EFFECTS OF MANIPULATOR RESTRAINTS ON HUMAN OPERATOR PERFORMANCE

R. E. Magdaleno
D. T. McQueer

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This report documents a portion of an analytical and experimental investigation of human pilot dynamics accomplished under Contract No. AF 33(655)-10855, NBS No. 7(539-5219-6840-562), sponsored by the Flight Control Division of the Air Force Flight Dynamics Laboratory. On a predecessor project, contract AF 33(616)-7001, Project No. 8219, Task No. 8219-5, a comprehensive report entitled Human Pilot Dynamics in Compensatory Systems: Theory, Models, and Experiments with Controlled Element and Forcing Function Variations, APPD-TR-65-15, July 1965, thoroughly documents the description of the pilot-vehicle closed loop system and forms the basis for the present efforts.

The research was performed by Systems Technology, Inc., Hawthorne, California, and under subcontract by the Franklin Institute Laboratories for Research and Development, Philadelphia, Pennsylvania. The project principal investigators were D. T. McRuer and Dunstan Graham of STI and E. S. Krendel of FPL. The Flight Control Division project engineers were Capt. J. E. Pruner and F. B. Pietrak.

The major contributors besides the authors and the principal investigators were William Reisener, Jr., in experimental planning and execution and R. J. Wasloko in experimental planning. An indispensable portion of the program, the design and development of analysis apparatus, was accomplished on the predecessor project by R. A. Peters and R. A. Ferrick. The authors would like to thank W. M. Sollow of FPL for his dedicated effort as the experimental subject and Diana Pachential of FPL for her diligence in data reduction. Finally, the many review comments and suggestions by R. O. Anderson, F. B. Pietrak, G. G. Frost and J. J. Woodcock have significantly improved the report.

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This technical report has been reviewed and is approved.

Chief, Control Criteria Branch
Flight Control Division
AF Flight Dynamics Laboratory

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This report is concerned with a series of experiments in which the effects of manipulator restraints, i.e., load dynamics imposed on the pilot, are central. The purposes of this investigation are to:

- Determine the load effects on the pilot's describing functions and performance measures for a representative variety of manipulator restraints and controlled elements.
- Provide inferential insight into the relative importance of limb position and output force sensors in manual control.

The results indicate that the pilot performs best with a spring restrained manipulator. With pure inertia restraint there is a large performance degradation unless the inertia is less than that given by the pilot's output limb acting on the manipulator. Generally, the pilot has good position feedback in that his describing function form is essentially invariant to a wide range of spring and inertia restraints for the same controlled element.
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SYMBOLS

$\alpha$  
Threshold value of the indifference threshold nonlinearity

A  
Muscle actuation signal

$b_a$  
Effective damping of limb output system

$b_b$  
Manipulator damping

$B_5$, $B_6$  
Forcing function designation defined on page 19

$c(t)$  
Limb position

e(t)  
Error time function

$F(t)$, $F_L$  
Limb-applied force

$F_m$  
Force on manipulator

$F_E$  
External force

$G_H$, $G_E$  
Actuation elements

$G_0$  
Rise dynamics, central computational delays, equalization and gain adjustment, synaptic and conduction delays to spinal centers involved, etc.

$G_{F_1}$  
Command feedforward

$G_{F}$  
Force feedback elements

$G_{L}$  
Load characteristics of output member and manipulator

$G_M$  
Load characteristics of manipulator

$G_{P}$  
Position feedback elements

$i(t)$  
Forcing function time function

$I_a$  
Effective inertia of limb

$I_{max}$  
Maximum inertia of manipulator

$I_{min}$ or $I_m$  
Minimum inertia of manipulator

$I_0$  
Manipulator inertia

$I_1$  
Specific value of manipulator inertia (page 19)

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\( \alpha \) | Low frequency phase approximation parameter |
\( \delta \) | Stick position |
\( \zeta_N \) | Damping ratio of second-order component of the neuromuscular system |
$\theta_i$  
Neuromuscular System Command

$\sigma_e$  
Standard deviation of error signal, $e(t)$

$\theta_i$  
rms value of the forcing function

$\theta_T$  
rms value of input to the indifference threshold

$\tau$  
Pure time delay

$\tau_e$  
Effective time delay

$\phi_{15}$  
Cross power spectral density between $i$ and $i$

$\phi_{1PL}$  
Cross power spectral density between $i$ and $P_L$

$\omega$  
Angular frequency, rad/sec

$\omega_c$  
System crossover frequency, i.e., frequency at which $|Y_pT_o| = 1$

$\omega$  
Forcing function bandwidth

$\omega_N$  
Unamplified natural frequency of second-order part of the neuromuscular system

\[ \approx \]  
Approximately equal to

\[ \text{Angle of} \]  
Angle of

\[ \text{db} \]  
Decibels; $10 \log_{10} \{ \}$ is a power quantity, e.g., spectrum; $20 \log_{10} \{ \}$ is an amplitude quantity, e.g., $Y_p$

\[ \text{Magnitude} \]  
Magnitude

\[ \text{Magnitude in db} \]  
Magnitude in dB

\[ \text{Inches} \]  
Inches

\[ \text{Increase} \]  
Increase

\[ \text{Decrease} \]  
Decrease

\[ x \]  
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SECTION I

INTRODUCTION

Within the last decade there has been a number of experimental programs aimed at finding the random-input describing function of the human operator in compensatory situations, Refs. 1, 2, and 3. This general control situation is illustrated in Fig. 1. The key task variables represented there are the manipulator load dynamics, the forcing function, and the controlled element characteristics. Most of the past work on human operator dynamics has been concerned with the effects of controlled element and forcing function. A comprehensive experimental and analytical study of human pilot dynamics has recently been completed by the Systems Technology-Franklin Institute team under U. S. Air Force Flight Dynamics Laboratory sponsorship. In the most extensive experimental series in this program (Ref. 1) the manipulator was eliminated as a task variable by using the same spring-restrained sidestick for a wide variety of controlled element and input bandwidth combinations. In another series (Ref. 8) the manipulator was an important experimental variable. There, limiting cases of a free-moving controller and a pressure (strain gauge) controller were used in addition to the spring-restrained sidestick.

This report is concerned with a third series of experiments in which the effects of manipulator restraints, i.e., load dynamics imposed on the operator, are central. The purpose of this investigation are to:

a. Determine the load effects on human operator describing functions for a representative variety of manipulator restraints and controlled elements

b. Provide inferential insight into the relative importance of limb position and output force senses in manual control.

These data and insights are needed to improve our understanding of two types of vehicle handling qualities and man-machine system problems:

a. The effects of manipulators on pilot dynamic responses and overall pilot-vehicle system performance. These
Figure 1. Single-Loop Manual Control System
relate both to manipulator types (wheel, center stick, side-stick, etc.) and to manipulator functions (force-displacement) characteristics.

b. The likely effects of control system nonlinearities (e.g., hysteresis, backlash, Coulomb friction, preload) on pilot-vehicle system stability. Practically, this should lead to a better understanding of some kinds of pilot induced oscillations, and to the establishment of necessary or sufficient conditions for their elimination.

The detailed experimental plan for the various configurations to be tested will be considered after a summary of previous works relating to manipulator restraints. The Pre-Experimental Analysis of Section II further sharpen and delineates desirable experiments.

A. SUMMARY OF EARLIER EXPERIMENTS PERFORMED BY SYSTEMS TECHNOLOGY—FRANKLIN INSTITUTE

1. Effects of Forcing Function and Controlled Element Variations on Describing Function Models (Ref. 1)

The extensive experimental series mentioned earlier (Ref. 1) yielded an excellent data base for modeling the overall human operator describing function, and to a certain extent the various subsystems involved. For some configurations, the data were of such low variability that the following relatively complex model form was the minimum necessary to yield an adequate fit.

$$ V_p = K_p \left( \frac{s}{s^2 + \omega_n^2} \right) \left( \frac{T_D s + 1}{T_C s + 1} \right) \left( \frac{T_K s + 1}{T_L s + 1} \right) \left( \frac{1}{T_{H_1} s + 1} \right) \left( \frac{1}{T_{H_2} s + 1} \right) e^{-j\omega t} \tag{1} $$

neuromuscular system terms

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where \( K_P \) = gain

\[
K_P = \frac{\frac{s T}{2}}{\frac{1}{T^2}}
\]

is indifference threshold describing function \( \left[ 1 - \left( \frac{a_T}{a_T \sqrt{2/n}} \right) \sqrt{2/n} \right] \) when \( a_T / T^2 \ll 1 \)

\[
\frac{T_J + 1}{T_J + 1} = \text{equalization characteristic, } T_J \text{ and } T_I \text{ values depend on form of controlled element}
\]

\( \tau \) = fixed time delay due to conduction times of the various subsystem elements

\[
\frac{T_K + 1}{T_K + 1} = \text{low frequency terms which are used to describe low frequency phase data often approximated by } e^{-j(\omega/\alpha)} \text{ for } \omega > 1/T_K \text{ or } 1/T_K
\]

\[
\frac{T_{HIJ} + 1}{T_{HIJ} + 1} \left[ \frac{1}{T_{HIJ}^2} + \frac{2T_{HIJ}}{2T_{HIJ}^2} + 1 \right] = \text{neuromuscular system terms often approximated by } 1/(T_{HIJ} + 1) \text{ or } e^{-\omega/\alpha}
\]

Equation 1 is the most refined version of the pilot model discussed in Ref. 1. The low frequency terms approximated by \( e^{-j(\omega/\alpha)} \) are new, i.e., the data trends supporting them had appeared before (Refs. 2 and 5), but were ignored due to suspected analyzer inaccuracies.

The third-order neuromuscular system elements are compatible with known characteristics, i.e., the second-order term is representative of the spring-mass system of the limb, while the first-order term is a simple approximation to actuation lags. These terms are also compatible with some aspects of transient responses (Ref. 5).

For many controlled elements an acceptable approximation to Eq. 1 over a restricted but fairly wide frequency range is

\[
Y_P = K_P \left( \frac{T_{HIJ} + 1}{T_{HIJ} + 1} \right) e^{-j(\tau + T_{HIJ})/2}
\]  

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The values of $T_L$ and $T_H$ depend on the controlled element. In general, the human operator selects them such that the magnitude of the open-loop system, $Y_pY_c$, has approximately a -20 dB/decade slope in the region of crossover. The details of the pilot adjustment rules, Ref. 1, are beyond the scope of this discussion. With the proper selection of $T_L$ and $T_H$, the open-loop system can be described by

$$Y_pY_c = \frac{\omega_n^2}{\omega_n^2 + \frac{2}{T_H} + \frac{T_L}{\omega_n^2}}$$

where

$$\tau_e = \tau + T_H - T_H$$

$$T_H = T_L \text{ when it is available at high frequency}$$

The lead time constant, $T_L$, can be used to reduce the effective time delay, $\tau_e$, when this lead term has not been required at low frequency to yield the -20 dB per decade slope of the open-loop system. Specifically for $Y_c = K_c/s^2$ the lead term is required at low frequency and therefore is not available for reducing the effective time delay, $\tau_e$.

2. Various Manipulators Experiments (Ref. 8)

The various manipulators experiments used three manipulator types (pressures, free-moving, and spring-restrained controls) three controlled elements and two input bandwidths. The pressure (strain gauge) control is at one extreme (essentially infinite spring) while the free-moving control had no restraint except its own very small inertia. The spring-restrained control is between these extremes. These manipulators were used in a lateral control task in which the displayed error moved horizontally.

The basic result of this series of experiments was that the pressure control had significantly less phase lag at high frequencies and the same or less phase lag at low frequencies compared to the free-moving control.
the spring-restrained control was intermediate). Further, the normalized mean-squared error was ordinarily smallest for the pressure control.

3. MATHEMATICALLY EQUIVALENT TRACKING SYSTEMS

Reference 4 investigated the effects on mean square error of dynamics in the loop as electronic controlled elements and/or as mechanical restraints. The basic hypothesis was that basic tracking performance would remain unchanged despite variations in mechanical restraints if the overall transfer function from control force to visual display was unchanged. In effect, this was an attempt to assess the importance of the position feedbacks.

The experiments were organized in three phases. The first used a spring-centered control stick with inertia, damping, and spring rate variable and $Y_c = K_c$. The second phase utilized a pressure stick plus controlled element dynamics identical to each of the force-displacement relationships used in the first phase. The third phase used a free-moving control similar to that in the various manipulators experiments mentioned earlier, although a very light spring restraint was added. The controlled element had the same form as in the other phases. Thus, phases one and two provided a comparison of control dynamics as mechanical restraints or as electronic controlled elements. Phases two and three provided the same type of comparison between a pressure control and a free-moving control similar to that discussed in the various manipulator experiments. Phases two and three included some additional experiments in which the controlled element was $Y_c = K_c$. These latter experiments afforded a comparison among the three manipulator types similar to the various manipulator experiments in the previous section.

The best results with each of the three manipulator types (phase one with very small inertia) and $Y_c = K_c$ show that the pressure control gave slightly less mean square error although all three were less than 1 db apart. Comparison of phase one with phase two showed that mean square error with mechanical restraints was significantly larger than with their electronic analogs. One possible explanation is that the human operator does utilize motor feedback to improve control although an alternate possibility does exist, viz., the human operator has a series equalization.
capability, Ref. 1, p. 185, which could well explain the differences between the two experiments. The verification of the hypothesis stated in Ref. 4 will require describing function measurements in addition to performance measures.

C. IMPLICATIONS OF THE REVIEW OF RECENT EXPERIMENTS

Current interpretations of the experiments discussed in Section A above go a long way toward providing a data base for the development of a mathematical description of the neuromuscular system. But this data base is confined to experiments with variations of controlled element, forcing function, and, to a certain extent, manipulator restraints. As a minimum the review in Sections A and B above indicates a need to investigate inertia effects and the interchange of dynamics due to mechanical restraints with those due to electronic controlled elements. This last point could be restated as: To what extent can the human act as a force output or a position output device? These, plus other interesting experiments, will be brought into sharper focus by the pre-experimental analysis to follow.
SECTION II
PRE-EXPERIMENT ANALYSIS

The purpose of this section is to investigate the implications of the neuromuscular system model on describing function measurements. As will be shown, the human operator can be described by a number of serially connected describing function boxes such that no one experiment can isolate the effects due to a particular box. A series of experiments is needed of which some are critical with respect to the question of the human operator being a force or position output device.

A. EXPERIMENTAL CONFIGURATION

As shown in the block diagram of Fig. 2, the variable-restraint experimental apparatus is configured so that a signal proportional to either the position of or force on the manipulator can be used to drive the controlled element. Limiting cases of free-moving and pressure manipulators have been investigated before, as have spring-restrained manipulators wherein the difference between force and displacement outputs is indistinguishable.
This apparatus configuration was especially contrived to investigate the ability of the human operator to change his force and/or position feedbacks when such a procedure is desirable to obtain good control. This configuration is similar to the one used in Ref. 4.

2. NEUROMUSCULAR SYSTEM FUNCTION DESCRIPTION AND IMPLICATIONS

A view of the neuromuscular system portion of the human operator model which was current at the experimental planning stage is presented in the simplified block diagram representation in Fig. 3. This block diagram is a control system engineering model. As such it is a functional rather than structural analog of the human. The loop structure adopted is intended primarily to be the minimum necessary to exhibit behavior representative of the human operator's neuromuscular system. (Note that in Fig. 2 the load, $G_L$,

where

$G_e$ = input dynamics, central computational delays, equalization and gain adjustment, synaptic and conduction delays to spinal centers involved, etc.

$G_{K1}$, $G_{K2}$ = actuation elements

$G_{F1}$ = force feedback elements

$G_{L}$ = load characteristics of output member and manipulator

$G_{P}$ = position feedback elements

$Y_{C}$ = controlled element dynamics

Figure 3. Total Open-Loop System for Position Control

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and the human operator are shown as separate entities, while in Fig. 3 the manipulator load characteristics have been absorbed into $G_D$, involving the dynamics of the manipulator system and the human operator's motor system.) This model was used to help establish the experimental plan.

The block $G_D$ represents the basic equalization capability of the human operator given by the terms $(T_{D1} s + 1)/(T_{D2} s + 1)$ in Eq. 1. Also included in $G_D$ are input dynamics, central computation delays, synaptic and conduction delays to spinal centers involved, etc. The purpose of the command feedforward, $G_{CF}$, is to provide a signal path that bypasses some of the neuromuscular system time delays and lags. Such an element is necessary to explain pursuit-like operations and the zero time delay follow-up of recognizable input signals (see, e.g., the Successive Organization of Perception [SOP] theory, Ref. 6). The actuation elements, $G_{A1}$ and $G_{A2}$, contribute lags which tend to show up in the third-order neuromuscular system elements in Eq. 1. As currently conceived, the force feedback element, $G_F$, consists primarily of Golgi tendon organs which have a moderately high threshold, i.e., they may be inactive unless forces are relatively large. The position feedback element, $G_P$, represents an ensemble of muscle spindles. An additional input into the box $G_P$, not shown in Fig. 3, is used to set the gain of the outer loop. The details of this input signal are beyond the scope of this report, although its effect will be briefly discussed in subsequent paragraphs.

The components of the motor-manipulator system element, $G_{LM}$, are illustrated in Fig. 4. For some manipulators the dynamics may be somewhat more complicated than those shown, although the spring-inertia-damper combination is sufficiently general to describe many situations of practical interest. The external force, $F_E$, can represent a variety of situations; for example, the output of a force-stability augmenter system.

The human elements of the system are actually far more complex than implied by the simple force-mass-damper-spring combination shown. A given motor system is not, in general, a single lumped mass; instead, several coordinates are actually present. For small motions, a single effective lumped mass can be used to represent the lowest frequency characteristics.
The value of this effective mass will depend, of course, on the muscle groups and body members being activated. For the pitch control task that was used in this study, the mass of the forearm and upper arm acting on the \( h \) in control stick radius yields an effective inertia on the order of three times the minimum stick inertia. This results in essentially a restraintless controller which can be compared with the free-moving control used in the roll axis studies (Ref. 8).

\[
F_L = F_R = \left[ (I_1 + I_2) s^2 + (b_1 + b_2) s + (k_1 + k_2) \right] \delta
\] (4)

Figure 4. Schematic Diagram of the Motor Load Dynamics

The presence of the spring in the human motor output system follows from a general review of physiological data, which show that the properties of the muscles as affected by the additional input to the position feedback box, \( G_p \), indicate an effective spring rate for muscle behavior. The internal damping element, \( b_1 \), is also indicated physiologically. These plus the applied force, \( F_L \), are the major elements contributed by the human.
or when $P_L$ is zero

$$\frac{G_L}{P_L} = \frac{1}{(I_a + I_b)s^2 + (b_a + b_b)s + (k_a + k_b)} \tag{5}$$

The closed-loop version of this second-order form is given in the neuromuscular terms of Eq. 1. Increasing the stick inertia or decreasing the stick spring rate decreases the natural frequency of the limb-manipulator system. The effective load dynamics, $G_L$, could be measured using cross-spectral techniques when $P_L$ is zero and a signal proportional to $P_L$ is available. In this condition,

$$\frac{G_L}{P_L} = \frac{G_{1L}}{G_{1P_L}} = \frac{1}{(I_a + I_b)s^2 + (b_a + b_b)s + (k_a + k_b)} \tag{6}$$

From which $I_a + I_b$, $b_a + b_b$, and $k_a + k_b$ can be deduced. The manipulator system dynamic parameters, $I_a$, $b_a$, and $k_a$, can be measured separately. Then using these two sets of measurements, one can determine the effective values of $I_a$, $b_a$, and $k_a$ which constitute those internal portions of the operator's load characteristics.

From Fig. 3 a signal related to $P_L$ is $A$, the muscle actuation signal (Electromyograph Signal). These signals have been used to drive artificial arms (e.g., Ref. 7). A limited number of runs were included in the experimental program; but due to difficulties in signal pickup, noise, and interpretation of active muscle groups, the data must be considered preliminary.

1. Position Control

Since signals internal to the human operator cannot be picked off easily, the effects on the overall measurements of the various blocks will be inferred by considering the describing function for the total open-loop system of Fig. 3 given by

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\[ e_{NL} = \frac{(G_F + G_A)G_A G_Y_c}{1 + G_A(G_K + G_F G_L)} \]  

\[ G_A = G_{A1} G_{A2} \]

\[ G_F = G_{F1} G_{F2} \]

Except at the very lowest and very highest frequencies of interest in manual control, the neuromuscular system has at least one of its feedback loops fairly tightly closed, i.e., \( 1 + G_A(G_K + G_F G_L) \approx G_A(G_K + G_F G_L) \). The open-loop describing function then becomes

\[ \frac{e}{z} = \left( 1 + \frac{G_F}{G_A} \right) \frac{G_A G_Y_c}{G_K + G_F G_L} \]

\( G_A \) is the describing function for the open-loop dynamics of the muscles, while the feedforward element, \( G_F \), was introduced originally into Fig. 3 as a likely means to reduce effective time delays for internally generated commands. Therefore, because of their nature, neither \( G_F \) nor \( G_A \) should change materially with changes in the form of \( G_L \) and \( Y_c \). Consequently, the open-loop describing function in terms of quantities likely to vary with changes in the task variables (\( Y_c \) or the manipulator restraints) is given by

\[ \frac{e}{z} \approx \frac{G_A G_Y_c}{G_K + G_F G_L} \]

Assuming that the force and displacement feedback quantities, \( G_K \) and \( G_F \), can be varied by the pilot as needed to maintain reasonable neuromuscular system dynamics, the relative proportions of each needed to maintain satisfactory neuromuscular system characteristics will vary as \( G_L \) is changed. Further, the total range of this variation may be constrained by the nature of the required \( m/e \) describing function demanded by the controlled element dynamics, \( Y_c \). From these considerations, it

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should be plain that the nature and extent of the variations of \( G_K \) and \( G_p \) can be investigated readily by making appropriate changes in \( Y_c \) and \( \dot{Y}_c \). For instance, systems consisting of pure-inertia manipulator plus pure-gain controlled element, pure-damping manipulator plus an integrator controlled element, or pure-spring manipulator plus a double-integrator controlled element all look like \( K_w/\dot{a}^2 \) if plant output is force (i.e., if \( G_p = 0 \)), but on a displacement basis \( (G_p \rightarrow e) \) look like \( K_c, K_w/\dot{a}, \) and \( K_w/\dot{a}^2 \), respectively.

As an example of what might occur under limiting case conditions, i.e., \( G_pG_L \gg G_K \) or \( G_K \gg G_pG_L \), consider the comparative measurements for a pure-inertia manipulator with those for a pure-spring manipulator, both with controlled elements of \( Y_c = K_c \) and \( \dot{Y}_c = K_w/\dot{a}^2 \). System "goodness" (performance and stability considerations) requires that \( n/\dot{n} \) be loglike in form, \( |n/\dot{n}| = |\dot{a}_p/\dot{a}_o| \), in the region of crossover. The \( G_c \)'s needed to accomplish this approximate \( |\dot{a}_c/\dot{a}_o| \) form for these control situations are noted below for the two limiting conditions of the neuro-muscular system, tight position loop \( (G_pG_L \gg G_K) \) and tight force loop \( (G_K \gg G_pG_L) \), given in Table I. The elements \( G_p \) and \( G_K \) are assumed to be constants for the mid-band frequencies of interest.

<table>
<thead>
<tr>
<th>MANIPULATOR AND CONTROLLED ELEMENT DYNAMICS</th>
<th>REQUIRED ( G_c )'S FOR POSITION CONTROL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>REQUIRED ( G_c ) FOR (</td>
</tr>
<tr>
<td></td>
<td>Tight position loop ( G_pG_L \gg G_K )</td>
</tr>
<tr>
<td>Restraint ( Y_c )</td>
<td>( \frac{M}{B} \propto G_pY_c )</td>
</tr>
<tr>
<td>Inertia</td>
<td>( K_c )</td>
</tr>
<tr>
<td>( K_w/\dot{a}^2 )</td>
<td>( \text{Lead} )</td>
</tr>
<tr>
<td>Spring</td>
<td>( K_c )</td>
</tr>
<tr>
<td>( K_w/\dot{a}^2 )</td>
<td>( \text{Lead} )</td>
</tr>
</tbody>
</table>

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To some extent the distinctions noted in the table may be difficult to realize, for one cannot be sure from $Y_p$ measures alone whether position feedback is dominant or whether the pilot has changed the equalization form in $G_e$. However, position feedback is most appropriate for the pure-inertial manipulators as a means for reducing the substantial lead equalization requirements otherwise needed in $G_o$.

Thus, the human operator will most likely attempt to achieve a tight position feedback loop when controlling a pure-inertial manipulator because the $G_e$ equalization requirements are less than those for a tight force feedback loop. Specifically with a tight force feedback, triple lead equalization in $G_e$ is necessary for the $K_0/s^2$ controlled element. It is highly unlikely that the operator can generate such extreme equalization.

For the pure-spring manipulator the required $G_e$ is the same regardless of which feedback loop is tight. Comparison of measurements for the two manipulators should indicate the degree to which the position loop can be "tightened."

2. Force Control

If the stick force transducer output is used as the input to the controlled element, as shown in Fig. 5, the block diagram must be modified by splitting $G_f$ into $G_{M}$, relating the force on and position of the manipulator, and $G_f/G_m$ relating the limb applied force, $F_l$, and the force on the manipulator, $F_M$ (note $F_M$ is the force across the interface in Fig. 4).
where

$$G_M = \frac{1}{I_a s^2 + b_a s + k_a}$$  \hspace{1cm} (10)$$

$$\frac{G_F}{G_M} = \frac{I_a s^2 + b_a s + k_a}{(1 + I_a) s^2 + (b_a + b_b) s + (k_a + k_b)}$$  \hspace{1cm} (11)$$

The total open-loop describing function for force control then becomes Eq. 7 divided by $G_M$ or

$$\frac{\theta}{\ddot{\theta}} = \frac{(G_F + G_A) G_C G_D}{1 + G_M(G_K + G_D G_C) G_M}$$  \hspace{1cm} (12)$$

Equation 12 differs from Eq. 7 in the absence of $G_M$, the manipulator dynamics, from the forward loop. $G_M$ remains in and must still be controlled, but the change in location of $G_M$ modifies the nature of the task-imposed constraints on the operator. For the total system to respond properly $|\theta/\dot{\theta}|$ must still approximate $|\omega_0/\omega_n|$ in the region of crossover and again assuming either a tight position or tight force loop Eq. 12 becomes

$$\frac{\theta}{\ddot{\theta}} = \frac{G_F G_C G_D}{G_K + G_D G_C}$$  \hspace{1cm} (13)$$

Using the same assumptions and development as for the position control situation, the required $G_A$'s are shown in Table II.

The control situation with the pure-inertia manipulator presents an interesting conflict regarding the selection of a neuromuscular feedback loop. For the $I_a = K_a$ controlled element, $G_A$ equalization requirements are less (lag versus triple lag) with a tight force loop. In addition, the manipulator position by itself is useless information as far as controlling $Y_C$, so to the extent that the operator can ignore manipulator position information it is expected that he will attempt to achieve a tight force feedback loop. However, for $I_C = K_C s^2$ the required equalization is less demanding (lag versus lead) with a tight position feedback.
loop. In fact, this equalization is less difficult to generate than that required for the pure-spring manipulator with the same controlled element, regardless of the feedback loop tightened (lead required in both cases).

**TABLE II**

| MANIPULATOR AND CONTROLLED ELEMENT DYNAMICS | REQUIRED G_0 FOR | \[|\mu/\omega| \neq |\omega_0/\omega|\] |
|---------------------------------------------|------------------|------------------|
| Relaxation \(Y_R\)                          | Tight position loop \(G_p G_L \gg 0\) \(G_p G_L \ll 0\) |
| Inertia \(K_O\)                             | Triple lag       | Lag              |
| \(K_O/s^2\)                                | Lag              | Lead             |
| Spring \(K_S\)                             | Lag              | Lag              |
| \(K_S/s^2\)                                | Lead             | Lead             |

C. SUMMARY OF PRE-EXPERIMENT ANALYSIS

The analysis has suggested a couple of critical experiments. For the position control configuration the combination of large inertia plus a double integrator controlled element requires extreme lead equalization capabilities if the pilot doesn't have good position feedback. For the force control configuration with large inertia and a pure-gain controlled element extreme lag equalization will be required unless the pilot can ignore position information (the appropriate thing to do). These two configurations will be included in the experimental plan discussed in Section IV.

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SECTION III

EXPERIMENTAL APPARATUS AND FORCING FUNCTION

The measurement situation was as follows. For position control tasks the pilot manipulated a stick (Fig. 6) which produced, as an electrical output signal, the pilot's stick position, \( \phi(t) \), which was fed to the controlled element, \( Y_o \) (refer to Figs. 2 and 3). For force control tasks a strain gauge produced an electrical output signal which was fed to the controlled element, \( Y_o \) (refer to Figs. 2 and 5). The system error (difference between the input and the controlled element output) was presented on a cathode ray oscilloscope display. Typically, the eye-to-scope distance was about 29 inches.

For position control tasks and \( Y_o = K_o \), the circuit gains were set so that \( K_o = K_1 \) gives the following deflection sensitivity on the display:

\[
K_1 = 1 \text{ inch (display)/6 deg (stick)}
\]

For the 4 inch stick moment arm, longitudinal motion of the operator's hand amounts to about 0.07 inches (stick) per degree of stick rotation. Accordingly, the sensitivity can be expressed in terms of the linear motion of the operator's hand by dividing the angular sensitivity (in inches per radian) by the moment arm, i.e.,

\[
K_1 = 1 \text{ inch/6 deg} \times 57.3 \text{ deg/rad} \times 0.25 \text{ inch}^{-1} = 2.38 \text{ inches/inch}
\]

For position control tasks and \( Y_o = K_o/s^2 \) setting \( K_c = K_{oa} \) gives

\[
K_{oa} = 0.2 \text{ inches/sec}^2 \text{ (display) per deg (stick)}
\]

For force control tasks and \( Y_o = f_o \) setting \( K_c = K_{pf} \) gives a force control sensitivity of \( K_{pf} = 8.77 \text{ inches (display)/ft-lb (stick)} \). For \( Y_o = K_o/s^2 \) setting \( K_c = K_{pf} \) gives \( K_{pf} = 0.5 \text{ inches/sec}^2 \text{ per ft-lb (stick)} \). In addition, when the manipulator is clamped (pressure controller) the torque-displacement relationship was found to be 79.8 ft-lb/rad.
The pitch axis of the manipulator shown in Fig. 6 was used for the various manipulator restrains experiments. The roll axis, which didn't have changeable restraint capability, was used in the Ref. 8 experimental series. The pitch axis inertia was variable over a 1500:1 range with the smallest value about one-third of the inertia given by the pilot's limb acting on a 4 inch radius. The largest inertia was considerably larger than any likely to be encountered in flight control systems with robweight. The range of restrains used was (damping and negligible):

\[
\begin{align*}
\text{Inertia} & : \\
I_{\text{min}} &= 0.008 \text{ ft-lb-sec}^2/\text{rad} \\
I_{\text{max}} &= 7.25 \text{ ft-lb-sec}^2/\text{rad} \\
\text{Spring Rate} & : \\
k_{\text{min}} &= 0 \\
k_{\text{max}} &= 27.2 \text{ ft-lb/rd}
\end{align*}
\]

Particular values used in Fig. 7 (next chapter) are:

\[
\begin{align*}
k_1 &= 1.09 \text{ ft-lb/rd} \\
k_2 &= 0.29 \text{ ft-lb-sec}^2/\text{rad}
\end{align*}
\]

A four minute run length was used. As in Ref. 1, the forcing function used was a sum of six equal amplitude sine waves with a bandwidth of 2.5 rad/sec, augmented by four high frequency sine waves each 20 db less than any of the low frequency group. The highest of the augmenting frequencies is 14 rad/sec. In the notation of Ref. 2 this is a B6 input. In the next section the present pitch axis data will be compared with the roll axis data taken with a B5 input (Ref. 8). The B5 input is the same as the B6 except that the augmenting frequencies are only 10 db less than any of the low frequency group. Note that these inputs have different effective bandwidths which may compromise the pitch axis-roll axis comparison. The above comparison is aided by the inclusion of data taken with an R0.40 input. This is unpublished data from a preliminary set of experiments in a series that is reported in Ref. 8.

The R0.40 is a sum of six equal amplitude sine waves with a bandwidth of 0.40 cps or 2.5 rad/sec. Thus the B5 inputs effective bandwidth is intermediate to that for the R0.40 and B5 inputs.
SECTION IV

EXPERIMENTAL DESCRIBING FUNCTION DATA AND INTERPRETATIONS

A. EXPERIMENTAL PLAN

This chapter presents the experimental matrix and the describing function data obtained for the investigation. The data will be presented in various aggregations designed to illustrate and illuminate the findings. Each set of data taken was an element in a grand design conceived to fulfill the experimental objectives discussed in Section II plus some to be discussed in this section. The resulting experimental matrix is shown in Figs. 7 and 8.

Not shown in Fig. 7 is an indication of the subjects and forcing functions used. These were restricted to one of each to keep the program down to a reasonable size. In addition not all the spring rate, inertia, and controlled element combinations shown in Fig. 7 were tested, since at the minimum of three runs per configuration actually used this would have resulted in a very large number of runs. Instead, the matrix, as indicated in Fig. 8, has selectively filled in those particular blocks where the findings would shed the most light on load effects. The circled numbers in the boxes indicate configurations used in the describing function comparisons. As discussed in Section III, the forcing function task variable was the augmented rectangular spectrum with bandwidth $\omega_k = 2.5 \text{ rad/sec}$, with $\omega_t = 1/2\omega$ for $Y_0 = K_0$, and $\omega_t = 1/4\omega$ for $Y_0 = K_0/\omega^2$. For $Y_0 = K_0$, exceptions were for the force control inertia variable and for configurations 4, 5, 6, and 7 where $\omega_t = 1/4\omega$. The subject was a light-airplane-qualified civilian pilot with extensive trucking experience who had participated in all the SIT-FL experiments discussed in Ref. 1, and who was the sole subject in the various manipulators experiments (Ref. 8).

Because of this extensive experience the subject was able to rapidly approach asymptotic values of performance on any given configuration, thereby permitting a large number of configurations to be examined at minimal cost. While more subjects would have been desirable, the exploratory and limited-effort nature of the experimental series made this unrealistic. To make the results as representative as possible, considerable efforts were made to tie-in to other data, including situations wherein the subject had already been shown to be reasonably representative of pilots in trucking situations (Ref. 1).
Figure 7. Various Manipulator Restraints Matrix
### Table: Controlled Element Sensitivity

<table>
<thead>
<tr>
<th>Controlled Element $Y_c$</th>
<th>Position Control Sensitivity</th>
<th>Inertial Restraint (no spring) $I_m = \text{minimum inertia}$</th>
<th>Spring Restraint (minimum inertia) $I = I_m$</th>
<th>Force Control Sensitivity</th>
<th>Pressure Controller (stick clamped) $K_{F1}$</th>
<th>Inertial Restraint (no spring) $I_m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_c$</td>
<td>$I_m$ 5$I_m$ 25$I_m$ l l 25$I_m$</td>
<td>k$1$ 5k$1$ 25k$1$ k$1$ 5k$1$ 25k$1$</td>
<td>$K_{F1}$ $K_{F1}$ $K_{F1}$</td>
<td>$K_{F1}$ $K_{F1}$ $K_{F1}$</td>
<td>$25$I$1$ 5$I_1$</td>
<td></td>
</tr>
<tr>
<td>$K_a$</td>
<td>$25$I$1$</td>
<td>$25$I$1$</td>
<td>$25$I$1$</td>
<td>$25$I$1$</td>
<td>$25$I$1$</td>
<td></td>
</tr>
<tr>
<td>$K_a/s^2$</td>
<td>$25$I$1$</td>
<td>$25$I$1$</td>
<td>$25$I$1$</td>
<td>$25$I$1$</td>
<td>$25$I$1$</td>
<td></td>
</tr>
</tbody>
</table>

### Table: Parameter Calculations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_i$</td>
<td>1 in.:display</td>
</tr>
<tr>
<td>$K_i$</td>
<td>6 deg. (stick)</td>
</tr>
<tr>
<td>$K_i$</td>
<td>2.5 in.:display</td>
</tr>
<tr>
<td>$K_i$</td>
<td>rad (stick)</td>
</tr>
<tr>
<td>$K_i$</td>
<td>1.2K$1$</td>
</tr>
<tr>
<td>$I_m$</td>
<td>0.0048 ft-lb-sec$^2$/rad</td>
</tr>
<tr>
<td>$I_1$</td>
<td>0.29 ft-lb-sec$^2$/rad</td>
</tr>
<tr>
<td>$I_m$</td>
<td>1,09 ft-lb/sec</td>
</tr>
<tr>
<td>$I_1$</td>
<td>0.89 lb/in.</td>
</tr>
<tr>
<td>$I_m$</td>
<td>7.25 ft-lb-sec$^2$/rad</td>
</tr>
<tr>
<td>$K_{F1}$</td>
<td>$K_i/K_1$</td>
</tr>
<tr>
<td>$K_{F1}$</td>
<td>$K_i/K_1$</td>
</tr>
<tr>
<td>$K_{F1}$</td>
<td>$K_i/K_1$</td>
</tr>
<tr>
<td>$K_{F1}$</td>
<td>$K_i/K_1$</td>
</tr>
<tr>
<td>$K_{F1}$</td>
<td>$K_i/K_1$</td>
</tr>
<tr>
<td>$K_{F1}$</td>
<td>$K_i/K_1$</td>
</tr>
</tbody>
</table>

For Pressure Controller the clamped sticks effective spring rate is

- $k_0 = 72.8$ ft-lb rad
- $8.77$ in. ft-lb
- $8.77$ in. ft-lb

Note that $K_{F1} = 1.2K_1$ and $K_{F1} = 1.2K_1$.

Thus Conf. 23 has a position control sensitivity given by $75K_1$.

### Figure 6: Various Manipulator Restraints Experiments

Forcing function bandwidth, $\omega_1 = 2.5$ rad/sec. The $\omega_1$'s are discussed on p. 21. Note that the Pressure Controller configurations can also be considered as position control tasks. The effective position control sensitivity can be computed by multiplying the force control sensitivity by the spring rate ($k_c = 75K_1$).
The configurations indicated in Fig. 8 were selected to fulfill the following experimental objectives:

1. Provide a comparison (tie-in) with either the pressure or free-moving manipulators in Ref. 8 which involved lateral control. For the position control experiments, this is the upper left hand entry in each submatrix. For the current pressure control experiments, the configuration with the best results was used. In addition, a comparison with the matrix of pilots (Ref. 1) results is given by 16 and 20.

2. Investigate the effects of restraint increases from the tie-in configurations (item 1 above).
   a. Spring increase from zero to maximum
      This is given by 1, 2, 3, 4, 5, 6 for $Y_C = K_C$ and 7, 8, 9, 10, 11, 12 for $Y_C = K_C/s^2$
   b. Inertia increase from $I_{min}$ to $I_{max}$
      This is given by 13 through 15, for $Y_C = K_C$ and 16 through 18 for $Y_C = K_C/s^2$

3. Investigate the transition from a free-moving control to a pressure control by increasing the spring rate and the controlled element gain in the same ratio. This reduces the stick position sensitivity while the force sensitivity is constant. Configurations 3, 11, 12, 13, 14, 15 for $Y_C = K_C$ and 3, 16, 17, 18, 19, 20 for $Y_C = K_C/s^2$ provide the comparison.

4. Investigate the effects of the interchange of mechanical restraints with controlled element dynamics (discussed in Sections I and II). This is given by comparing 1 and 3 with 19. The first two have $Y_C = K_C$ and inertia of $I_{min}$ and $I_{max}$ respectively while 19 has $Y_C = K_C/s^2$, $I_{min}$ and a spring restraint.

5. Investigate the approach to a pressure controller via large inertia, i.e., the pilot controlling the force on a large inertia should perform as well as with the pressure controller (10 and 18) for $Y_C = K_C$ and 20 for $Y_C = K_C/s^2$). In addition, the effects of reducing inertia are given by configurations 17 and 20.

B. EXPERIMENTAL DATA

The data will be discussed relative to the objectives outlined above and the summary of the pre-experiment analysis. Frequent reference will be made to the extended crossover model form given by Eq. 3 repeated here.

$$V_P Y_C = \frac{VC}{V_{th}} \left( V_{th} + \frac{2}{s} \right)$$

(14)

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where

\[ a = \text{crossover frequency} \]

\[ \tau_a = \tau + \tau_N - \tau_{nd} \]

\[ a = \text{approximation to low frequency terms (Eq. 1)} \]

The \( \tau_N \) component of \( \tau_a \) contains the first-order effects of the neuromuscular system within the measurement bandwidth, i.e.,

\[ \tau_N = \tau_N^* + \tau_N^{	ext{on}} \]

(15)

actuation lag
effective time constant
of second-order terms of
motor load dynamics (Eq. 1)

Thus, \( \tau_a \) will tend to be increased by increases in inertia and decreases in spring rate.

1. Tie-Ins

a. With Pressure and Free-Moving Controllers (Roll Control)

The comparison of the spring-restrained control stick with the pressure and free-moving controllers is shown in Figs. 9 and 10 for \( Y_a = K_a \) and Figs. 11 and 12 for \( Y_a = K_a/a^2 \). In general, the present describing functions and mean square errors fall between the earlier results with the \( R0.40 \) and \( R5 \) inputs. This is consistent with the present \( K_{\text{in}} \) input bandwidth being intermediate to the other two (p. 19). The only exception is for Fig. 11 where the earlier pressure control had a higher crossover frequency in spite of the higher input bandwidth. This implies that pitch axis pressure control is not quite as good as roll control.

b. With matrix of pilots (Fig. 12)

The data from Ref. 1 (spring-restrained stick) for \( Y_a = K_a/a^2 \) is compared with the tie-in configuration \( 5 \) and with \( 2 \) in Fig. 13. There are slight differences from the matrix of pilots results. The crossover frequency for the matrix of pilots \( (3.25 \text{ rad/sec}) \) was intermediate to that for \( 5 \) \( (2.8 \text{ rad/sec}) \) and \( 2 \) \( (3.6 \text{ rad/sec}) \). The best of the present configurations, \( 2 \), had the same \( \tau_0 \) as the pilots, but apparently a larger \( a \). The difference in mean square
error is partly due to the lower input frequencies used for the matrix of pilots even though the basic envelopes was the same. This comparison indicates little difference between pitch and roll tracking for spring-restrained manipulators.

2. Load Effects of Various Restraints

a. Relative RMS error $e_0/e_1$ (dB), for various Spring Rate and Control Sensitivities

1) $Y_c = X_c$ (Fig. 14)

Relative RMS error is essentially constant for spring rates from zero to maximum 1 6 9 10. Performance decreases if control sensitivity is increased in proportion to spring rate except when spring rate reaches the pressure controller configuration, 9 11 12 23. There is further improvement at the smaller control sensitivities for the manipulator clamped configurations.

2) $Y_c = \frac{X_c}{e_2}$ (Fig. 15)

Relative RMS error has a shallow minimum at an intermediate spring rate and control sensitivity which is significantly better than for zero spring 5 2. For the pressure controller performance has a minimum at an intermediate control sensitivity. The addition of the spring, at constant control sensitivity, improves performance over that for zero spring 9 10 23, except for the largest spring, 20.

b. Effects of spring increases on pilot describing function

1) $Y_c = X_c$ (Fig. 16)

Although spring increases had no effect on relative RMS error, the crossover frequency is largest for configuration 2, $e_0 = 6$ rad/sec, dropping off to about 5 rad/sec for no spring 1 and max spring 10. Configuration 5 also has larger low frequency gain although there is no significant change in phase for a large range of spring rates. Also included is Fig. 16 is the best pressure controller configuration, 23. It has the lowest DC gain but one of the highest crossover frequencies (6 rad/sec).

The nearly constant crossover frequency and phase lag can possibly be explained by presuming little change in the position loop gain (since required excursions are unchanged) and some change in force loop gains (since the required forces increase) while

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Kc remains more or less fixed. The essentially unchanged amplitude and phase characteristics indicate a fairly tight position loop.

2) \( Y_C = \frac{K_C}{s^2} \) (Fig. 17)

Crossover frequency is constant except for a slight decrease for the stiffest spring while \( \tau_0 \) decreases slightly as spring rate increases. The \( \tau_0 \) decreases indicate that the spring increases help push the second order neuromuscular lag to higher frequencies. In addition, the best of the Pressure controller configurations, \( \mathcal{O} \), had lower gain at low frequency. This is offset by a lower \( \tau_0 \) in the crossover region such that \( \sigma/\gamma \) is about the same as \( \mathcal{O} \).

The basic trend in the data is that \( K \) causes \( \tau_0 \), which correlates with the findings of the various manipulators experiments (Ref. 8). This trend is modified somewhat by the discussion in Section 3.3. on p. 22.

c. Inertia increases

1) \( Y_s = K_C \) (Fig. 18)

Inertia increases cause steady decline in gain and crossover frequency with a proportional increase in \( \sigma/\gamma \). There is little effect on the phase for \( 1 \), \( 2 \) and \( 3 \). These data appear as typical \( Y_C - K_C \) data, so the neuromuscular system position loop must be a major factor in retaining the similar forms in the face of such drastic inertia changes. The decrease in gain may be due to actuation limiting since the required forces are increasing roughly proportional to inertia.

The basic effect is:

- \( I \) causes \( \omega_c \), \( s/\gamma \), \( \tau_0 \) and \( c \) no change

2) \( Y_C = \frac{K_C}{s^2} \) (Fig. 19)

Inertia increases cause steady decline in gain, increase in \( \sigma/\gamma \) and an increase in \( \tau_0 \). There is a resonance at high frequency for the larger inertia's. Clearly the inertia increases are reducing \( \gamma_0 \) of the second-order neuromuscular lag which affects \( \tau_0 \) and for the larger inertia's the break point is within the measurement bandwidth. Here, without question, the position loop of the neuromuscular system plays a central role in retaining the characteristic \( K_C \).

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features since the lead equalization capabilities are used up at low frequencies to compensate for the controlled element.

The basic effects to note are (neglecting the highly variable phase data at the lowest frequency)

\[ I \downarrow \text{causes } \delta_c, \frac{\delta_c}{\delta}, \tau_c, \alpha \downarrow \]

3. Approach toward a pressure controller via increases in position control sensitivity and spring rate such that ratio is constant.

   a. \[ Y_c = K_c \text{ (Fig. 20)} \]

   There is a significant increase in \( \delta_c/\delta_1 \) and decrease in \( \omega_c \) at the larger gains and spring rates improving somewhat for the pressure controller (which has the same force control sensitivity as the spring restraint). The phase changes are small implying a fairly tight position loop. The amplitude changes are not likely to be due to equalization changes since the phase doesn't vary.

   b. \[ Y_c = \frac{K_c}{s^2} \text{ (Fig. 21)} \]

   Intermediate values of spring rate and control sensitivity result in a small increase in \( \omega_c \), less \( \delta_c/\delta_1 \), some increase in low frequency gain and a small decrease in \( \tau_c \). These observations plus those on the \( \delta_c/\delta_1 \) results (Fig. 15) indicate that the intermediate values of spring rate and control sensitivity yield the best performance (Configurations (1), (2), (2), and (3)). The larger spring rates help in increasing the natural frequency of the control stick, thereby helping reduce \( \tau_c \) while the larger control sensitivities enable smaller stick motions.

4. Pilot as a position versus a force output device — interchange of mechanical restraints with controlled element dynamics.

   a. Figure 22 compares the effects of moving a double integration from the manipulator restraint to the controlled element.

   Configurations (1) (inertia restraint and \( Y_c = K_c \)) and (3) (spring restraint and \( Y_c = K_c/s^2 \)) show grossly different pilot behavior. Configuration (1) is typical
of that for \( Y_C = K_C \) (Figs. 9 and 16 and Ref. 1) whereas configuration (9) is typical of that for \( Y_C = K_C/s^2 \).

For \( Y_C = K_C \), increasing the inertia to its maximum, configuration (5), degrades the amplitude such that it has the same gain and crossover frequency as configuration (9), but the phase is fundamentally different, i.e., the large lagging phase angles at low frequency do not appear.

In addition, the \( \omega_0/\xi_1 \) is considerably smaller for configuration (5) than for configuration (9). Configuration (9) is also shown in Fig. 25.

These data are strong evidence that the pilot has good position feedback. The basic clues are that:

1) configuration (13) (inertia and \( Y_C = K_C/s^2 \)) is controllable which would require triple lead equalization if the pilot didn't have good position feedback capability (Table I, p. 14).

2) a fundamental difference exists in phase characteristics and performance for essentially the same amplitude characteristics near crossover and above (5 and 19).

5. Approach toward a pressure controller via large inertia

a. \( Y_C = K_C \) (Fig. 23)

This shows that the pilot controlling the force on an unrestrained very large inertia performs almost as well as for the pressure controller configuration with the same force sensitivity. Also shown is the effect of reducing the inertia by a factor of 5, for which the pilot reduces his low frequency gain in an attempt to prevent large motions of the inertia. Performance deteriorates slightly and \( \omega_0 \) increases slightly. Smaller values of inertia were tested, as indicated by Fig. 7, but performance rapidly deteriorated as the operator's output motions drove the manipulator against the mechanical stops. The data, particularly configuration (7), show that to a certain extent the pilot can ignore position information when he has to.

b. \( Y_C = K_C/s^2 \) (Fig. 24)

The comments for \( Y_C = K_C \) generally apply here except that inertia reduction causes a reduction in gain both at low and mid-band frequencies.
Figure 9. Comparison of Pitch Axis (Spring Restraint) and Roll Axis (Free Moving) Averaged Open-Loop Describing Functions ($\gamma_0 = K_C$)

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Input</th>
<th>Restraints</th>
<th>$\gamma/\gamma_0$ (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B6</td>
<td>$I_{\text{min}} + k_1$</td>
<td>-10.8</td>
<td></td>
</tr>
<tr>
<td>R0.40</td>
<td>Free Moving</td>
<td>-12.7</td>
<td></td>
</tr>
<tr>
<td>B5</td>
<td>Free Moving</td>
<td>-4.8</td>
<td></td>
</tr>
</tbody>
</table>

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Figure 10. Comparison of Pitch Axis (Pressure Control) and Roll Axis (Pressure Control) Averaged Open-Loop Describing Functions ($Y_C = X_C$)
Figure 11. Comparison of Pitch Axis (Pressure Control) and Roll Axis (Pressure Control) Averaged Open-Loop Describing Functions \( \gamma_c = \frac{\sigma_c}{\sigma_i} \)
Figure 12. Comparison of Pitch Axis (Spring Restraint) and Roll Axis (Free Moving) Averaged Open-Loop Describing Functions [$\xi_{c} = \xi_{c}^{2}$]
Figure 13. Comparison of Pitch Axis (Spring Restraint) and Roll Axis (Spring Restraint) Averaged Open-Loop Describing Functions $\left[\frac{Y_c}{C} = \frac{Y_c}{C_o}\right]$
Figure 14. Averaged Relative RMS Error, \( \sigma_e/\sigma_k \) (db), for Various Spring Rates and Position Control Sensitivities. Given by Circled Configuration Number (\( \gamma_0 = \gamma_C \)).
Figure 15. Averaged Relative RMS Error, \( \sigma_r / \sigma_2 \) (db), for Various Spring Rates and Position Control Sensitivities. Given by Circled Configuration Number \( (Y_c = K_c / \sigma_2) \).
Figure 16. Averaged Open-Loop Describing Functions for $Y_C = K_C$ with Spring Rate as Parameter
**Figure 17. Averaged Open-Loop Describing Functions**

For $Y_o = K_o/s^2$ with Spring Rate as Parameter

**Table:**

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Restraint</th>
<th>$K_c$</th>
<th>$\alpha_p/\alpha_d$(db)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure Controller ($73 \times k_1$)</td>
<td>$\frac{73}{5} K_o$</td>
<td>0.4</td>
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<tr>
<td>$I_{min} + 25k_1$</td>
<td>$K_o$</td>
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</tr>
<tr>
<td>$I_{min} + 5k_1$</td>
<td>$K_o$</td>
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</tr>
<tr>
<td>$I_{min} + k_1$</td>
<td>$K_o$</td>
<td>1.3</td>
<td></td>
</tr>
<tr>
<td>$I_{min}$</td>
<td>$K_o$</td>
<td>2.4</td>
<td></td>
</tr>
</tbody>
</table>

*Missing Conf @ points are essentially the same as Conf 13*

*Effective Position Control Sensitivity*

(See Fig. 8)

- -347°
- -359°
- -364°
- -392°
Figure 18. Averaged Describing Functions for $Y_c = K_c$ with Inertia as a Parameter

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Restraint</th>
<th>$\beta_1$</th>
<th>$K_c$</th>
<th>$\alpha_p/\alpha_1$ (db)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{min}$</td>
<td>$\frac{1}{2}$</td>
<td>$I_{min}$</td>
<td>$\frac{1}{2}$</td>
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<tr>
<td>$5I_{min}$</td>
<td>$\frac{1}{2}$</td>
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<td>$\frac{1}{2}$</td>
<td>-10.5</td>
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<td>$I_1$</td>
<td>$\frac{1}{2}$</td>
<td>-8.7</td>
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<tr>
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<td>$\frac{1}{2}$</td>
<td>$I_1$</td>
<td>$\frac{1}{2}$</td>
<td>-5.5</td>
</tr>
<tr>
<td>$25I_1$</td>
<td>$\frac{1}{2}$</td>
<td>$I_1$</td>
<td>$\frac{1}{2}$</td>
<td>-6.3</td>
</tr>
</tbody>
</table>
Figure 19. Averaged Open-Loop Describing Functions for
$\gamma_d = K_c/\omega^2$ with Inertia as Parameter.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Restraint</th>
<th>$K_c$</th>
<th>$\gamma_\phi/\gamma$ (db)</th>
</tr>
</thead>
<tbody>
<tr>
<td>○ ○</td>
<td>$I_{\text{min}}$</td>
<td></td>
<td>2.4</td>
</tr>
<tr>
<td>□ □</td>
<td>$5I_{\text{min}}$</td>
<td></td>
<td>2.7</td>
</tr>
<tr>
<td>△ △</td>
<td>$25I_{\text{min}}$</td>
<td></td>
<td>3.7</td>
</tr>
<tr>
<td>○ ○</td>
<td>$I_f$</td>
<td></td>
<td>3.3</td>
</tr>
<tr>
<td>○ ○</td>
<td>$5I_f$</td>
<td></td>
<td>5.5</td>
</tr>
<tr>
<td>○ ○</td>
<td>$2.5I_f$</td>
<td></td>
<td>9.2</td>
</tr>
</tbody>
</table>
Figure 20. Averaged Open-Loop Describing Functions for
Increases in Spring Rate and Control Sensitivity
($Y_0 = K_c$)

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Figure 21. Averaged Open-Loop Describing Functions for $Y_\text{e} = K_0/s^2$ with Spring Rate and Control Sensitivity as Parameters.
Figure 22. Averaged Open-Loop Describing Functions for the Effects of Dynamics Location

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Figure 23. Averaged Open-Loop Describing Functions for $Y_c = K_c$, Force Control with Inertia as Parameter

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Restraints</th>
<th>$K_c$</th>
<th>$\sigma_p/\sigma_s$(db)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure Controller</td>
<td>$I_{max} = 25I_1$</td>
<td>$K_F$</td>
<td>-9.0</td>
</tr>
<tr>
<td></td>
<td>$5I_1$</td>
<td></td>
<td>-7.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-6.3</td>
</tr>
</tbody>
</table>
Figure 24. Averaged Open-Loop Describing Functions for $y_n = x_n/s^2$, Force Control with Inertia as Parameter

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Restraints</th>
<th>$K_f$</th>
<th>$\sigma_x/\sigma_i$ (db)</th>
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</thead>
<tbody>
<tr>
<td>0 (23)</td>
<td>Pressure Controller</td>
<td></td>
<td>3.0</td>
</tr>
<tr>
<td>△ (23)</td>
<td>$I_{max} = 25I_1$</td>
<td>$K_{Fa}$</td>
<td>7.0</td>
</tr>
<tr>
<td>□ (23)</td>
<td>$5I_1$</td>
<td></td>
<td>7.9</td>
</tr>
</tbody>
</table>

$\omega$ (rad/sec)
SECTION V
CONCLUSIONS

This study, an exploratory investigation of the effects of load dynamics on human operator performance, provides inferential insight into the relative importance of limb position and output force senses in manual control. Conclusions relative to a large number of specific findings are given in the data interpretation in the text. The more general findings with respect to the five experimental objectives listed on page 24 are summarized below.

1. For spring restraints there was no practical difference in performance between the present pitch tracking experiments and those obtained from an earlier program for roll tracking.

2. Effects of manipulator restraints:
   a. For an "easy" controlled element \( \gamma_c = K_c \), performance was constant over a wide range of spring rates, while for a difficult controlled element \( \gamma_c = K_c/a^2 \) performance was best at an intermediate spring rate.
   b. With no spring restraint, increasing the inertia above that contributed by the pilot’s limb degrades performance considerably for both \( \gamma_c = K_c \) and \( \gamma_c = K_c/a^2 \).

3. The pilot has nearly the same performance with the best pressure control configuration as with the best spring-restrained configuration.

4. For position control tasks the pilot can operate as a position output device, i.e., his describing function is appropriate for the controlled element. The force-displacement characteristics are largely swamped by a tight position feedback loop.

5. For \( \gamma_c = K_c \) the human operator can control the force on an unrestrained very large inertia, effectively ignoring the extraneous position cues. System performance is little different than for the pressure controller. However, he is not as successful for \( \gamma_c = K_c/a^2 \); there is a large performance decrement from the pressure control configuration.
REFERENCES


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EFFECTS OF MANIPULATOR RESTRAINTS ON HUMAN OPERATOR PERFORMANCE

Final Technical Report

Magdaleno, R. E.

McAuer, R. P.

December 1966

This report is concerned with a series of experiments in which the effects of manipulator restraints, i.e., load dynamics imposed on the operator, are central. The purpose of this investigation is to:

a. Determine the load effects on the human operator's describing functions and performance measures for a representative variety of manipulator restraints and controlled elements.

b. Provide inferential insight into the relative importance of limb position and output force senses in manual control.
Human Response
Manipulators
Human Engineering
Flight Control Systems
Pilot Models

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