesized that the human operator is capable of utilizing proprioceptive position cues to improve performance in manual control tasks. This information is represented as $G_P(s)$ in Fig. 2.2.1. In order to establish the presence of this path, two methods of controlling plant dynamics were considered. In the first method known as on-stick dynamics, a mechanical analog of the plant was presented to the human operator. In the second condition known as off-stick dynamics, the same plant was simulated on the analog computer and was subject to control from an immovable force stick. Conditions were adjusted so that the overall relationship between force and plant output in the two systems was identical.

In the on-stick dynamics case the system dynamics were provided by the variable dynamics control stick. The parameters selected were

$K = 2$ lb-ft per radian, $J = .075$ lb-ft per radian per second^2, and a viscous friction term of .1 lb-ft per radian per second. The differential equation representing the control stick was:

$$t_h(t) = .075\, \ddot{\theta}_M + .1\, \dot{\theta}_M + 2\, \theta_M \qquad (3.2.1)$$

The first term on the right side of the equation represents the contribution of the control stick moment of inertia. The second and third terms representing spring constant and viscous friction were simulated electrically using the variable dynamics circuitry. This system is underdamped with a damping ratio of .13 and an undamped natural frequency of 5.1 radians per second.

In the second test condition, the arm of the variable dynamics control stick was rigidly coupled to a motionless force transducer. A voltage proportional to force was presented to the system dynamics on the analog computer. The relationship between the human torque input and the system output was identical to that used in the on-stick dynamics condition.

All testing was performed in an enclosed booth which contained only the operator and necessary equipment. A test condition is shown in Fig. 3.2.1. The booth was constructed to allow the operator to be as free as possible from external disturbances which might detract

Figure 3.2.1 Test Conditions for Experimentation

from his performance. Each operator wore headphones which emitted low volume white noise which masked any auditory cues from the booth or its surroundings. The experimenter was able to interrupt the noise source to converse with the operator.

Performance was computed on the basis of the integral squared error. The ratio of the integral squared error to the integral squared input signal is known as the normalized performance index. Had the operator not exhibited any control action and left the control stick in its center position the resulting normalized performance index would be 1.00. The lower the score the better the performance. The subjects were informed of the nature of the scoring. Only the last two minutes of each test period were used for scoring purposes. This allowed a fifteen second warmup period for the subject and the recording equipment. After each test the subject was informed of his error score.

An input forcing function for the closed loop system was obtained from a shift register generator. To obtain a random appearing signal, the output of an 18 stage shift register generator was filtered with a low pass filter of the form:

$$H(j\omega) = \frac{C_1}{\left(1 + j\,\frac{\omega}{\omega_C}\right)^2}$$

It was possible to vary the degree of difficulty of the problem by adjusting ω_C, the cut-off frequency of the filter. A low cut-off frequency would provide an easy signal to track while a higher cut-off frequency would make the task more difficult. For this experiment the filter had a cut-off frequency of 1 radian per second. The amplitude distribution of the input forcing function was measured and found to be approximately Gaussian with a zero mean value. Further details of the noise source are presented in Appendix A.

The system error was displayed with a Fairchild oscilloscope that was positioned approximately twenty-four inches from the operator. The magnitude of the error was indicated by the horizontal deflection of a dot from a stationary center line on the oscilloscope screen. The display gain was adjusted so that 2 1/2 inch deflection was equivalent to a tracking error of two volts. Two volts corresponded to a position control stick deflection of one radian or the application of two pound-feet of torque to the stationary force stick. The forcing function was adjusted so that the input signal never required a control action in excess of either one radian of displacement or two pound-feet of torque.

Six paid subjects were used for this experiment. All were subjected to ten 2-minute pre-test trials in a tracking task different from those used in the major experiment. On the basis of the results in the pre-test, the subjects were divided into two matched groups for the remaining five days of experimentation.

The on-stick group was tested for two days in the on-stick dynamics apparatus followed by one day in the off-stick dynamics apparatus, then one day in the on-stick apparatus, and the final day in the off-stick apparatus. The off-stick group was subjected to a similar program but began the experiment in the off-stick condition. One day of testing consisted of twelve trials each lasting two minutes and fifteen seconds. Approximately forty-five seconds of rest followed each trial.

Results and Conclusions

All of the subjects had performance characteristics which were somewhat similar. Data obtained from averaging among each group of three subjects is presented in Fig. 3.2.2.

To interpret the results of this experiment, consider Eq. (2.2.3) which is repeated as Eq. (3.2.1).

$$\frac{\Theta_C}{E}(s) = \frac{G_E\, G_L\, Y_C}{G_K + G_L\, G_P} \qquad (3.2.1)$$

In the on-stick dynamics case the plant was present as a part of $G_L(s)$. $Y_C(s)$ was a unity gain element. In the off-stick dynamics case $Y_C(s)$ contained the plant dynamics and $G_L(s)$ was a unity gain element. For both cases the resulting combination of $G_L(s)Y_C(s)$ was the same.

To establish the presence of $G_P(s)$ again consider Eq. (3.2.1). For both test situations the operator experienced reaction forces

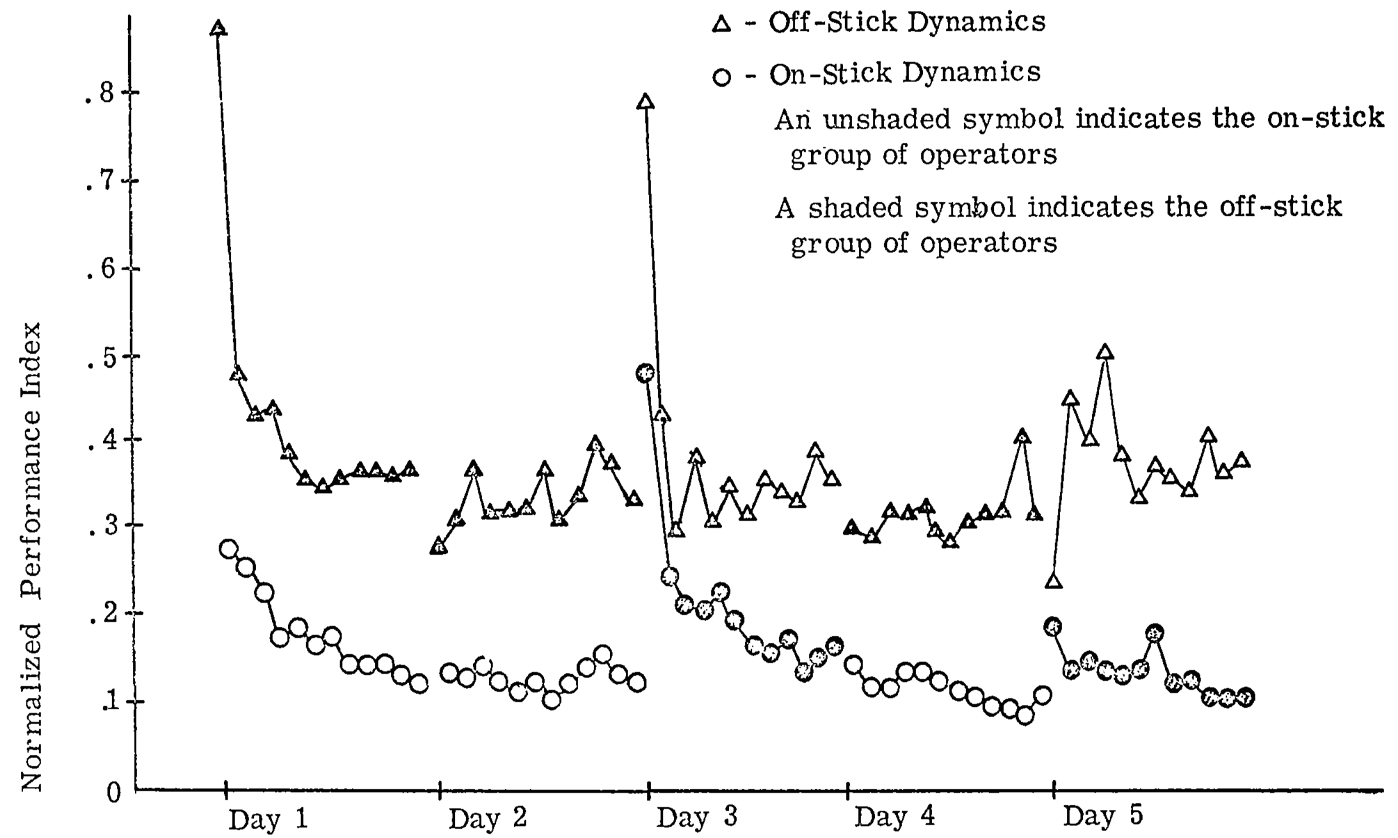

Figure 3.2.2 Average Operator Performance in Compensatory Tracking Task as a Function of Test Condition and Days of Training.

from the control stick. In the off-stick dynamics case the immobility of the control stick eliminated the possibility of obtaining proprioceptive motion cues. If the proprioceptive position path, $G_P(s)$, does not exist in the operator for the on-stick dynamics, Eq. (3.2.1) is identical for the two cases. This condition is indicated in Eq. (3.2.3) if

$$G_P(s) = 0 \tag{3.2.2}$$

then Eq. (3.2.1) becomes

$$\frac{\Theta_C}{E}(s) = \frac{G_E \, G_L \, Y_C}{G_K} \tag{3.2.3}$$

Under these conditions Eq. (3.2.3) assumes the same form for both test conditions. If this were the case, similar performance would be expected in both experimental situations. Since the results of this experiment indicate performance differences for the two cases, the assumption that $G_P(s) = 0$ is not supported by the experimental data obtained in this experiment.

The experimental results show that performance was superior with the on-stick dynamics. Since proprioceptive force information was available in both cases, this indicates that when possible the human utilizes position feedback to improve performance.

A possible explanation for the performance improvement in the on-stick dynamics situation may be obtained by examining Eq. (3.2.1).

If we make the assumption that the operator makes extensive use of proprioceptive position information and ignores the force cues, Eq. (3.2.1) then becomes:

$$\frac{\Theta_C}{E}(s) = \frac{G_E\, G_L\, Y_C}{G_L\, G_P} = \frac{G_E\, Y_C}{G_P} \qquad (3.2.3)$$

The availability of proprioceptive position feedback information allows the operator to eliminate the effects of the manipulator characteristics. Since $Y_C = 1$, the external plant requires only lag compensation and the control problem becomes relatively simple.

When the operator is deprived of position cues, as in the off-stick dynamics condition, Eq. (3.2.1) becomes:

$$\frac{\Theta_C}{E}(s) = \frac{G_E\, G_L\, Y_C}{G_K} \qquad (3.2.4)$$

The dynamics included in Eq. (3.2.4) are more difficult than those in Eq. (3.2.3). This causes the performance in the off-stick dynamics condition to be poorer than that in the on-stick condition.

Learning trends are evident in the data representing both sets of experimental conditions. It is interesting to note that there are negligible transfer effects associated with the two conditions. Experience in one test condition was apparently of little aid in preparing the operator for the other test condition.

This experiment indicates that the joint presence of force and position feedback information results in better performance than the presence of force information alone. This conclusion is in agreement with the experimental evidence provided by Notterman and Page [41].

The describing function, which is a linear approximation to a non-linear element's transfer characteristics for a particular class of forcing functions, is a useful tool for the analysis of nonlinear systems [49]. The reader is referred to Appendix C for a discussion of random input describing functions and their experimental calculation.

Figure 3.2.3 represents the overall open-loop transfer function $Y_P(j\omega)Y_C(j\omega)$ for the test condition in which the plant dynamics were presented to the operator in the form of mainpulator characteristics. Figure 3.2.4 shows $Y_P(j\omega)Y_C(j\omega)$ when the plant dynamics were computer simulated and controlled by an immovable force stick. Each of these curves was computed from ten minutes of tracking data.

An attempt was made to fit each of the describing function, by the method described in Appendix C, with a transfer function of the form:

$$Y_P(j\omega)Y_C(j\omega) = \frac{K_h e^{-j\omega\tau_h}}{j\omega + a_h}$$

The transfer function approximation to the describing function is plotted as a solid line in each of the figures. $Y_P(j\omega)Y_C(j\omega)$ represents the combined open loop transfer function of the operator and the plant.

For each of these test conditions it was possible to select values of the three parameters of Eq (3.2.5) to enable the transfer function

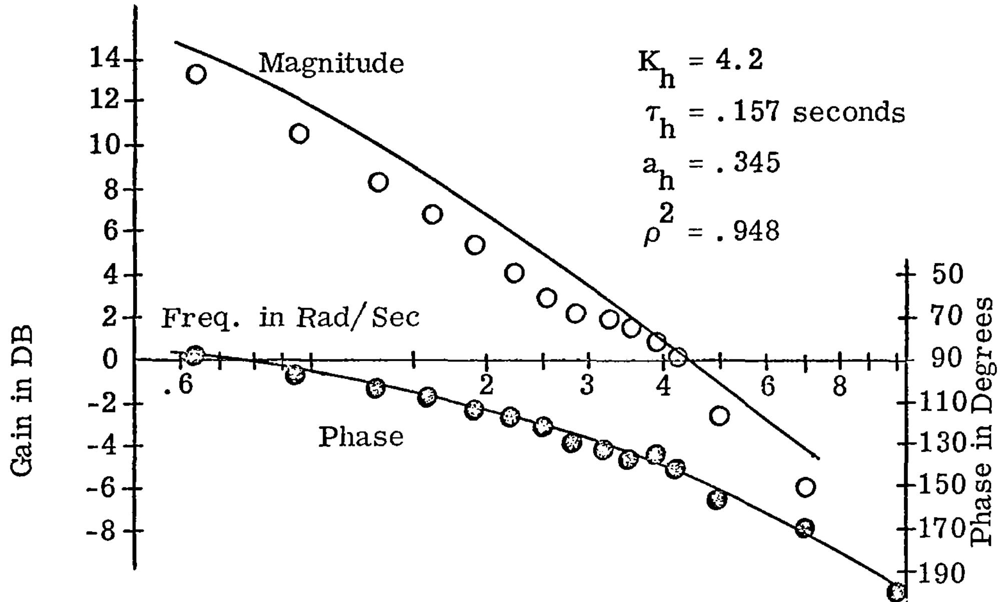

Figure 3.2.3 Describing Function Representation of $Y_P(j\omega)Y_C(j\omega)$ in On-Stick Dynamics Condition of Experiment 1. Solid Lines Represent Linear Transfer Function Approximation

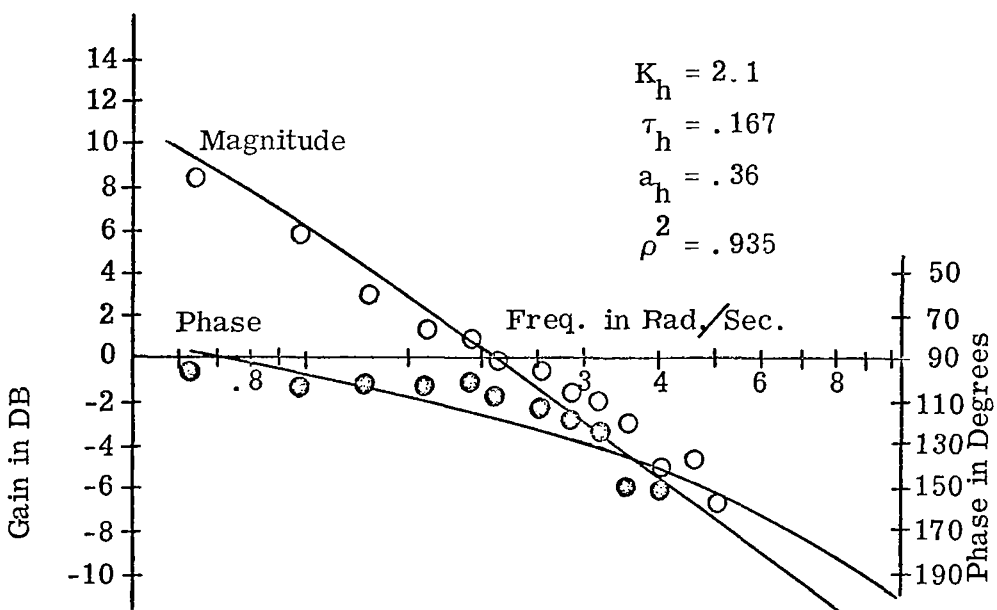

Figure 3.2.4 Describing Function Representation for $Y_P(j\omega)Y_C(j\omega)$ in Off-Stick Dynamics Condition of Experiment 1. Solid Lines Represent Linear Transfer Function Approximation.

to represent the experimental data reasonably well. The parameters of the transfer function, as indicated on the figures, were obtained by the methods discussed in the Appendix C. The value of ρ^2 indicates the ratio of the signal power accounted for by the describing function to the total signal power present in the plant output. This could be considered as a measure of the usefulness of the describing function representation of the combined operator and plant.

For the data of Fig. 3.2.3, a value for K_h of 4.2 was utilized by the operator. The computed value of $\tau = .157$ seconds is shorter than the value of reaction time normally obtained by experimental means with human subjects. The time delay computed in this experiment is based on a continuous control process whereas reaction times are usually based on discrete responses. This could account for the difference.

Figure 3.2.4, which represents the combined open loop characteristics of the operator and plant in the off-stick dynamics test condition, is represented by different values in the transfer function approximation. The most noticeable change in the describing function data in these two cases is the large decrease in the gain parameter. Under the conditions of the experiment, rapid control action often resulted in oscillation of the plant. The decrease in gain noted under these conditions could possibly be attributed to the operator's desire to avoid uncontrolled oscillation. It was therefore probably related to the operator's appraisal of the stability of the system.

The calculated value of the time constant for this experiment was about the same as that obtained from the previous data.

The describing functions shown in Figs. 3.2.3 and 3.2.4 are in very close agreement to the characteristics obtained by McRuer in his experiments with pilots [37]. The agreement of these characteristics to Table 2.2.1 is also very evident.

As noted in Appendix C, there are certain restrictions which must be imposed concerning the interpretation of these describing functions. They were obtained from random input forcing functions. Different results might be obtained for a different class of input forcing functions. The effect of plant gain is also discussed in the appendix. McRuer has studied this condition [37] and found that variations in plant gain tend to affect the low frequency characteristics but not the characteristics of the describing function near and above the gain crossover frequency.

3.3 Experiment 2, Control of Unstable and Nonstationary Plants when Presented as Manipulator Characteristics

The results of the previous experiment indicate that the joint presence of force and position proprioceptive cues result in better performance than the presence of force cues alone. Since only one set of plant characteristics was examined, it is not possible to determine from this data whether the operator was capable of using proprioceptive position feedback to minimize the effects of the manipulator characteristics or whether he became highly skilled with the dynamics presented.

The following experiment was designed to include a very broad range of manipulator configurations. Many were selected because they were out of the range of ordinary human operator experience. The ability of the operator to maintain relatively constant performance with a wide variety of manipulator characteristics would provide further evidence to suggest that it was proprioceptive position information and not a knowledge of the plant which was responsible for the performance differences noted in Experiment 1.

In the first part of this experiment, operator performance was measured with several values of spring constant and viscous friction with $Y_C = 1$. The coeficient values selected were:

$$K_1 = 2 \text{ lb-ft/radian} \tag{3.3.1}$$

$$K_2 = 0 \text{ lb-ft/radian} \tag{3.3.2}$$

$$K_3 = -2 \text{ lb-ft/radian} \tag{3.3.3}$$

$$B_1 = .8 \text{ lb-ft/radian/second} \tag{3.3.4}$$

$$B_2 = .3 \text{ lb-ft/radian/second} \tag{3.3.5}$$

$$B_3 = 0 \text{ lb-ft/radian/second} \tag{3.3.6}$$

$$B_4 = -.1 \text{ lb-ft/radian/second} \tag{3.3.7}$$

A trial consisted of two minutes of tracking with one of the above characteristics added to the control stick. The manipulator moment of inertia which was reduced to

$$J = .040 \text{ lb-ft/radian/second}^2 \tag{3.3.8}$$

was present in all the conditions.

Two subjects who had participated in Experiment 1 were used in this experiment. Each operator controlled each of the conditions presented in random order a total of five times. A random signal filtered at two radians per second, as described in Appendix A, was used as an input forcing function. The normalized performance index based on the integral of the squared error was again used as in Experiment 1.

In the second part of this experiment the spring and viscous friction parameters were varied sinusoidally through the values studied in Part 1. This time variation was included to indicate conclusively that it was limb feedback and not the operator's "learning" of the plant which was accounting for invariance in performance.

Three sinusoidal frequencies were selected for the periodic variation of the parameters. The lowest was selected to provide a rate of variation which was relatively slow compared to the time scale of operator activity. At the low frequency, a complete cycle of the parameter value required ten seconds. At the intermediate frequency of 4.4 radians per second, the operator was supplying an appreciable amount of control signal power. The highest frequency of parameter variation, 25 radians per second, was selected to coincide with the natural tremor frequency of the human upper limb.

Values of the parameters were varied as indicated in Eq. (3.3.9) and (3.3.10). These equations were chosen so that the parameter would reach each of the extremes used in the first part of the experiment.

$$K = 2 \sin \omega t \tag{3.3.9}$$

$$B = .35 + .45 \sin \omega t \tag{3.3.10}$$

Results and Conclusions

Figure 3.3.1 shows the average performance for each of the spring constants tested. The operator provided slightly better control capability for the two extremes of spring constant.

An attempt was made to compare performance with the same plant simulated on the computer. It was not possible to obtain data with the unstable plants due to the inability of the operator to hold the target on the display screen.

Although there was some variation of performance associated with changes in the spring constant, these variations were rather small

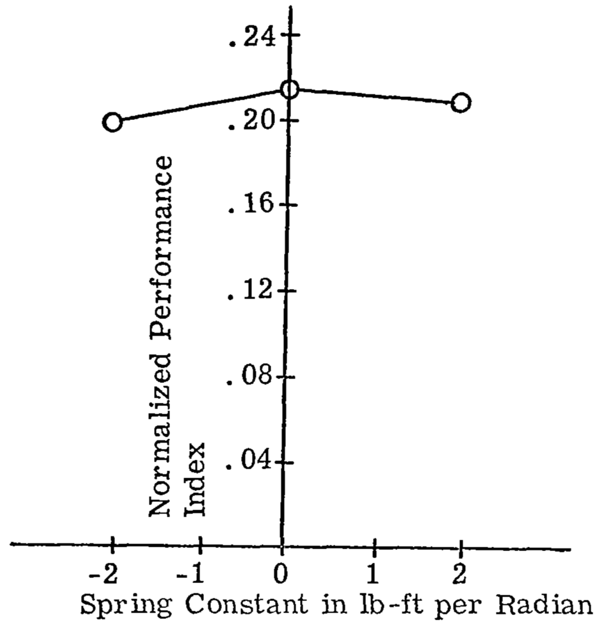

Figure 3. 3. 1 Control Performance as a Function of Control Stick Spring Constant

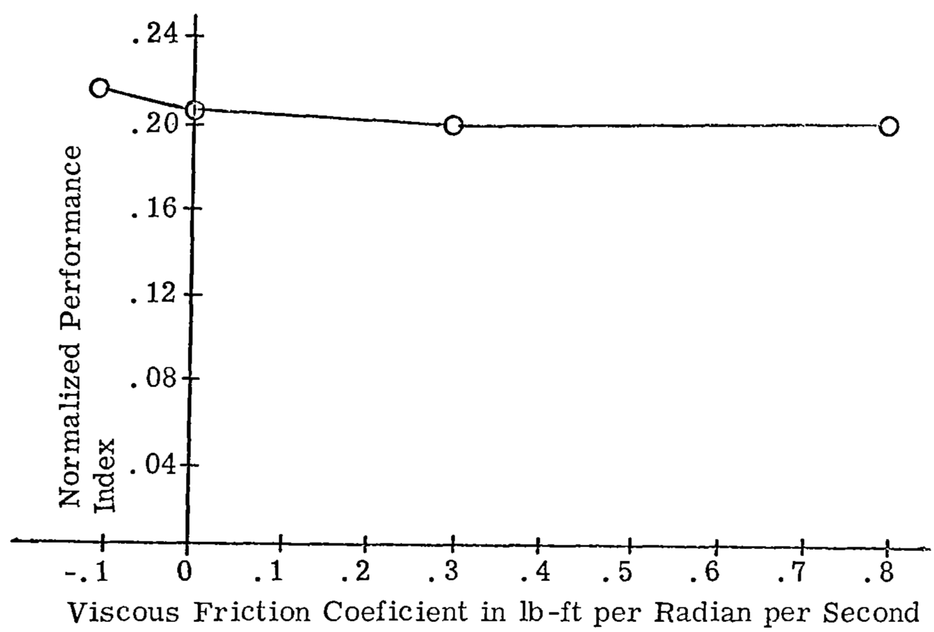

Figure 3. 3. 2 Control Performance as a Function of Viscous Friction Coeficient

compared to those resulting when position cues are not present. The operator expressed a preference for the positive spring. He attributed his better performance with the negative spring to the increased concentration on the task demanded by the unstable system.

Figure 3.3.2 indicates the operator performance resulting from control of the three values of viscous friction. The variation in performance was relatively slight. Of particular interest was the lack of any outstanding performance difference between the stable control stick with the positive viscous friction and the unstable control stick containing the negative viscous friction. The operator stated a preference for the positive viscous friction.

The effect of time variations in the spring and viscous friction are shown in Figs. 3.3.3 and 3.3.4. The performance variation is relatively slight. In the case of the time varying spring constant the operator sensed two distinct conditions depending on the frequency of the variation. For the lowest frequency, the operator sensed that indeed the spring constant was changing. For the higher frequencies the operator had the sensation that a sinusoidal disturbance torque was being applied to the control stick. The similar performance in all of these cases indicates that the operator was capable of operating quite consistently even when his control stick was exhibiting these rather strange characteristics.

The describing function representation of the combined operator

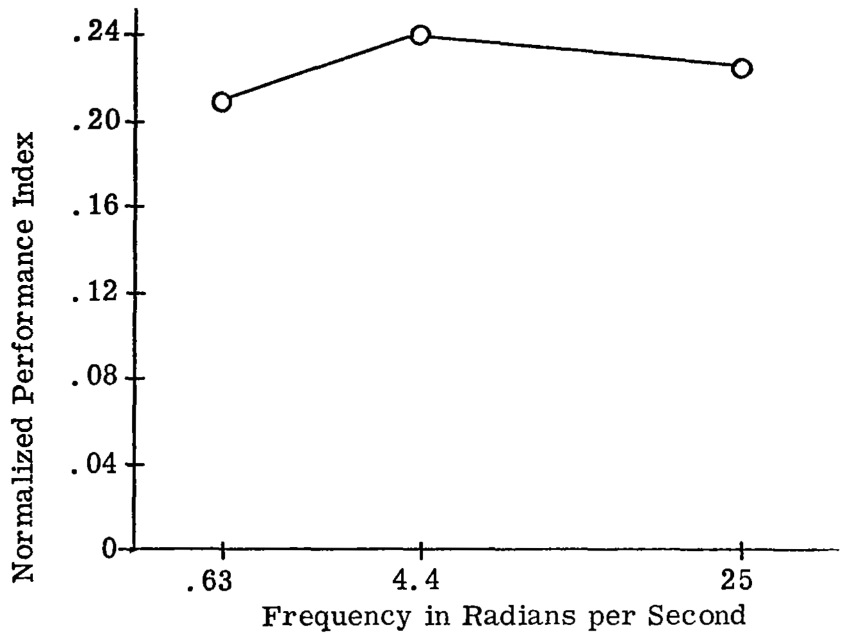

Figure 3. 3. 3 Tracking Performance as a Function of Sinusoidal Variation of the Spring Constant.

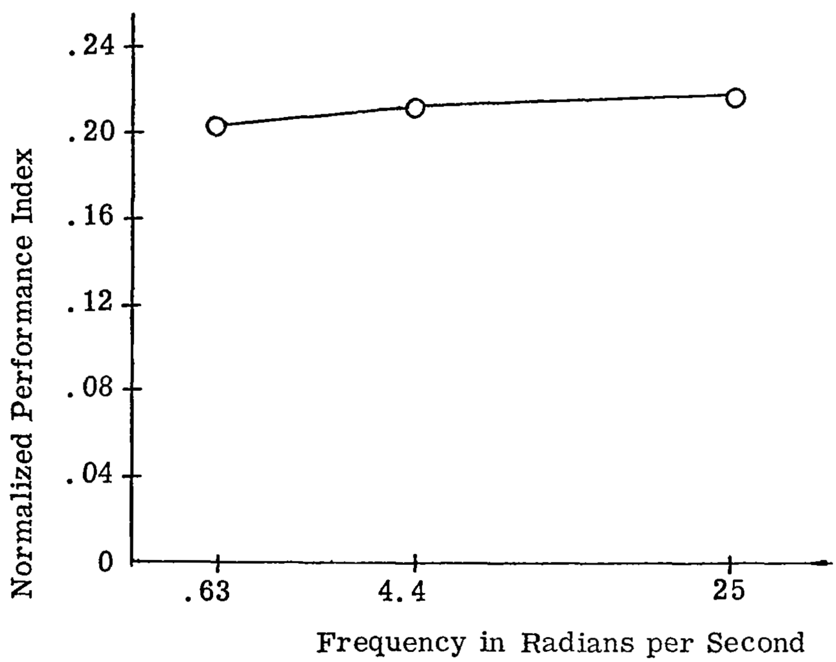

Figure 3. 3. 4 Tracking Performance as a Function of Sinusoidal Variation of the Viscous Friction Coeficient.

and plant in these control situations is shown in Figs. 3.3.5, 3.3.6, 3.3.7, 3.3.8. Comparison of these figures discloses a remarkable amount of similarity existing among the describing functions. In all of these cases the describing function accounted for over 80% of the signal power present in the plant output. The agreement with the conditions of Table 2.2.1 is evident.

The parameters associated with a linear transfer function approximation to each of the describing functions are indicated on the figures. The fairly consistant values of K_h and τ_h are further indications of the minimal effects the manipulator characteristics had on operator control performance.

The results of this experiment support the conclusions which were drawn from Eq. (2.2.10) which is repeated as Eq. (3.3.11).

$$\frac{\Theta_C}{E}(s) = \frac{G_E\, G_L\, Y_C}{G_L\, G_P} = \frac{G_E\, Y_C}{G_P} \qquad (3.3.11)$$

The presence of limb position feedback, $G_P(s)$, results in an open loop transfer function which is relatively independent of the characteristics of the manipulator.

This conclusion regarding the invariance of tracking performance with changes in manipulator configurations is important to the evaluation of the control technique developed in Section 2.2 and evaluated experimentally in the following experiment. In this technique, the

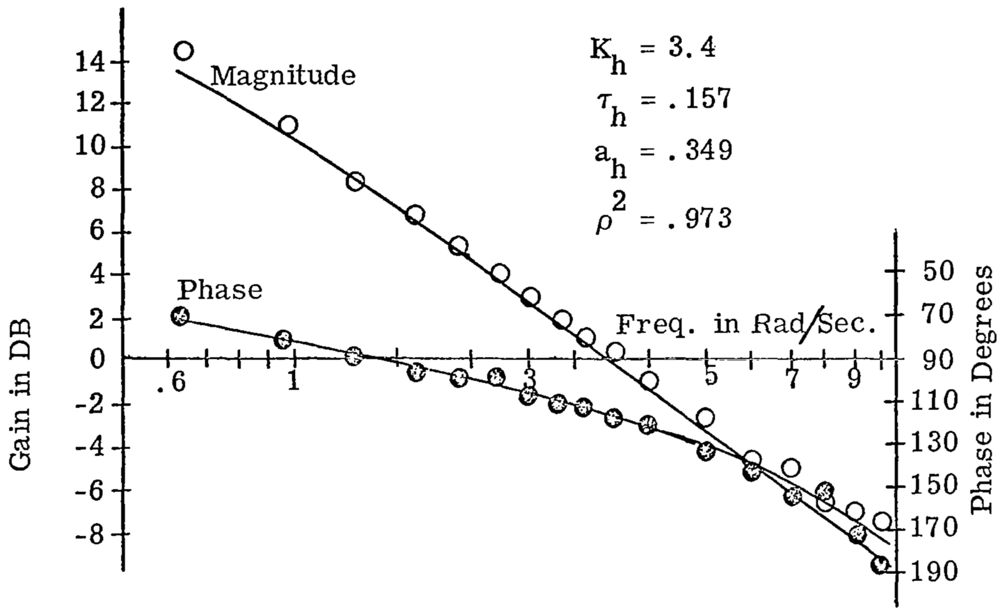

Figure 3.3.5 Describing Function Representation of $Y_P(j\omega)Y_C(j\omega)$ in Compensatory Tracking with K = 2 lb-ft per Radian. Solid Lines Represent Linear Transfer Function Approximation.

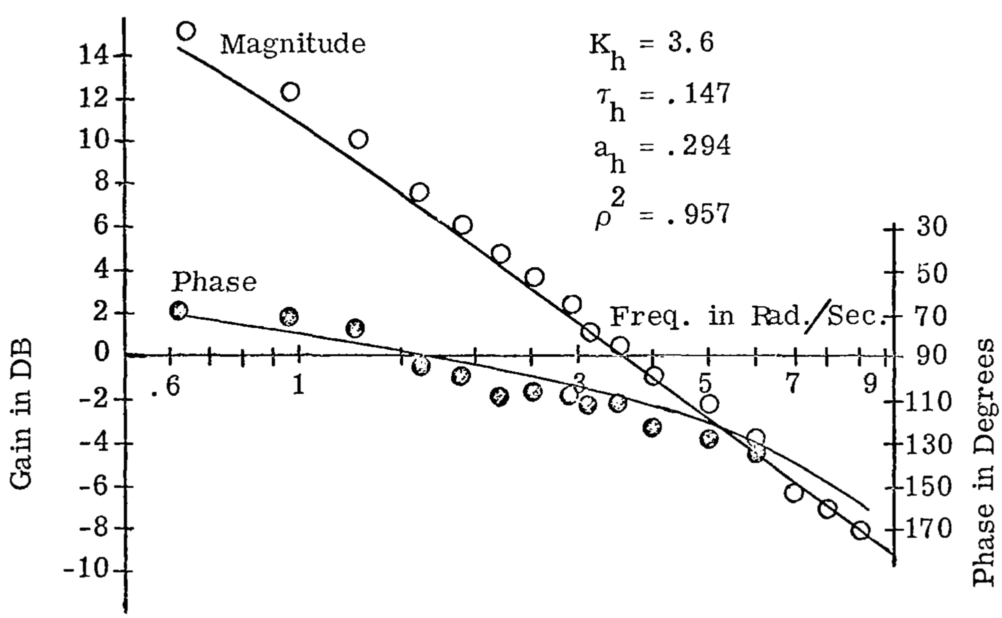

Figure 3.3.6 Describing Function Representation of $Y_P(j\omega)Y_C(j\omega)$ in Compensatory Tracking with K = -2 lb-ft per Radian. Solid Lines Represent Linear Transfer Function Approximation.

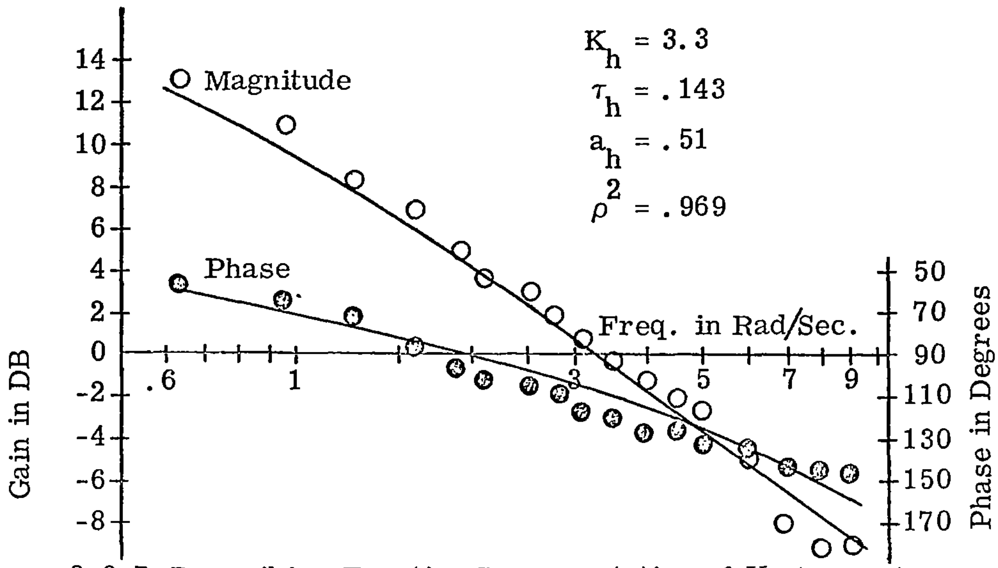

Figure 3.3.7 Describing Function Representation of $Y_P(j\omega)Y_C(j\omega)$ in Compensatory Tracking with B = .8 lb-ft per Radian per Second. Solid Lines Represent Linear Transfer Function Approximation.

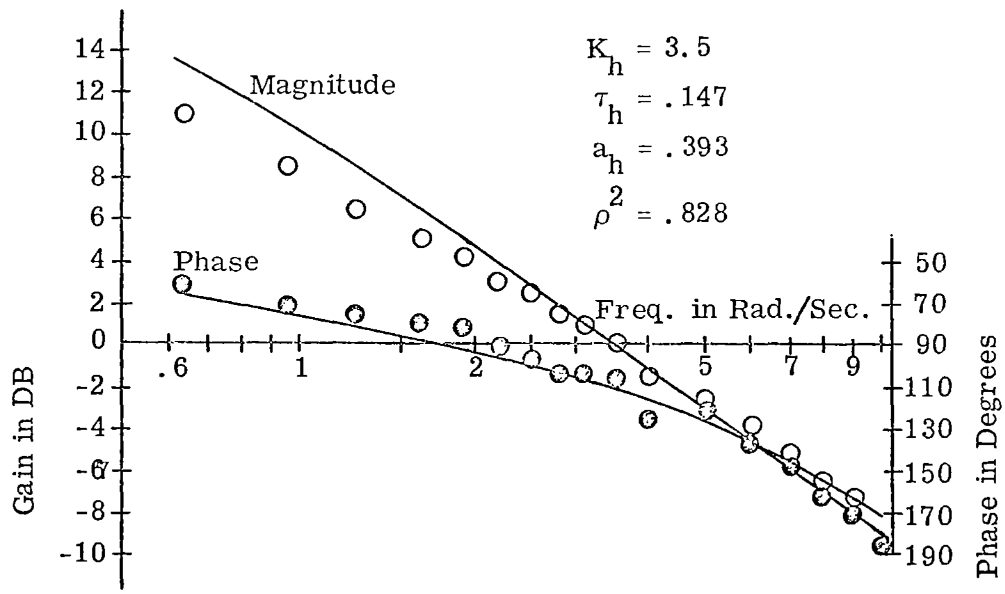

Figure 3.3.8 Describing Function Representation of $Y_P(j\omega)Y_C(j\omega)$ in Compensatory Tracking with B = -.1 lb-ft per Radian per Second. Solid Lines Represent Linear Transfer Function Approximation.

complexity of the actual plant is reduced by modeling the plant characteristics on the control stick. This reduction in plant complexity may result in an increase in the complexity of the control stick characteristics. This experiment indicates that any change in the control stick characteristics appears to have a negligible effect on operator performance.

3.4 Experiment 3, Operator Compensation Using Control Stick Dynamics

This section contains experimental evidence relevant to the techniques discussed in Chapter 2 for altering the control characteristics of the human operator. This experiment examines a direct application of the technique to a linear second order system.

For this experiment a linear second order plant was selected having the transfer function

$$Y_C(s) = \frac{1}{.16\,s^2 + .1\,s + 1} \tag{3.4.1}$$

Two control situations were considered. In the first, as shown in Fig. 3.4.1, the position output of the control stick was used as the plant control variable. The control stick had only inertia characteristics of .075 pound-feet per radian per second squared. The plant was simulated on an analog computer.

In the condition of Fig. 3.4.2 the control stick was constructed

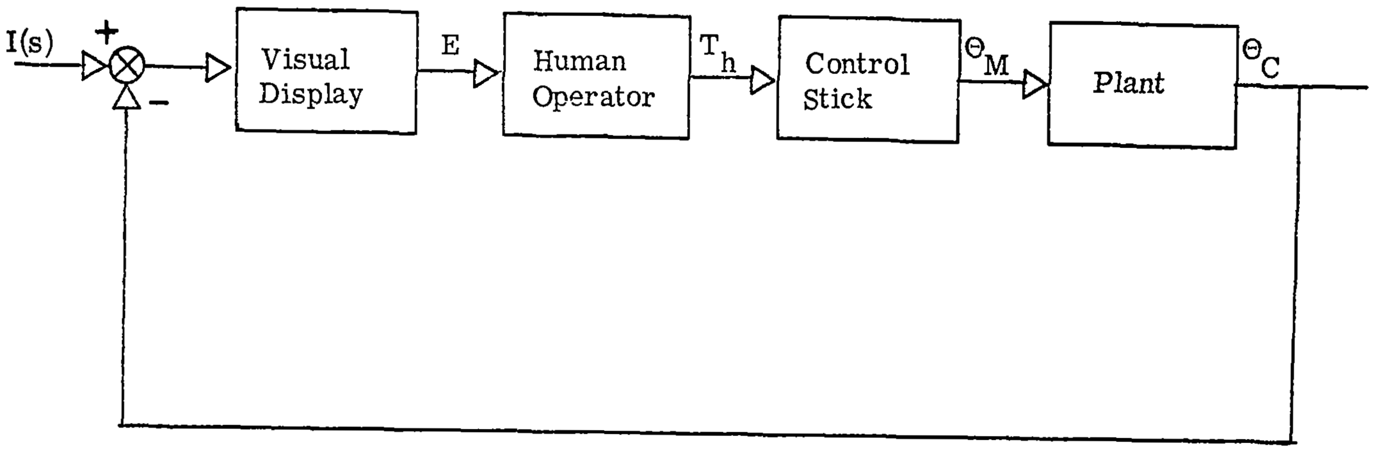

Figure 3.4.1 Control of Plant with a Position Control Stick

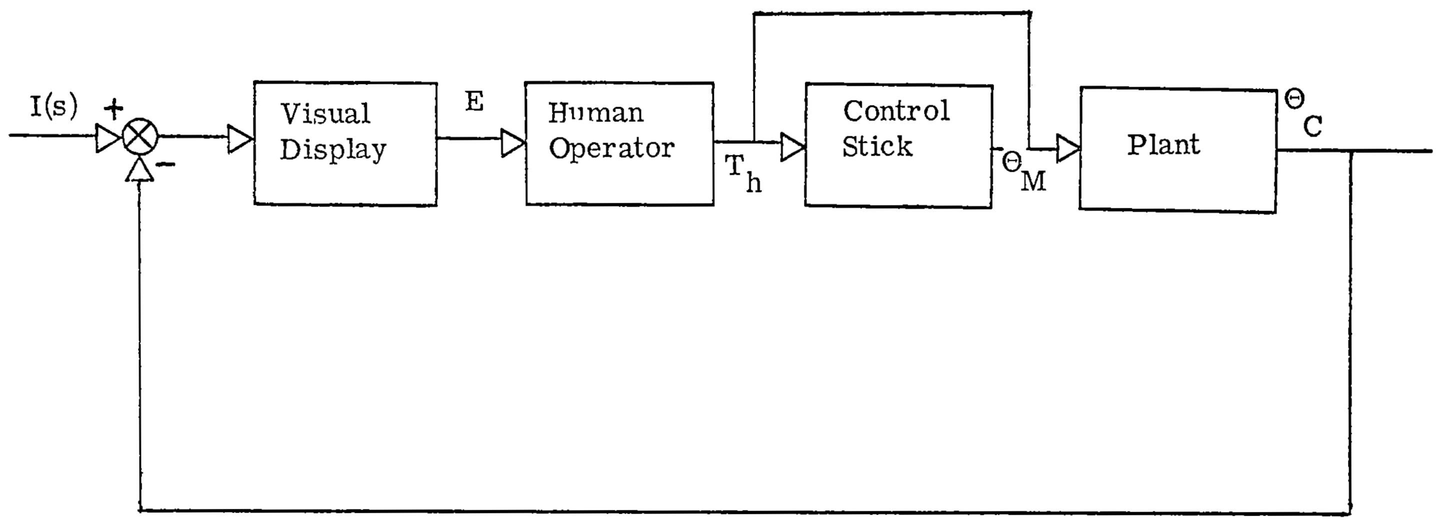

Figure 3.4.2 Control of Plant with a Control Signal Proportional to the Torque Applied by the Operator to the Control Stick.

to have mechanical characteristics analogous to the plant of Eq. (3.4.1). This condition will be referred to as a matched control stick.

$$J = .16 \text{ lb-ft/rad/sec}^2 \tag{3.4.2}$$

$$B = .1 \text{ lb-ft/rad/sec} \tag{3.4.3}$$

$$K = 1 \text{ lb-ft/rad} \tag{3.4.4}$$

$$\omega_n = \sqrt{\frac{K}{J}} = 2.5 \text{ rad/sec} \tag{3.4.5}$$

$$\xi = \frac{B}{2\sqrt{JK}} = .125 \tag{3.4.6}$$

One subject who had participated in the previous experiment was selected for this experiment. He was required to track a low frequency random signal generated by a shift register generator and filtered by a 1 radian per second low pass filter. The performance measure used was the normalized performance index as defined in Experiment 1.

Results and Conclusions

The results of this experiment are presented graphically in Fig. 3.4.3. These data represent the performance of one operator for ten trials in each of the control situations. The improved performance resulting from the use of the matched control stick is obvious.

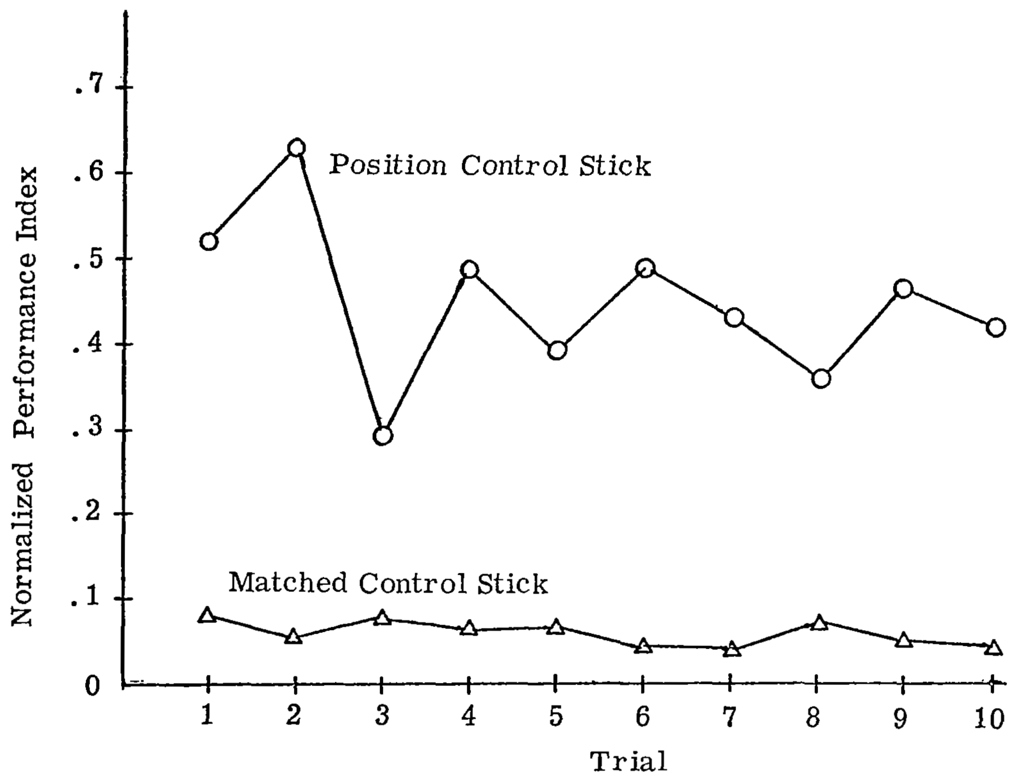

Figure 3.4.3 Comparison of Two Control Techniques Controlling a Second Order Plant

The apparent plant when using the matched manipulator technique is given by Eq. (3.4.7)

$$\hat{Y}_C(s) = \frac{Y_C}{G_M} = \frac{K_C}{K_M} \tag{3.4.7}$$

The extent to which $\hat{Y}_C(s)$, the apparent plant approximated a gain element can be determined by comparing the results of this experiment with those of Section 3.2. In the on-stick dynamics condition there were no external plant dynamics. For this case $Y_C(s)$ was a unity gain element. The close agreement between the performance scores of Section 3.2 and those obtained in the matched control stick case in this section seems to indicate that the plant appeared to the operator as a gain element.

This chapter has experimentally supported many of the assertions presented in Chapter 2 through an analysis of the functional block diagram of the human operator. In particular the experimentation has suggested the presence of a proprioceptive loop which contains position information. It has also been shown that this position information enables the operator to have characteristics independent of the manipulator dynamics when controlling a pure gain plant with a position control stick. The final experiment in this chapter has shown that improvements may be achieved in manual control situations by exploiting the beneficial aspects of limb proprioceptive feedback.

In Chapter 4 the matched manipulator technique developed in Chapter 2 is extended to include a broader range of plants. Experimental evidence is presented to indicate the performance improvement which may be obtained.

CHAPTER IV

EXTENSION OF THE MATCHED MANIPULATOR CONTROL TECHNIQUE

4.0 Abstract

In this chapter several extensions of the technique developed in Chapter II are considered. It is experimentally shown that with specified modifications, the technique can improve performance in linear systems of higher than second order, linear systems with transport time delay, and nonlinear systems. A situation was investigated in which the force cues were instrumental in improving operator performance.

4.1 Introduction

The previous chapter discussed the method of applying the technique developed to a linear second order plant. This and the following sections will attempt to generalize these conclusions to a larger set of plants.

Extension of the theory of the operator compensation technique to include plants of higher than second order was examined in Experiment 4 in Section 4.3. A third order linear plant with a pole at the origin was selected for testing.

Experiment 5 of Section 4.4 evaluated possible alternative methods of achieving the desired correspondence between manipulator position and plant output. In the process, two nonlinear third order plants were investigated.

Experiment 6 of Section 4.5 was the first of two experiments which looked at special types of manual control problems. Experiment 6 investigated the applicability of the compensation technique to systems including time delay.

Experiment 7 in Section 4.6 looked at the special problem of controlling unstable plants. A comparison of control techniques was made for controlling plants of the form $1/s^2$, $1/s^3$, $1/s^4$.

4.2 Extension of the Matched Manipulator Control Technique to Linear Systems of Greater than Second Order

In Section 3.4 the control method of Section 2.2 was experimentally evaluated. In controlling a linear second order system, a performance improvement was obtained by associating characteristics of the control stick with characteristics of the plant. With a second order system a natural association was possible since the control stick was also described by a second order differential equation. In this section a technique will be described for extending this method to plants of higher than second order.

Plants with poles at or near the origin which require greater than first order lead compensation from the operator in order for $Y_P(j\omega)Y_C(j\omega)$ to agree with Table 2.2.1 present an especially difficult challenge to the human operator. Plants whose poles contribute only very short transient responses are of no great difficulty regardless of their number. Indications of the degree of difficulty involved may be obtained by noting the skill which is required to fly a helicopter. The helicopter is basically a third order system. The dynamics of a submarine involve fourth order differential equations.

A direct application of the matched manipulator technique to situations involving higher order differential equations is possible. The main difficulty is providing mechanical elements which provide reaction torques proportional to the third and higher derivatives of their motion. Such elements may be obtained by using coupled mechanical systems or they may be simulated using equipment such as the variable dynamics control stick which is described in Chapter V. Since there are likely to be instances when neither of the above methods is possible, a method will be developed which requires only second order characteristics to be provided on the control stick.

Inspection of Eq. (4.2.1) indicates that $\hat{Y}_C(s)$, the apparent plant, may still assume a less complex form than $Y_C(s)$, the actual plant, even if the manipulator is not an analog of the plant.

$$\hat{Y}_C(s) = \frac{Y_C}{G_M} \qquad (4.2.1)$$

For the linear case $Y_C(s)$ may be factored into a sequence of second order elements if the degree of the plant is even, and a sequence of second order elements plus one first order element if the degree of the plant is odd. The manipulator characteristics may be associated with any of the second order elements. This will decrease the complexity of the apparent plant.

As an example consider the case of the following linear third order plant.

$$Y_C(s) = \frac{K_C}{(A_C s^2 + B_C s + 1)(D_C s + E_C)} = \left[\frac{K_C}{A_C s^2 + B_C s + 1}\right]\left[\frac{1}{D_C s + E_C}\right] \quad (4.2.2)$$

If the second order portion of Eq. (4.2.2) is implemented on the control stick as shown if Fig. 4.2.1, the resulting problem for the operator is reduced in difficulty since:

$$\hat{Y}_C(s) = \frac{Y_C}{G_M} = \frac{Y_C}{\dfrac{K_M}{A_M s^2 + B_M s + 1}} = \frac{1}{D_C s + E_C} \frac{K_C}{K_M} \quad (4.2.3)$$

As in the second order case of Section 2.3, the presence of errors in the manipulator mechanical parameters tends to increase the complexity of the apparent plant. If in Fig. 4.2.1 we may define the parameter differences as

$$\epsilon_A = A_C - A_M \quad (4.2.4)$$

$$\epsilon_B = B_C - B_M \quad (4.2.5)$$

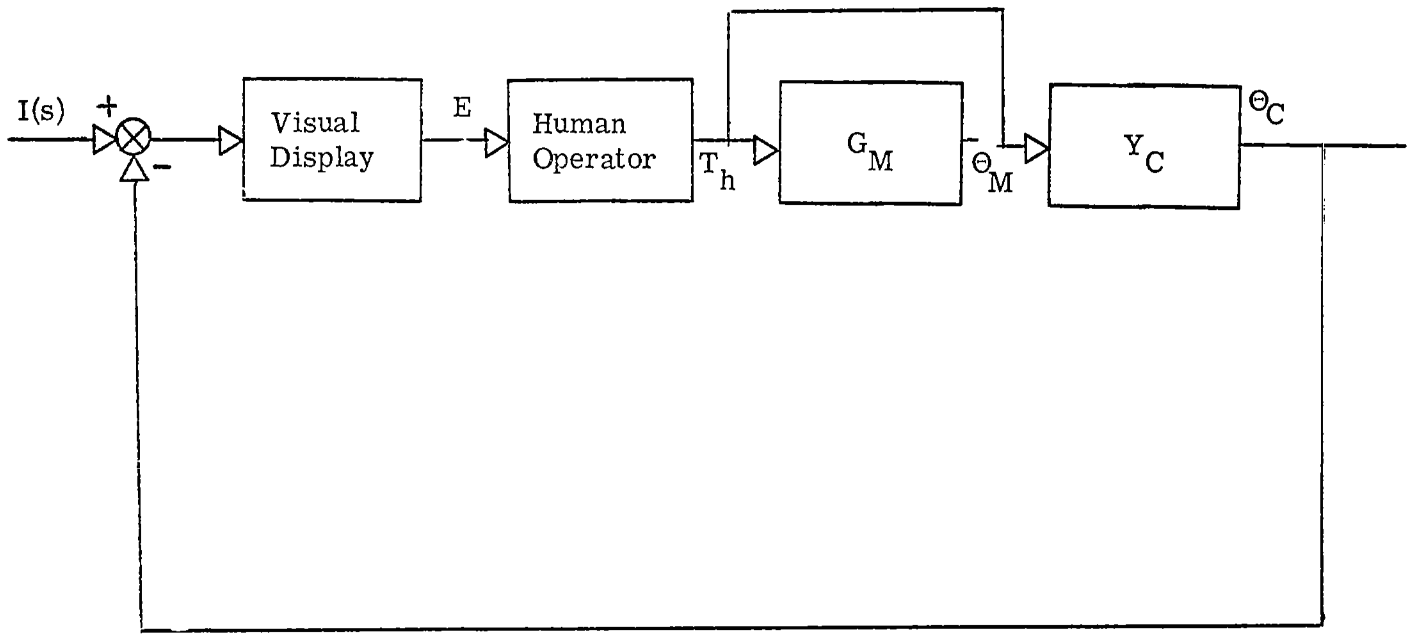

Figure 4.2.1 Partitioning of a Third Order Linear Plant to Reduce the Order of $\hat{Y}_C(s)$, the Apparent Plant.

the apparent plant will take the form

$$\hat{Y}_C(s) = \frac{K_C}{K_M} \frac{A_M s^2 + B_M s + 1}{(A_C s^2 + B_C s + 1)(D_C s + E_C)}$$

$$= \frac{K_C}{K_M} \frac{A_C s^2 + B_C s + 1 + \epsilon_A s^2 + \epsilon_B s}{(A_C s^2 + B_C s + 1)(D_C s + E_C)}$$

$$= \left[\frac{1}{D_C s + E_C} + (\epsilon_A s^2 + \epsilon_B s)\frac{Y_C}{K_C}\right]\frac{K_C}{K_M} \qquad (4.2.6)$$

It can be seen that the error analysis is very similar to that of Section 2.3. Extension to higher order systems of the same form is direct. The advantages to be obtained by closely matching the control stick and a portion of the plant will be examined experimentally in the next section.

4.3 Experiment 4, Manual Control of a Third Order Linear Plant by Partitioning

This section contains experimental verification of the technique of partitioning linear plants of higher than second order. The plant selected for this experiment was obtained by adding a pole at the origin to the plant used in Experiment 3 of Section 3.4.

$$Y_C(s) = \frac{1}{s(.16 s^2 + .1 s + 1)} \qquad (4.3.1)$$

Using the technique developed in Section 4.2, this plant was separated into two parts.

$$Y_C(s) = \left[\frac{1}{s}\right]\left[\frac{1}{.16\,s^2 + .1\,s + 1}\right] \qquad (4.3.2)$$

With the second order portion of Eq. (4.3.1) implemented on the operator's control stick, the apparent plant became:

$$\hat{Y}_C(s) = \frac{Y_C}{G_M} = \frac{1}{s} \qquad (4.3.3)$$

$Y_C(s)$ was simulated on an analog computer. Two methods of controlling this plant were compared. The first method used a position control stick of the same type used in previous experiments. The second method used the torque applied by the operator to the control stick as the control variable.

One operator who had participated in the previous experimentation was used in this test. As in the test of Section 3.4 a low frequency random noise signal low pass filtered at one radian per second was used as the input forcing function.

Results and Conclusions

The results of this experiment are presented in Fig. 4.3.1. Each of the control techniques was evaluated for ten trials, each of two minutes duration. The performance data indicates that the partial

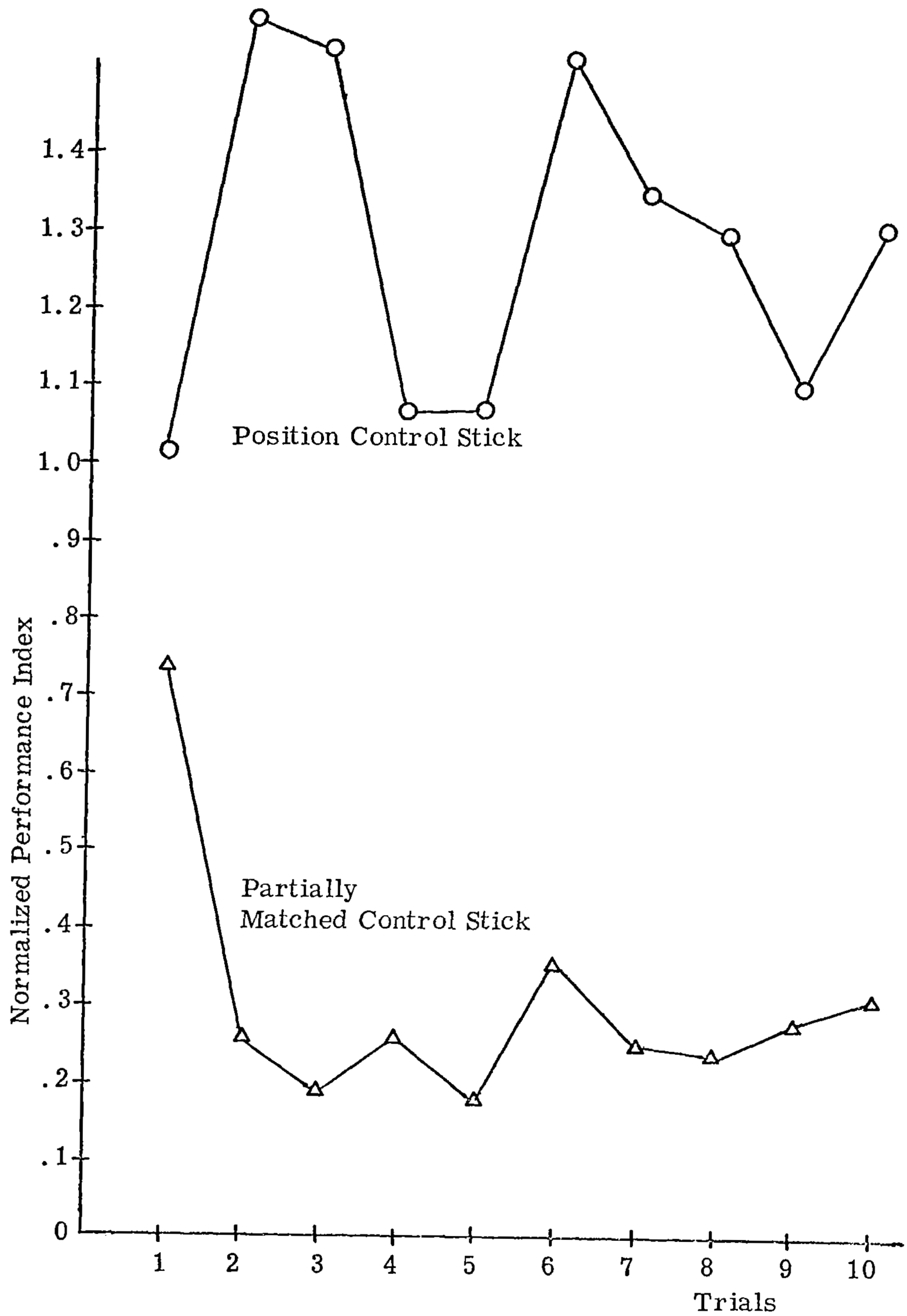

Figure 4. 3. 1 Comparison of Operator Performance Using a Position Control Stick and a Partially Matched Control Stick.

implementation of the plant characteristics resulted in a lower performance index than control of the same plant with the position stick. With the position control stick the operator's performance index was consistantly above unity indicating that better control performance would have been obtained if the control stick would have been left stationary in the center position. Even with the limited amount of data presented,it appears that the performance variability was much greater in the condition in which the operator used the position control stick. It may also be noted that the performance differences between the two control techniques does not seem to change appreciably as a function of the number of trials.

The results of this experiment tend to support the assertion that a partial implementation of the plant dynamics on the operator's control stick improves performance over what would be obtained by conventional control techniques such as a position control stick. Although not demonstrated through experimentation, it seems reasonable to assume that a complete implementation of the plant dynamics would probably result in better performance than the partial implementation.

4.4 Experiment 5, Role of Proprioceptive Force Cues in Manual Control

The discussion of Section 2.2 indicated that the major advantage to be gained from the presence of proprioceptive force cues was the indication they provided of control effort. This experiment investigates the possible performance benefit these cues might provide. In the four smaller experiments which comprise this section, several control situations were examined which pertain to the usefulness of the force information experienced by the operator.

The basic plant selected for use in this experiment is indicated in Eq. (4.4.1).

$$Y_C(s) = \frac{1}{.004\,s^3 + .075\,s^2 + .15\,s + 2}$$

$$= \frac{1}{.004(s + 18.2)(s^2 + .55\,s + 27.5)} \qquad (4.4.1)$$

For the second order portion

$$\omega_n = 5.25 \text{ radians/second}$$

$$\xi = .05$$

Part 1

In the first part of this experiment, control of the plant of Eq. (4.4.1) was examined under two control situations. In the first case the third order plant characteristics were implemented on the variable dynamics control stick. An approximation to the third derivative of the control stick position was obtained using the analog computer. This allowed the control stick to simulate the entire third order plant.

Using the matched manipulator control technique the torque applied to the manipulator was sensed and used as a control signal for the plant. In the second control situation the position signal from a control stick was used as the control variable.

One subject who had previous experience in compensatory tracking participated in this experiment. The input signal used for tracking was obtained by low pass filtering the noise source at 2 radians per second.

<u>Results and Conclusions from Part 1</u>

The results from Part 1 of this experiment are shown in Fig. 4.4.1. The results are similar to those obtained elsewhere when the same two techniques are compared.

Figures 4.4.2 and 4.4.3 present the describing functions obtained from the data. Figure 4.4.2 shows the results obtained when the plant was controlled by a position type control stick. Figure 4.4.3 shows the results obtained when the manipulator was an analog of the plant characteristics.

The shape of the describing function in Fig. 4.4.2 indicates that the operator was not successful in providing the necessary compensation required to make the open loop describing function assume the form specified in Table 2.2.1. The inability of the operator to control the oscillation of the plant is indicated by the peak in the describing

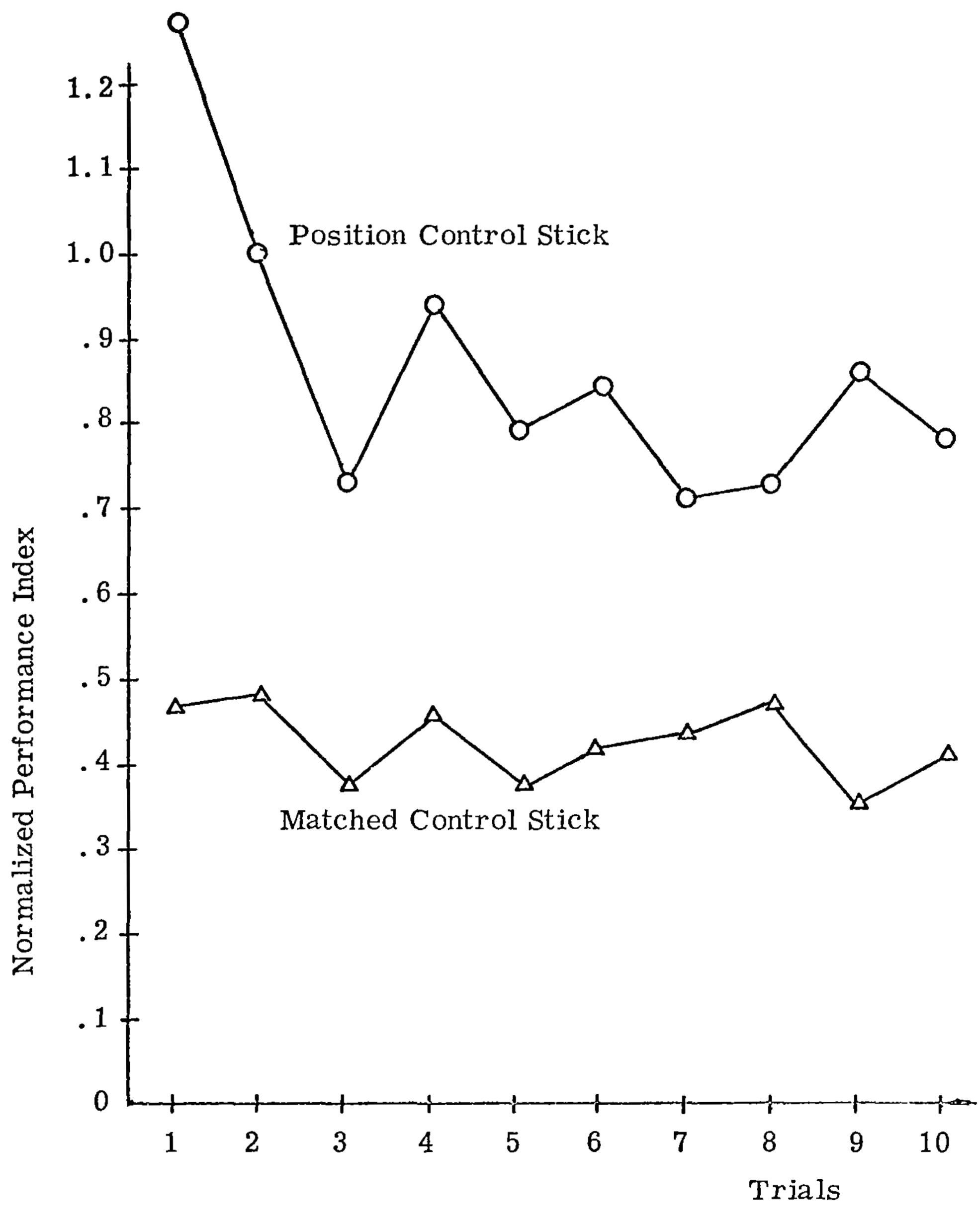

Figure 4.4.1 Comparison of Position Control Stick and Matched Control Stick Controlling a Third Order Plant.

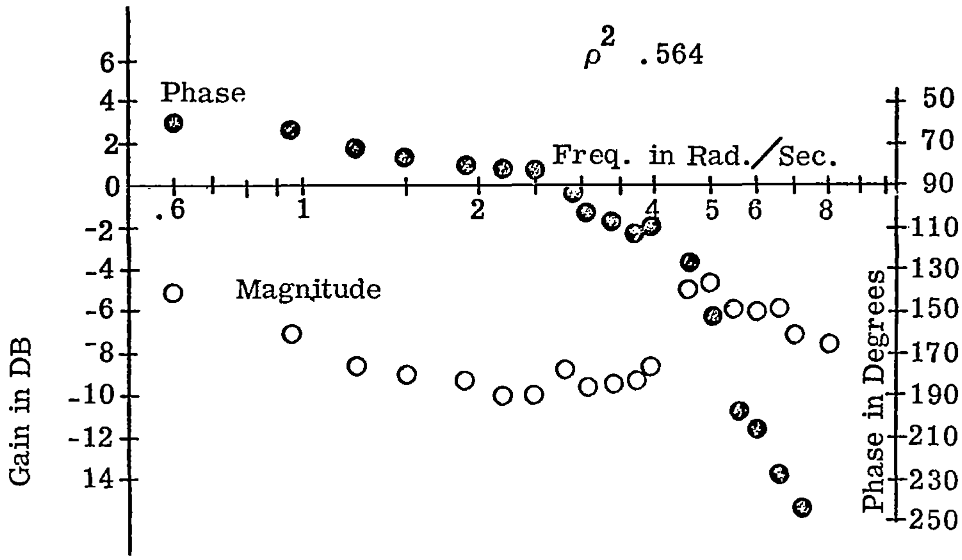

Figure 4.4.2 Describing Function Representation of $Y_P(j\omega)Y_C(j\omega)$ with Operator controlling a Third Order Plant with a Position Control Stick

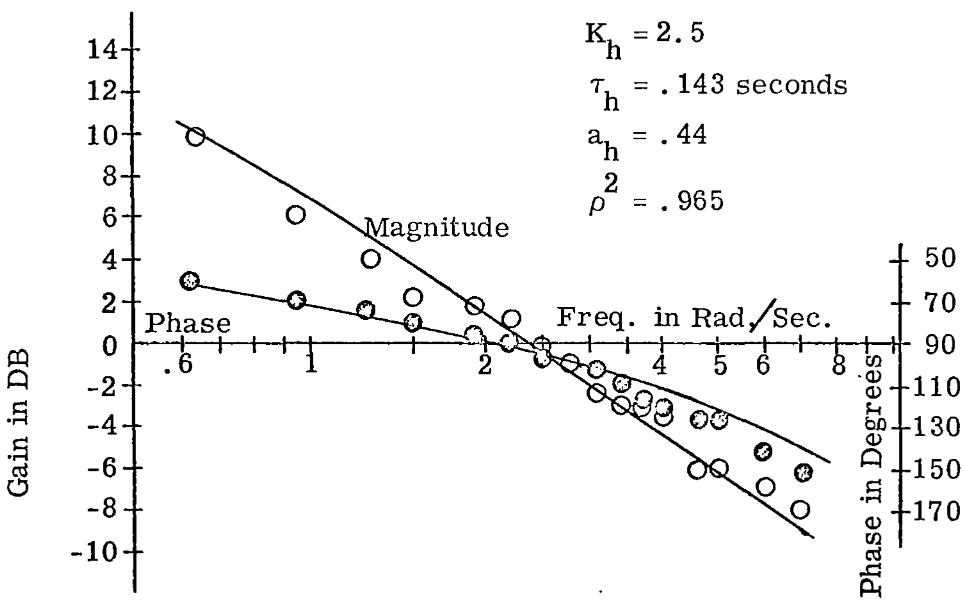

Figure 4.4.3 Describing Function Representation of $Y_P(j\omega)Y_C(j\omega)$ with Operator Controlling a Third Order Plant with a Matched Control Stick. Solid Lines Indicate Transfer Function Approximation

function which occurs at about five radians per second. The very low gain associated with the describing function is also related to the operator's concern with system stability. For this experiment the describing function accounted for only 56% of the operator's output power. The describing functions for the previous cases accounted for over 90% of the operator's output power. The results from this experiment seem to suggest that the operator departs from the characteristics of Table 2.2.1 when the characteristics of the plant become increasingly more difficult. The relatively low correlation coefficient obtained for the data of Fig. 4.4.2 seems to indicate that the more complex the plant characteristics the less effective is a linear representation of the combined operator and plant.

Figure 4.4.3 indicates that the matched manipulator technique resulted in a very different form of the operator describing function than was obtained using a position control stick with the same plant. The characteristics of the describing function agree quite closely with Table 2.2.1. The describing function of Fig. 4.4.3 accounts for 96% of the signal power present in the plant output. This high correlation suggests that the operator was operating in a more linear mode than was the case represented by Fig. 4.4.2. The three parameter linear approximation to the describing function of Fig. 4.4.3 indicates reasonably close agreement to the linear approximations for Figs. 3.3.5, 3.3.6, 3.3.7, 3.3.8, and 3.2.4. The slight decrease in gain noted in Fig. 4.4.3 indicates that the operator experienced only slightly more difficulty in controlling the third order plant simulated on the analog computer than he experienced controlling characteristics presented only on the control stick. The presence of the external plant had little effect on the open loop describing function. This supports the conclusion reached in Section 3.4 which was based on control performance.

Part 2

In the second part of this experiment the advantage of providing the operator with reaction force cues was evaluated. Two control conditions were compared using the same plant as in the first part of this experiment. In the first condition the operator had the full mechanical feel of the plant as simulated on the control stick. In the second condition compensation having the characteristics of the plant inverse followed the position output of the control stick. This condition is discussed in Section 2.4 and was shown to provide a correspondence between the manipulator position and the plant output. Under this condition, however, the reaction forces experienced by the operator were not related to the system control effort. It was desired to determine if any performance differences would be noted in these two control methods.

Results and Conclusions from Part 2

The data obtained from the one subject who participated in this experiment is shown in Fig. 4.4.4. There does not appear to be any significant difference in the operator performance in these two control situations. The results of this experiment indicate that in the case of linear plants, compensation in the form of the inverse plant offers approximately the same degree of performance improvement as the matched manipulator control technique. The following experiment examines a condition in which there is a performance difference between the control methods studied in part 2.

Part 3

The third section of this experiment examined a control situation similar to Part 2. In this part, however, the plant was changed to include nonlinear characteristics. The viscous term, which involves the first derivative of the plant output, was changed from the linear form used in the first two parts of this experiment to the nonlinear characteristics of Fig. 4.4.5. This nonlinearity imposed a velocity limit on the plant. This is a common type of nonlinearity which might result, for example, if an induction motor is being used to position a mechanical load. In this case the maximum angular velocity of the motor would be determined by the line frequency and the number of poles of the motor. Increased excitation could not cause the motor to rotate faster.

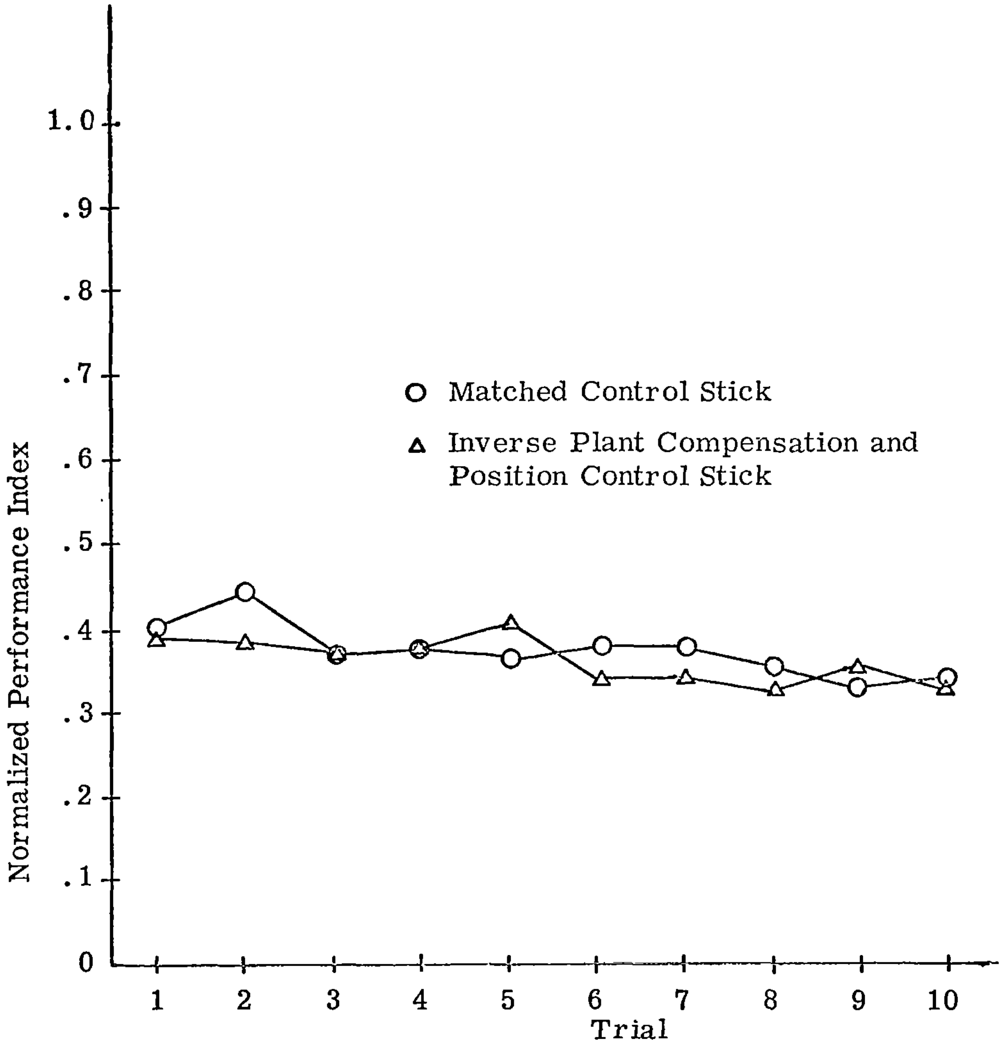

Figure 4.4.4 Comparison of Operator Performance Using Matched Control Stick and Inverse Plant Compensation with a Position Control Stick.

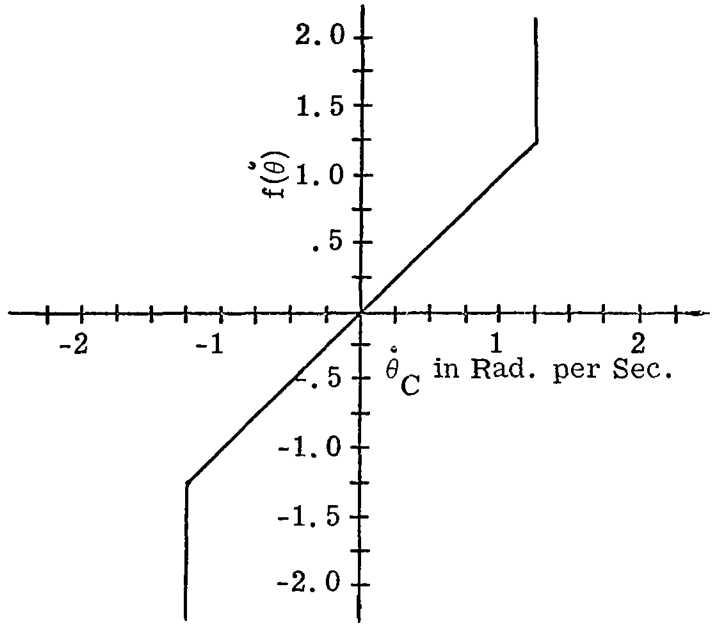

Figure 4.4.5 Saturation Characteristics of Viscous Friction Element.

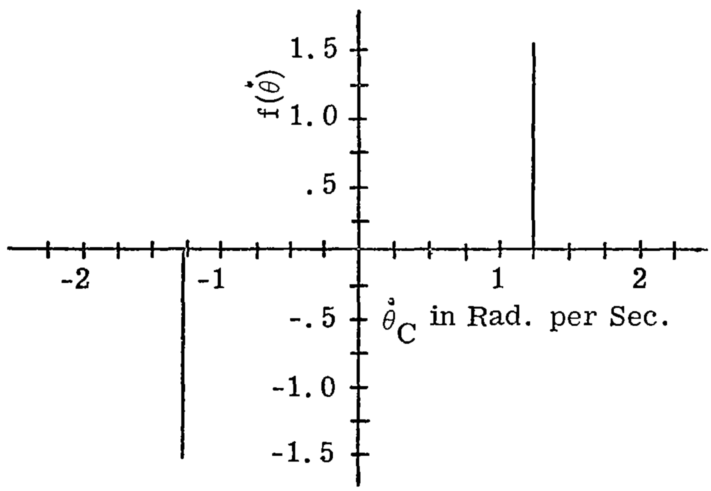

Figure 4.4.6 Saturation and Dead Band Characteristics of Viscous Friction Element.

Two control conditions were evaluated. In the first the control stick was constructed as an analog of the plant. In this condition the operator was able to sense through the force and position cues, the characteristics of the nonlinear plant. In the second condition position control of the plant was used. In this condition compensation in the form of the plant inverse was included between the control stick and the plant. The reaction forces experienced by the operator were only those resulting from the inertia of the control stick.

The differential equation describing the plant was

$$t_h(t) = .004\,\dddot{\theta}_C + .075\,\ddot{\theta}_C + .15 f(\dot{\theta}_C) + 2\,\theta_C \qquad (4.4.2)$$

$t_h(t)$ is the input signal to the plant. When using the method of Section 2.2 it is a scalar multiple of the force applied by the operator. In the second condition of this experiment $t_h(t)$ is the output signal from the compensation network. θ_C is the plant output. $f(\dot{\theta}_C)$ is a nonlinear function and is shown graphically in Fig. 4.4.5.

An examination of Eq. (4.4.2) and Fig. 4.4.5 indicates that the plant inverse was not defined for values of $\dot{\theta}_C$ larger than 1.25 radians per second. The nonlinearity imposed a maximum velocity on the plant output. The domain in which the inverse was defined included only those plant output states in which the velocity was less than the maximum velocity determined by the nonlinearity. The diagram of Fig. 2.4.5 indicates that the compensation acted on the entire domain of control stick output states. This domain of control stick output states included some conditions for which the inverse was not defined. Under conditions in which the inverse was not defined the combination of the plant and its inverse was no longer a unity gain element and the correspondence between the plant output and the manipulator position was destroyed.

Results and Conclusions from Part 3

The results of this experiment are shown in Fig. 4.4.7. One subject participated in forty trials, each of two minutes duration. Twenty of the trials were in each of the two test conditions. The conditions were alternated in blocks of five trials.

The velocity limit of the plant was such that it was possible and likely that the operator would cause his control stick to exceed this velocity in the normal course of the experiment in the absence of restraining mechanical characteristics. Exceeding the velocity limit resulted in a loss of correspondence between the manipulator and the plant. This was accompanied by an oscillation as the control stick velocity was decreased into the region in which the plant inverse was defined.

When the plant characteristics were included on the control stick the operator was able to sense accurately the region in which the

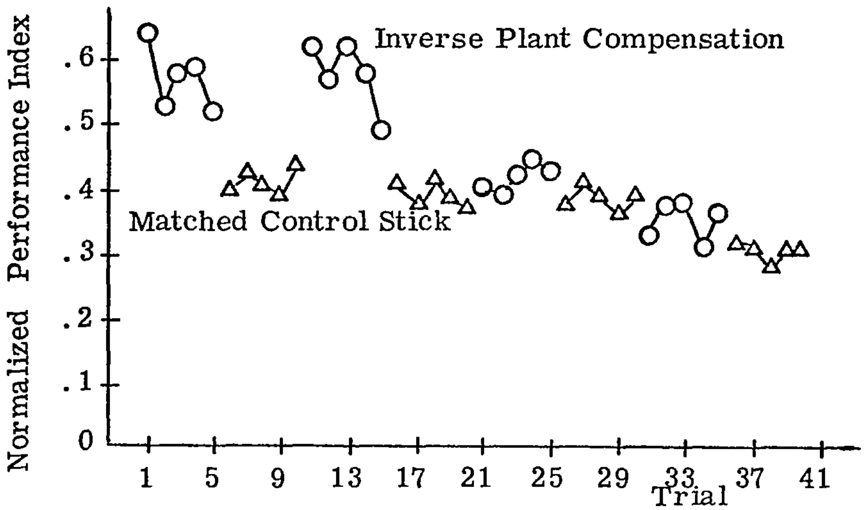

Figure 4.4.7 Comparison of Operator Performance with Nonlinear Plant Using Inverse Plant Compensation and Matched Control Stick.

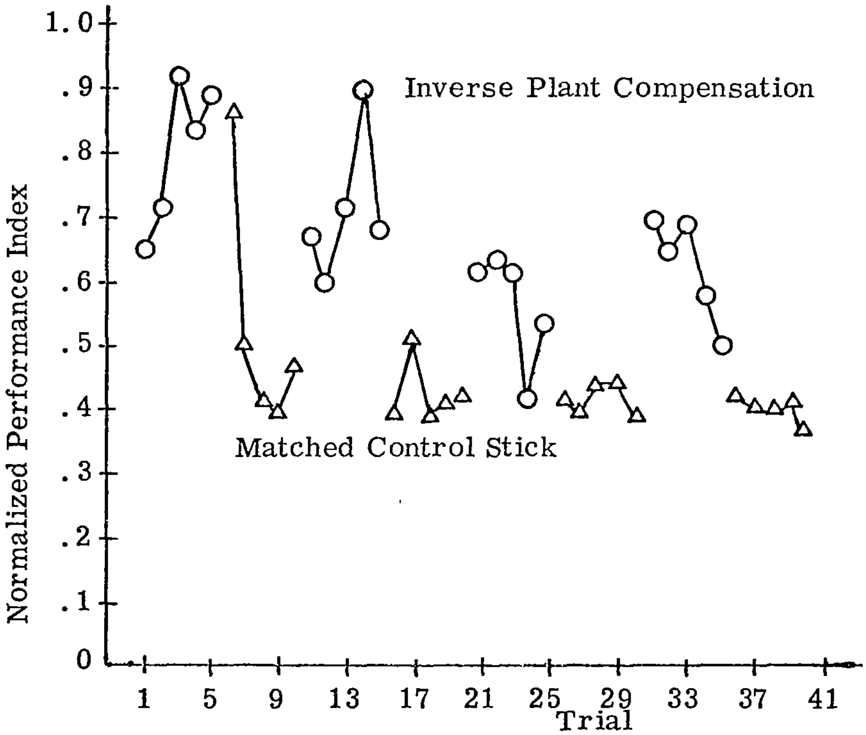

Figure 4.4.8 Comparison of Operator Performance with Nonlinear Plant Using Inverse Plant Compensation and Matched Control Stick.

nonlinearity began. Since the best strategy of the operator was not to exceed the linear region of operation, the presence of the force feedback could provide information to improve performance.

The results of the experiment indicate that throughout the first twenty trials performance was generally superior when the mechanics of the control stick restricted the manipulator velocity. Toward the conclusion of the experimental trials the performance in the two conditions seemed quite similar.

After several trials the operator began to sense that very rapid motions tended to cause oscillation in the visual display of the system error. As he attempted to limit his velocity the performance approached that of the condition when the operator experienced full feel of the plant. The extent to which this improvement in performance resulted from experience in feeling the plant dynamics in the alternate conditions cannot be determined from this data.

This experiment has demonstrated that the presence of proprioceptive force cues can modify control performance in some types of manual control situations.

Part 4

In this experiment the function describing the viscous effects of the plant is shown in Fig. 4.4.6. The dead band in the viscous friction term resulted in a limit cycle oscillation of the plant output. Experimentally it was determined that the best method of controlling this plant was to attempt to always drive it in a controlled manner at its maximum velocity. If the manipulator exceeded the velocity range for which the plant inverse was defined,a loss of correspondence between the manipulator and the plant resulted. If the manipulator velocity was too slow the plant would begin oscillating in its limit cycle.

Results and Conclusions from Part 4

Figure 4.4.8 shows the results of this experiment. The data seems to suggest that the presence of the plant feel characteristics on the control stick contributed to the operators control capability. Even after forty trials, performance remained superior in the control situation in which the operator experienced the nonlinearity through the resulting force cues.

The results of this group of four experiments seems to suggest that in the linear case the presence of reaction force cues related to the characteristics of the plant is of no benefit to the operator. Performance was about the same for both contraol methods.

In the nonlinear cases studied, the force cues provided supplementary information which indicated the nature of the nonlinearity. The force information also indicated the regions in which the plant inverse was not defined. The results of the last experiment indicate that the operator is capable of making use of force information when such information is relevant to his control problem.

4.5 Experiment 6, Application to Time Delay Systems

With exploration of the moon and planets now technologically possible, a great deal of effort has been exerted to study some of the unique control problems such exploration will present. The time delay in the communications link due to the finite velocity of radio propagation is of particular interest. The round trip transit time for a signal to reach the moon from the earth and return is about 2.5 seconds.

This time delay presents stability problems with closed loop control systems. A technique has been proposed whereby telefactors or robot type mechanisms will be used as human substitutes in hostile or unknown environments. Such devices would be constructed to duplicate the motion of a part of the human body much as manipulators are used to handle radioactive materials in heavily shielded chambers. Because such devices require feedback to perform their function, their usefulness will be impaired by the transport time delay. The matched manipulator control technique is capable of satisfactory operation even without immediate visual feedback from the plant. For this reason it might offer additional advantages in systems containing a time delay.

Two additional conditions were studied with the same second order linear plant used in Section 3.4. In the first condition the plant plus delay was controlled with a position control stick. In the second condition the control stick was a mechanical analog of the plant. The entire delay was lumped into one delay element. In actual practice there would be a delay associated with transmission of the initial command and a second delay associated with the return transmission of the plant output.

The operator provided a control input to the system but was not aware of the associated plant response until τ second later. This time delay tended to disassociate the input and output of the system and disguise the true nature of the plant. By providing a physical analog of the plant on the control stick, the operator was exposed to all the characteristics of the plant except the time delay.

The purpose of these two experiments was to explore the degradation of performance that occurred with both the position stick and the matched control stick when a time delay was introduced in the visual feedback path.

Time delays of .375 and .750 seconds were obtained from the spatial separation of the record and playback heads of an Ampex FM tape recorder. With the exception of the time delay, all conditions were identical with those of Section 3.4.

Results and Conclusions

The effect of time delay on the two control schemes is shown in Figs. 4.5.1, 4.5.2, and 4.5.3. Figure 4.5.1 shows operator performance with the position control stick for time delays of 0 seconds, .375 seconds, and .750 seconds. Figure 4.5.2 shows performance for the same time delays using the matched control stick. In all cases the introduction of time delay resulted in an increase in the normalized performance index. Average performance for each of the time delay situations for a position control stick and matched control stick is shown in Fig. 4.5.3. The rate of performance degradation was about the same for the two control techniques.

The clear superiority of the matched control stick was maintained in both of the time delay situations. In the case of the .75 second time delay, the human contributed no effective control action when using the position control stick. His performance coefficient was usually greater than unity showing that he would have performed better had he chosen to not attempt to control the plant at all.

With the matched control stick the human retained control of the system under both time delay conditions. The performance with the matched control stick with time delay was almost as good as that of the position control stick with no time delay.

There appear to be several reasons for this difference in

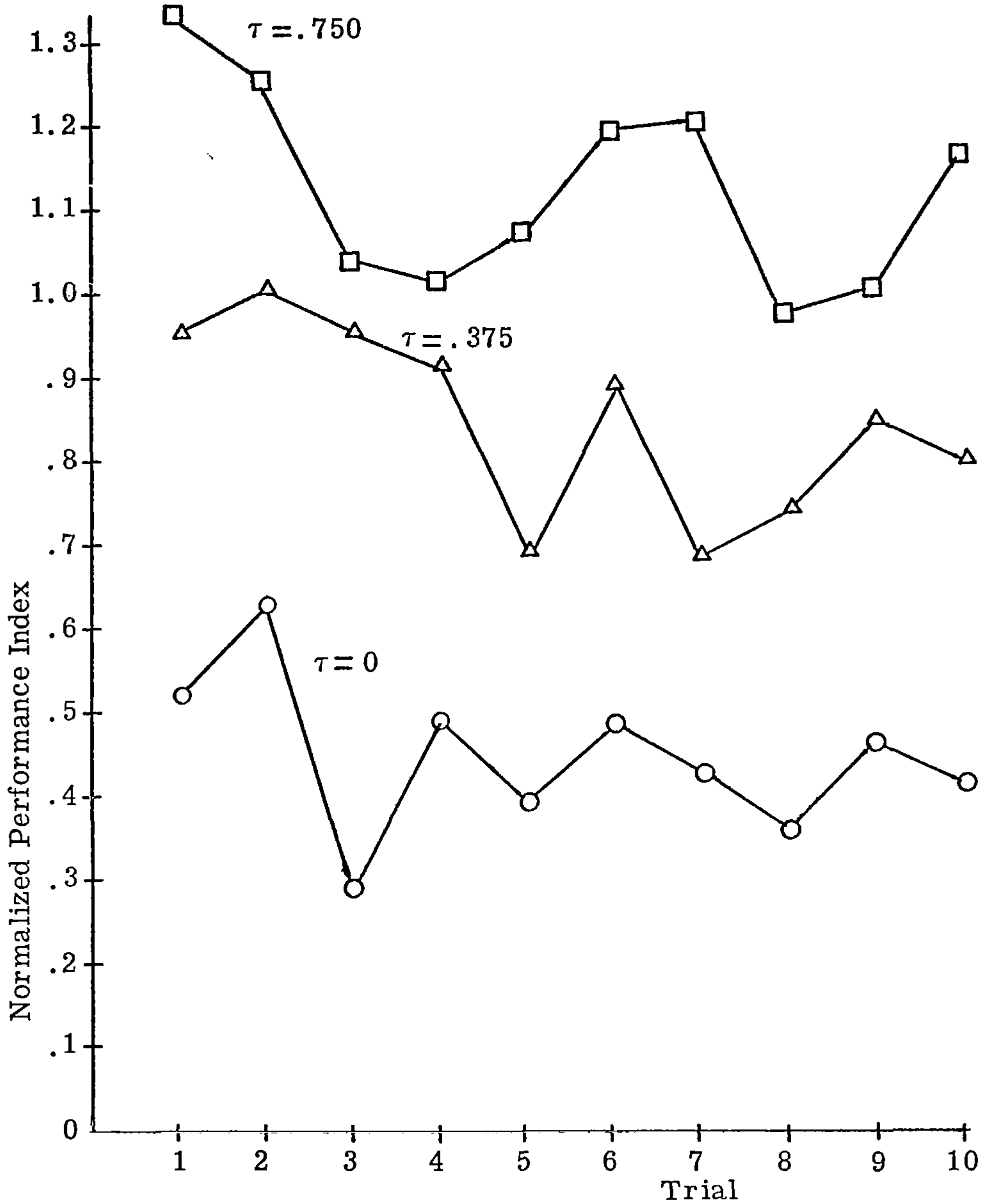

Figure 4.5.1 Operator Performance with a Position Control Stick for Three Values of System Time Delay, τ.

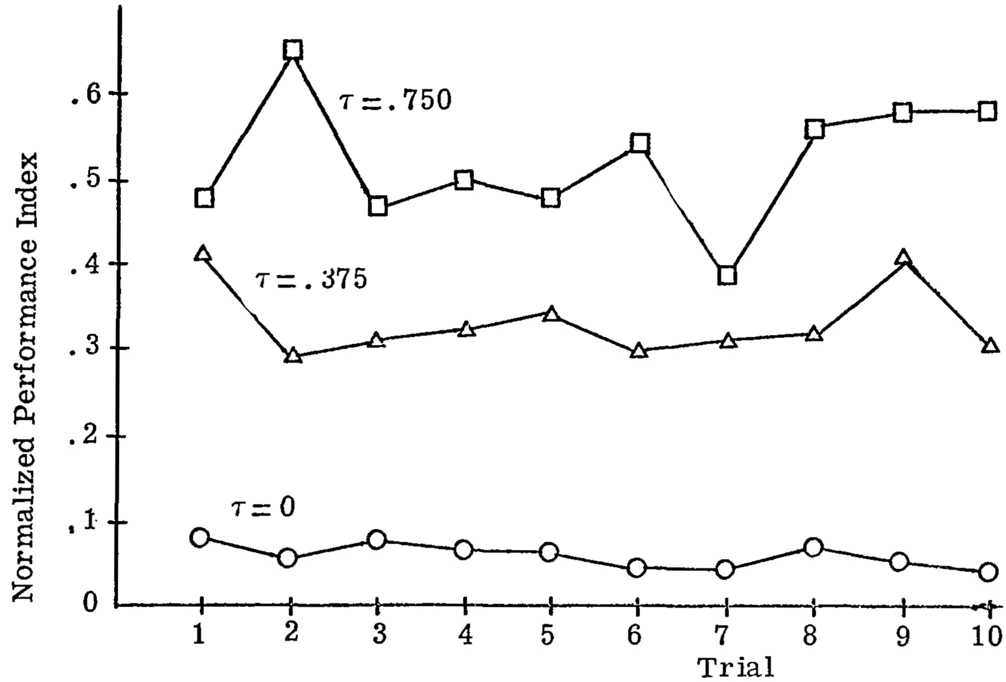

Figure 4.5.2 Operator Performance with Matched Control Stick for Three Values of System Time Delay, τ.

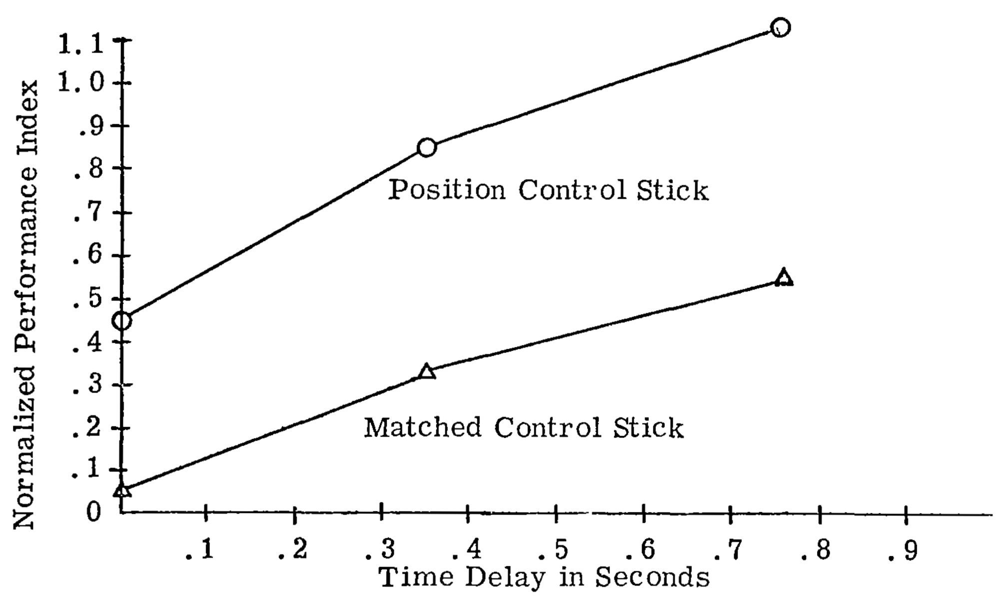

Figure 4.5.3 Average Operator Performance Using Position Control Stick and Matched Control Stick as a Function of System Time Delay, τ.

performance. When using the position control stick, the human was required to either formulate a transfer function of the process so that he could predict the system output resulting from his inputs, or he had to rely on visual feedback. The former task was quite difficult and would probably require a considerable amount of training. The use of visual feedback became less useful due to the time delay and performance deteriorated. With the longer time delays there was a tendency toward instability. The use of the matched control allowed formulation of an open loop control effort. The proper torques were generated to move the control stick and the output of the plant followed τ seconds later. Since the control effort itself was open loop there was no problem of instability. Performance deteriorated as the time delay increased mainly due to the operator's inability to predict the future values of the forcing function.

4.6 Experiment 7, Control of Unstable Plants of the Form $1/s^2$, $1/s^3$, $1/s^4$

In this section the problem of controlling plants of the form $1/s^2$, $1/s^3$, $1/s^4$ will be considered. This type of plant can present a severe challenge to the human operator due to its instability. Section 2.4 has indicated that the technique of Section 2.2 is not directly applicable to unstable systems. Because of the instability there is not a functional relationship existing between the plant input and output as defined in Section 2.4.

As a possible method of controlling plants of this type a modification of the control scheme of Section 2.2 will be considered. Instead of constructing the manipulator in the form of an analog of the plant, the manipulator will be constructed according to a slightly different criteria. The poles of the manipulator will differ from those of the plant and will be determined by a single parameter, δ, as indicated in Eq. (4.6.1).

$$G_M(s) = \frac{K_M}{K_C}\left(\frac{s}{s+\delta}\right)^n Y_C \qquad (4.6.1)$$

n is the order of the pole at the origin in the plant. For a second order plant

$$n = 2$$

$$Y_C(s) = \frac{1}{s^2}$$

$$G_M(s) = K_M\left(\frac{s}{s+\delta}\right)^2 \frac{1}{s^2} = \frac{K_M}{(s+\delta)^2} = \frac{K_M}{s^2 + 2\delta s + \delta^2} \qquad (4.6.2)$$

in terms of the difference coefficients of Section 2.3

$$\epsilon_A = 2\delta \qquad (4.6.3)$$

$$\epsilon_B = \delta^2 \qquad (4.6.4)$$

Using Eq. (2.2.16), $\hat{Y}_C(s)$, the apparent plant becomes:

$$\hat{Y}_C(s) = \frac{Y_C}{G_M} = \frac{\frac{K_C}{s^2}}{\frac{K_M}{s^2 + 2\delta s + \delta^2}} = \frac{K_C}{K_M}\left[1 + (2\delta s + \delta^2)\frac{Y_C}{K_C}\right] \qquad (4.6.5)$$

The introduction of the parameter δ has the effect of establishing a mismatch between the plant and the manipulator. The effect of the mismatch on the apparent plant is shown in Eq. (4.6.5). Several values of δ were investigated to determine experimentally the effect they had on the complexity of the apparent plant. Based on this experimental work, a value of $\delta = 1\ \text{sec}^{-1}$ was selected for use in the experiments of this section.

Using $\delta = 1$, operator control of second, third, and fourth order systems was investigated. In all cases the manipulator was limited to second order characteristics of the forms shown in Eq. (4.6.2). As a comparison, control with a position control stick with the same plant was also investigated.

One operator participated in this experiment. The input forcing function was obtained by low pass filtering the noise source at one radian per second. The plants were investigated in sequential order starting with the second order.

Results from Control of Second Order Plant

The results obtained from the experimentation with the second order plant are shown in Fig. 4.6.1. Operator performance with the position control stick was rather poor over the entire duration of the test. This was possibly due to his inexperience in controlling unstable plants. Control with the manipulator characteristics determined by Eq. (4.6.2) with $\delta = 1$ resulted in better performance than was obtained by position control of the same plant.

Control of a Third Order Plant

The results obtained for the control of a $1/s^3$ third order plant are shown in Fig. 4.6.2. This data represents the performance obtained for ten trials of the compensatory tracking task using the same random input forcing function as was used in the first part of this experiment. A comparison was not possible with performance obtained using position control since the operator was not capable of keeping the plant output within the range of values which could be displayed on the oscilloscope screen.

The results of this experiment indicate that by using the manipulator characteristics of Eq. (4.6.2), the operator was capable of controlling the third order plant used in this experiment. Performance, as would be expected, was poorer than that obtained in the control of the second order system but much better than that which resulted from control with a position control stick.

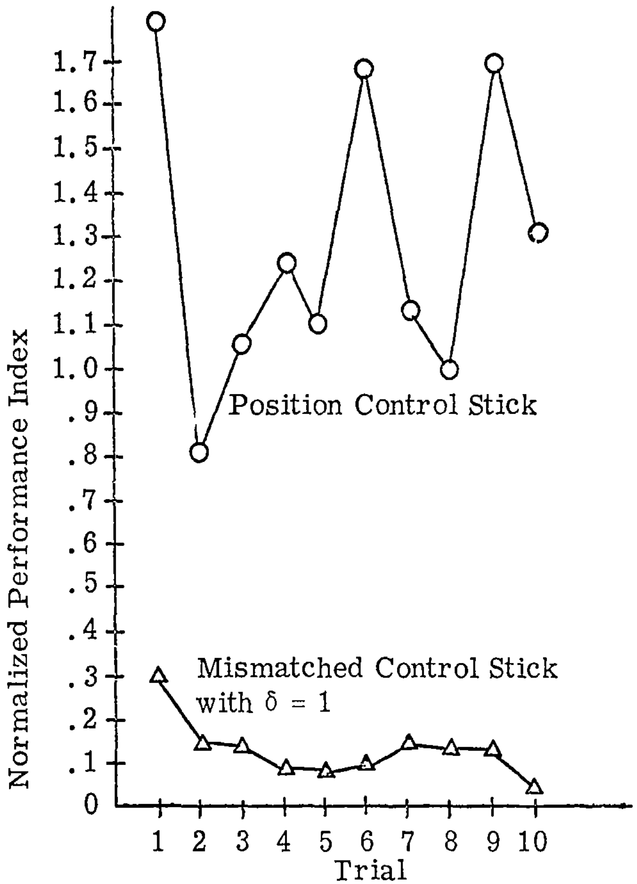

Figure 4.6.1 Control of $1/s^2$ Plant with Position Control Stick and Mismatched Control Stick with δ = 1.

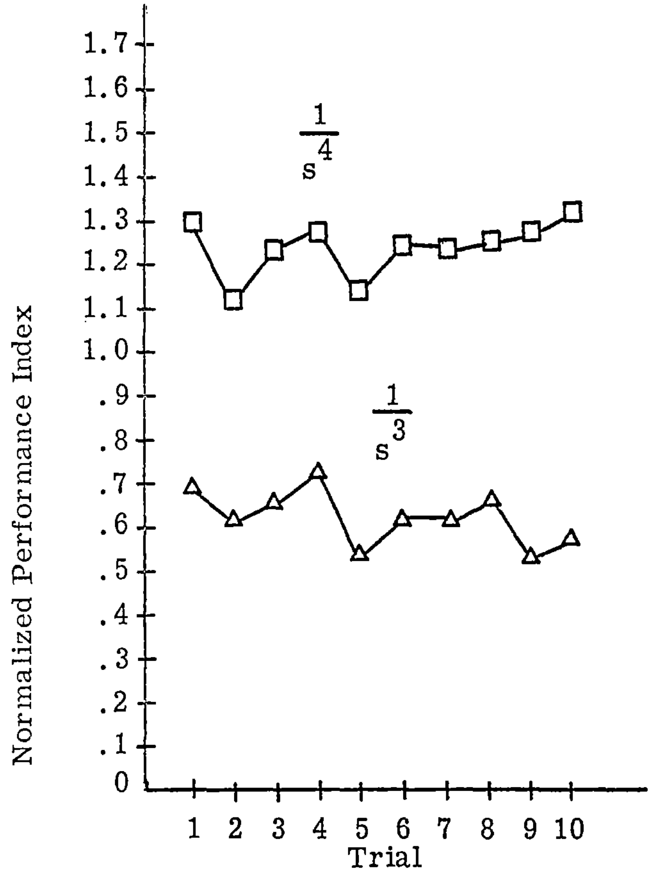

Figure 4.6.2 Control of $1/s^4$, $1/s^3$ Plant with Mismatched Control Stick with δ = 1.

Control of a Fourth Order Plant

Figure 4.6.2 displays the results obtained from operator control of a $1/s^4$, fourth order plant. Again the operator was unable to control the plant using a position control stick. Comparison of Fig. 4.6.2 with Fig. 4.6.1 indicates that the operator performance in this fourth order system was approximately the same as that obtained with the second order plant with control from a position control stick. This type of performance would be anticipated from an analysis of the apparent plant as indicated in Eq. (4.6.5).

The experiments of this section indicate that an extension of the matched manipulator technique to include unstable plants is possible. In controlling unstable plants it appears to be advantageous to introduce a parameter error in the manipulator as indicated in Eq. (4.6.1). Selection of the form of this error may be determined by experimentation.

The following chapter discusses the characteristics and design features of the variable dynamics control stick.

CHAPTER V

VARIABLE DYNAMICS CONTROL STICK

5.0 Abstract

This chapter contains information relevant to the variable dynamics control stick which was used in the experimentation of Chapters III and IV. The design philosophy, specifications, circuit description, and areas of application are described.

5.1 Introduction

The variable dynamics control stick, Figs. 5.1.1, 5.1.2, 5.1.3, is the major piece of apparatus which was designed and constructed for the experimentation contained in this document. Coupled to a conventional type control stick is an Inland Motor Company torque motor capable of providing 22 lb-ft of torque to the control shaft. Transducers mounted on the control stick sense angular position, velocity and acceleration. To provide the variable dynamics characteristics, voltage functions of the control stick position, velocity and acceleration are constructed on the analog computer. By applying these voltage functions to a power amplifier which drives the motor, it is possible to generate analogous torques on the control stick. These torques have the same effect as the reaction torques generated by inertia, viscous, and spring elements. Control of the voltage function results in control of the mechanical characteristics of the control stick.

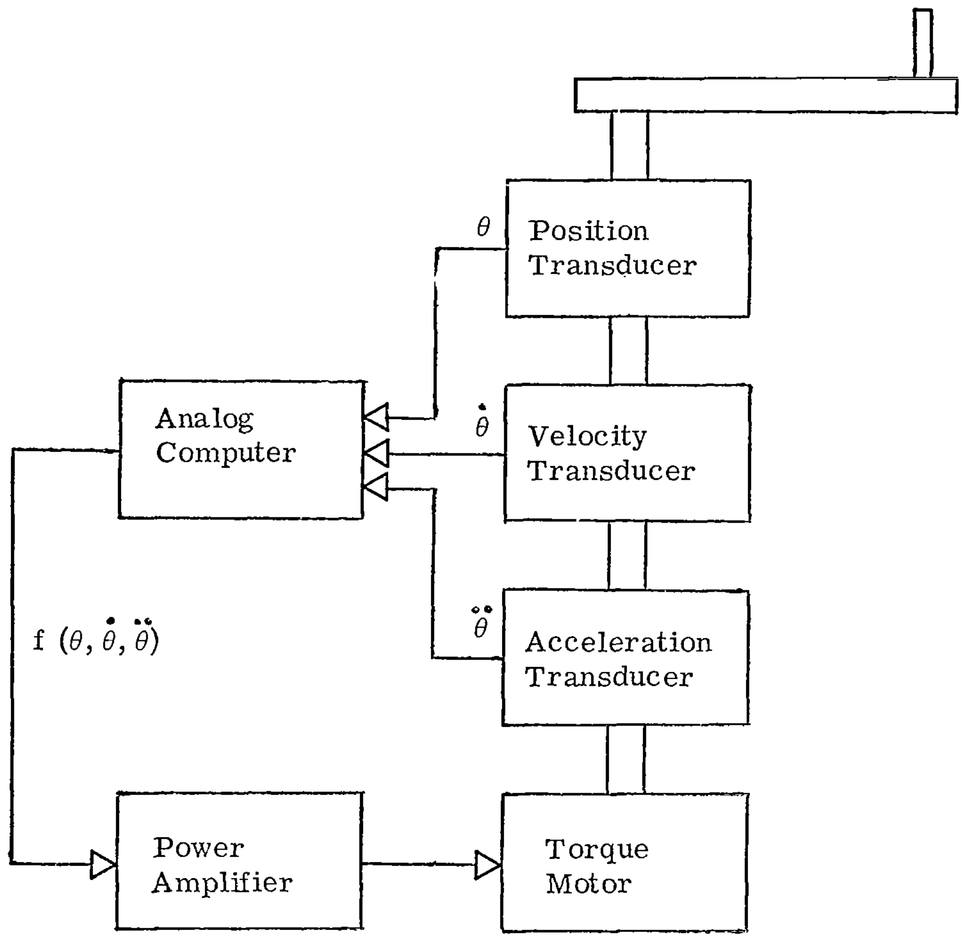

Figure 5. 1. 1 Functional Representation of the Variable Dynamics Control Stick

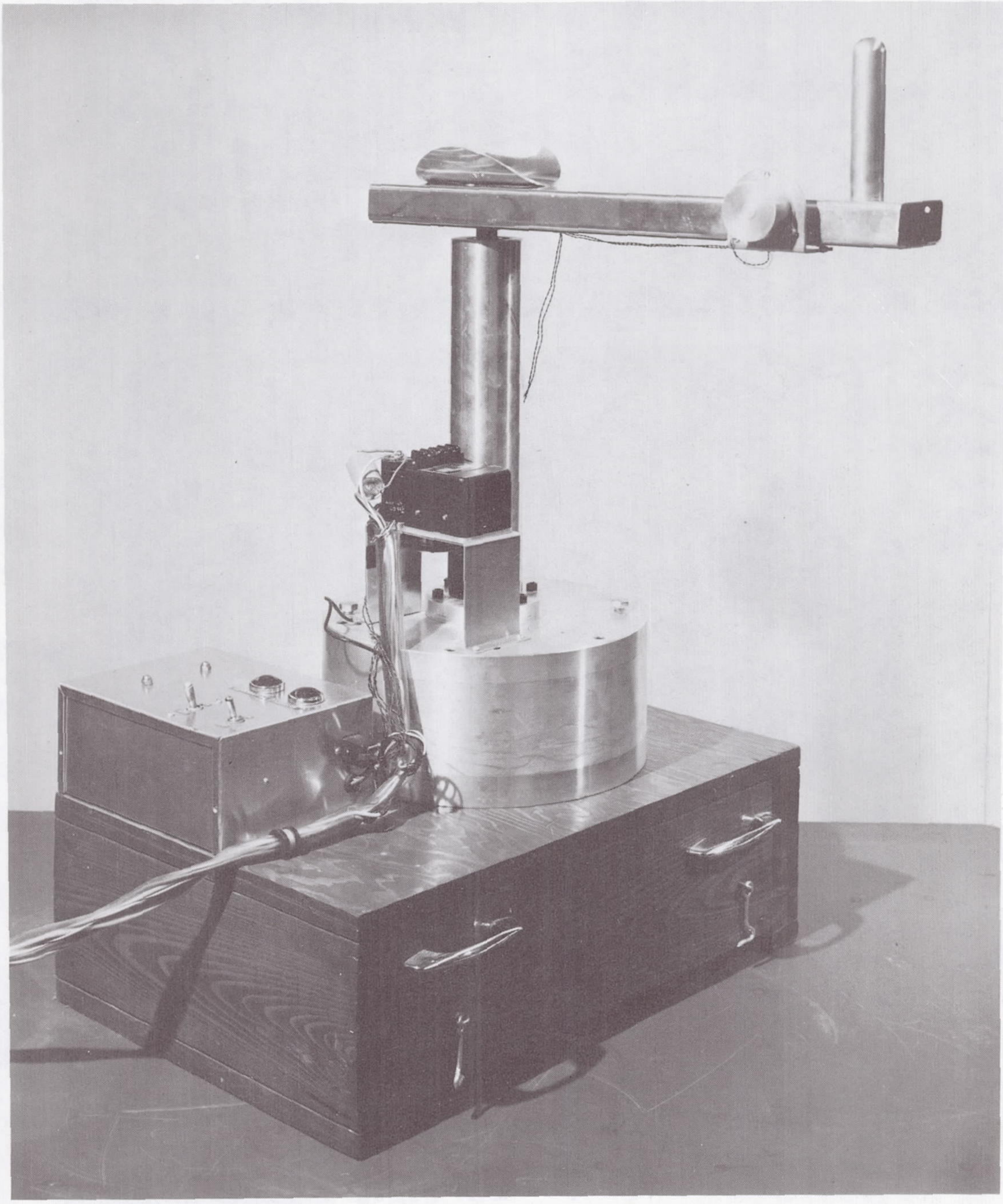

Figure 5.1.2 Variable Dynamics Control Stick

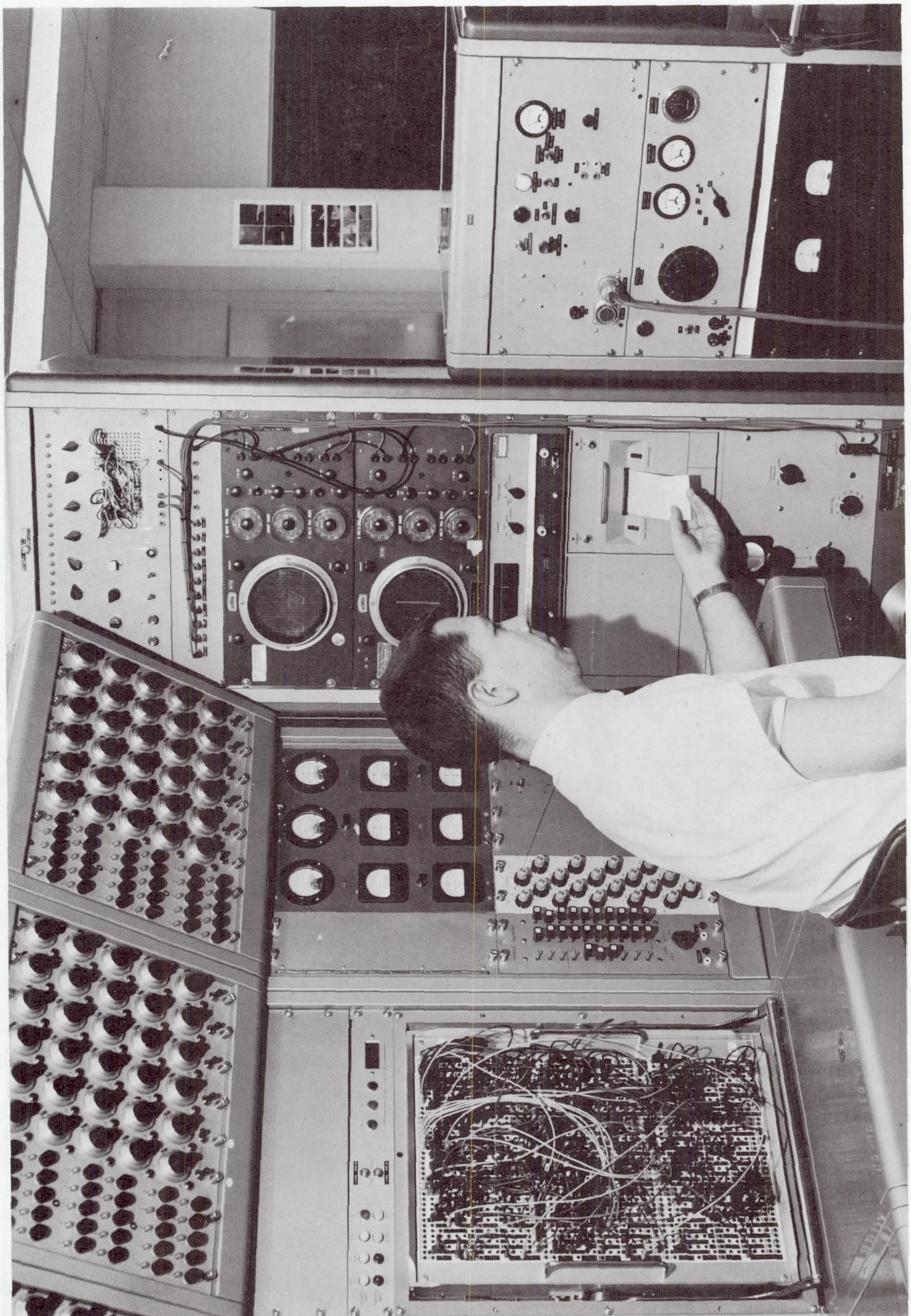

Figure 5.1.3 Analog Computer and Power Console

The differential equation which describes the rotation of the control stick is presented in Eq. (5.1.1).

$$t_h(t) = J_S\ddot{\theta} + B_S\dot{\theta} + F_S(\dot{\theta}) + f(\ddot{\theta}, \dot{\theta}, \theta) \tag{5.1.1}$$

$t_h(t)$ is the torque contribution of the operator. The values of J_S, B_S, and F_S, intrinsic stick characteristics, are shown in Section 5.3. The torque applied by the torque motor is indicated as the function of the position, velocity, and acceleration of the control stick. For the linear case where "f" is just a weighted sum of the outputs of the control stick transducers, the following differential equation applies.

$$f(\ddot{\theta}_M, \dot{\theta}_M, \theta_M) = a_1\,\ddot{\theta}_M + a_2\,\dot{\theta}_M + a_3\,\theta_M \tag{5.1.2}$$

$$t_h(t) = (J_S+a_1)\ddot{\theta} + (B_S+a_2)\dot{\theta} + a_3\theta + F_S(\dot{\theta}) \tag{5.1.3}$$

From Eq. (5.1.3) it can be noted that the operator experiences the same reaction torques he would experience if the control stick were constructed to have equivalent mechanical characteristics.

From the function supplied by the computer, "a_1" is associated with an additional moment of inertia, "a_2" is associated with a viscous friction element, and "a_3" is associated with a spring constant. All three of these characteristics can be varied electronically by use of the analog computer.

Since there are no restrictions on the forms of the voltage function from the computer, nonlinear functions and time varying functions may easily be formed with any of the techniques normally used in analog computer simulation. The effect of other forms of torque disturbances may easily be examined by supplying the apparatus with the appropriate voltage waveforms.

5.2 Operating Characteristics

The apparatus associated with the variable dynamics control stick is contained in three different units which are interconnected by cables. In addition to the control stick and the computer, a portable console houses the amplidyne which is used as a power amplifier to drive the motor.

The motor characteristics are shown in Fig. 5.2.1. The manufacturer specifies a 1% tolerance on linearity between armature current and developed torque. To maintain this linearity throughout the device it is necessary that the power amplifier be compensated so that a scalar relationship is established between the applied voltage and the current used to drive the torque motor.

Figure 5.2.3 indicates the inner control loop which is used to assure linearity between the input voltage and output current of the amplidyne. In its operation the motor armature current is sensed by measuring the voltage developed across a 1 ohm resistor which is in series with the armature. This voltage is proportional to the motor torque. The error existing between the actual motor torque and the

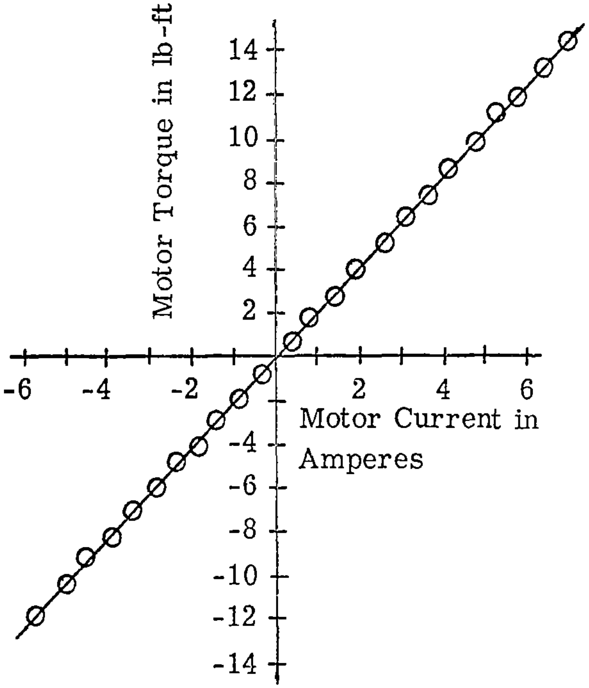

Figure 5.2.1 Experimental Relationship Between Armature Current and Motor Torque

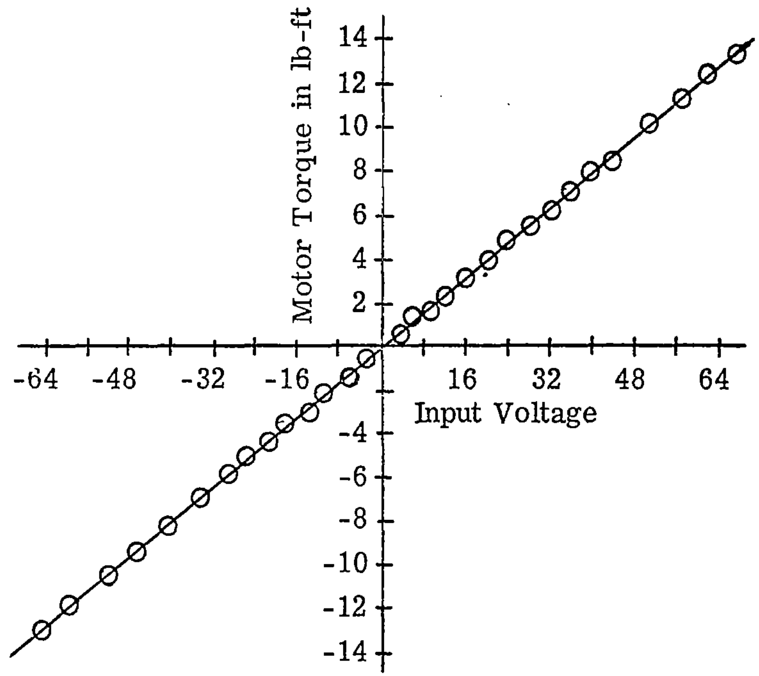

Figure 5.2.2 Experimental Relationship Between Input Voltage and Motor Torque in Variable Dynamics Apparatus

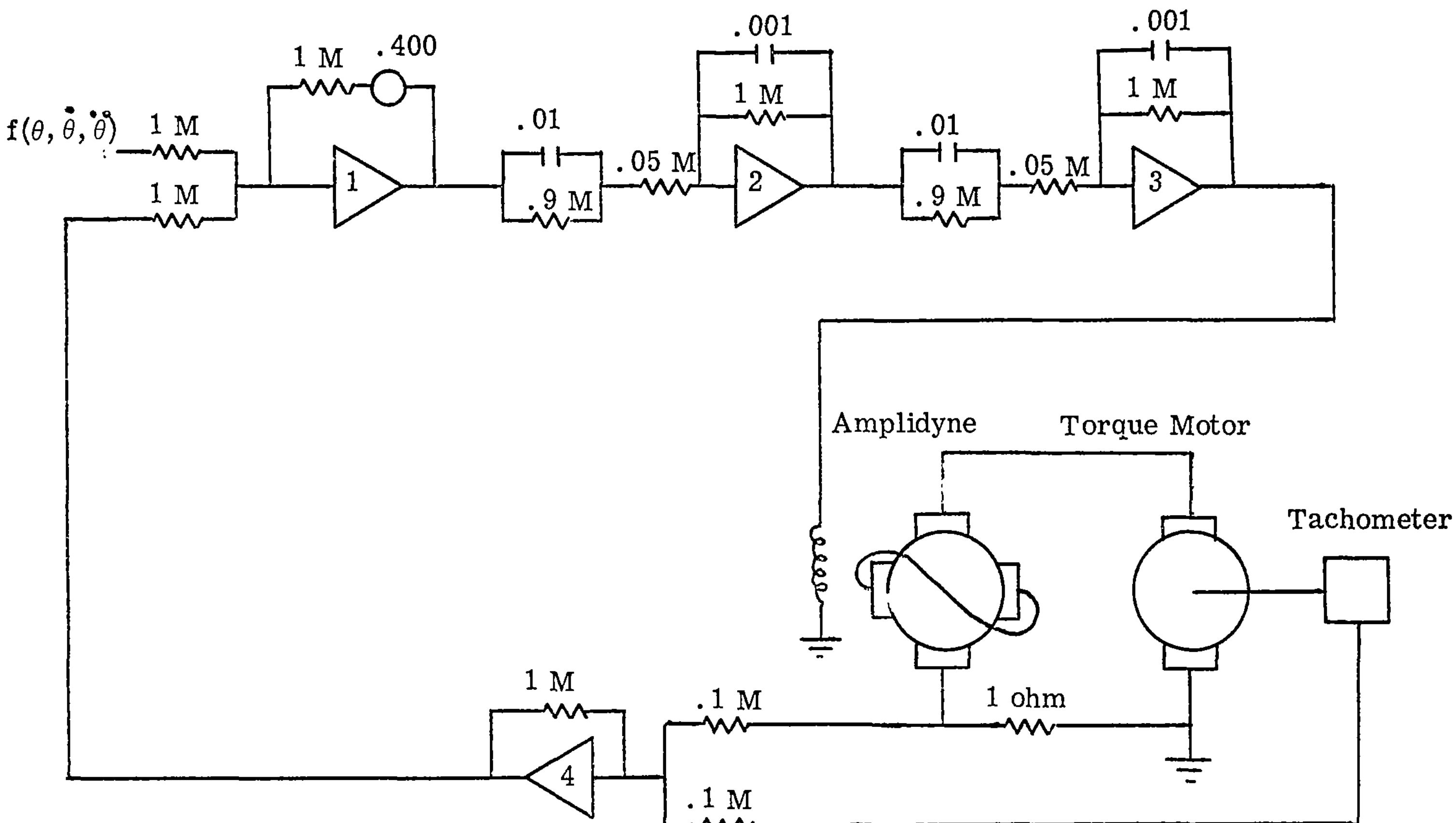

Figure 5.2.3 Control Loop for the Voltage to Torque Converter Portion of the Variable Dynamics Control Stick

desired torque is amplified, passed through a compensating filter, and then applied to the control winding of the amplidyne. The overall closed loop frequency response of the circuitry of Fig. 5.2.3 is shown in Fig. 5.2.4. To be useful, the frequency response of the apparatus must be appreciably better than that of the operator. This device fulfills that requirement. Figure 5.2.2 shows the overall linearity of the apparatus in transforming voltages into analogous torques.

5.3 Specifications

Some of the relevant physical constants associated with the variable dynamics control stick are indicated below

Tracking Stick Moment of Inertia	J_S = .075 lb-ft/sec^2
Tracking Stick Viscous Friction	B_S = .047 lb-ft/rad/sec
Tracking Stick Coulomb Friction	F_S = .16 lb-ft
Position Transducer	K_θ = .637 rad/volt
Velocity Transducer	$K_{\dot{\theta}}$ = 3.12 rad/sec/volt
Acceleration Transducer	$K_{\ddot{\theta}}$ = 12.4 rad/sec^2/volt
Motor Torque Constant	K_{TM} = 2.16 ft-lb/amp
Overall Torque Constant	K_T = 2.01 ft-lb/volt

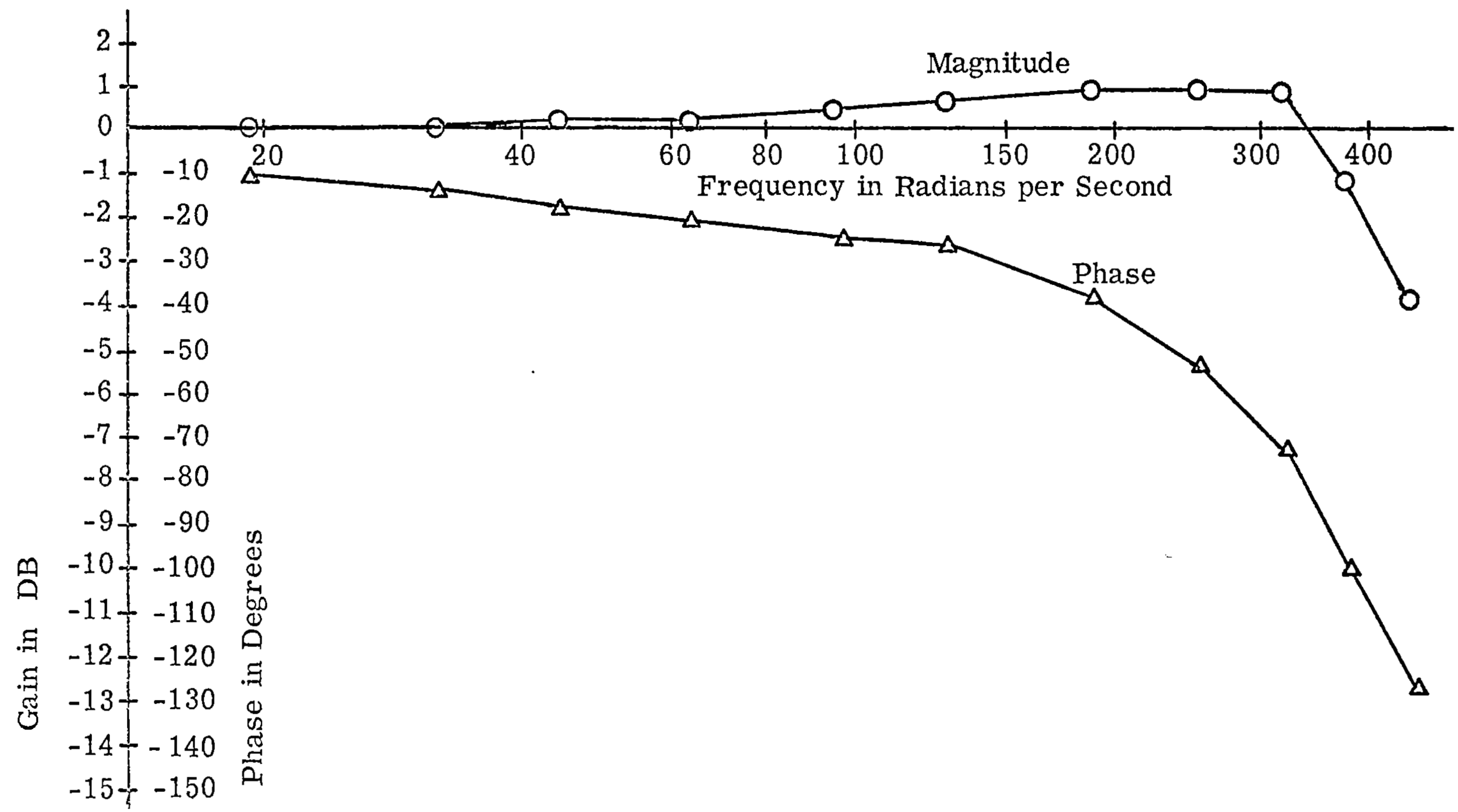

Figure 5.2.4 Closed Loop Frequency Response of the Voltage to Torque Conversion Portion of the Variable Dynamics Control Stick

CHAPTER VI

CONTRIBUTIONS, CONCLUSIONS, AND SUGGESTIONS FOR FUTURE RESEARCH

6.0 Abstract

In this chapter, the contributions of this research are summarized and reviewed. Certain aspects worthy of further investigation are discussed.

6.1 Summary

This research has attempted to introduce a new control technique for use in closed loop control systems containing a human operator. Researchers interested in manual control problems represent several formal disciplines. Chapter I was written to provide a minimal background and introduction to related work currently proceeding in the areas of control engineering, pyschology, and physiology. The research included in this document has drawn freely from all of the above mentioned areas of knowledge.

A functional block diagram of the human operator was studied in Chapter II. Through simplifying assumptions and manipulation of this block diagram, a technique for utilizing the available proprioceptive feedback from the human limb was developed. Based on the functional block diagram of the operator, it was shown that under appropriate conditions the utilization of limb feedback may allow a simplification of the operator's manual control problem.

The matched manipulator control technique was developed to make use of the proprioceptive information available to the operator through the motion and reaction forces of the control stick. By constructing the manipulator to be a mechanical analog of the plant and using the torque applied by the operator as the control variable, several advantages were obtained. The operator was relieved of the problem of supplying lead compensation in the control of the plant. The torque applied by the operator was linearly related to the control force applied to the plant. This enabled the operator to gain information relative to the control effort. This chapter also included an analysis of the effect of a parameter mismatch between the control stick and the plant and a discussion of the use of compensation in the form of the inverse plant.

Chapter III contains the experimental support for many of the statements and assertions stated in Chapter II. It was experimentally demonstrated that the operator is capable of using limb position feedback to simplify the control of specially constructed manipulator characteristics. Operator control of manipulator position was shown to be relatively independent of the form of the manipulator characteristics. Performance was found to be relatively invariant over a wide range of unstable, stable, and time varying control stick configurations.

This chapter concluded with an experimental test of the matched manipulator control technique. Use of the technique resulted in an improvement in the operator's control performance. The extent of the improvement anticipated is a function of the difficulty of the plant.

Chapter IV included several extensions of the technique developed in Chapter II. Methods of controlling higher order linear systems, unstable systems and nonlinear systems were discussed and experimentally demonstrated. The matched manipulator control technique was found to be particularly useful in the control of plants with saturation types of nonlinearities.

Describing function models of the human operator were developed for many of the experimental studies from Chapters III and IV. A set of rules was presented whereby a three parameter linear approximation to the describing function in each of the cases was developed. The linear transfer functions were shown to agree quite closely to the describing function representation in several of the test situations. The particularly simple form of the transfer function indicated that the operator could be reasonably well described by the set of rules itemized by McRuer and presented in Table 2.2.1.

The describing function models of Chapters III and IV indicate that the use of the technique of Chapter II greatly reduced the variability of the parameters in the simplified linear approximation to the describing function. When using the operator compensation technique, the describing function was shown to account for over 90% of the operators output power.

Chapter V contains design details and performance information for the variable dynamics control stick developed for this experimentation. Data is presented indicating that the device is extremely linear over its full range, up to twenty-two lb-ft, of torque. A frequency response curve for the compensated amplidyne indicates that performance is good over frequencies ranging from 0 to 300 radians per second. Circuits used for control and operation of the device are also included.

Chapter VI contains conclusions and suggestions for future extension of this work.

Three appendices are included. The first, Appendix A, discusses the properties of the pseudo-random noise generator which was used to provide a random low frequency forcing function for use in the tracking experiments. The second appendix verifies analytically that there are no interactions in the describing function analysis computer programs due to discreteness in the noise generator and discreteness in the autocorrelation analysis and Fourier integration.

6.2 Contributions

The author believes that that this document and the research that preceeded it has resulted in two major contributions. The first is the control technique developed in Chapter II. This technique when properly applied can result in extremely high compatibility between the human operator and his electromechanical environment. The use of limb feedback as an added information channel in manual control has been shown to offer a substantial improvement in performance of the human operator. Although specifically developed for the configuration of a compensatory tracking task, its use in other control situations should be relatively straightforward.

The second major contribution is the variable dynamics control stick. This research tool has allowed the investigation of operator performance in a wide variety of control situations which were not possible with previously available apparatus. In Section 6.3 where suggestions for further research are included, suggestions are included for utilizing the variable dynamics device in several areas of investigation.

6.3 Suggestions for Future Research

Two forms of further research seem worth pursuing. The first and most obvious form is that of extension and verification of some of the ideas and techniques developed in this document. The second set of suggestions results from the author's belief that the variable dynamics control apparatus offers many possibilities for continued research.

The manual control technique developed in this research was based on the intuitive conclusion that the best possible characteristics to include on the operator's control stick was an analog of the plant he was to control. The possibility exists that performance may be improved by selecting a slightly different criterion for determining the control stick dynamics. An investigation to determine the best criterion for providing an interaction between the operator and the apparatus could possibly be based on a scheme of parameter optimization for the control stick characteristics.

As a more generalized problem, the question of performance optimization for manual control schemes in which cost functions other than those related strictly to tracking error should be considered. Of particular interest would be an investigation of the operator's ability to include control effort as a part of the performance measure for the control system. The control scheme developed in this research is unique in that the system control effort is a linear multiple of the effort extended by the operator. The operator should have sufficient information to enable him to operate well under many different performance indices. It should be possible for the operator to effectively make trade-offs between tracking performance and control effort. This would be a particularly valuable characteristics for use in many types of control situations.

The functional block diagram of the human operator presented in Chapter II is based on some rather gross approximations of the characteristics of the contributing neuromuscular transducers. A very valuable contribution to the area of manual control would be made if a successful investigation could be conducted which would yield further characteristics of the force and position proprioceptive feedback paths. The design of an experiment which will yield this information is not a trivial task. It would be especially desirable if such an investigation would furnish simple transfer functions which could be placed in the neuromuscular blocks of Fig. 2.2.1. Even relatively crude data concerning the effective gain of the feedback elements would be valuable.

Extension of this research to include control of unstable plants of a more general nature might prove productive. The suggestions and results formulated for the case of repeated roots at the origin should provide a starting point for such research.

As a matter of interest to the military, an application of the operator compensation technique to situations where the plant dynamics are those of high performance aircraft, helicopters, and submarines should be performed. The technique developed may offer performance advantages when used as part of the overall control system or may be used as a training aid in ground simulators.

There are several areas of research where the variable dynamics apparatus might be a very valuable research tool. One of the symptoms of advanced cases of some neuromuscular diseases is a deterioration in the stability of the human limb. In advanced cases of Parkinson's disease, for example, attempts at controlled motion may result in uncontrolled oscillation. It may be possible to diagnose such diseases at an earlier stage than is now possible by testing the limb control ability of a patient with the variable dynamics apparatus. Any tendency for instability in the operator could be enhanced by providing unstable conditions on the control apparatus. The use of negative viscous friction is an example of a control stick condition which tends to cause operator instability.

APPENDIX A. PSEUDO-RANDOM NOISE GENERATOR

The low frequency random voltage used as a tracking signal was obtained from an 18 stage shift register generator as shown in Fig. A.1. By performing a modulo two addition of the outputs of two stages and introducing the result in the first stage, the shift register will require

$$Z = 2^n - 1 \tag{A.1}$$

shifts before a sequence is repeated. This can be shown to be the maximum length sequence which can be generated using an n stage register.

The binary signal obtained from one of the stages is put into a form such that the two binary states are represented by + 100 volts and - 100 volts. This signal is then filtered. The output of a low pass filter closely resembles what would be obtained if Gaussian white noise were filtered.

The signal has some peculiarities. The power spectrum of the pseudo-random noise is discrete. This is due to the periodic nature of the binary signal. The period of the binary signal is

$$T = \frac{Z}{f_c} \tag{A.2}$$

T is the period of the signal and f_c is the clock frequency of the shift register. For an 18 stage shift register

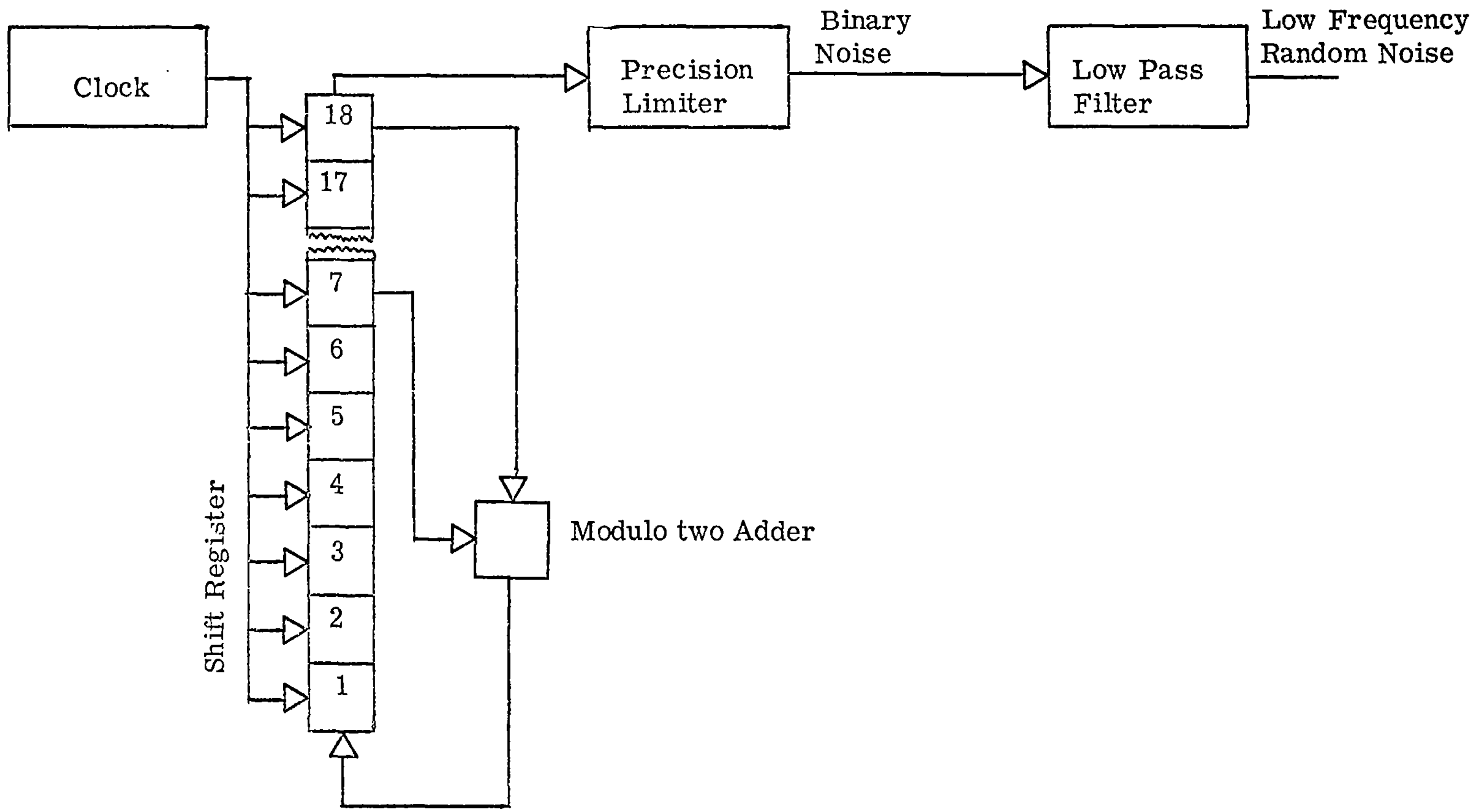

Figure A.1 Generation of Low Frequency Pseudo Random Forcing Function using a Shift Register Generator

$$T = \frac{2^n - 1}{f_c} = \frac{262,143}{f_c} \qquad (A.3)$$

For clock frequencies of the order of 10 hz a repetition will not occur for several hours.

The clock frequency selected is a function of the cutoff frequency of the low pass filter used to filter the binary signal. The clock frequency must be high compared to the cutoff frequency so that the binary nature of the input signal is obscured. It has been found experimentally by Gilson [25] that too high a clock frequency results in a skewness in the amplitude distribution of the filter output. For

$$\frac{f_c}{f_b} \approx 20 \qquad (A.4)$$

The resulting output signal has an approximate Gaussina amplitude distribution. f_b is the filter cutoff frequency. For the cutoff frequencies of 1 radian per second and 2 radians per second used in the experiments of Chapter IV, clock frequencies of 3 cps (18.7 radians per second) and 6 cps (37.4 radians per second) were used.

The normalized autocorrelation functi on obtained from the binary output of an 18 stage shift register generator can be shown to be [27]

$$R_{xx}(\tau) = 1 - |\tau| \frac{2^n}{2^n - 1} = 1 - |\tau| \, (1.0000038) \text{ for } \tau \leq \frac{1}{f_c} \text{ seconds} \qquad (A.5)$$

$$R_{xx}(\tau) = -\frac{1}{2^n - 1} = -.0000038 = 3.8 \times 10^{-6} \text{ for } \tau \geq \frac{1}{f_c} \text{ seconds} \qquad (A.6)$$

$R_{xx}(\tau)$ appears as shown in Fig. A.2. For τ greater than $1/f_c$ seconds, $R_{xx}(\tau)$ is approximately zero. It can be shown [27] that the autocorrelation function and the power spectral density of a time function are Fourier transform pairs. The spectral density, $\Phi_{xx}(\omega)$, of the output of the shift register can be shown to be [27]

$$\Phi_{xx}(\omega) = \frac{1}{Z^2}\delta(\omega) + \sum_{n=-\infty}^{\infty} \frac{Z+1}{Z^2}\left[\frac{\sin\frac{\omega_n}{2f_c}}{\frac{\omega_n}{2f_c}}\right]^2 \delta(\omega - \omega_n) \qquad (A.7)$$

$$\omega_n = \frac{n\,2\pi\, f_c}{Z} \qquad (A.8)$$

$$\frac{\omega_n}{2f_c} = \frac{n\pi}{Z} \qquad (A.9)$$

$\Phi_{xx}(\omega)$ is a discrete spectrum with a harmonic separation of

$$\Delta f = \frac{f_c}{Z} \qquad (A.10)$$

For the two clock frequencies used Eq. (A.10) gives

$$\Delta f_1 = \frac{3}{262,143} = 11.4 \times 10^{-6} \text{ hz} \qquad (A.11)$$

$$\Delta f_2 = \frac{6}{262,143} = 22.8 \times 10^{-6} \text{ hz} \qquad (A.12)$$

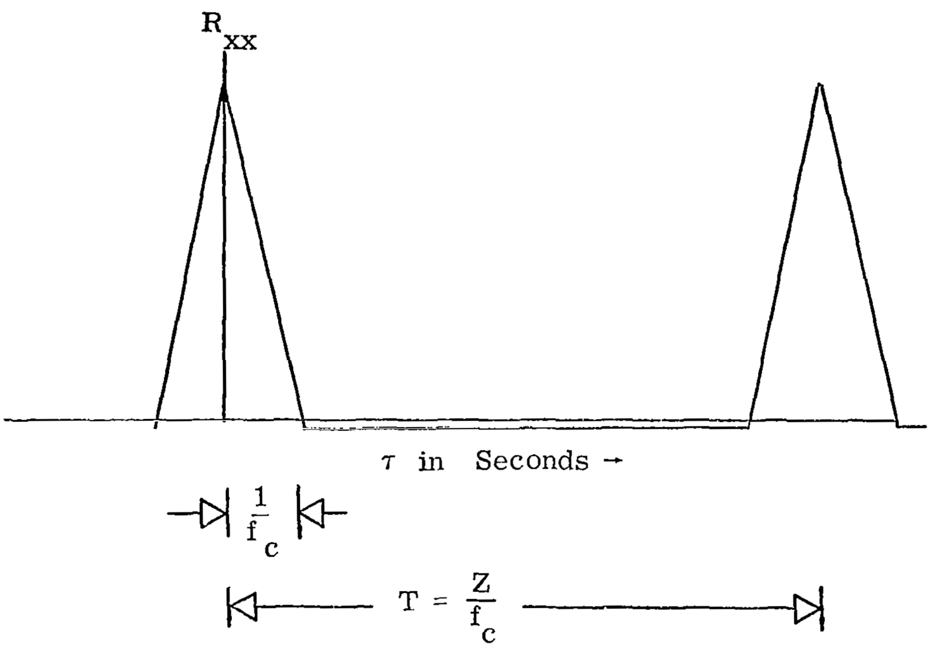

Figure A. 2 Autocorrelation Function of a Repetitive Binary Signal

Although the spectrum is discrete the interval between frequencies is extremely small for relatively low clock frequencies.

The envelope of the spectrum of Eq. (A.7) is of the form

$$f(x) = \left[\frac{\sin x}{x}\right]^2 \tag{A.13}$$

The magnitude of this function is down 3 db for

$$\frac{\omega_n}{2\pi} = f_n = \frac{(1.39)\, 2f_c}{2\pi} = .44\, f_c \tag{A.14}$$

The magnitude is zero for

$$f_n = f_c \tag{A.15}$$

$\Phi_{yy}(\omega)$, the spectral density of the filter output of Fig. A.1 can be shown to be

$$\Phi_{yy}(\omega) = \Phi_{xx}(\omega) \left| H(j\omega) \right|^2 \tag{A.16}$$

It is desired that the characteristics of $\Phi_{yy}(\omega)$ be determined by $H(j\omega)$. Therefore, it is desirable that $\Phi_{xx}(\omega)$ appear as white noise. This condition can be approximated by making f_c large as shown in Eq. (A.14). Φ_{xx} is 3 db down at 1.4 cps (8.8 radians per second) for $f_c = 3$ cps and is 3 db down at 2.8 cps (17.6 radians per second) for $f_c = 6$ cps. At these frequencies the second order low pass filters used have attenuated the signal by about 40 db. Therefore the portion of the frequency spectrum which contributes significantly to $\Phi_{yy}(\omega)$ is fairly flat as is desired.

The reader if referred to the document by Hampton [27] for a more thorough discussion of pseudo-random noise generators and their characteristics.

APPENDIX B. DIGITAL TECHNIQUE FOR OBTAINING DESCRIBING FUNCTION DATA

Describing functions were obtained from a computer analysis of a part of the data from Chapters III and IV. The computation is based on the technique developed by Blackman and Tukey [11].

As implemented, the technique involves sampling of the data at 20 times per second over the 110 second duration of the analysis. This results in 2200 discrete values, which are appropriately manipulated to construct the autocorrelation function of the input signal. The computer then performs the required integrations to compute the Fourier transform of the autocorrelation which is the power spectral density.

A potential problem exists if the sampling frequency of the computer is not fast enough. If the sample rate is too slow the discrete representation of the autocorrelation function may not contain enough data points to allow the numerical integration methods to represent adequately the power spectral density.

To show that the method is satisfactory in this analysis, it must be shown that the autocorrelation function of the data used in this experiment is represented by many data points in its discrete representation in the digital computer.

As a demonstration, consider the analysis of the power spectral density of the low frequency random noise generated by the shift register generator of Fig. A.1. The spectral densities of the input, x(t), and output, y(t), of the linear filter are related by

$$\Phi_{yy}(\omega) = H(j\omega)\, H(-j\omega)\, \Phi_{xx}(\omega) \tag{B.1}$$

$H(j\omega)$ is the transfer function of the filter. Taking the inverse Fourier transfor , where * represents time domain convolution, gives

$$F^{-1}[\Phi_{yy}(\omega)] = F^{-1}[H(j\omega)\, H(-j\omega)\, \Phi_{xx}(\omega)] \tag{B.2}$$

$$R_{yy}(\tau) = F^{-1}[H(j\omega)\, H(-j\omega)] * F^{-1}[\Phi_{xx}(\omega)] \tag{B.3}$$

$$R_{yy}(\tau) = F^{-1}[H(j\omega)\, H(-j\omega)] * R_{xx}(\tau) \tag{B.4}$$

Equation (B.4) shows the relationship existing between the auto-correlation function of the input and output of a linear filter. It will now be shown that $R_{yy}(\tau)$ is represented by several data points in the computer.

For a linear first order low pass filter with cutoff frequency ω_c

$$H(j\omega) = \frac{1}{1 + j\frac{\omega}{\omega_c}} \tag{B.5}$$

$$H(-j\omega) = \frac{1}{1 - j\frac{\omega}{\omega_c}} \tag{B.6}$$

$$H(j\omega)\,H(-j\omega) = \frac{1}{1 + \frac{\omega^2}{\omega_c^2}} = \frac{\omega_c^2}{\omega_c^2 + \omega^2} \qquad \text{(B. 7)}$$

$$F^{-1}\left[\frac{\omega_c^2}{\omega^2 + \omega_c^2}\right] = \frac{\omega_c}{2}\, e^{-\omega_c|\tau|} \qquad \text{(B. 8)}$$

For values of ω_c of 1 and 2 radians per second used in Chapters III and IV, the time constants are 1 and .5 seconds. To obtain the autocorrelation $R_{yy}(\tau)$, the function shown in Eq. (B. 8) must be convolved with $R_{xx}(\tau)$ as shown in Eq. (B. 4). $R_{xx}(\tau)$ was discussed and plotted in Fig. A. 2 of the previous appendix. The width of the triangular autocorrelation function is related to the clock frequency of the noise generator. For a worst case evaluation we may consider $R_{xx}(\tau)$ to be represented by $\delta(\tau)$. This would be approximated for a very high clock frequency. The convolution of the function of Eq. (B. 8) with a delta function yields the original function. For this case $R_{yy}(\tau)$ is identical to Fig. A. 2.

Since the sample rate in the computer is 20 samples per second, the portion of Fig. B. 2 lying within one time constant of the origin would be represented by 40 data points for a 1 radian per second filter and 20 points for a 2 radian per second filter. In actuality the autocorrelation is represented by more than the above number of points since the assumptions made regarding $R_{xx}(\tau)$ is a limiting worst case.

From this calculation it may be concluded that no large errors are introduced by the digital computation of the autocorrelation function and its Fourier transform. The reader is referred to Blackman and Tukey [11] for a thorough treatment of the computational technique.

APPENDIX C. DESCRIBING FUNCTION REPRESENTATION OF THE HUMAN OPERATOR

In this appendix the random input describing function will be introduced and discussed as a means of representing the frequency domain characteristics of the human operator. Describing functions obtained by the methods discussed in this appendix are presented in several sections of this document. The method used to obtain a transfer function approximation to the describing function is also discussed.

There are many situations which arise in control system analysis in which it is desired to characterize a nonlinear element in a manner other than cataloging the element's response to a large variety of control inputs. Describing function techniques are based on the observation that many nonlinear elements may be represented in a form similar to linear elements for a particular class of forcing functions.

A common type of describing function is known as a sinusoidal describing function. For the nonlinear element as shown in Fig. C.1, the sinusoidal describing function is defined as the complex ratio of the fundamental component of the output signal to that of the input. In general this function will depend on the magnitude of the input signal.

There is some difficulty in applying the sinusoidal describing function analysis to closed loop systems such as Fig. C.2. Harmonics of the input forcing function which are present in the output are

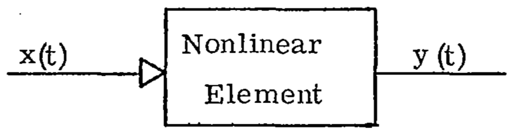

Figure C. 1 Nonlinear System

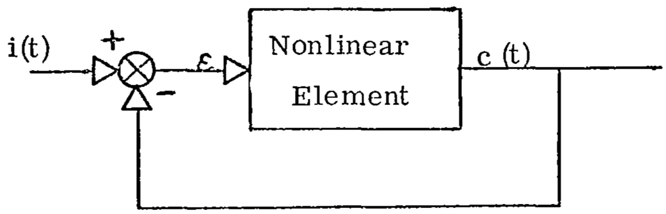

Figure C. 2 Closed Loop Nonlinear System

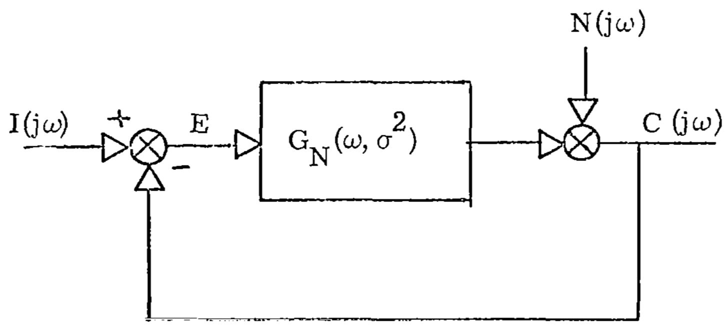

Figure C. 3 Inclusion of Remnant Noise to Account for Uncorrelated Power in the Output Signal introduced to the input again through the feedback path. The resulting signal is then not sinusoidal and the describing function representation of the nonlinear element may no longer be valid for this new class of inputs. If the nonlinear element has the characteristics of a low pass filter, which is often the case, the effects of this higher harmonic generation is usually slight. The sinusoidal describing function technique has proved itself to be extremely useful in the analysis of many nonlinear systems.

The random input describing function is defined as the complex ratio of the portion of the output signal which is linearly correlated to the input, to the input itself. This type function is especially well suited for the analysis of human operators since prediction of the forcing function is not possible due to its random nature. In the sinusoidal describing function the magnitude of the input forcing function often enters into the describing function representation. In random input describing functions it is the variance, σ^2, of the random input which would enter into the representation.

In general the describing function cannot account for all of the characteristics of the nonlinear element. A second component, $N(j\omega)$, which represents the difference between the actual system and describing function approximation must be introduced as shown in Fig. C.3. This additional component is usually referred to as the remnant. The relative magnitude of the remnant may be considered an indication of the element's departure from linearity.

The random input describing function for a particular stationary input may be defined in terms of the spectral density and cross spectral density of x(t) and y(t) from Fig. C. 1.

$$G_N(\omega) = \frac{\Phi_{xy}(j\omega)}{\Phi_{xx}(\omega)} \qquad (C.1)$$

The spectral densities may be defined in terms of the Fourier transforms of x(t) and y(t).

$$\Phi_{xx}(j\omega) = \Phi_{xx}(\omega) = \lim_{T \to \infty} \frac{1}{T}\left[X_{T_o}(-j\omega)\, X_{T_o}(j\omega)\right] \qquad (C.2)$$

$$= \lim_{T \to \infty} \frac{1}{T}\left|X_{T_o}(j\omega)\right|^2$$

$$X_{T_o}(j\omega) = \int_{-T_o}^{T_o} x(t)\, e^{-j\omega t}\, dt \qquad (C.3)$$

$$\Phi_{xy}(j\omega) = \lim_{T \to \infty} \frac{1}{T}\left[X_{T_o}(j\omega)\, Y_{T_o}(-j\omega)\right] \qquad (C.4)$$

$$Y_{T_o}(j\omega) = \int_{-T_o}^{T_o} y(t)\, e^{-j\omega t}\, dt \qquad (C.5)$$

The spectral density and cross spectral density used in Eq. (C. 1) may also be obtained by taking Fourier transforms of the autocorrelation function and cross correlation function as indicated in Eqs. (C. 6) and (C. 7).

$$\Phi_{xx}(\omega) = F[R_{xx}(\tau)] = \int_{-\infty}^{\infty} R_{xx}(\tau)\, e^{-j\omega\tau}\, d\tau \tag{C.6}$$

$$\Phi_{xy}(j\omega) = F[R_{xy}(\tau)] = \int_{-\infty}^{\infty} R_{xy}(\tau)\, e^{-j\omega\tau}\, d\tau \tag{C.7}$$

The correlation functions are defined as follows

$$R_{xx}(\tau) = \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} x(t)\, x(t - \tau)\, dt \tag{C.8}$$

$$R_{xy}(\tau) = \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} x(t)\, y(t - \tau)\, dt \tag{C.9}$$

The random input describing function may be computed from experimental data by using Eq. (C.8) and Eq. (C.9) to form the required autocorrelation and cross correlation functions and then using Eqs. (C.6) and (C.7) to compute the power spectral density of the input signal and the cross spectral density of the input and output signal. Equation (C.1) may then be used to compute the describing function.

In the experimentation associated with this research the operator is embedded in a control loop much as in Fig. C.2. A direct application of the method just described would suggest that, $G_N(\omega)$, the describing function of the operator, may be determined from:

$$G_N(\omega) = \frac{\Phi_{\epsilon c}(j\omega)}{\Phi_{\epsilon\epsilon}(\omega)} \tag{C.10}$$

For computational ease it is more convenient to express this relationship in terms of input i(t) and output c(t) of the closed loop system.

$$\frac{\Phi_{i\epsilon}(j\omega)}{\Phi_{ii}(\omega)} = \frac{1}{1 + G_N(\omega)} \tag{C.11}$$

$$\frac{\Phi_{ic}(j\omega)}{\Phi_{ii}(\omega)} = \frac{G_N(\omega)}{1 + G_N(\omega)} \tag{C.12}$$

$$\frac{\dfrac{\Phi_{ic}(j\omega)}{\Phi_{ii}(\omega)}}{\dfrac{\Phi_{i\epsilon}(j\omega)}{\Phi_{ii}(\omega)}} = G_N(\omega) \tag{C.13}$$

$$\Phi_{i\epsilon}(j\omega) = F[R_{i\epsilon}(\tau)] = F\left[\int_{-T}^{T} i(t)\,\epsilon(t-\tau)\,dt\right] \tag{C.14}$$

$$\epsilon = i - c \tag{C.15}$$

$$\Phi_{i\epsilon}(j\omega) = F\left\{\int_{-T}^{T} i(t)\,i(t-\tau)\,dt - \int_{-T}^{T} i(t)\,c(t-\tau)\,dt\right\}$$

$$= F[R_{ii}(\tau) - R_{ic}(\tau)] = F[R_{ii}(\tau)] - F[R_{ic}(\tau)]$$

$$= \Phi_{ii}(\omega) - \Phi_{ic}(j\omega) \tag{C.16}$$

therefore:

$$G_N(\omega) = \frac{\Phi_{ic}(j\omega)}{\Phi_{ii}(\omega) - \Phi_{ic}(j\omega)} \tag{C.17}$$

To compute the describing functions used in this research a PDP 1 digital computer was used. Analog data signals of i(t) and c(t) were digitally analyzed to obtain $R_{ii}(\tau)$ and $R_{ic}(\tau)$. Fourier transforms of $R_{ii}(\tau)$ and $R_{ic}(\tau)$ gave the required spectral densities $\Phi_{ii}(\omega)$ and $\Phi_{ic}(j\omega)$. Equation (C.17) was then used to compute the describing function.

As a measure of the effectiveness of the describing function representation a linear correlation function can be formed which gives the ratio of the linearly correlated output power spectrum to the total output power.

$$\rho^2 = \frac{\text{linearly correlated output power}}{\text{total output power}} \tag{C.18}$$

$$= \frac{\int_0^\infty \Phi_{ii}(\omega) \left| \frac{G_N(\omega)}{1 + G_N(\omega)} \right|^2 d\omega}{\int_0^\infty \Phi_{\epsilon c}(\omega)\, d\omega} \tag{C.19}$$

$$\Phi_{ic}(j\omega) = \frac{G_N(\omega)\, \Phi_{ii}(\omega)}{1 + G_N(\omega)} \tag{C.20}$$

$$\rho^2 = \frac{\int_0^\infty \left|\Phi_{ic}(j\omega)\right|^2 d\omega}{\int_0^\infty \Phi_{ii}(\omega)\,\Phi_{cc}(\omega)\,d\omega} \qquad \text{(C.21)}$$

Describing Function Representation of the Human Operator

In attempting to analyze the control characteristics of the human operator with describing function techniques it is necessary to determine the effects of the magnitude of the input forcing function and gain associated with the plant. McRuer [37] has determined experimentally that there is no evidence of nonlinear behavior in the sense of describing function variation with variance of the forcing function. For varying values of K_C, the plant gain, there was evidence of fairly large variability in the describing function for very low frequencies compared to the gain crossover frequency. For frequencies in the range of gain crossover there was little variation in the describing function due to changes in the gain of the plant.

Based on the experimental data of McRuer it was felt that it was unnecessary to consider further the effects of system gain on the operator describing function.

Describing function representations of the data obtained from several of the experiments are presented in Chapters III and IV. An attempt was made to approximate these describing functions with McRuer's crossover model of the human operator, which is indicated in Eq. (C.22). This representation is called the crossover model because it has been found to represent the frequency domain characteristics of human operators in the frequency range near gain crossover.

$$Y_P(j\omega)Y_C(j\omega) = \frac{K_h e^{-j\omega\tau_h}}{j\omega + a_h} \qquad (C.22)$$

$Y_P(j\omega)Y_C(j\omega)$ is the combined open loop transfer function of the operator and the plant. McRuer has asserted that the operator attempts to make this function assume approximately a 6 db per octave roll-off in the region where the gain is unity.

In Eq. (5.2.1) K_h, τ_h and "a_h" were selected according to the following criteria.

1) τ_h was selected so that $\omega\tau_h$, the phase contribution of the time delay, was $\frac{\pi}{4}$ radians at the frequency at which the total phase lag was $\frac{3\pi}{4}$ radians.

2) K_h was selected to be numerically equivalent to the frequency at which the gain was unity. This assumed that the contribution of the parameter "a_h" to the total gain was insignificant at this frequency.

3) "a_h" was selected to allow agreement of phase at low frequencies. A frequency at which the phase was approximately $\frac{\pi}{4}$ was selected. The time delay contribution to the phase was subtracted from the actual phase. "a_h" was selected so that the denominator of Eq. (C.22) accounted for the remaining phase at the frequency selected.

Providing that the linear transfer function approximation to the describing function appears valid, the above parameters provide a simple way of characterizing operator performance.

In terms of linear control system theory, K_h is usually selected to be as large as possible consistent with good stability. In terms of the model it is felt that stability considerations also govern the human operator's choice of his control gain.

τ_h represents a pure time delay. Its presence in the assumed form of the transfer function is probably related to reaction time of the human. Tests with human subjects have usually disclosed reaction times in excess of 150 milliseconds.

The importance of the parameter "a_h" is not as well understood as that of the others. It represents a gain limitation for very low frequencies and also effects the phase behavior at low frequencies. Jackson [31] has found that a two parameter representation of the operator, eliminating a_h, gives fairly close agreement to the experimental data.

REFERENCES

1. Adams, J.A. and Creamer, L.R., "Proprioceptive Variables as Determiners of Anticipatory Timing Behavior," Human Factors, 1962b, 4, 217-222.

2. Akashi, H. and Mahmood, S., "Performance of Human Operators Under Various System Parameters," Publication of the Department of Mechanical and Aerospace Engineering, University of Kansas, June 1965.

3. Bahrick, H.P., "An Analysis of Stimulus Variables Influencing the Proprioceptive Control of Movements," Psychological Review, 64, 324-328.

4. Bahrick, H.P., Bennett, W.F., and Fitts, P.M., "Accuracy of Positioning Responses as a Function of Spring Loading in a Control," Journal of Experimental Psychology, 1955a, 49, 437-444.

5. Bahrick, H.P., Fitts, P.M., and Schneider, R., "Reproduction of Simple Movements as a Function Influencing Proprioceptive Feedback," Journal of Experiment Psychology, 1955b, 49, 445-454.

6. Barker, D., Symposium on Muscle Receptors, New York, Oxford University Press, 1961.

7. Bates, J.A.V., "Some Characteristics of a Human Operator," Journal of the Institute of Electrical Engineers, London, 1947, 94, Part II, A, 298-304.

8. Bekey, G.A., "The Human Operator as a Sampled-Data System," IRE Transactions of the Professional Group on Human Factors in Electronics, September 1962, HFE-3.

9. Best, C.H., Taylor, N.B., The Physiological Basis of Medical Practice, Chapter 62, Baltimore, Williams and Wilkins, 1966.

10. Birmingham, H.P., and Taylor, F.V., "A Design Philosophy for Man-Machine Control Systems," Proceedings of the IRE, December 1954, 1748-1758.

11. Blackman, R.B., and Tukey, J.W., The Measurement of Power Spectra, New York, Dover Publications, 1958.

12. Bowen, W.P., Applied Anatomy and Kinesiology; the Mechanism of Muscular Movement, Philadelphia, Lea and Febiger, 1953.

13. Briggs, G.E., Fitts, P.M., and Bahrick, H.P., "Effects of Force and Amplitude Cues on Learning and Performance in a Complex Tracking Task," Journal of Experimental Psychology, 1957, 54, 262-268.

14. Burrows, A.A., "Control Feel and the Dependent Variable," Human Factors, 1966.

15. Crossman, E.R.F.W. and Goodeve, P.J., "Feedback Control and Fitt's Law," unpublished.

16. Davis, R.C., "The Pattern of Muscle Action in Simple Voluntary Movement," Journal of Experimental Psychology, 31, 1942, 247-366.

17. Elkind, J.I., "Tracking Response Characteristics of the Human Operator," Human Factors Operations Research Laboratories Memorandum No. 40.

18. Elkind, J.I., Green, D.M., and Starr, E.A., "A Technique for Measurement of Time-Varying Dynamic Response Characteristics of Human Operators," International Congress on Human Factors in Electronics, IRE, May 1962.

19. Fenn, W.O. and Marsh, B.S., "Muscular Force at Different Speeds of Shortening," Journal of Physiology, 85, 277, 1935.

20. Fenn, W.O., "The Mechanics of Muscular Contraction in Man," Journal of Applied Physics, 1938, 9, 165-177.

21. Fleishman, E.A. and Rich, S., "Role of Kinesthetic and Spatial-Visual Abilities in Perceptual-Motor Learning," Journal of Experimental Psychology, 1963, 66, 6-11.

22. Fulton, J.R. and Pi-Suner, J.A., "A Note Concerning the Probable Function of Various Afferent End-Organs in Skeletal Muscle," American Journal of Physiology, 1928, 83, 554.

23. Gerard, R.W. and Taylor, R.E., "A General Survey of Muscle and Nerve-Physiological Orientation," American Journal of Medicine, 1953, 15, 83.

24. Gibbs, C.B., "The Continuous Regulation of Skilled Responses by Kinesthetic Feedback, "British Journal of Psychology, 1954, 45, 25-39.

25. Gilson, R.P., "Some Results of Amplitude Distribution Experiments on Shift Register Generated Pseudo-Random Noise," IEEE Transactions on Electronic Computers, Vol. EC-15, No. 6, December 1966, pp. 926-927.

26. Graham, D., and McRuer, D., Analysis of Nonlinear Control Systems, New York, John Wiley and Sons, 1961.

27. Hampton, R.T.L., "A Hybrid Analog-Digital Pseudo-Random Noise Generator," University of Arizona, ACL Memo No. 83.

28. Held, R., "Plasticity in Sensory-Motor Systems, " Scientific American, November 1965, 213, 5.

29. Howell, W.C., Briggs, G.E., "Information Input and Processing Variables in Man-Machine Systems: A Review of the Literature," Technical Report NAVTRADEUCEN 508-1, October 1959.

30. Howland, D. and Noble, "The Effects of Phvsical Constants of a Control on Tracking Performance, " Journal of Experimental Psychology, 1953, 46, 353-360.

31. Jackson, G.A., "Measuring Human Performance With a Parameter Tracking Version of the Crossover Model," Doctoral Dissertation, The University of Michigan, 1967.

32. Jones, R.W., "The Ubiquity of Control Systems in Biological Processes, " Course Notes Physiological Systems, Northwestern University, Evanston, Illinois.

33. Loofbourrow, G. and Gellhorn, E., "Proprioceptively Induced Reflex Patterns, "American Journal of Physiology, 1948, 154, 3, 433-438.

34. Magdaleno, R. E. and McRuer, D.T., "Effects of Manipulato Restraints on Human Operator Performance," Technical Report Air Force Flight Dynamics Laboratory, TR-66-72, December 1966.

35. Matthews, P.B.C., "Central Regulation of the Activity of Skeletal Muscle, " from The Role of the Gamma System in Movement and Posture, New York, Association for the Aid of Crippled Children, 1964.

36. McElhannon, V.B., "An Analysis of the Center of Gravity of the Arm During Certain Simulated Industrial Movements," Proceedings of the San Diego Sympsoium for Biomedical Engineering, 1964.

37. McRuer, D.T., Graham, D., Krendel, E., and Reisener, W., "Human Pilot Dynamics in Compensatory Systems," Air Force Flight Dynamics Laboratory TR-65-15, 1965.

38. McRuer, D.T. and Magdaleno, R.E., "Human Pilot Dynamics with Various Manipulators," Technical Report Air Force Flight Dynamics Laboratory, TR-66-138, December 1966.

39. Merton, P.A., "Speculations on the Servo Control of Movement," CIBA Foundations Symposium: The Spinal Cord, London, 1953.

40. Noble, M.E., Bahrick, H.P., "Response Generalization as a Function of Inter Task Response Similarity," Journal of Experimental Psychology, 1956, 51, 405-412.

41. Notterman, J.M. and Page, D.E., "Evaluation of Mathematically Equivalent Tracking Systems," Perceptual and Motor Skills, 1962, 15, 683-716.

42. Orlansky, J., "Psychological Aspects of Stick and Rudder Controls in Aircraft," Aeronautical Engineering Review, 1949, 8, 1-10.

43. Ralston, H.J., "Uses and Limitations of Electromyography in the Quantitative Study of Skeletal Muscle Function," American Journal of Orthodontics," 47, 7, July 1961, 521-530.

44. Ruch, T.C. and Patton, H.D. Physiology and Biophysics, Philadelphia, W.B. Saunders Co., 1965.

45. Scott, M.C., "Measurement of Kinesthesis," Research Quarterly, 1955, 26, 324-341.

46. Simmons, G.F., Introduction to Topology and Modern Analysis, New York, McGraw-Hill, 1963.

47. Stevens, S.S., Handbook of Experimental Psychology, New York, Wiley, 1951.

48. Summers, L.G. and Ziedman, K., "A Study of Manual Control Methodology with Annotated Bibliography," NASA Contractor Report, NASA CR-125, 1964.

49. Thaler, G.J. and Pastel, M.P., Analysis and Design of Nonlinear Feedback Control Systems, New York, McGraw-Hill, 1962.

50. Wasicko, R.J. and Magdaleno, R.E., "Effects of Nonlinearities on Human Operator Tracking Performance; a Review of the Literature," AMRL-TR-65-158, October 1965.

51. Weiss, B., "Role of Proprioceptive Feedback in Positioning Response," Journal of Experimental Psychology, 1954, 47, 215-224.

52. Westbrook, C.B. and McRuer, D.T., "Aircraft Handling Qualities and Pilot Response Characteristics," May 1957.

53. Wilkie, R., "The Relation Between Force and Velocity in Human Muscle," Journal of Physiology, 110, 1949, 249-280.

54. Young, L.R., Green, D.M., Elkind, J.I., and Kelly, J.A., "The Adaptive Dynamics Response Characteristics of the Human Operator in Simple Manual Control," NASA TN D-2255.

55. Young, L.R. and Stark, L., "Biological Control Systems—A Critical Review and Evaluation," NASA Contractor Report, NASA CR-190, 1965.

NASA-Langley, 1968 —— 5 CR-1248