A SURVEY OF SELECTED RESEARCH ON HUMAN CONTROLLER CHARACTERISTICS

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SUMMARY

A survey of research on human-operator characteristics is presented. Particular emphasis is placed on the progress in developing human-operator models for manual control tasks of increasing complexity and on the effects of acceleration stress on describing-function models. The results reviewed indicate that quasi-linear models for single-loop manual control systems have been developed to a sufficient degree of precision and refinement for many manual control situations. Examples of the utility of relatively crude pilot models in several pilot-vehicle systems analysis and design problems are described. However, results for more complex control tasks (e.g., multiaxis, multiloop, and task transitions) indicate that pilot models for these control situations are fairly primitive and require additional research. Relatively meager results of tests conducted under high sustained accelerations, vibration, and short-term weightlessness indicate these environments can result in marked changes in pilot describing-function models and in pilot performance. Some remarks are presented in the final section of the paper on some limitations and deficiencies of human-operator models and on the direction of current research on human controller characteristics.

FIGURE LEGENDS

Fig. 1.- Single-loop manual control system.

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NOTATION

AR	amplitude ratio
A_X	longitudinal acceleration, g
A_Y	lateral acceleration, g
A_Z	normal acceleration, g
b_j	mimic coefficient (measurement by mimicking technique)
$c(t)$	operator control output
$\bar{c}^2$	mean square pilot control output
$F(t)$	operator applied force, lb
f	frequency, cps
g	acceleration of gravity; $1\ g = 32.2\ \text{ft/sec}^2$
h_p	pressure altitude, ft
I	transinformation, $\int_0^\infty \log_2\left[\frac{1 + S(f)}{N(f)}\right] df$, bits/sec
I_1	tracking task transinformation, $\int_0^\infty \log_2\left[\frac{1}{1 - \rho^2(f)}\right] df$, bits/sec
I_3	transinformation applied to error reduction task, $W_{eff}\log_2\left(\frac{1}{1 - r^2}\right)$, bits/sec
$i(t)$	forcing function
K	controlled-element gain
K_p	pilot static (zero-frequency) gain
K_1,K_2	variable gains in parameter-tracking operator analysis
M	Mach number
$m(t)$	system output
$n_c(t)$	human-operator remnant
$\bar{n}^2$	mean square uncorrelated pilot control output

RMS	root-mean square value
r	correlation between $i(t)$ and $m(t)$ amplitudes at each sample point
s	Laplace transform variable
T	sampling period in sampled-data analysis, sec
T_1	human operator lag equalization, sec
T_2	divergence time to double amplitude, sec
t	time, sec
t_o	time at which controlled element transitions occur, sec
t_1	time at which operator detects transition, sec
W_{eff}	effective forcing function bandwidth, cps
$x(t)$	operator input (measurement-by-mimicking technique)
Y_c	controlled element or vehicle transfer function
Y_pY_c	open-loop system describing function
$y(t)$	operator output (measurement-by-mimicking technique)
$z(t)$	mimic model output
$\epsilon(t)$	tracking error (also mimicking model matching error)
ζ	damping ratio
ρ	correlation coefficient
$\bar{\rho}_a{}^2$	average linear coherence, $\left(\frac{1 - \bar{n}^2}{\bar{c}^2}\right)$
τ	variable parameter in parameter-tracking analysis
τ_e	effective time delay
Φ_{cc}	pilot's output power spectral density
Φ_{ii}	forcing function power spectral density
Φ_{ic}	cross power spectral density between i and c
Φ_{im}	cross power spectral density between i and m

$\Phi_{i\epsilon}$	cross power spectral density between i and ϵ
Φ_{nn}	closed-loop remnant power spectral density
Φ_{nn_c}	open-loop remnant power spectral density
$\Phi_{\epsilon\epsilon}$	error power spectral density
ω	angular frequency, radians/sec
ω_c	open-loop system crossover frequency, $\lvert Y_p Y_c \rvert = 1$
ω_n	vehicle longitudinal short-period frequency, radians/sec

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1. INTRODUCTION

Human pilot dynamic characteristics must be described in mathematical terms consistent with flight control engineering practice if manned flight control systems are to be treated analytically. However, the versatility and adaptability of the human pilot have made such mathematical descriptions difficult. During the past decade, considerable progress has been made in developing techniques for analyzing pilot-vehicle systems that can be used in evaluating and designing manual control systems.

This development has been made possible by the evolution and refinement of analysis, or identification, techniques for determining human-operator characteristics in various control tasks and the development of models descriptive of human behavior in these tasks (1 to 9). Numerous experiments have been carried out on the human operator in increasingly complex control tasks (3, 4, 10 to 15). Although these studies provided much information on pilot performance and dynamic response for a wide range of simulated control tasks, relatively little is known about how these characteristics may vary with the environmental extremes imposed on the crew of advanced aircraft or spacecraft. Accordingly, some effort was devoted, during the past five years, to studying the effects of acceleration stress on human physiological responses, on control task performance, and on associated human-operator characteristics (11, 16 to 21).

The purpose of the present paper is to provide a review of selected research on human controller characteristics with emphasis on three main areas (Table 1):

(1) A review of research on human-operator models including brief sketches of techniques used for analysis, the status of human-operator models, and the effects of acceleration on pilot performance and on pilot models.

(2) A brief summary of some simple applications of the man-machine system concept to handling qualities analysis, control system failure analysis, and piloted simulator technology.

(3) A brief discussion of some deficiencies of current human-operator models.

Since this paper is a status report on human-operator research, experiments are not described in detail and the reader is referred to the original source material where appropriate. In addition to the references cited, two fairly comprehensive bibliographies on human controller research have been published (22, 23).

2. HUMAN-OPERATOR MODELS

Research on human-operator characteristics has been confined largely to the simple single-loop compensatory manual control system illustrated in Fig. 1. In these studies, the forcing function $i(t)$ was random or random-appearing, and only single inputs $e(t)$ and outputs $c(t)$ for the human operator were considered. Further, the controlled element (or vehicle) dynamics were idealizations of those normally associated with aircraft or spacecraft. Recently, increased attention has been given to more complex control situations including multiaxis control, multiloop control, and control-task transitions where the controlled element dynamics are suddenly varied to simulate a control system failure. The purpose of this section of the paper is to review the identification techniques that have been developed and used to define human-operator characteristics in these control situations, to indicate, briefly, the present status of human-operator models for these control tasks, and to provide some information on the effects of environmental stresses (e.g., acceleration and vibration) on human-operator performance and models.

2.1 Identification Techniques

Figs. 2 and 3 illustrate two widely used signal analysis techniques for determining the dynamic characteristics of the human pilot. In Fig. 2, the block diagram of Fig. 1 is recast in a simpler form suitable for a describing function approach to the problem of identifying human operator properties. In this approach, the actual noisy, nonlinear, time-varying characteristics of the human controller are represented by a linear operator $Y_p(\omega)$ and a remnant $n_c(t)$ added to the output of $Y_p(\omega)$ as shown. Also shown on this figure are the pertinent relationships for identifying the main elements in the system so that the powerful tools of power spectral density analysis can be used. Much of the research on human-operator characteristics (e.g., 1 to 4, 16) has used either analog or digital computers to obtain the required power and cross-power density measurements.

Another analysis technique for determining human-operator describing functions is the model-matching method illustrated in Figs. 3(a) and 3(b). In Fig. 3(a), a parameter-tracking method (6) is described; the parameters K_1, K_2, and τ of an assumed pilot model are adjusted on-line to minimize the difference between pilot model and human pilot control outputs. In Fig. 3(b), an identification technique (8) is shown. This technique uses an analog model of the human operator composed of a sum of weighted orthonormal filters. A form of the method of steepest descent is used to determine the values of the weighting coefficients b_j which minimize the difference $\epsilon(t)$ between the model output $z(t)$ and the human operator control output $y(t)$.

Although power spectral density and model-matching analysis techniques can be used to determine human-operator characteristics (where changes occur over 10 seconds or more*), they are not suitable for describing short-term adaptive characteristics. Short-term pilot adaptation is important when the controlled element dynamics suddenly change as a consequence of a control-system failure. To circumvent the measurement problem, investigators (9 and 11) used ensemble averages of tracking error waveform time histories or visually inspected and analyzed time-history records (Fig. 4) of human-operator response to sudden control-task changes. In Fig. 4(a), pertinent response quantities are shown for a case where the controlled element dynamics $Y_c(s)$ were suddenly varied at time t_o from 2 to $-8/s^2$. In Fig. 4(b), $Y_c(s)$ was varied from $8/s^2$ to $-16/s^2$ at time t_o.

Some of the relevant characteristics of human-operator identification techniques are summarized in Table 2 and both the advantages and disadvantages of the various techniques are indicated. Reference to a "good theoretical base" for the power spectral density approach in Table 2 implies a solid mathematical foundation. For the parameter tracking, model matching technique, a solid mathematical or theoretical basis is lacking, although some progress has recently been made (7).

2.2 Status of Human Operator Models

The analysis techniques described in the preceding section have been used for studying the characteristics of a human operator performing control tasks, ranging from relatively simple single-axis tasks to fairly complex tasks, including multiaxis, multiloop, and transition control situations. Some of the results of these studies which pertain to the development of human-operator models for control tasks of increasing complexity will be reviewed in this section.

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*For reasonable precision, sample lengths of about 2 minutes or more are required for power spectral density analysis (4), and 10 seconds or so for measurement-by-mimicking analysis (8).

2.2.1 Single axis models

Several models of the human operator in single axis control tasks have been proposed, for example, the quasi-linear describing function model (4), the constant rate, sampled-data model (12), and information rate-limited models (10) and (11). The primary features of these models are described in Fig. 5.

In the comprehensive and systematic study sponsored by the U.S. Air Force (4), describing function models for the human pilot were developed and validated for a wide range of forcing functions and controlled-element dynamics. In Fig. 5(a), the simplest model form is referred to as a crossover system and consists of two variable terms: the system crossover frequency ω_c and the pilot's effective time delay τ_e. In (4), the variation of these two parameters with forcing-function or controlled-element changes are systematically explored and defined. Time variations of these parameters are reflected, in general, by the magnitude of the remnant term which, though neglected in the simple model described here, can assume considerable importance.* Since the model in Fig. 5(a) describes, fairly accurately, results for a variety of forcing functions and controlled elements in the important gain crossover region, it is a convenient approximation for many engineering purposes. Quasi-linear describing function models suitable for more precise pilot-vehicle system studies are described in (4).

Another description of the human operator that has received some attention is the constant-rate, sampled-data model in Fig. 5(b). This model, studied by Bekey (12), comprises a first-order hold, followed by a linear transfer function. The use of a first-order hold implies that the operator will continue to operate on the last sample he has received. For the particular control situation studied by Bekey (i.e., forcing function bandwidths greater than 6 radians per second and simple gain controlled elements), there was some evidence of sampling behavior. The sampled-data models were capable of matching experimentally measured peaks in the spectra of human operator control outputs, and continuous (describing-function) models were not. In more recent studies (4) pilot control outputs for a range of forcing functions and controlled-element dynamics did not reveal any evidence of constant rate sampling behavior.

Figs. 5(c) and 5(d) show an information-rate transmission model and rate of transmission of information properties of the human operator. The concept of the human controller as an information-rate processor was studied (10 and 11). The results shown, taken from (11), attempt to obtain an information-rate measure insensitive to the shape of the input spectrum. The model in Fig. 5(c) assumes two parallel information

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*It is indicated in (4) that the remnant increases as the task difficulty (e.g., forcing function bandwidth or order of the controlled element dynamics) increases.

processing channels. One channel is required to monitor the incoming signal and establish a course of action (such as, establishing and maintaining the parameter of a pseudo transfer function); this requires the processing of information at a rate I_1. Concurrently, the operator is also required to track the input signal and minimize the system error. Information processing for this task is indicated by I_3. Thus, the operator's total capacity for processing information is assumed to be diminished by the sum of I_1 and I_3. Though the model shown is crude and is based largely on conjecture, the results that stem from this description (Fig. 5(d)) appear to integrate available data into a form relatively independent of input spectrum shape. The line representing maximum achievable rate of transinformation is based on an assumed visual acuity of the human operator of 1 minute of arc (11).

2.2.2 Multiaxis models

In comparison to research results on human-operator characteristics in single-axis or single-loop manual control systems (Figs. 1 and 2), results on multiaxis control situations are relatively meager. Recently, Levison and Elkind (11) conducted experiments to determine how to modify current models of single-axis systems to provide good representations of the human in two-axis control tasks. The three control situations considered included homogeneous control (input power spectra and controlled elements same in both axes), heterogeneous input spectra (different forcing function bandwidths in each axis), and heterogeneous controlled elements (different controlled element dynamics in each axis). Results for the homogeneous and the heterogeneous controlled situations are presented in Figs. 6 and 7, respectively. For the homogeneous case where $Y_c(s) = K/s^2$ in each axis, very little difference is observe between human operator describing functions for single- and dual-axis tasks. For heterogeneous dynamics (Fig. 7), significant differences are shown between open-loop system describing functions for one and two gain controlled-element axes. (The controlled element for the second axis was K/s^2). These particular results indicate that appreciable lead equalization, required for controlling the second axis, is also used in controlling the first axis. In single-axis control, no lead equalization was used.

2.2.3 Multiloop models

Multiloop manual-control systems differ appreciably from multiple single-loop systems, such as those just discussed, and represent, in general, a more complex control situation. To provide some data on pilot dynamics in this type of task, the experimental situation described in Fig. 8 was studied by Stapleford (11). A block diagram of the multiloop task investigated is shown in Fig. 8(a), and the display used is shown in Fig. 8(b). The fundamental distinction between this system and multiple single-loop systems is the interaxis coupling (roll-yaw in the present example) inherent in the controlled-element dynamics selected.* From a preliminary set of experiments, three basic sets of controlled-element dynamics evolved, corresponding to three levels of Dutch roll damping: stable, slightly unstable, and unstable near the limit of pilot controllability. The pilots were required to adopt a multiloop control mode (stabilize inner heading loop and command control of bank angle) for the two unstable control situations. The results of this study (11) indicated that the quasi-linear pilot model and the adjustment rules developed for single-loop systems (4) apparently apply to multiloop system command loops. They also indicated that the single-loop model sometimes applies to inner-loop characteristics of the pilot.

2.2.4 Short-term adaptive model

The study of pilot dynamic response to rapidly changing controlled-element dynamics has some significance for the manual control of aircraft. Results could be applied to the analysis of pilot-vehicle systems following failure of part of the flight control system, a stability augmenter, or other emergency situations. Some studies attacked (9 and 11) the complex problem of describing human-operator short-term adaptive characteristics. As noted earlier, conventional identification techniques are not applicable to this problem, and time-domain analysis was resorted to. In (9), the analysis of the average tracking-error waveform following various task transitions (e.g., gain and polarity changes in simple gain controlled elements and polarity changes in velocity control) provided some initial information on short-term adaptive characteristics of the human controller. For the idealized and simple transitions considered, the pilot adapted in 0.4 to 0.8 second and the error reduced to steady-state levels 1 to 3 seconds following transition. Complex control transitions, involving both polarity and gain changes for position control and polarity changes for velocity control, significantly increased adaptation time relative to that for simple transitions (i.e., gain changes in position control). The complex transition mode-switching model (11), identified in Fig. 9, describes four response phases. Transition occurs at time t_o, the start of the second phase. The pilot continues to control with pretransition adaptation Y_{p_1}. At time t_1, he has detected the transition and immediately following t_1, adopts either an optimal or a suboptimal mode of control. The nonlinear optimal control mode, as shown, is the simplest form used. One possible suboptimal form of control is to vary the control amplitude. The switching time t_2 (not shown) is determined by time-optimal control logic.

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*In the vehicle equations of motion, rolling moment due to yawing velocity, and yawing moments due to rolling velocity and aileron deflection were included.

Following the reduction of error and error rate to acceptable levels, the operator adopts the appropriate post-transition describing function form Y_{p_2}. Weir (11) discussed several important limitations of this model; these and several others are noted in Table 3 which summarizes briefly the foregoing discussion on the status of human operator models.

2.3 Environmental Stress Effects

The intent of this portion of the paper is to review results of several research programs devoted to studying the effects of acceleration stress on human physiological responses, control task performance, and on associated pilot describing function characteristics. Portions of these programs, relevant to the present paper, are outlined in Table 4.

2.3.1 Sustained acceleration

This section provides a brief review of the effects of high sustained acceleration on pilot performance and dynamic response.

In Fig. 10, a summary plot is presented indicating the primary effects of acceleration on quasi-linear pilot describing functions. In the upper portion of the figure, results from (16) are plotted to indicate average decrements in open-loop system crossover frequency as a function of acceleration. In the lower part of the figure, variations with acceleration of the pilots' average linear coherence (an inverse measure of relative remnant at the pilots' output) are indicated. The primary effect of sustained acceleration on quasi-linear pilot models appears to be an appreciable decrease in open-loop crossover and a substantial increase in remnant. Most of the latter was attributed to increased time-varying behavior (16).

2.3.2 Combined acceleration and vibration

The effects of combined sustained and vibrational stresses on pilot control and monitoring capabilities investigated (17 and 21) include sustained accelerations of about 3.5 g (EBI) combined with vibration of 11 cps up to about ±3 g.

Fig. 11 provides averaged results for two pilots for normalized task errors (Fig. 11(a)) and for dial reading errors (Fig. 11(b)) as a function of vibration level. The dial reading errors were taken from (21). The effects of vibration on control task performance are quite apparent, with performance deteriorating rapidly above about ±1.5 g.

Describing function data, which are not presented because of their inconsistency, do suggest, however, that the pilot's ability to lead (which is necessary to compensate for vehicle dynamics attenuation above 0.9 radian/sec) is impaired. This "result" is not incompatible with pilots' comments during the test program. When there was no vibration, the pilots were able to follow the target motion in the display and could easily follow error reversals and error rate. As vibration was introduced, the actual display indications became a blur,* particularly at the higher vibration levels, and the pilots presumably lost their ability to extract error-rate information from the display. This observation, if verified, may have important applications to display design for vehicles susceptible to appreciable vibrations in the crew compartment (e.g., launch vehicles, helicopters, current and projected transports, low-level high-speed aircraft, etc.).

The results in Fig. 11(b) show an increase in gross dial reading errors which parallels, roughly, the increase in control-task errors shown in Fig. 11(a). Again the errors increased rapidly as the vibration level exceeded approximately ±1.5 g.

2.3.3 Short-term weightlessness

The results discussed in this section were obtained in a study conducted some time ago by the NASA on an F-104 B airplane. The primary results of this study are provided in Figs. 12 through 15. During a preliminary series of tests, pilot reaction times, both simple and complex, and percentage of control reversals during the complex reaction-time trials were obtained. For these tests, a scope display and controller with unit gain dynamics to the display were used. The pilot's task was to follow random-step, unidirectional inputs to the display (simple reaction time) and random dual-directional steps (complex reaction time). In later tests, the pilot was given control tasks similar to those of the sustained acceleration and combined acceleration-stress studies. The results selected for discussion are for a fairly difficult task, that is, a very lightly damped vehicle (see Table 4).

To provide some indication of the actual acceleration levels imposed on the pilot and the type maneuvers performed to produce the "weightless" environment, a typical time history is given in Fig. 12. Accelerations of about 0.02 to 0.05 g are observed for the 0 g portion of the time history.

Results from the preliminary study on reaction time are illustrated in Fig. 13. Zero gravity had very little effect on simple reaction time

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*This was referred to as diplopia, or "double vision," by one of the subjects of the study who was a medical doctor, as well as pilot.

(Fig. 13(a)). The complex reaction time increased significantly at both 0 and 3 g relative to the 1 g flight value. It should be noted that these results are mean values for about 15 to 20 runs. Although these results are relatively meager, the trends suggest an appreciable effect of 0 g (and 3 g) on the central nervous system.

The increase in the percentage of control reversals at 0 and 3 g, relative to that at 1 g (Fig. 13(b)), parallels the increase in complex reaction time, lending additional support to the possibility of "central data processor" changes due to weightlessness.

The results in Fig. 14 show the effects of varying the acceleration environment on normalized mean-square error (Fig. 14(a)), on normalized error spectra (Fig. 14(b)), and on the error spectrum (Fig. 14(c)). The relatively large increase in mean-square error between 1 and 0 g flight shown in Fig. 14(a) (vehicle dynamics "A") is due to: (1) a moderate increase in normalized error spectra at forcing function frequencies shown in Fig. 14(b), and (2) a large increase in the error peak near the vehicle short-period frequency (Fig. 14(c)).

From the describing functions of an open-loop pilot-vehicle system presented in Fig. 15 several observations may be made.

(a) Open-loop system crossover decreased from about 1.5 to 0.8 radian/sec between the ground and flight situations.

(b) The attenuation at crossover is about 6 dB/octave which satisfies one of the two "optimal control" strategies required for minimizing mean-square error.

(c) Phase margins for all three cases considered are roughly 75° to 80°.

(d) The crossover frequencies in all cases are relatively low and below those for which appreciable forcing function power exists; this accounts for most of the relatively large normalized error shown in Fig. 14(a) for the 1 g ground and 1 g flight runs. Most of the increased error at 0 g resulted from the pilot's "chasing" the lightly damped, short-period motions.

3. SOME APPLICATIONS

In this section some fairly simple applications of human-operator models to pilot-vehicle system analysis problems are illustrated. Some of the available publications in this area ((24) to (36)) provide considerable evidence of the utility of these models for manual control system analysis and design. The pilot models applied in these studies ranged from those considered fairly crude and primitive to those reflecting the latest knowledge in this area. In the following subsections, the man-machine system concept is used for analyzing vehicle handling qualities problems, control-system failures, and problems related to piloted-simulator technology (specifically motion-cue requirements and a design problem related to the development of a full-scale lunar landing simulator).

3.1 Handling Qualities Analysis

Much of the experimental pilot-vehicle system research by the NASA is concerned with vehicle handling qualities characteristics, and one of the products of this research is handling qualities criteria based on subjective pilot impressions. A pilot-opinion rating schedule, extensively used in this type of research, is shown in Table 5. Correlates between the results of experimental and analytical pilot-vehicle system studies would establish a basis for predicting pilot-opinion trends in manual control studies.

In (27) and (28) an attempt was made to correlate pilot describing function parameters (specifically pilot gain and lead) with pilot opinion. Results (28) and analysis of the data (37) are presented in Fig. 16. The pilot-response data, which formed the basis for the boundaries shown, were obtained by the method described in (28).* The pilot-response boundaries for a pitch control task (Fig. 16(a)) and a roll control task (Fig. 16(b)) were derived during the handling quality studies described in (28) and (37). Also shown in Fig. 16 are three pilot-response regions corresponding to "best tested" vehicle dynamics (Region I), control-sensitivity problem (Region II), and tendency to overcontrol (Region III).

These results indicate that pilot opinion is strongly influenced by lead-equalization requirements and by the levels of gain he must adopt. The near-optimal control area for both cases is confined to relatively small lead and to a restricted gain region. Though the correlations between pilot opinion and pilot dynamics are considered qualitative, it is felt that current pilot models and pilot-vehicle systems analysis techniques can estimate pilot opinion adequately for many manual control-system design studies.

3.2 Analysis of Control-System Failure

In a study of a pilot's ability to control during simulated stability augmentation system failures (34), simplified pilot models

*This method is based on matching human pilot performance with that of an assumed analog pilot with variable static gain and lead parameters. Though it is considered a fairly crude identification technique, the results are believed to reflect, qualitatively, pilot adaptation to changes in task difficulty.

were used to interpret and analyze the results. In Fig. 17, the five cases studied are shown in relation to steady-state pilot-opinion boundaries for short-period longitudinal handling qualities established in an earlier study (28). The present discussion will be confined to case B, in which a sudden failure of a pitch damper was simulated. The general pattern of the control problem is indicated in Fig. 18. Time histories of aircraft response to pitch-damper failures for case B are presented in Fig. 18(a). Fig. 18(b) presents normalized tracking performance data in time-history form for the initial and repeat runs shown in Fig. 18(a). As shown by these results, the pilot-aircraft combination becomes unstable immediately following the damper failures. These results and those from a case documented in flight in which control was completely lost (results not shown) were analyzed to determine whether pilot-vehicle system concepts and crude pilot models could be used to predict the experimental results. The analysis consisted in determining the pilot model associated with good (pretransition) vehicle dynamics, and assuming the pilot retained this model form during the initial stages following damper failure. (More recent results (Fig. 9) indicate that retaining pretransition dynamics is one of the important short-term adaptive characteristics of the human operator.) The method described in (28) was used to determine pretransition pilot models for the cases selected for analysis. Results of the analysis are presented in Fig. 19. In Fig. 19(a) the correlation of the predicted results and the experimental results is expressed in terms of the decrement in damping due to the destabilizing influence of the pilot. The damping decrement is simply the difference between the unaugmented airplane damping and the closed-loop damping of the pilot-airframe system for an unadapted pilot model. The correlation based on closed-loop stability expressed in terms of divergence times to double amplitude T_2 is provided in Fig. 19(b). These fairly good correlations are additional evidence of the utility of these techniques for studying manual control systems.

3.3 Piloted Simulator Technology

3.3.1 Motion-cue effects

Although piloted flight simulators are being used extensively for research and training purposes, relatively little systematic information is available on motion-cue requirements for these devices. Despite the fact that the effects and importance of motion cues in piloting tasks are incompletely understood, motion generators of increasing complexity are being designed and constructed for use in various piloted simulator laboratories.

In a recent study Meiry (35) made a fairly detailed examination of the effects of motion cues in simple manual control tasks. He compared pilot describing functions and tracking performance in both fixed and moving-cockpit simulators, and considered the effects of both horizontal rotation (yawing motions) and rolling motion. Some of the results of his study are presented in Figs. 20 to 23.

Human-operator describing functions are presented in Fig. 20 for a velocity control task both with and without yawing motion inputs. (Only the semicircular canal portion of the vestibular system was stimulated.) The results show a considerable reduction of operator phase lag for the moving simulation relative to the fixed-base situation. For these data, a decrease in the human's effective time delay from about 0.2 to 0.1 second is indicated. Control task performance also improved for the combined mode (visual plus motion inputs).

In Fig. 21, results of tests conducted to determine the effects of motion with respect to the gravity vector are presented. In this case both the semicircular canals and otoliths are stimulated by rolling motions. The describing function shown indicates the operator adopts a pure gain mode of control with motion inputs. For visual inputs only (35), the operator's describing function assumes the form shown for the visual mode in Fig. 20. Apparently, for frequencies to at least 5 radians per second, the motions considered permit the human to compensate completely for the effective time delay observed in control situations with only visual inputs.

Figs. 22 and 23 show a block diagram and the main results for a difficult control task in which considerable lead equalization by the human operator is required to stabilize the system, particularly for the larger values of ω_d^2. The orientation task (Fig. 22) was specifically designed to provide results that would demonstrate the importance of the vestibular sensors in certain control situations. Comparison of root-mean-square errors for the visual and combined visual and motion modes as a function of divergence frequency (Fig. 23) clearly demonstrates the contributions of the vestibular system to the performance of this task. Considerably higher divergence frequencies can be controlled when motion inputs are provided, presumably because of the operator's ability to compensate with more lead (35). Additional pertinent results on motion-cue effects in various flight control tasks are provided by Young (11).

3.3.2 Lunar landing simulator design problem

Pilot models were also found useful in the piloted-simulator design problem described in (14). In this study, multiloop pilot describing functions, developed for a lunar landing task, were used for predicting closed-loop system performance for three alternative designs for a full-scale lunar landing simulator. Based on open-loop response calculations, one of the three competing simulator designs appeared significantly superior to the other two systems. This system was also considerably more complex than the others. However, closed-loop response calculations for a translational control task, based on the use of multiloop pilot models, indicated no clear-cut superiority of the more complex system relative to one of the simpler alternative designs. These results formed the basis for a decision to recommend that the simpler system be implemented.

4. MODEL DEFICIENCIES

In the preceding section of this paper, human-operator research results were reviewed in the form of a status report on model development and on some applications of pilot models to man-machine analysis and design problems. In this final section, some of the recognized deficiencies in available human-operator research results are discussed, and current research, directed toward resolving some of these deficiencies, are briefly described.

4.1 Deficiencies in Information

Although human-operator models for single-loop compensatory display systems have been developed and appear suitable for engineering applications to many manual control problems, limited information in several areas may restrict the general applicability of results, obtained under idealized laboratory conditions, to operational flight situations. These areas are briefly reviewed.

4.1.1 Motion-cue effects

Most of the research devoted to developing a pilot model has been conducted with only visual information presented to the pilot. Previously it was indicated that angular motion cues caused significant changes in human-operator describing functions and, for the examples selected, improved control performance. Other results obtained in piloted flight simulators (13, 28, 34, 37, 38) indicate that motion cues for certain control situations have a marked effect on pilot control performance. It is clear, even for simple, single-loop, manual systems, that much additional research is needed to determine the effects of motion cues on human-pilot models and their relative importance in piloting tasks.

4.1.2 Display and control factors

Current quasi-linear pilot models are based primarily on experiments studying interactions between forcing function, controlled-element dynamics, and human-operator dynamics (4). Very little systematic work has been done on interactions involving display or control dynamics. In (4) manipulator dynamics were essentially removed with the exception of a small spring constant. In operational flight control systems, different types of manipulators (wheel, center stick, side-arm controller) are used, and the dynamics of each type (damping, inertia, spring constant, breakout characteristics, may vary over a fairly wide range. The size and the dynamic characteristics of flight displays may also vary. Although these factors are known to influence pilot performance and opinion, it is not clear to what extent research should (or could) be directed toward studying these effects in a systematic and general way.

4.1.3 Environmental stress effects

Results in a preceding section indicated that appreciable changes in pilot models and performance occurred during sustained accelerations, combined acceleration and vibration, and short-term weightless flights. The pertinence of these results to fundamental research on human-operator characteristics is that significant changes were observed and it would be desirable to correlate them with observed psychological or physiological factors (16). However, much additional research is needed before pilot-vehicle system analysis techniques can be used to predict even qualitative changes in pilot performance during exposure to specific environmental stresses.

4.1.4 Idealization effects

Because of the difficulties of measuring human-operator characteristics and of controlling experimental variables in operational simulators or flight environments, most of the research has been carried out under idealized control situations in the laboratory. For example, forcing function and controlled-element idealizations of those encountered in flight control tasks are generally used. (Controlled-element idealizations K, K/s, $K/(s - 2)$, and K/s^2 were used in (4).) Consequently, little information of general use is available on the effects of aircraft short-period parameters, such as frequency $\omega_n{}^2$ and damping $2\zeta\omega_n$, on pilot dynamics. The possible importance of these parameters is indicated in Fig. 24. These results, taken from (36), show appreciable effects of vehicle longitudinal short-period frequency and damping on system open-loop crossover frequency. To a certain extent, the deficiencies discussed here, and others, such as, task or mission effects, use of nonpilot subjects, effects of instructions to the test subjects, may be overcome by the use of a certain amount of "artistry" in the application of available pilot models. Research results which would reduce the need for artistry would increase the usefulness of describing-function models and encourage their more widespread use.

4.2 Deficiencies of Complex Task Models

Human-operator models for multiaxis, multiloop, and controlled-element transition control tasks are subject to the same deficiencies described above for simple control tasks, as well as to those resulting from a limited data base. For example, in the two-axis control task results (11), Levison considered only two sets of controlled-elements dynamics, that is, position control and acceleration control. In the multiloop study (11), Stapleford used a restricted set of vehicle Dutch roll dynamics; and in the investigation of human-operator short-term adaptive behavior (11), Weir considered simple and idealized controlled-element transitions. Consequently, human-operator models developed to describe human-control behavior in these complex tasks are primitive in comparison to those developed for the single-loop control situation. It is evident that much further research is required to develop and validate existing models, or to evolve new concepts for studying human behavior in these more complex control situations.

4.3 Direction of Current Research

Current research is being directed toward resolving some of the limitations, restrictions, and deficiences of currently available models of human-control behavior. For convenience this research can be described under two categories: (a) current model refinement, and (b) investigation of possible new approaches.

4.3.1 Current model refinement and extension

Current research to refine and extend the use of models of the human controller includes the following:

(a) A study of motion cues of primary importance to the pilot. Results are expected to augment, substantially, information on the roles of motion cues in piloting tasks and on their interactions with human-operator models.

(b) A study to develop a theory of manual control displays. Results of this study are expected to provide information on interactions between display characteristics and human-controller data and to lead to a more rational basis for manual control display design.

(c) Continuation of the studies on multiaxis, multiloop, and task transition control, with increasing emphasis on further development of models and their validation for more realistic (less idealized) manual flight-control tasks.

(d) Studies of optimal behavior in manual control systems. Obermayer et al. (11) are applying techniques of modern optimal control theory to the study of manual control systems. They demonstrated significant effects of the specific performance criteria used* on human-operator control strategies and describing functions.

4.3.2 Possible new approaches

Some of the more promising alternative, or new, approaches to describing human-operator control behavior are described by Elkind (15). Combined sampled-data and information rate-limited concepts, for example, show considerable promise in circumventing some of the problems anticipated in extending the quasi-linear describing function approach to more complex control situations. Other approaches to the study of manual control systems, which are currently being explored, are described in (11).

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*One of the four performance criteria considered was mean-square-error minimization, the criteria which is usually assumed to be minimized by the human operator in describing function analysis.

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Table 1. Outline of Major Topics Covered

Human Operator Research

Human Operator Models	Some Applications	Model Deficiencies
Identification Techniques	Handling Qualities Analysis	Limited Information
1) Spectral Analysis		1) Motion-Cue Effects
2) Model Matching	Control System Failures	2) Display and Control Factors
3) Time History Analysis		3) Environmental Stress Factors
	Piloted Simulator Technology	4) Idealization Effects
Model Status	1) Motion Cue Effects	
1) Single Axis	2) Lunar Landing Simulator	Complex Control Task Models
2) Multiaxis		1) Multiaxis
3) Multiloop		2) Multiloop
4) Adaptive		3) Adaptive
Environmental Effects		Current Research
1) Sustained Acceleration		
2) Vibration		
3) Zero g		

Table 2. Characteristics of Identification Techniques

Method	Measurement technique	Advantages	Disadvantages
Spectral analysis	Analog, digital watt-hour meters	1. Fairly good theoretical base 2. Good precision 3. Large body of data available	1. Measurements relatively tedious and time consuming (off-line analysis) 2. Requires synthesis of human operator describing function 3. Need special purpose analyzer or fairly large digital computer
Model matching (parameter tracking)	Analog	1. On-line analysis 2. Ease of application 3. Direct measure of human "transfer function"	1. Theoretical base weak 2. Precision of results may be poor under certain conditions
Model matching (mimicking)	Digital	1. Essentially, on-line analysis 2. Precision good 3. Useful for time-varying analysis	1. Requires on-line digital computer capability 2. Requires synthesis of human operator describing function
Synthesis, using time histories of tracking runs	Digital, analog	1. Only available method for describing short-term human adaptive characteristics	1. Synthesis of human adaptive model required 2. Analysis fairly tedious and time consuming

Table 3. Status of Human-Operator Models

Control task	Type model	Remarks	References
Single axis	Quasi-linear	Thoroughly and systematically documented. Models explain most of observed results. Human-operator adjustment rules well-defined. Readily applied to pilot-vehicle system analysis.	4
	Sample data	Alleviates need for "remnant" concept used in quasi-linear analysis. May be more consistent with physiological or psychological evidence. Data limited.	12
	Information theory	Poses concept of constancy of information rate processing. Has potential for quantifying pilot "work load." Data limited and models primitive.	10, 11
Multiaxis	Quasi-linear	Single axis quasi-linear models applicable to two-axis situation only where dynamics same (Forcing functions can be heterogeneous). Limited data.	11
Multiloop	Quasi-linear	Single axis quasi-linear models applicable, but with some reservation. Data limited. Results apply to specific case.	11
Single axis, step transition in vehicle dynamics	Adaptive (mode switching)	Model based on four stages: 1) pretransition steady state; 2) pretransition retention; 3) time-optimal nonlinear control; 4) post-transition steady state. Results meager. Model fairly primitive.	11

Table 4. Acceleration Environments Studied

Environment	Vehicle dynamics	Facility	Pilot	Source
Sustained acceleration: 10 g (EBO) 10 g (EBI) 7 g (EBD)	$Y_c = \dfrac{13.4(1 + 2.3\,s)}{s\left(\dfrac{s^2}{11.3} + \dfrac{2(0.53)}{3.35}\,s + 1\right)}$	NADC Johnsville centrifuge	A B C	(16)
Combined stress: Sustained acceleration, 3.5 g (EBI) Vibration,* 0 g ±1.5 ±2.0 ±3.0	$Y_c = \dfrac{1.3}{\dfrac{s^2}{0.92} + \dfrac{2(0.64)}{0.96}\,s + 1}$	Ames five-degree-of-freedom simulator (with vibration chair)	D	(17)
Zero acceleration: 1 g (ground) 1 g (flight) 0 g (flight)	$Y_c = \dfrac{13.0(1 + s)}{s\left(\dfrac{s^2}{16} + \dfrac{2(0.06)}{4}\,s + 1\right)}$ (Dynamics "A")	F-104 B aircraft	E	(11)
1 g (ground) 1 g (flight) 0 g (flight)	$Y_c = \dfrac{13.0(1 + s)}{s\left(\dfrac{s^2}{36} + \dfrac{2(0.04)}{6}\,s + 1\right)}$ (Dynamics "B")			

*Vibration frequency, 11 cps

Table 5. Pilot Opinion Rating Schedule

	Adjective rating	Numerical rating	Description	Primary mission accomplished	Can be landed
Normal operation	Satisfactory	1	Excellent, includes optimum	Yes	Yes
		2	Good, pleasant to fly	Yes	Yes
		3	Satisfactory, but with some mildly unpleasant characteristics	Yes	Yes
Emergency operation	Unsatisfactory	4	Acceptable, but with unpleasant characteristics	Yes	Yes
		5	Unacceptable for normal operation	Doubtful	Yes
		6	Acceptable for emergency condition only*	Doubtful	Yes
No operation	Unacceptable	7	Unacceptable even for emergency condition*	No	Doubtful
		8	Unacceptable - dangerous	No	No
		9	Unacceptable - uncontrollable	No	No

*Failure of a stability augmenter.

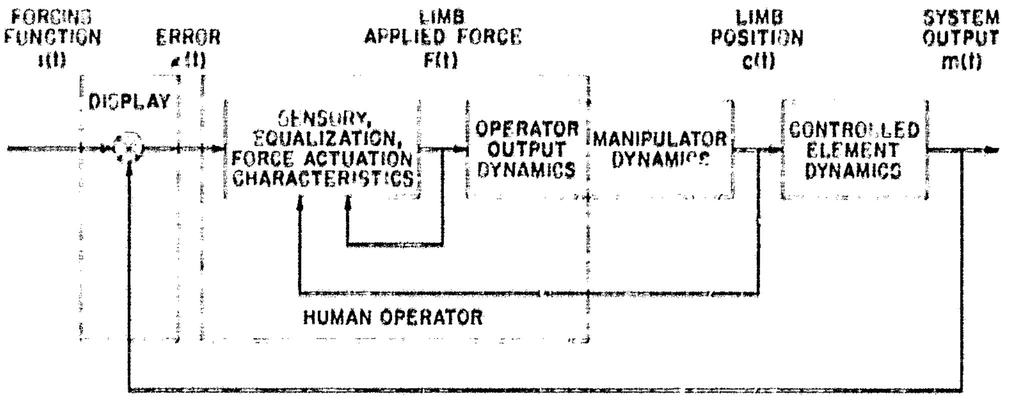
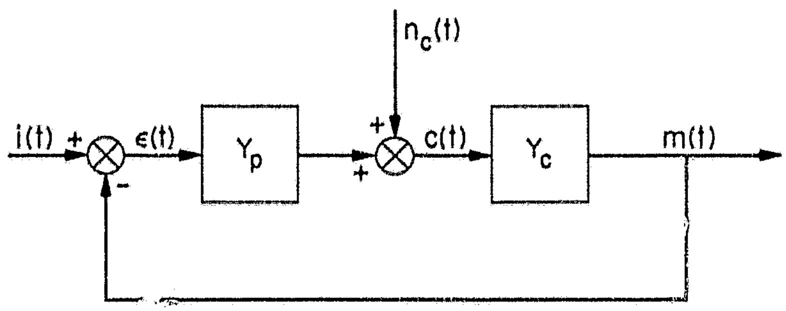


Fig. 1.- Single-loop manual control system.



$$Y_p = \frac{\phi_{ic}(\omega)}{\phi_{i\epsilon}(\omega)} \qquad \phi_{nn} = \left|\frac{1}{1 + Y_p Y_c}\right|^2 \phi_{nn_c}$$

$$Y_c = \frac{\phi_{im}(\omega)}{\phi_{ic}(\omega)} \qquad \rho^2 = 1 - \frac{\phi_{nn}}{\phi_{cc}}$$

Fig. 2.- Pertinent relationships in quasi-linear model identification by spectral analysis.

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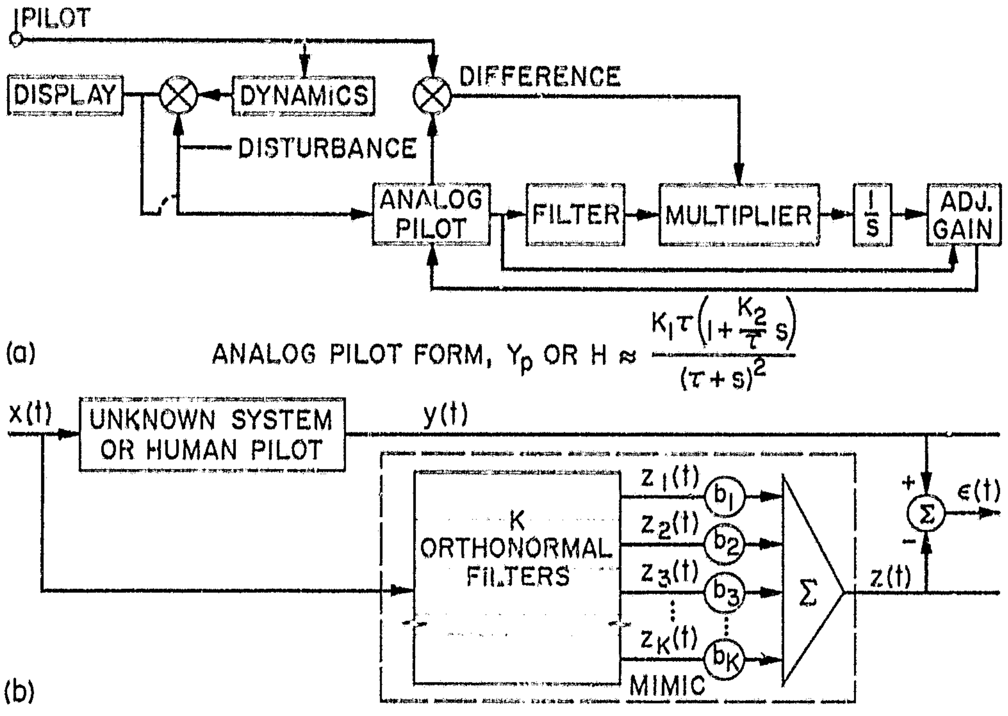
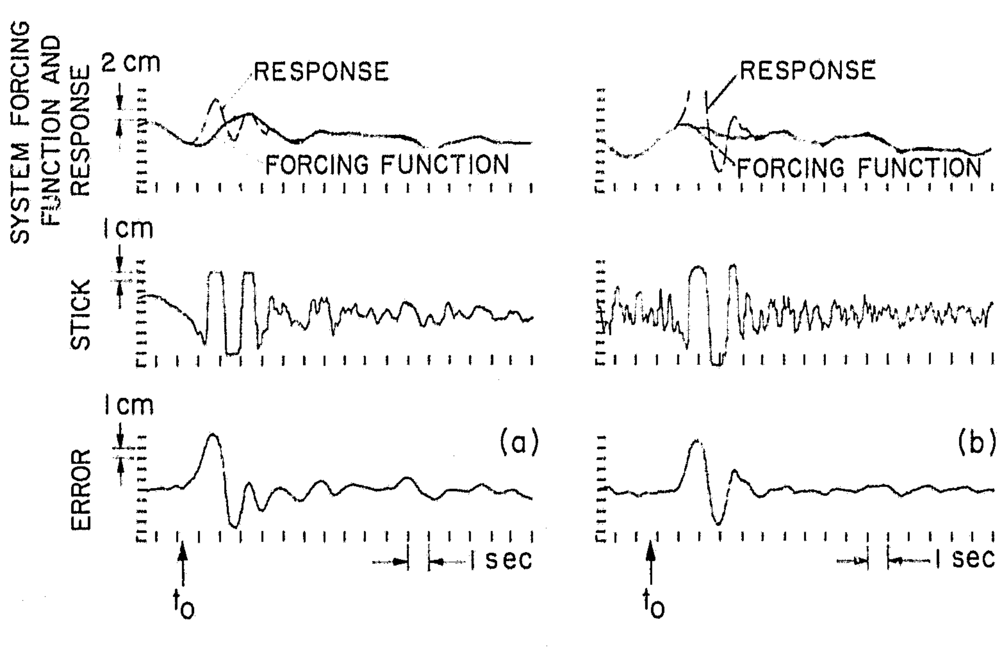


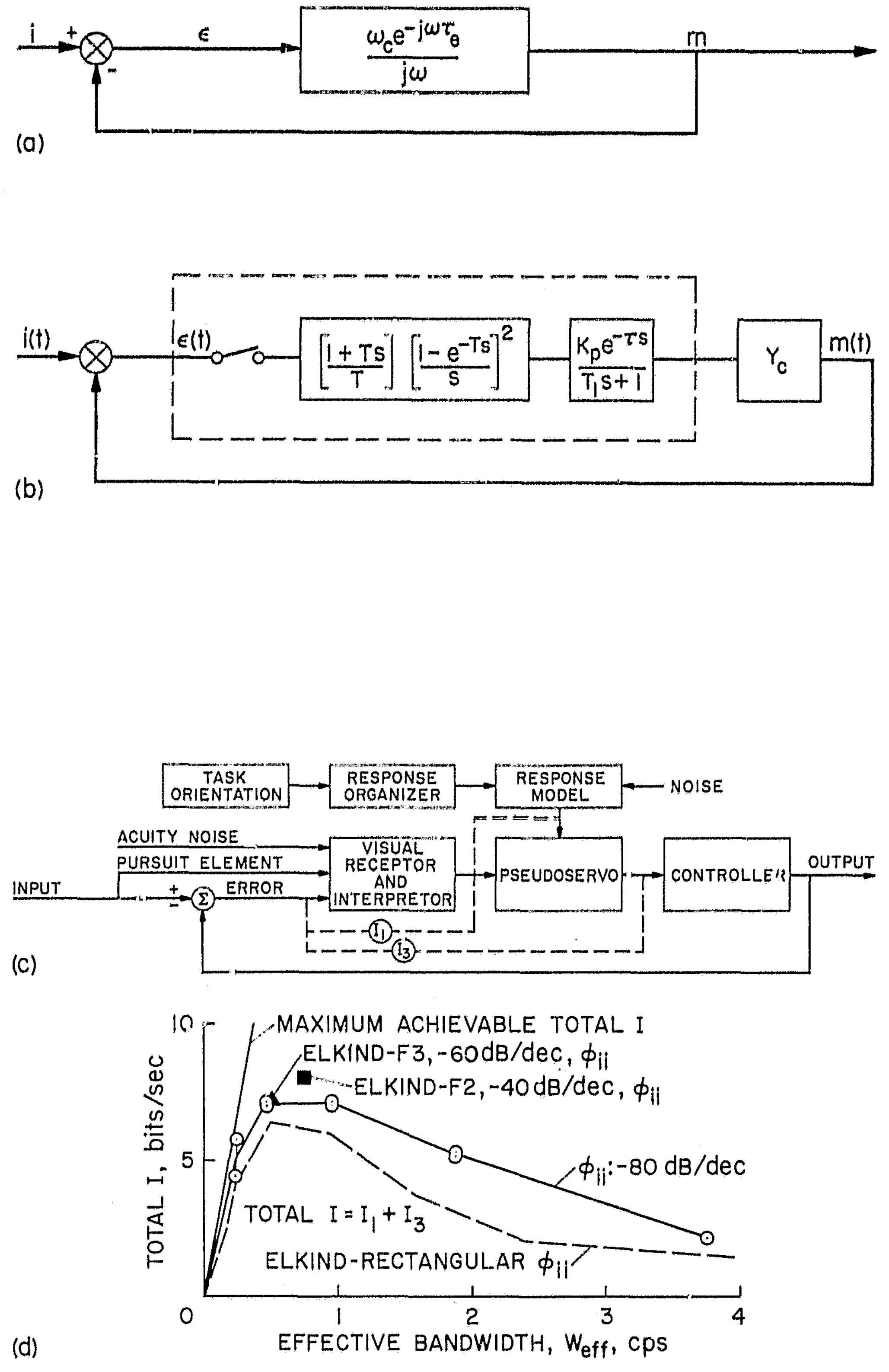
(a) Measurement by parameter tracking.
(b) Measurement by mimicking.

Fig. 3.- Model matching identification techniques.



(a) $Y_c(s)$ varied from 2 to $-8/s^2$ at time t_0.
(b) $Y_c(s)$ varied from $8/s^2$ to $-16/s^2$ at time t_0.

Fig. 4.- Typical control task transition time histories.



(a) Quasi-linear open-loop crossover model.
(b) Quasi-linear constant rate sampling model.
(c) Parallel channel information processing model.
(d) Information rate transmission properties.

Fig. 5.- Human operator models and properties.

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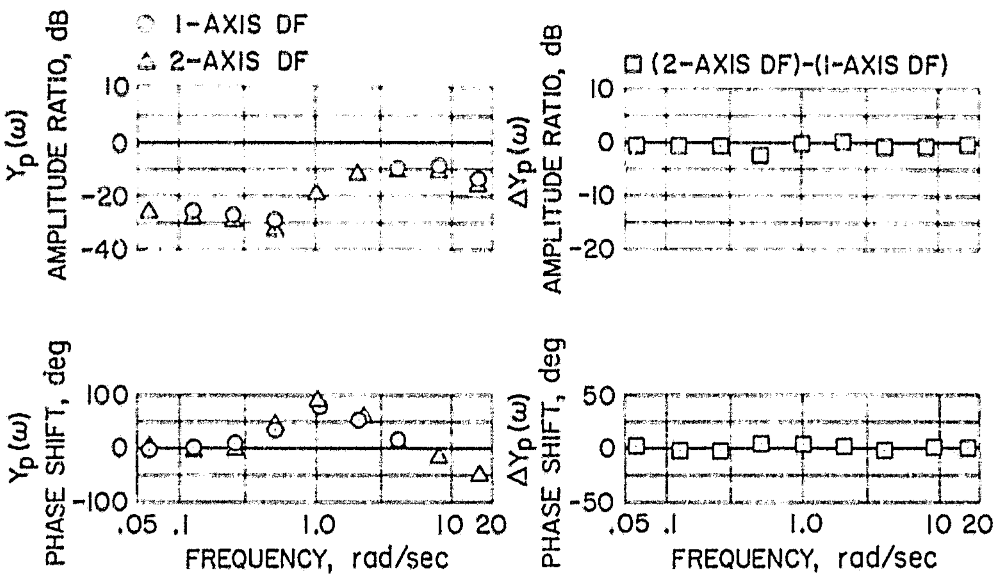


Fig. 6.- Human controller describing functions (homogeneous control).

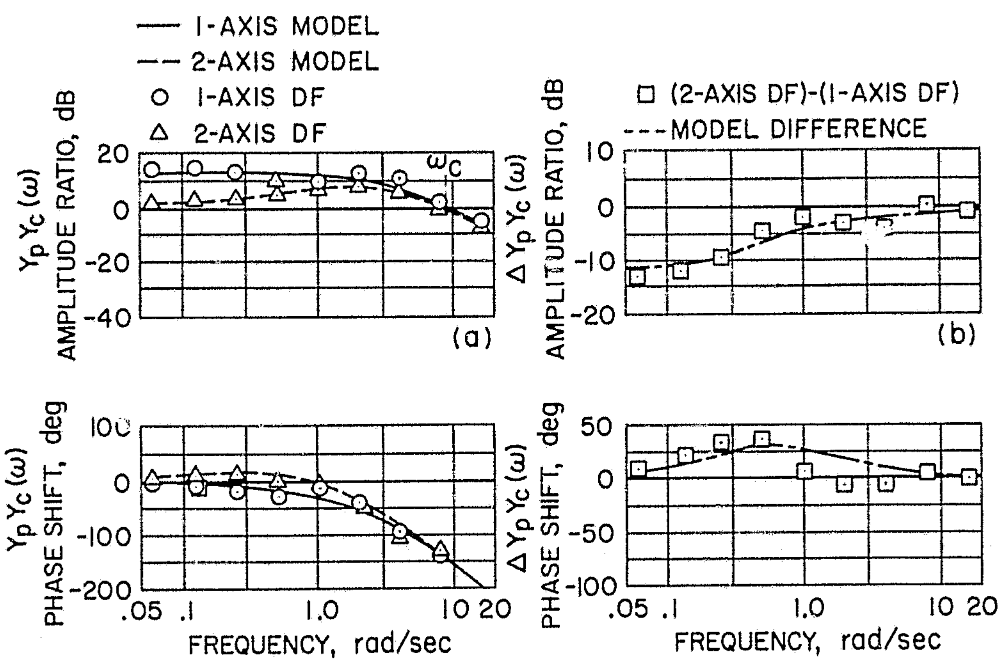
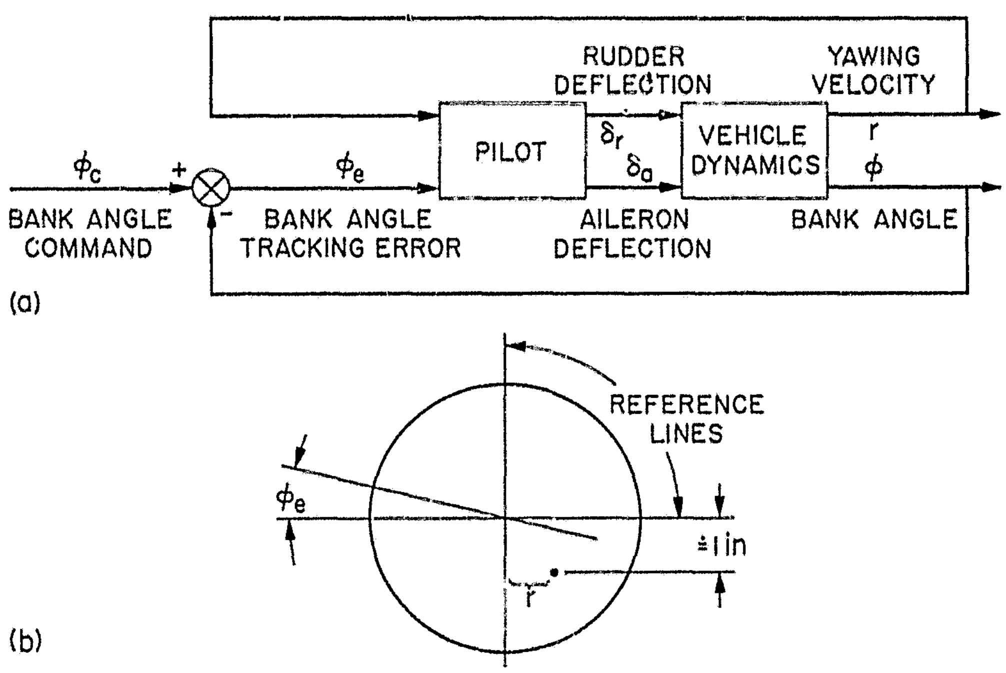


Fig. 7.- Open-loop describing functions (heterogeneous dynamics).



(a) Block diagram of bank angle multiloop control task.
(b) Pilot's display.

Fig. 8.- Multiloop control task.

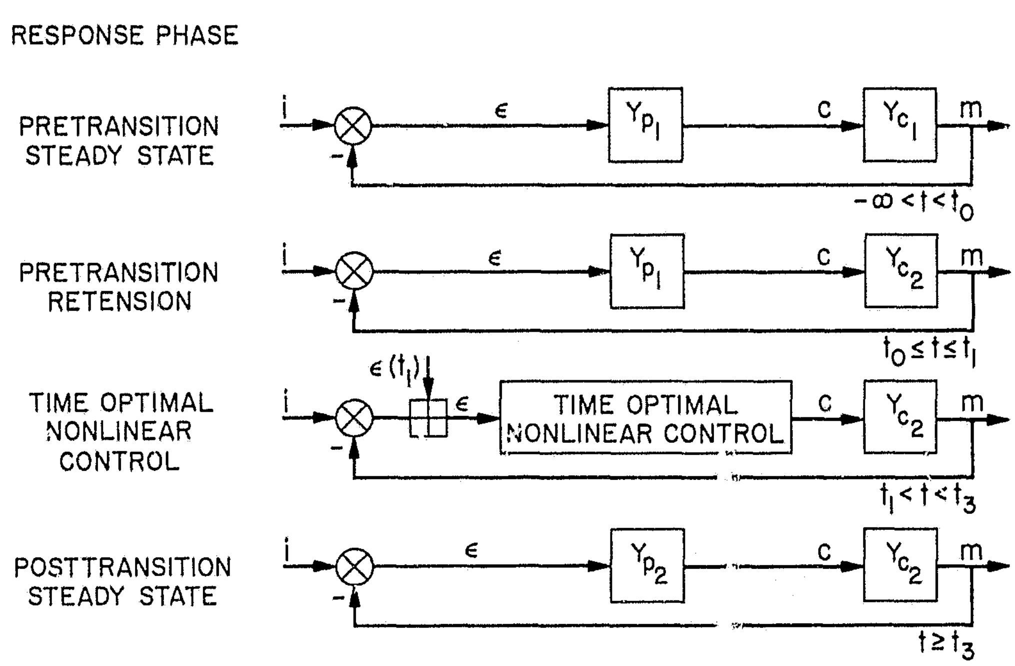


Fig. 9.- Mode-switching human-operator adaptive model.

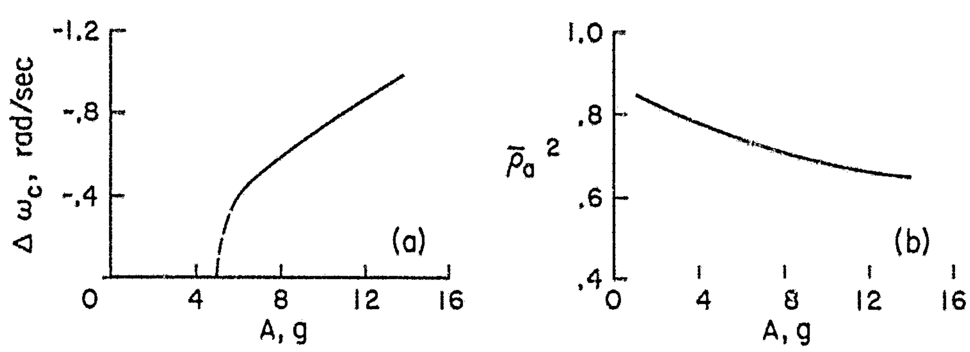


Fig. 10.- Effects of acceleration on quasi-linear model characteristics.

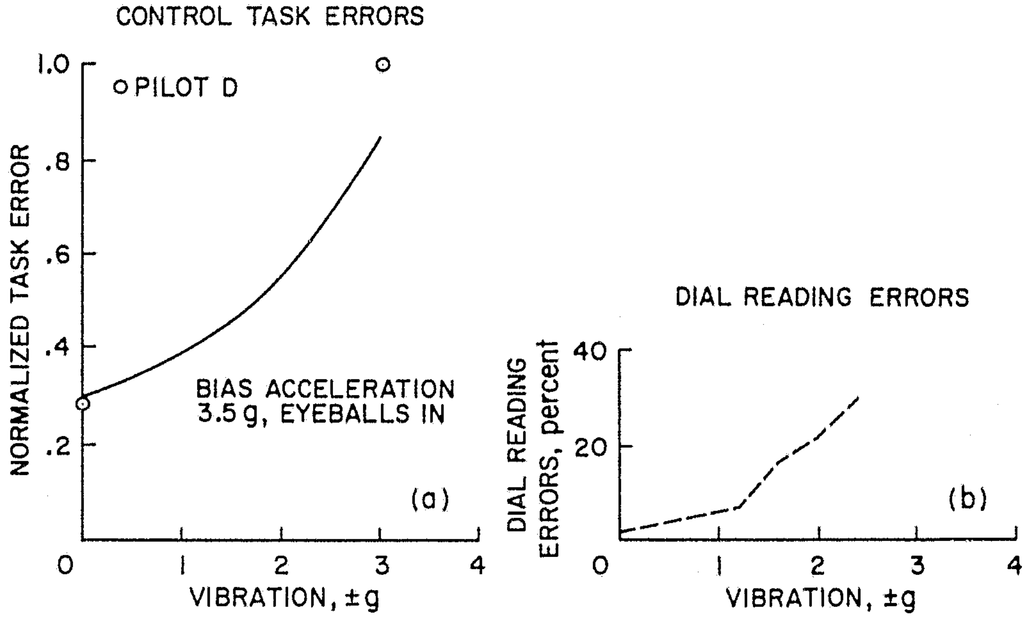


Fig. 11.- Effects of vibration on task performance.

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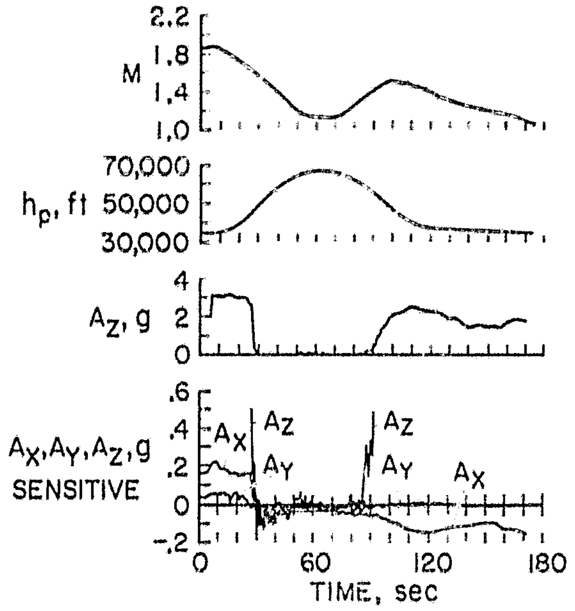

Fig. 12.- Typical time history of zero-gravity maneuver (F-104B).

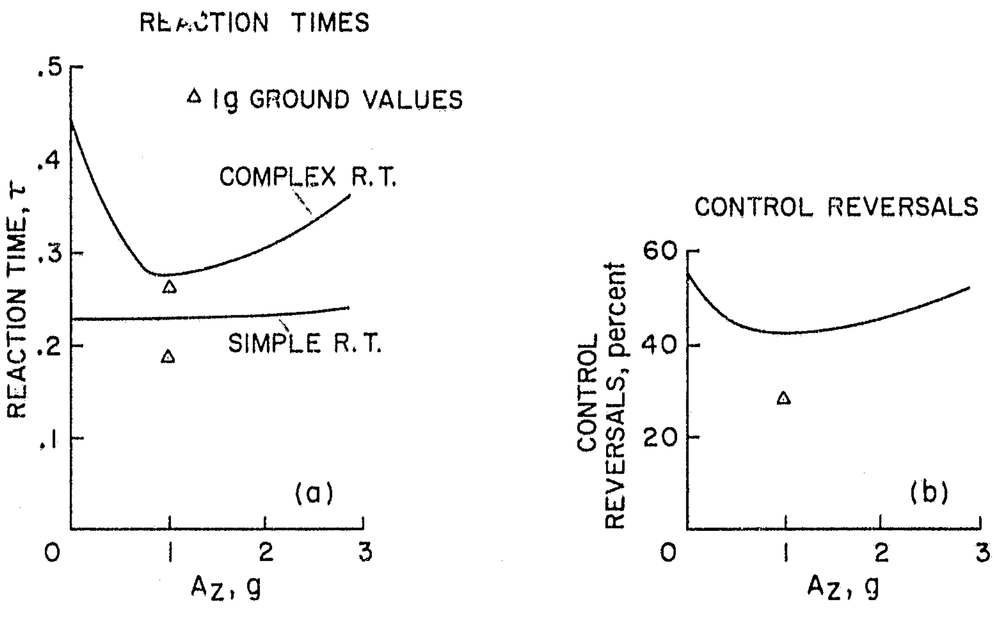

Fig. 13.- Reaction time and control reversal results.

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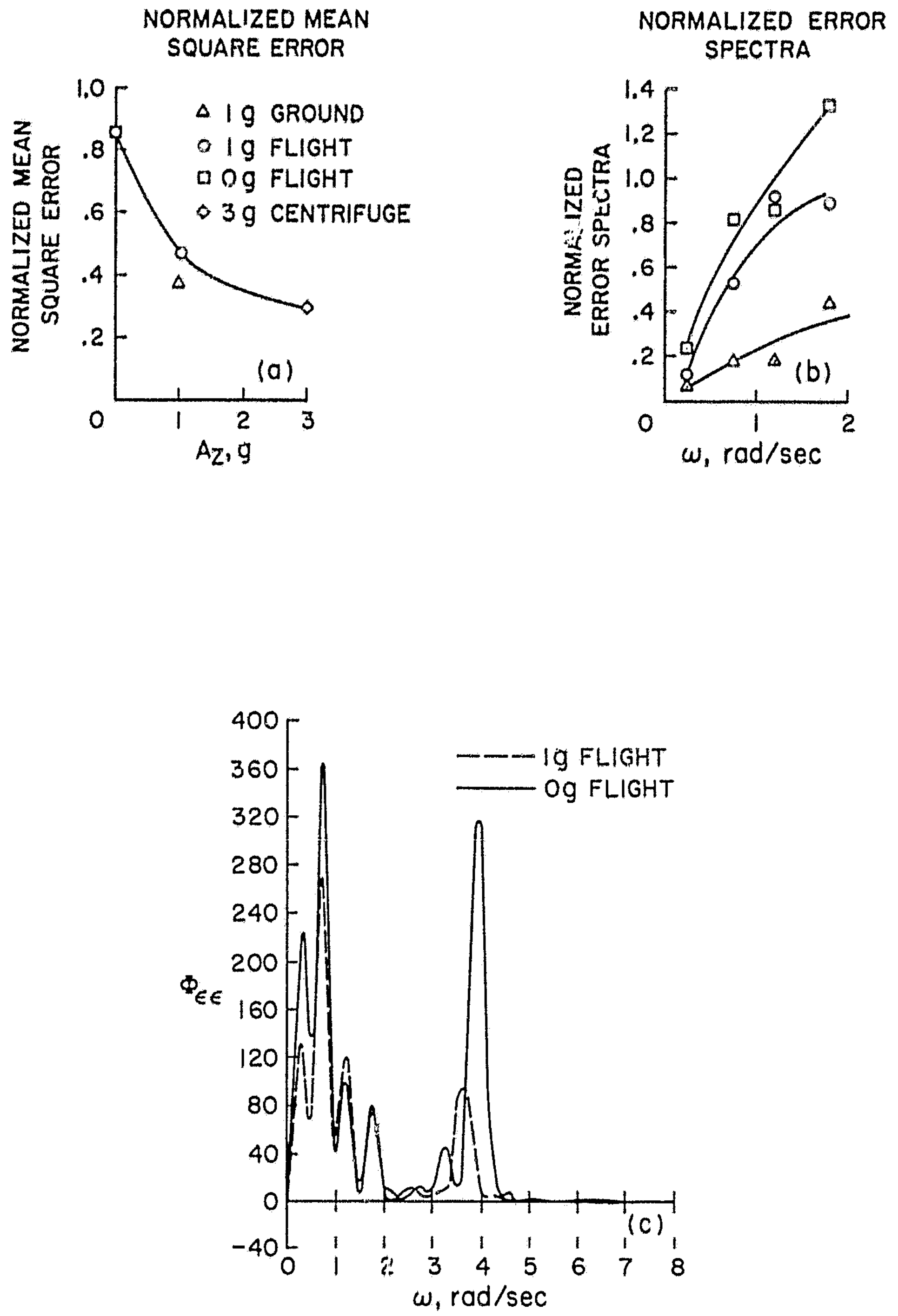


(a) Normalized mean square error.
(b) Normalized error spectra.
(c) Error spectra.

Fig. 14.- Effects of short-term weightlessness on task performance (dynamics "A").

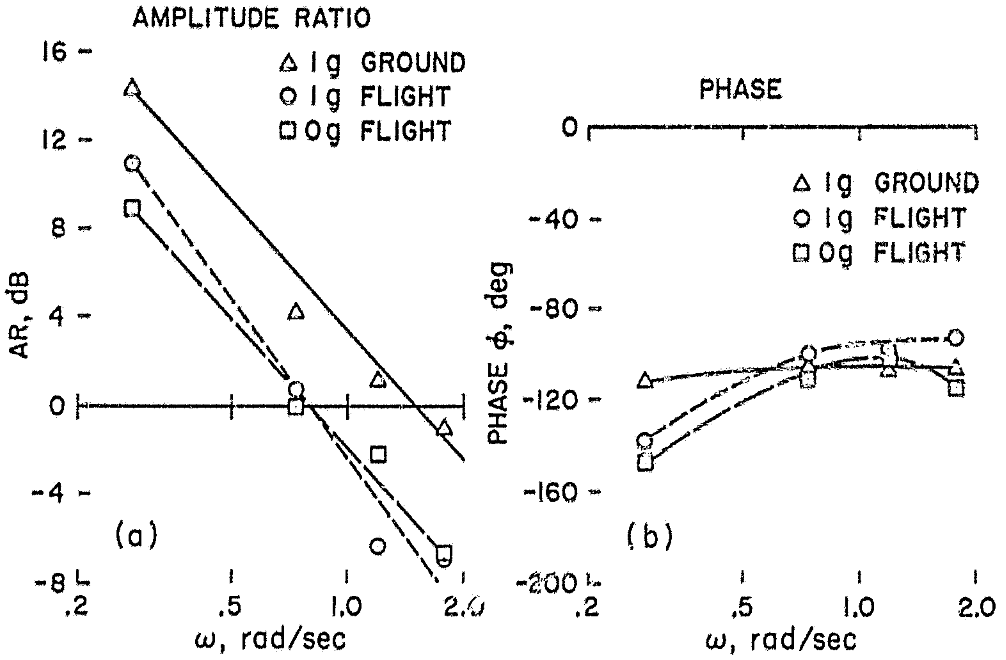


Fig. 15.- Effects of short-term zero gravity on open-loop describing functions.

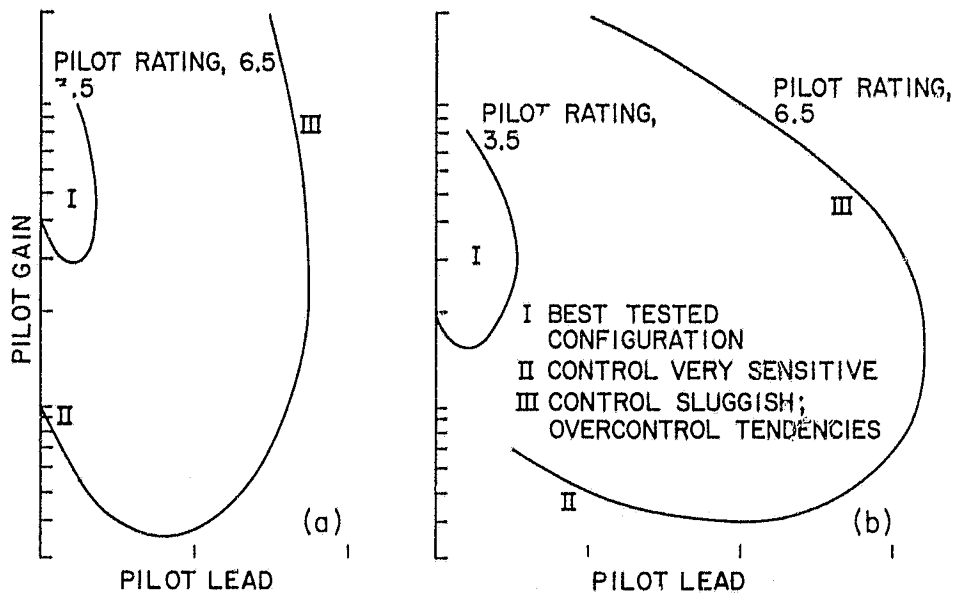


Fig. 16.- Correlation of pilot-opinion and pilot-response measures.

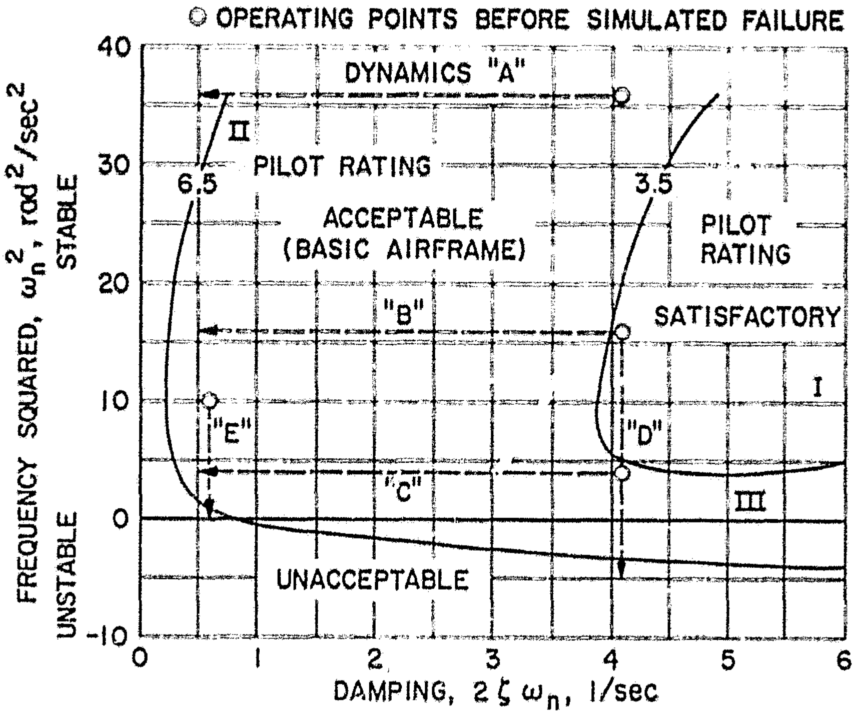
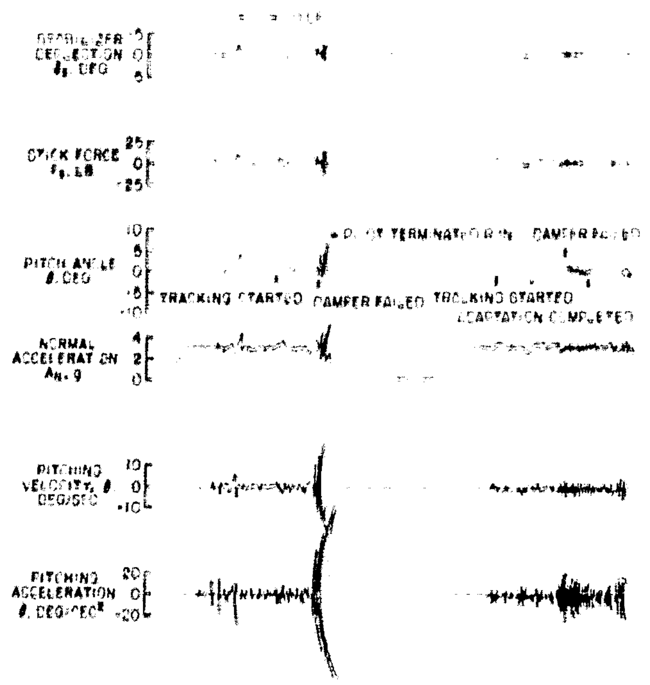
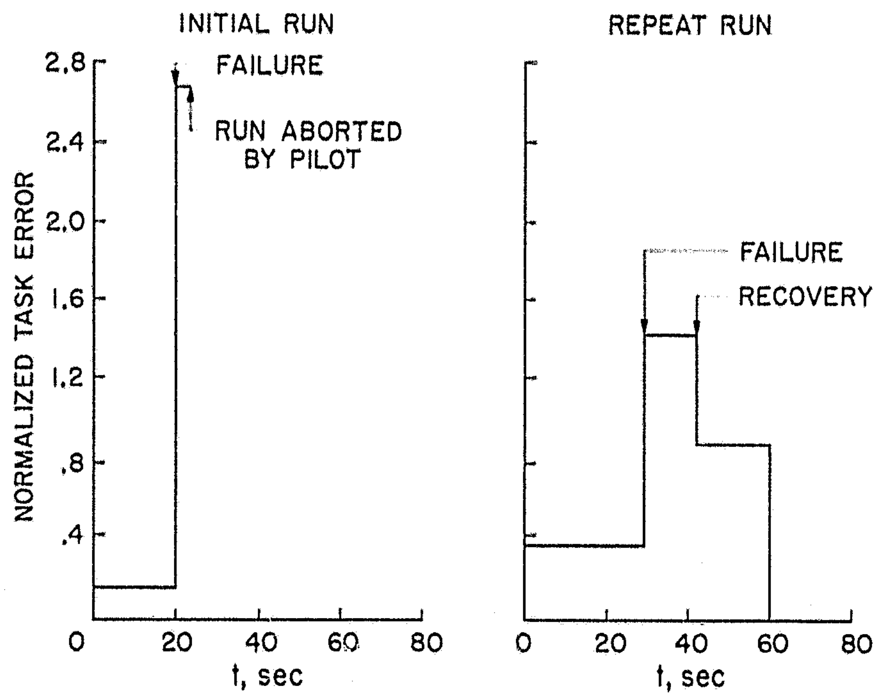


Fig. 17.- Stability augmentation system failures considered.





(a) Time history.
(b) Task performance.

Fig. 18.- Moving-simulator evaluations of pilots' ability to cope with sudden pitch-damper failure (case B, Fig. 17).

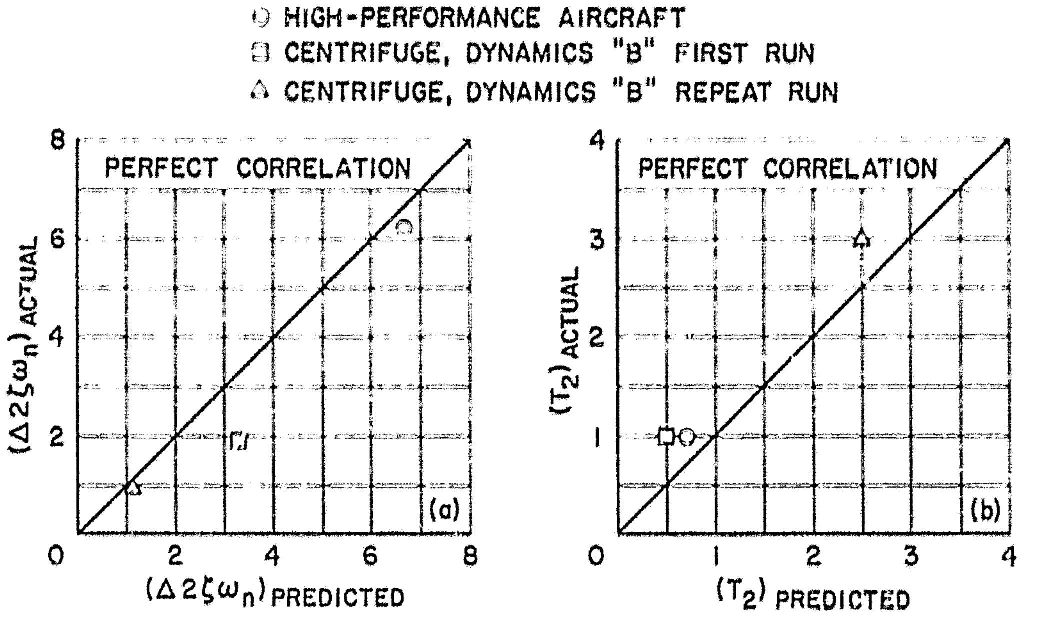


Fig. 19.- Correlation of predicted and actual results.

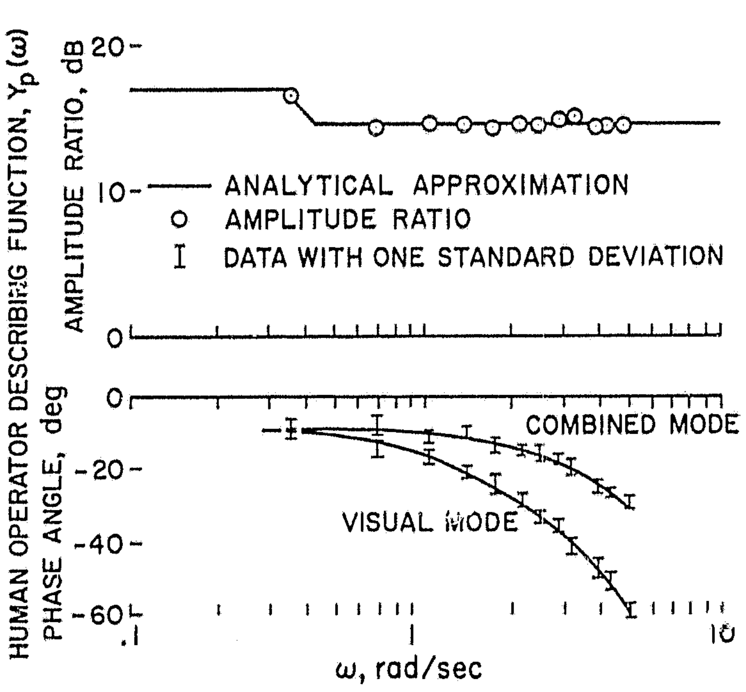


Fig. 20.- Describing functions of the human operator in visual and combined mode (horizontal rotation).

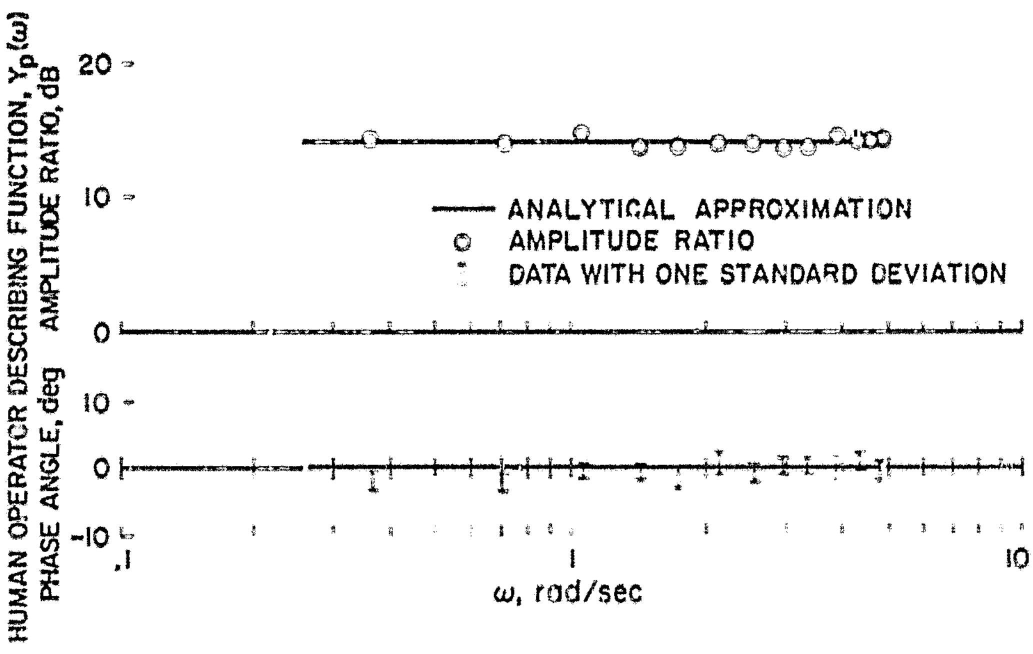


Fig. 21.- Describing function of the human operator in motion mode (rotation with respect to the gravity vector).

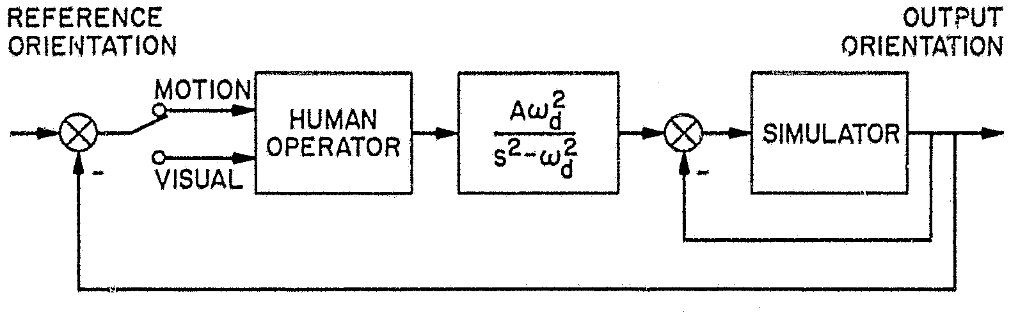


Fig. 22.- Control of inverted pendulum with visual or motion feedback.

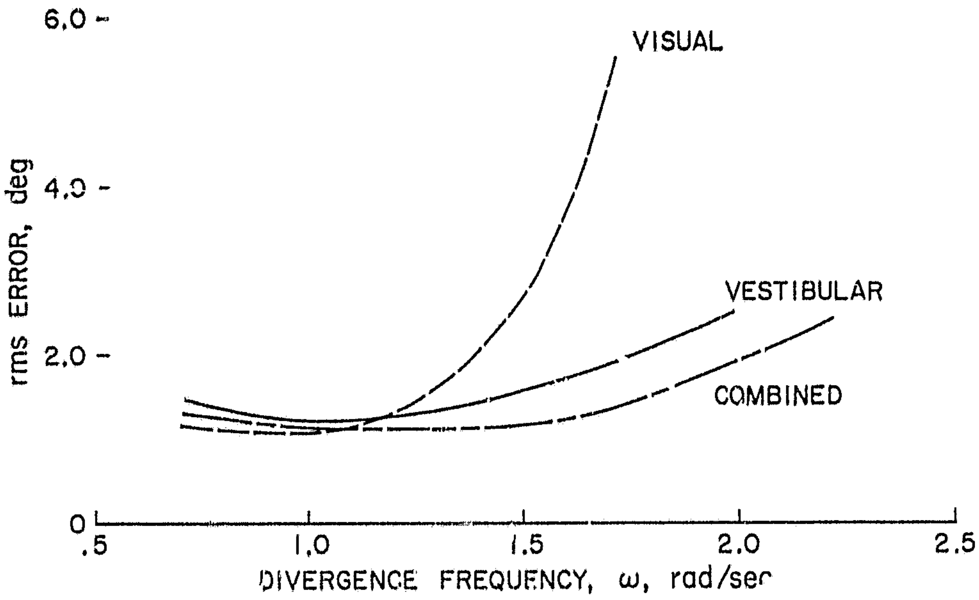


Fig. 23.- RMS errors for control of inverted pendulum.

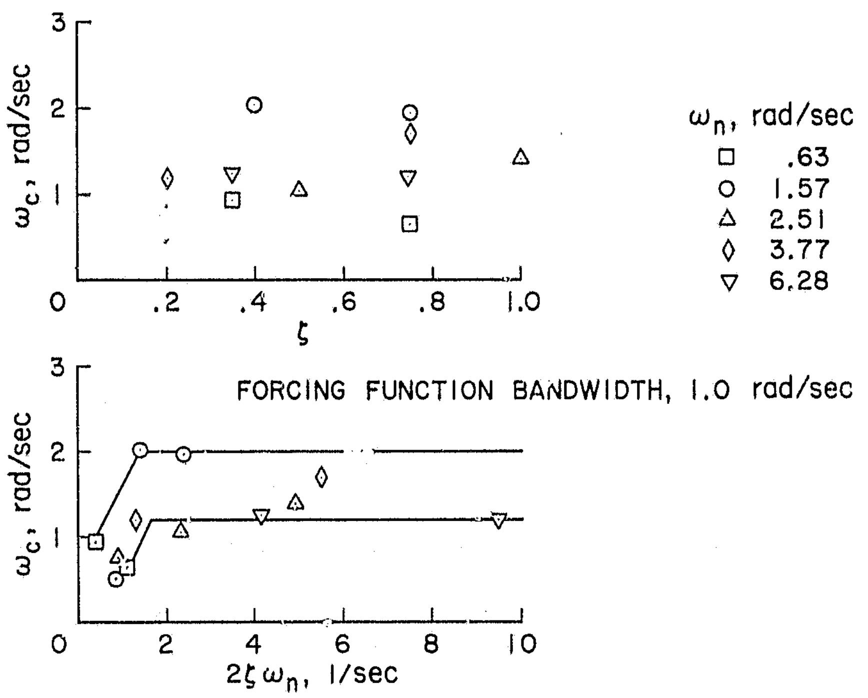


Fig. 24.- Effects of airplane short period frequency and damping on open-loop system crossover frequency.