The Effect of Part-Simulation of Weightlessness on Human Control of Bilateral Teleoperation: Neuromotor Considerations

Kevin Corker and Antal Bejczy
Jet Propulsion Laboratory, California Institute of Technology
Pasadena, California 91109

Experimental investigations have been undertaken at JPL to study the effect of weightlessness on the human operator's performance in force-reflecting position control of remote manipulators. A gravity compensation system has been developed to simulate the effect of weightlessness on the operator's arm. In the experiments, a universal force-reflecting hand controller (FRHC) and task simulation software were employed. The controller device is a backdrivable six-dimensional isotonic joystick which conforms to the range of motion of the operator in position control. The simulation software provides experimenter manipulable task parameters which interact with the hand controller in real time operation. In light of anticipated disturbances in neuromotor control specification on the human operator in an orbital control environment, two experiments were performed in this study: (i) investigation of the effect of controller stiffness on the attainment of a learned terminal position in the three dimensional controller space, and (ii) investigation of the effect of controller stiffness and damping on force tracking (subject to unit pulse disturbance) of the contour of a simulated three dimensional cube using the part-simulation of weightless conditions: . The results of the experiments: (i) support the extension of neuromotor control models, which postulate a stiffness balance encoding of terminal position, to three dimensional motion of a multi-link system, (ii) confirm the existence of a disturbance in human manual control performance under gravity compensated conditions, and (iii) suggest techniques for compensation of weightlessness induced performance decrement through appropriate specification of hand-controller response characteristics. These techniques are based on the human control model, and instituted through FRHC control parameter adjustment.

INTRODUCTION

Remote manipulators (teleoperators) are devices that extend human manipulative abilities to operational environments that are either hostile to or remote from the human operator. Teleoperation is distinguished by the explicit and active inclusion of the human operator (HO) in the ongoing control of the teleoperated device. The operator brings to the control task impressive intellectual and analytic capabilities, as well as, a rich and subtle control language in the movement and proprioceptive functions of the human arm and hand. This study addresses bilateral control in space teleoperation in which the transmission of control signals and the reception of feedback information occurs simultaneously at the operator's hand. The critical elements in this control are (i) the neuromotor characterisitcs of the HO's arm and hand, including motion control functions, their stability, and their sensitivity to environmental perturbations (in particular micro-gravity effects in control of space teleoperators) and (ii) the hand controller that serves as a control and feedback transmission device in consonance with the human neuromotor parameters in motion control.

In the investigation of human/teleoperator control interactions in the orbital operational environment, we have employed a model describing human neuromotor control as a linear damped harmonic oscillator, i.e.,

$$I\ddot{\theta} + B\dot{\theta} + K\theta = N \qquad (1)$$

where: θ, $\dot{\theta}$, $\ddot{\theta}$ represent joint position, angular velocity, and acceleration, respectively, for the links of the kinematic chain effecting end point position, I represents system inertia, B represents system viscosity, and K represents system stiffness. N, the torque input to the system, is assumed to account for the various nonlinearities and nonstationary physiological characterisitics of actual muscle movement. The control methods inferred from this model, eg., impedance control (Hogan, 1982), or stiffness control for end point positioning (Polit and Bizzi, 1978), have been the focus of recent neuromotor research. (See Corker (1984) for a review of this research base). We explore the application of this model for the specification of the end point position in teleoperator control. It is of value to man/machine interface design that neuromotor control models be formulated in the same terms as control system descriptions for the hand controller. Human neuromotor parameters and hand controller characteristics interact as coupled systems to produce the total system response. If human and teleoperator control, in position and the first and second time derivatives (velocity and acceleration), are expressed with a similar nomenclature and found to obey similar control laws, interactions can be described, and compensations for machine or human limitations in control can be more easily accommodated in the design for optimal system function.

The first experiment was undertaken to verify and extend to teleoperator control current theories in human achievement of final limb position, as a function of balanced stiffness among muscle groups contributing to movement. The second experiment examined the effects of micro-gravity on force tracking performance using computer generated resistance planes in the control volume of the FRHC, and tested compensation techniques to counteract environment induced performance disruption.

EQUIPMENT

Hand Controller.

The JPL universal FRHC provides a generalized bilateral force-reflecting control of teleoperated manipulators. In a departure from the standard practice of master/slave control systems requiring kinematic and dynamic replication between the master and the slave, the FRHC control function is implemented through a hand controller that can be dissimilar to a particular slave arm both dynamically and kinematically. The hand controller is a six degree of freedom (DOF) isotonic joystick which can be backdriven by commands from the control computer (Figure 1). The control algorithms of the FRHC (i) transform the operator's six-dimensional hand motion into an equivalent six-dimensional motion of the particular slave hand, and (providing appropriate instrumentation of the manipulator) (ii) transmit ("reflect") the acting forces from the slave arm back to the operator's hand. Thus the FRHC as a man-machine interface device performs feedforward and feedback motion, and force transformation and transmission between the operator's hand and the remote manipulator's hand.

The FRHC provides feedback to the operator identifying position and velocity mismatch between the commanded endpoint and the actual (or simulated) manipulator end point. This feedback is instituted as a stiffening and damping of the FRHC motion through active backdrive of torque motors affecting the FRHC handgrip motion. The controller feedback gains K_p,K_v, and K_f (for sensor based force reflection) are software manipulable and were varied in the course of the experimentation reported. These gains can be varied independently for each of the six DOFs of the hand controller (Bejczy and Salisbury, 1980).

Simulation Software.

In this investigation the FRHC was decoupled from control a physical manipulator so that task parameters and disturbance inputs could be closely controlled by the experimenters.

A task simulation system was developed based on the following concept: the computer, the FRHC and the operator form a closed loop, the computer simulates a slave arm to be driven by the FRHC (Figure 2). In the feedforward path, positioning commands received from the controller are interpreted and processed in the computer. In feedback, the force and torque resulted from the simulated task environment are computed and sent by the computer to the FRHC to back drive the joint motors (Fong and Corker, 1984).

The simulation system was used in both experiments to manipulate the characterisitics of the response of the FRHC to operator task performance.

EXPERIMENTS

The purpose of the first experiment was to verify and extend the linear harmonic oscillator model of human neuromotor control to control of a teleoperator device in three dimensional space. This verification of the model was undertaken to provide a basis for analyzing performance in the zero gravity performance scenerio, described in Experiment Two.

Experiment One.

A terminal position for the hand controller was learned in the three dimensional control space of the FRHC by blindfolded subjects. The reattainment of that position was subject to stiffness constraints imposed through the simulation system. The stiffness imposed, by software specification of stiffness gain on the three translational axes of motion, either resisted or augmented the operator's movement to the learned target position. The conditions of stiffness and the magnitude of the gain were an operator dependent function based on prior calibration of system response stability for each partcipant in the study. The simulation system provided the capability to (i) specify augmentative and resistive stiffness vectors for an arbitrary position in three dimensional operator referenced Cartesian coordinates, (ii) record the achieved position (AP) to .01 inch accuracy in the free space of operator movement. Figure Three illustrates the task workspace in relation to the FRHC.

A repeated measures analysis of variance (ANOVA) was performed to determine if the target, resisted AP, and augmented AP differed significantly from each other across subjects, and to determine if that difference was orthogonal among the axial coordinates (X,Y,Z) defining those positions.

The analysis indicates a significant effect of stiffness gain (K_p) on position. The null hypothesis that stiffness would not affect achieved position in relation to the target is rejected with a $p < .001$, ($F_{(2,14)} = 18.21$). The analysis also indicates no significant difference among axes of motion, and no significant interaction between stiffness and axis, thereby supporting the hypothesis that the effect of stiffness gain is orthogonal among axes.

The results of this experiment indicate that achievment of final position in three dimensional space, effected through coordinated multi-joint motion of a multi-articulated limb system, is affected by an imposed stiffness on the moving limb. This effect differs between an augmentative and resitive stiffness in relation to a target position (learned in the absence of imposed stiffness conditions). The resultant APs are reliably short of the target in the case of resistive stiffness and beyond the target in the case of augmentative stiffness. This directional deviation is orthogonal among the major translation axes defining the AP in relation to the target. The model of multi-articulated limb control that can be inferred from these data is currently under development.

The results support the concept of stiffness balance as a position specification in human neuromotor control, and provide an extension of that model to three dimensional positioning with a control manipulanda. The results indicate a lack of precision in blind limb placement, even for a trained position, as a function of an imposed change in the relative stiffness of the muscles driving the limb movement. This effect is observed despite the availabilty of kinesthetic feedback as to the limb's actual position. The inference drawn from these results is that changes in relative muscle stiffness as a function of a zero g operating environment could potentially affect blind limb positioning in control.

Experiment Two.

The second experiment examines the effect of a zero gravity operating environment on human performance in manual control of a teleoperator in a bilateral position control mode. In order to provide an experimental platform for this research, a mechanical gravity compensation system for the upper limb has been designed and fabricated. The system is based in part on work performed at Case Western University, as reported in NASA CR-1234 (1968). The system supports the operator's upper arm an hand throughout the range of motion for control of the force reflecting hand controller (FRHC).

The system was designed to meet the following suspension requirements:

1) The compensation system should provide a constant force at the center of mass of each limb segment that is equal and opposite the gravity force acting on that limb. Determination of that force requirement is as follows:

For a limb in an arbitrary position in a 1g environment, Figure 4 illustrates the parameters of interest.

Where:

F_o = Force of support of shoulder girdle
M_1, M_2, M_3 = Mass of Limb segments
T_1, T_2, T_3 = Torque about shoulder, elbow, and wrist
L_1, L_2, L_3 = Length of limb segments
l_1, l_2, l_3 = Length to center of mass for each segment
$\theta_1, \theta_2, \theta_3$ = Segment angle to gravity perpendicular

Force balance requires that:

$$F_o = g\,(M_1 + M_2 + M_3)$$

In this design each limb segment will be supported at the center of mass of each segment. Consequently, the compensation forces (f_1, f_2, f_3) can be calculated independent of the joint torques, assuming frictionless coupling at the joints.

The arm and hand of each subject were analysed to determine the approximate weight and center of mass of each limb segment using anthropometic measurement and regression techniques developed by Clauser et al. (1969). The approximate weight determined the particular spring system to be used. Each spring system was adjustable within a range of +/- .25 lbs.; as is described below. The exact segment balance was determined by examining the response of a suspended and relaxed subject to a unit pulse disturbance, and adjusting spring tension to result in a balanced positive and negative amplitude for the response trajectory.

System Design:

The suspension system consists of two parts:

a) Negator springs to provide a constant gain spring tension for vertical compensation. The torque from the spring can be adjusted to balance the individual limb segment weight by selecting the width and breadth of the spring, and adjusting the selected spring by varying the interior diameter of the spring coil through adjustment of the radius of the take up spool. The exact spring characteristic to torque relationship has been developed for several classes of spring coils. Figure 5 shows several details. The limb segment is secured using velcro pads and the placement of the spring support is adjustable.

b) For translational motion and as a support for the negator springs an x-y roller bearing system was designed and fabricated (see Figure 5). The system will be adjustable for a standing and seated operator and mounted in front of the FRHC control/display panel.

Figure 6 illustrates an operator using the compensation system and the FRHC in control simulation experiments.

The second experiment made extensive use of the simulation system capability to configure a software defined interactive workspace for the FRHC, and to present that workspace to the operator proprioceptively, through FRHC backdrive.

In this experiment the task was defined as moving the FRHC along the surface inside or outside a simulated box , a typical task which can generate force feedback in all possible directions. The hand controller is free moving inside/outside the ´virtual´ box and encounters backdriving force when exceeding the workspace limits. This backdriving force is determined by one unique parameter called ´position error´ defined as

$$\underline{E} = \underline{X} - \underline{X}_o \qquad (2)$$

where

$\underline{E}$ is the position error,

$\underline{X}$ is the hand controller´s position,

$\underline{X}_o$ is the workspace limit.

Subjects learned to follow the outline of the three dimensional cube defined by force resistance within the working space of the hand controller. This three dimensional tracking trajectory was approximately 27 inches around the perimeter of the force cube and was completed in 20 seconds. A unit pulse disturbance of approximately 70 msec. duration and 65 in-lbs. in amplitude, defined through the simulation system, was delivered randomly in a 4 second window as the subjects performed the trajectory. The disturbance was delivered randomly in the positive or negative direction along each axis of motion.

Subjects performed the force tracking task under conditions of micro-gravity, through suspension, and in one gravity. The velocity feedback gain (damping) of the hand controller was varied between maximum stable value for each subject, and one quarter that value

A test sequence consisted of ten trials in each of two damping gain conditions in both a suspended and unsuspended operating state. FRHC position data were collected for each of the three translational axes of motion at a rate of 70 msec^{-1}.

Results:

The velocity profile of each trial for each subject was subjected to a spectral analysis through the application of a Fast Fourier Transform (FFT) technique. The data were so treated to enable statistical analysis of the effects of the imposed conditions on the amplitude of response for a specified frequency range. The FFT resulted in amplitude data for frequencies from 0 to 15 Hz. digitized in .10 Hz. steps. The data were further reduced by averging amplitudes for the first five Hertz.

The averaged performance in simulated zero g shows a higher amplitude response to disturbance in each axis of motion illustrated in Figure 7. Statistical analysis indicates a significant difference in amplitude of response to disturbance as a function of the axis observed with an $F_{(2,4)} = 9.23$. The differential response among axes of motion is in keeping with the results of an analysis of damping effects on control reported in Corker (1984).

The level of damping applied did not result in significant effects in the averaged data. An analysis of the individual response to damping was undertaken to investigate this lack of effect. Figure 8 illustrates the result of this analysis. Averaged across axes, damping in one g performance has the expected effect. However, in the suspended condition the response pattern of the subjects diverged. Group 1 response amplitudes indicate that the effect of damping is enhanced in the suspended condition resulting in response amplitudes further reduced than those of one g performance. Group 2 showed the opposite effect in response to damping in the suspended condition.

The factors contributing to the differential response to damping under zero g performance are currently being investigated. It is hypothesised that some individual´s response to control in the zero g condition result in an impedance mismatch between control damping and stiffness and the neuromotor activation state that results in the instability observed.

CONCLUSION

The results indicate the potential utility of relatively simple models of neuromotor control processes in investigating the interaction of the human operator and controller in teleoperation. Stiffness manipulation in the control system significantly affected the accuracy of final position attainment in three dimensional space. Gravity compensation for the human operator through part-simulation resulted in increased instability in the operator´s response to disturbance in a force tracking task. Additionally, preliminary data indicate that this increased instability can be successfully compensated, in some subject´s, by selection of hand controller damping and stiffness parameters to match reduced natural damping which obtains as a function of the micro-gravity conditions.

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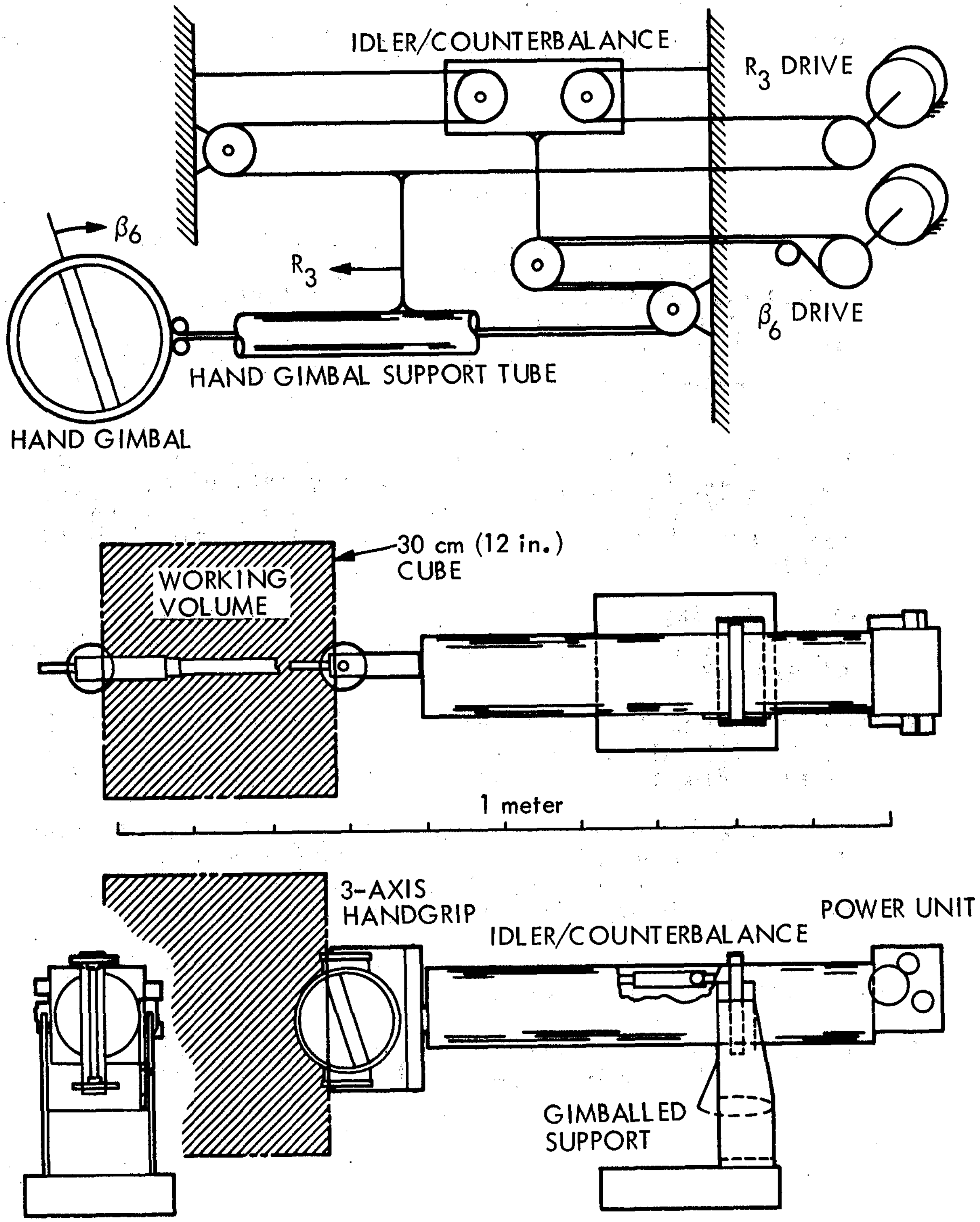
Figure 1. FRHC Mechanical Design Schematic



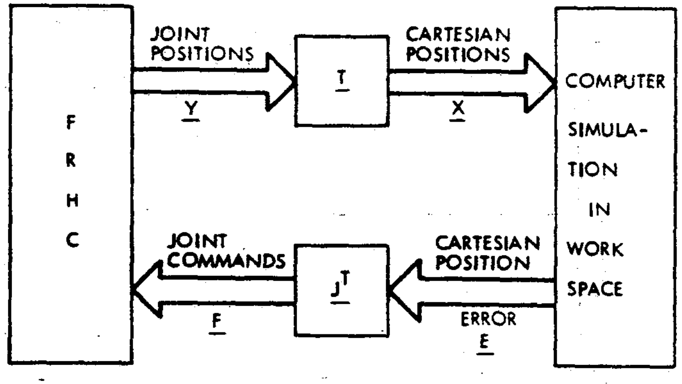


Figure 2.

FRHC Backdrive simulation system configuration.

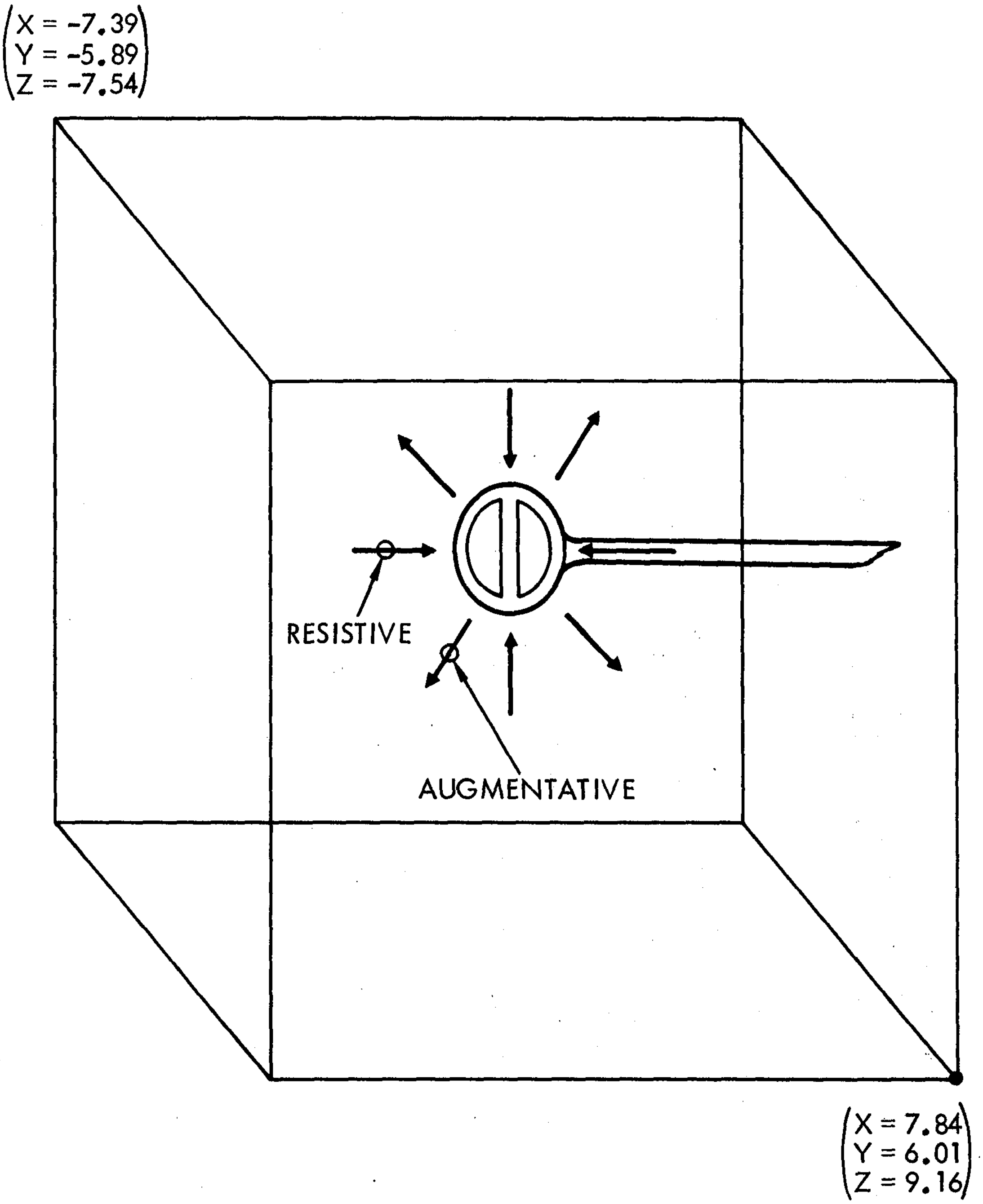


Figure 3.
Working Volume of FRHC

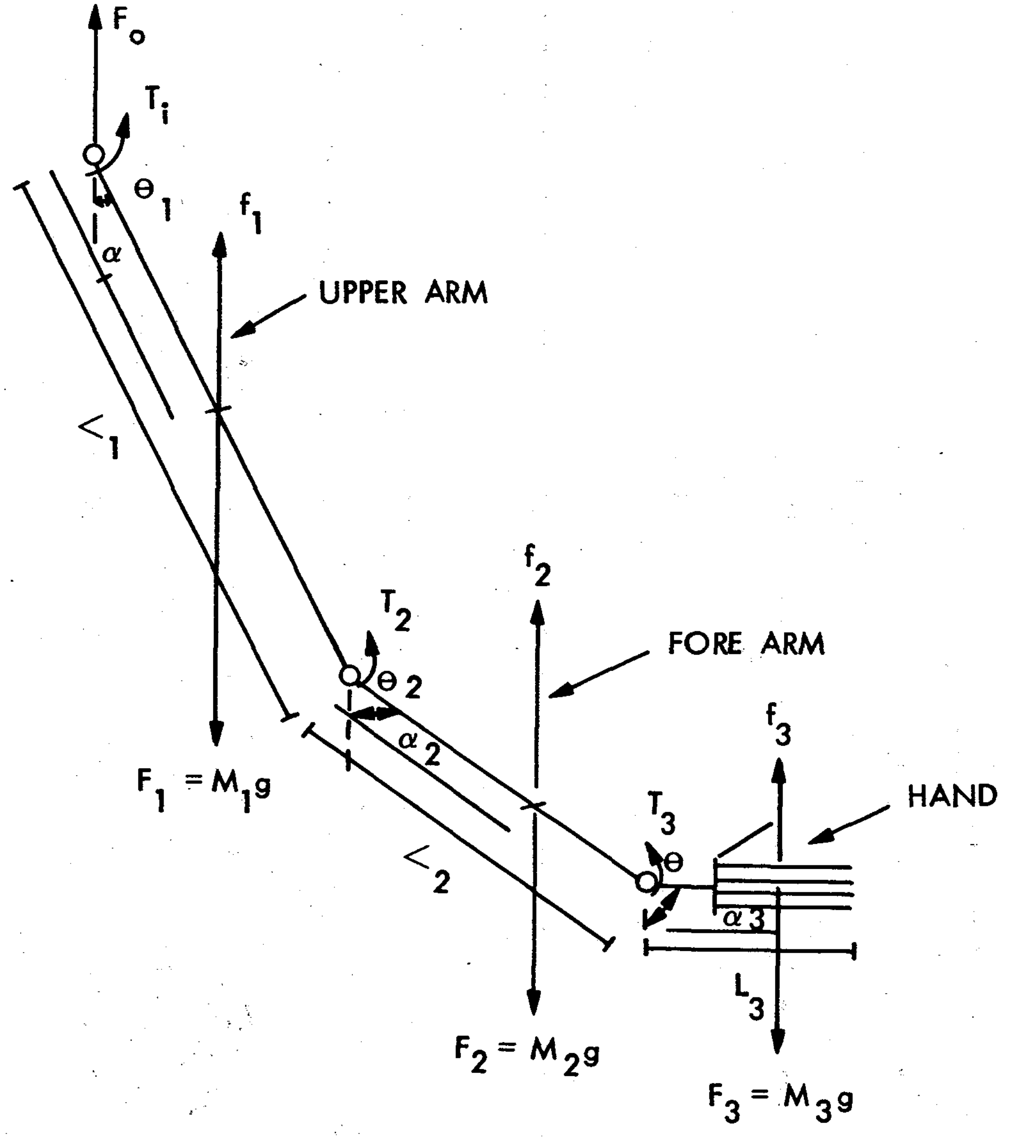
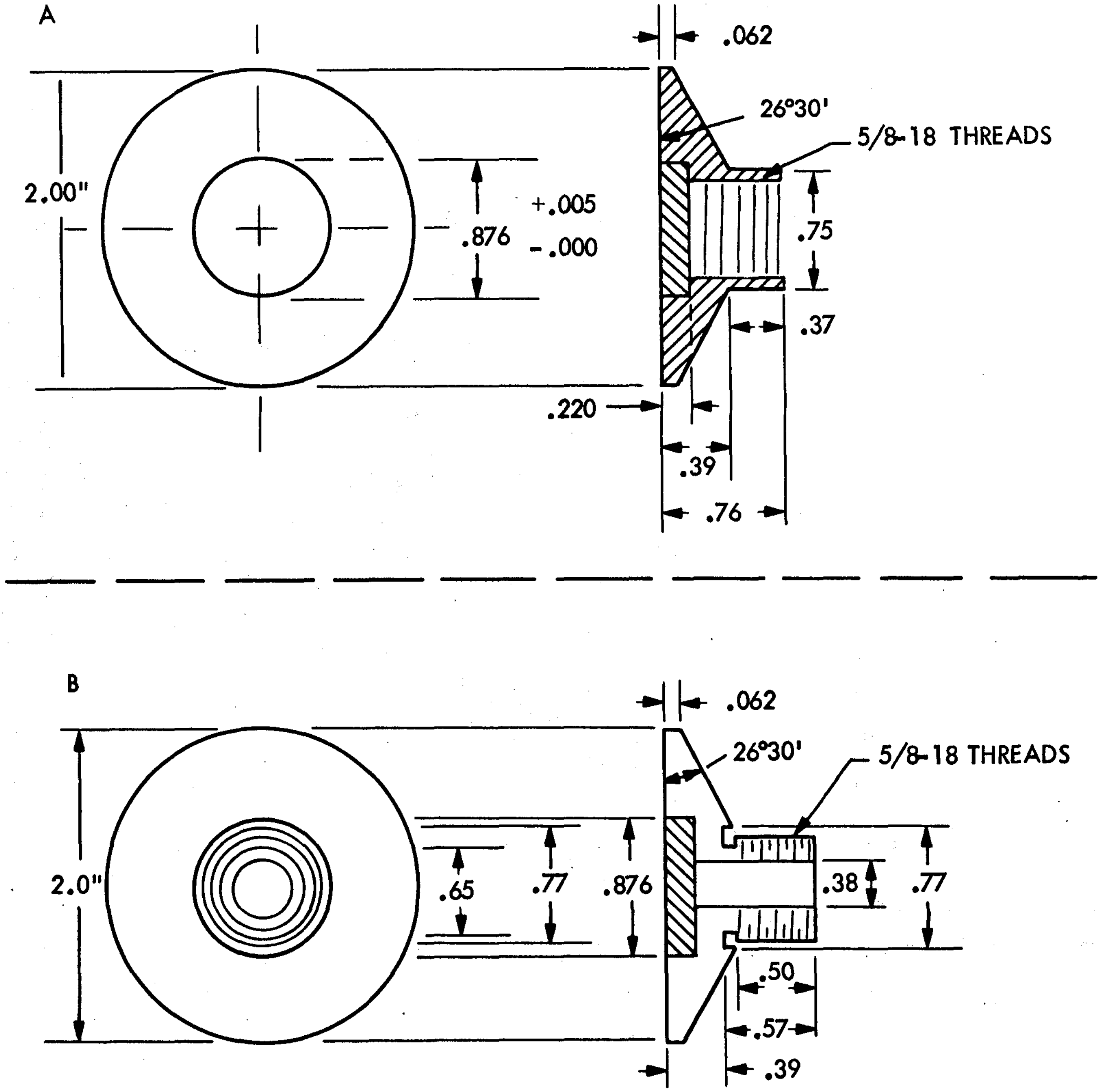


Figure 4.

ARM COMPENSATION FOR 1 GRAVITY: MASS AND FORCE FACTORS

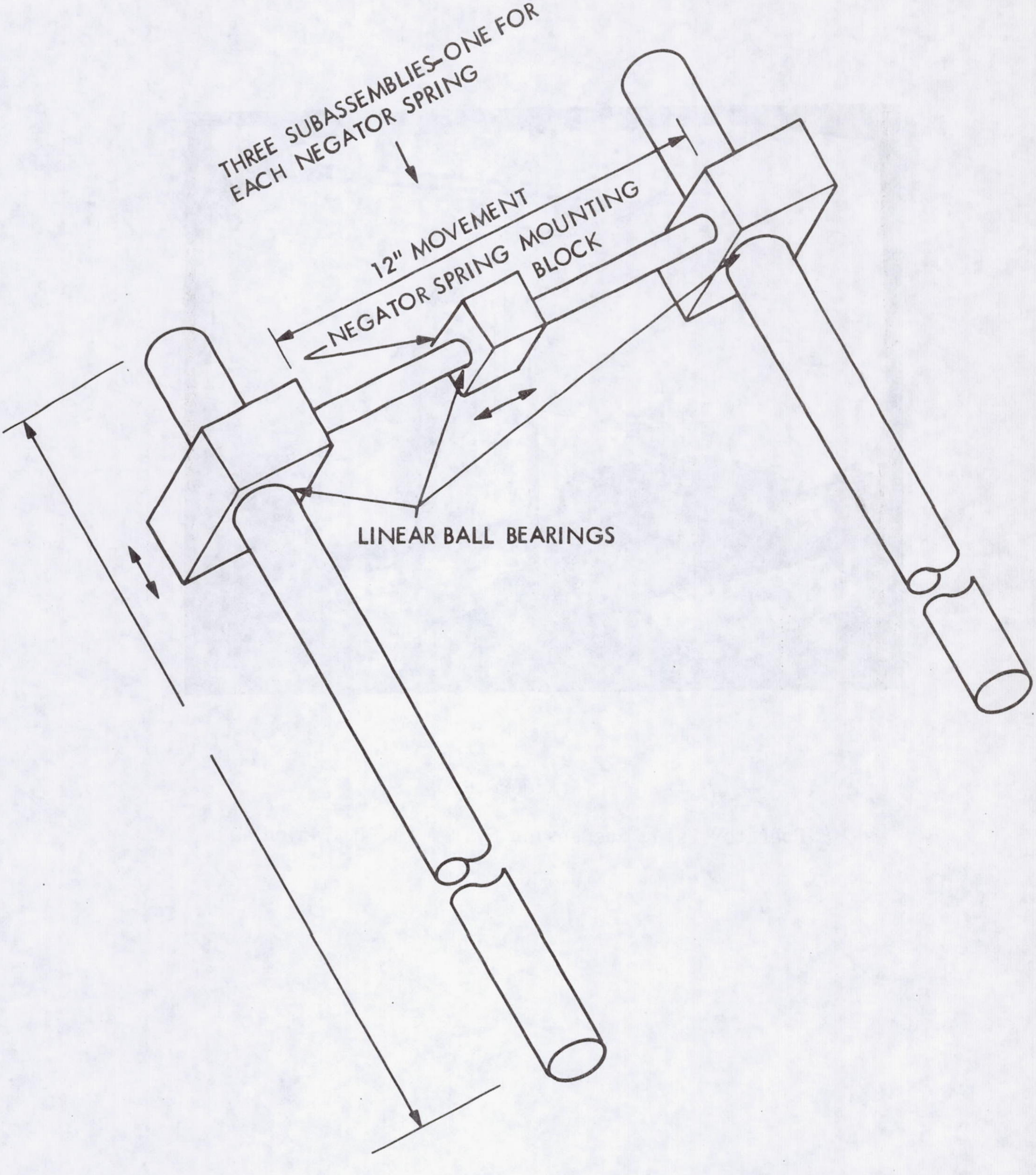
Figure 5.
Variable Radius Take-up Spool



MAKE FROM 7075 T7 ALUM OR QUIV.
CONICAL SPOOL NEGATOR SPRING
SK 2-24-83 REV. B

Figure 5.

X-Y Translation Support System



TRANSLATION MOTIONUNIT
SK 2-25-83

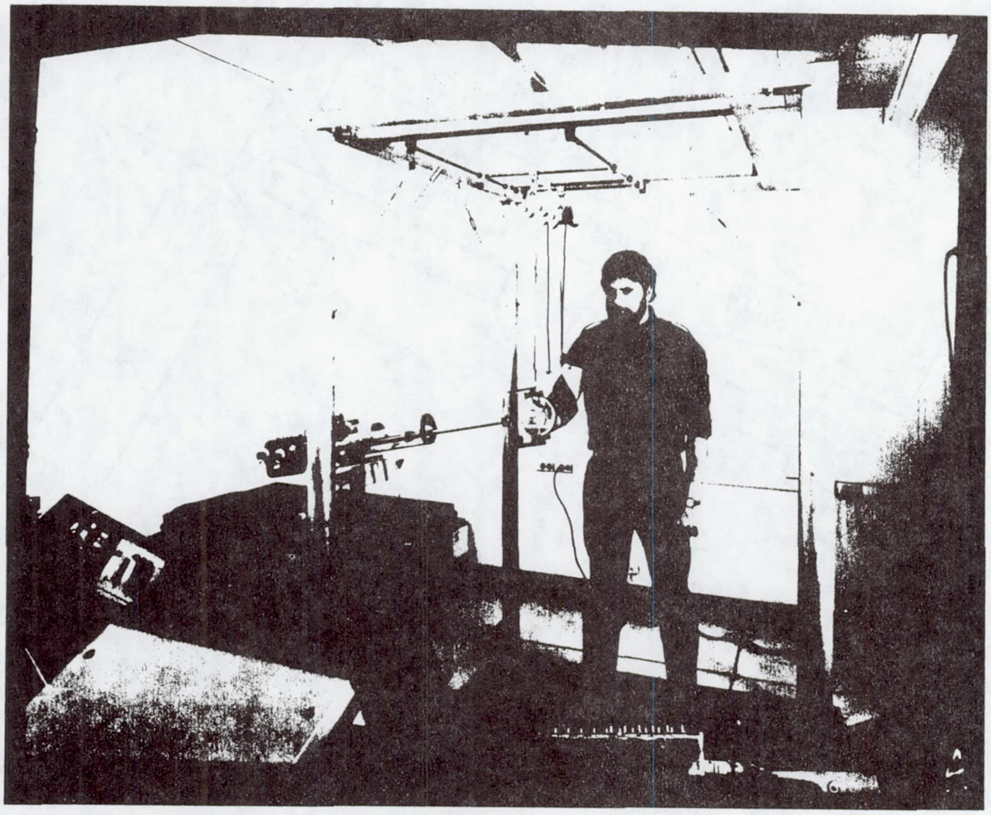


Figure 6.

Operator Using Suspension System in Simulation Task.

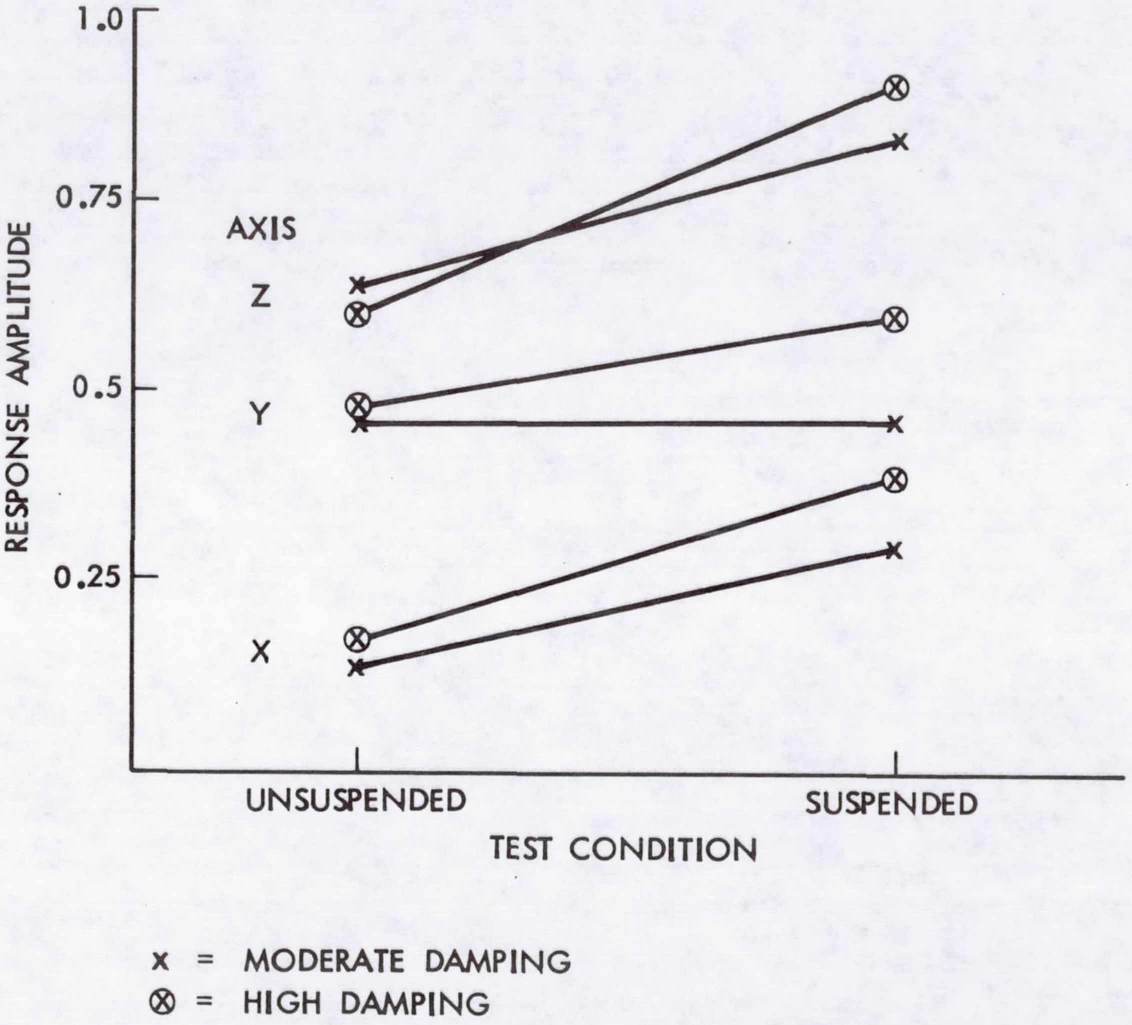


Figure 7.

RESPONSE TO DISTURBANCE INPUT
AS A FUNCTION OF DAMPING AND OPERATING CONDITION

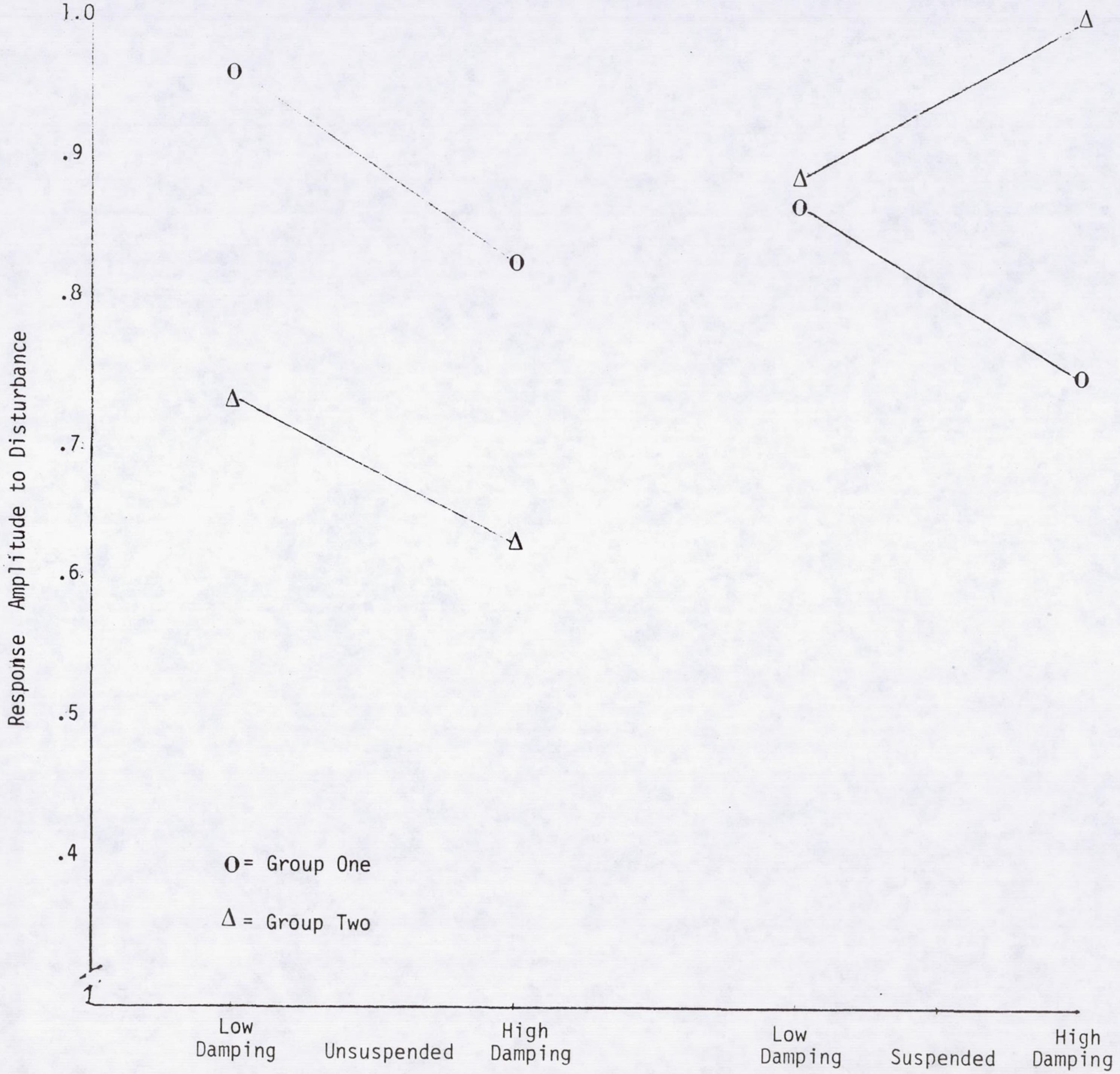

Response Amplitude to Disturbance
1.0
.9
.8
.7
.6
.5
.4
O = Group One
Δ = Group Two
Low Damping
Unsuspended
High Damping
Low Damping
Suspended
High Damping

Figure 8.