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THE EFFECTS OF LONGITUDINAL CONTROL-SYSTEM DYNAMICS ON PILOT OPINION AND RESPONSE CHARACTERISTICS AS DETERMINED FROM FLIGHT TESTS AND FROM GROUND SIMULATOR STUDIES

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SUMMARY

The results of a fixed-base simulator study of the effects of variable longitudinal control-system dynamics on pilot opinion are presented and compared with flight-test data. The control-system variables considered in this investigation included stick force per g, time constant, and deadband, or stabilizer breakout force. In general, the fairly good correlation between flight and simulator results for two pilots demonstrates the validity of fixed-base simulator studies which are designed to complement and supplement flight studies and serve as a guide in control-system preliminary design. However, in the investigation of certain problem areas (e.g., sensitive control-system configurations associated with pilot-induced oscillations in flight), fixed-base simulator results did not predict the occurrence of an instability, although the pilots noted the system was extremely sensitive and unsatisfactory. If it is desired to predict pilot-induced-oscillation tendencies, tests in moving-base simulators may be required.

It was found possible to represent the human pilot by a linear pilot analog for the tracking task assumed in the present study. The criterion used to adjust the pilot analog was the root-mean-square tracking error of one of the human pilots on the fixed-base simulator. Matching the tracking error of the pilot analog to that of the human pilot gave an approximation to the variation of human-pilot behavior over a range of control-system dynamics.

Results of the pilot-analog study indicated that both for optimized control-system dynamics (for poor airplane dynamics) and for a region of good airplane dynamics, the pilot response characteristics are approximately the same.

*Title, Unclassified

For one problem area, where pilot-induced oscillations were experienced in flight, pilot-analog tracking-response characteristics indicated a very critical adjustment of gain (or force commanded per unit error) was required to avoid either poor response or instability. While this adjustment could be made by the human pilots on the fixed-base simulator, it could not be coped with in flight apparently because of adverse motion-feedback effects. These results suggest that pilot-analog tracking-response characteristics, which exhibit a critical dependence on variations in pilot-analog gain, may provide a useful criterion for predicting tendencies toward pilot-induced oscillations in flight.

INTRODUCTION

With the vast increase in complexity of manned-aircraft systems, variable stability and control airplanes and ground-based simulators have been utilized more intensively to study the basic problem areas of these systems. Generally, these studies have been directed toward providing information which can be used to integrate properly the major subsystems of the airplane, such as the pilot, controls, airframe and information display to the pilot. Flight investigations with variable stability and control airplanes, such as those reported in references 1 and 2, have provided useful design data in the field of longitudinal handling qualities. However, very little information exists upon which to base an evaluation of the general adequacy of ground-based simulators. Some information is provided in reference 3, where the carrier landing-approach problem was investigated both in flight and on a ground simulator, with the same pilots participating in both phases of the study.

The development at the Ames Aeronautical Laboratory of a variable longitudinal stability and control system airplane and of suitable ground-based simulators has provided an opportunity to conduct a general study of the adequacy of simulators over a wide range of longitudinal stability and control characteristics. As a part of this program, both flight tests and fixed-base simulator tests (i.e., no motion feedback to pilot) were performed over a range of control-system dynamics, and evaluations by two pilots were obtained. The airplane used is that described in reference 1, but for the present tests the stabilizer was mechanically disconnected from the stick to avoid the undesirable position-feedback characteristics of the earlier control system. The control-system parameters varied during these studies included stick force per g (i.e., control sensitivity), deadband (stabilizer breakout force), and system time constant.

In addition to the simulator tests with human pilots, tests were conducted with a simple analog representing the pilot in an attempt to obtain some information on how the pilot adapts to large variations in control-system dynamics.

Most of the simulator and flight tests were conducted for constant and relatively poor airframe dynamics corresponding to test conditions of 0.80 Mach number at 35,000 feet. However, a very brief study was also made on the simulator to assess the effects on pilot opinion and on the pilot analog of a change in airframe dynamics from the unacceptable region to the good region as defined in reference 2.

The present report describes the fixed-base simulator and the simple analog model of a human pilot. The results of the simulator studies with human-pilot control are presented and compared with the results of flight tests to determine the extent to which simulators, which do not duplicate the motion feedbacks to the pilot, can be used to supplement flight tests and serve as a guide in control-system design. Also, the tracking performance of the analog pilot is matched to that of one of the human pilots in the simulator in order to provide some information on (1) the preferred mode of pilot behavior for control response rated good or optimum by the human pilot and (2) problem-area modes of pilot behavior for control response rated unacceptable by the human pilot.

NOTATION

F_s	stick force, lb
g	acceleration of gravity, lg = 32.2 ft/sec^2
K_c	control system static gain, $\frac{\delta_s}{F_s}$, deg/lb
$K_{\dot{\theta}}$	aerodynamic transfer function gain coefficient, 1/sec
K_p	pilot-analog static gain, lb/deg
n	airplane normal acceleration, g
P.E.	pilot tracking efficiency $\frac{100\int(\theta_i^2-\epsilon^2)dt}{\int\theta_i^2 dt}$, percent
R	target range, ft
rms	root mean square, mils
s	Laplace operator
T	length of tracking run, sec
T_c	first-order control system time constant, sec

T_I	pilot-analog lag representing integration or smoothing of error, sec
T_L	pilot-analog lead representing utilization of error-rate information, sec
T_N	pilot-analog neuromuscular lag, sec
$T_{\dot{\theta}}$	aerodynamic transfer function first-order lead, sec
V	airplane velocity, ft/sec
δ_S	stabilizer deflection, deg
δ_{stick}	stick deflection, in.
ϵ	tracking error, deg
$\phi(\tau)$	autocorrelation function of target motion, cm^2
$\phi(\omega)$	power spectrum of target motion, cm^2
ω	angular frequency, radians/sec
ω_n	airframe short-period undamped frequency, radians/sec
τ	autocorrelation time variable, sec
τ_p	pilot-analog visual reaction time, sec
ζ	airframe short-period damping ratio
γ	airplane flight-path attitude, deg
θ	airplane pitch attitude, deg
θ_o	$K\theta + \frac{V}{R}\int \gamma \, dt$, deg
θ_i	target input, deg

Subscripts

min	minimum acceptable value
BA	best available value

max maximum acceptable value

D deadband

DESCRIPTION OF AIRPLANE AND FIXED-BASE SIMULATOR

Airplane

The airplane used in the flight investigation was a YF-86D equipped with a modified longitudinal control system wherein stabilizer position was commanded by stick force through a servo system. The modified system is essentially the same as that described in detail in reference 1 except that for the present study a mechanical disconnect system was provided to enable testing with the stabilizer disconnected from the stick. For take-off and landing, the normal control system is used. A mechanical schematic diagram of the original airplane control system and the system as modified for the present study is presented in figure 1. Figure 2 is an electrical schematic diagram of the modified control system. Figure 3 presents the stick force versus stick position relationship. The bungee and damper used to restrain the stick gave a natural undamped frequency of the control stick in the disconnected mode of about 20 radians per second, and a damping ratio of about 1.0. The effective stick length (center of grip to pivot) is about 21 inches.

Fixed-Base Simulator

The forward half of an F-86A airplane provided the cockpit environment for the simulator. A general view of the cockpit base and a detailed view of the interior of the cockpit are shown in figure 4. The bungee and damper used to restrain the stick were similar to those used in the flight-test airplane. Small differences in the effective lever arm of the bungee resulted in a difference in slope of the stick force versus stick position relationship as shown in figure 3, and in minor differences in the undamped natural frequency and damping ratio for the control stick used in the simulator. The effective length of the stick used in the simulator is about 22 inches. A block diagram of the variable control-feel simulator with pilot tie-in is presented in figure 5.

TASKS USED IN PILOT EVALUATIONS

Flight Test

Evaluation of general flying qualities, tracking of fixed distant objects, such as clouds, and formation flying were used as tasks by the

pilots in evaluating the various control-system configurations. No provision was made for measuring the pilots' efficiency in these various tasks. The experience and fixed-sight tracking performance for the two pilots "A" and "B" of the present study are presented in reference 4 where they are identified as pilots "C" and "B", respectively.

Fixed-Base Simulator

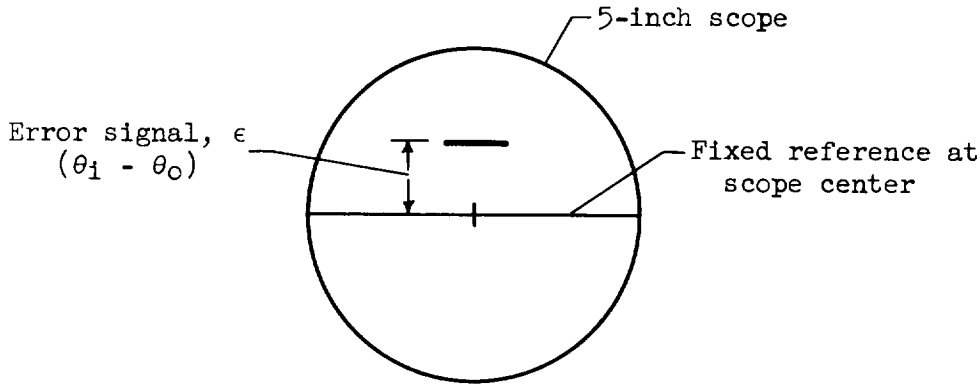
Description of task.- The choice of an appropriate task for the simulator study was considered fairly critical since it was felt that either too difficult or too simple a task would mask the effect on pilot opinion of the control-system variables under consideration. A long-range tracking task was finally selected in which the target input motions comprised the sum of four sine waves to provide a random-appearing task to the pilots. The frequency and amplitude components of the target motion are shown in the table below.

	Sine-wave component			
	1	2	3	4
Amplitude, rms, cm	1.17	0.835	0.45	0.316
Task 1 frequency, radians/sec	.277	.741	1.21	1.80
Task 2 frequency, radians/sec	.66	1.68	2.87	4.27
Task 3 frequency, radians/sec	1.38	3.54	6.03	8.98

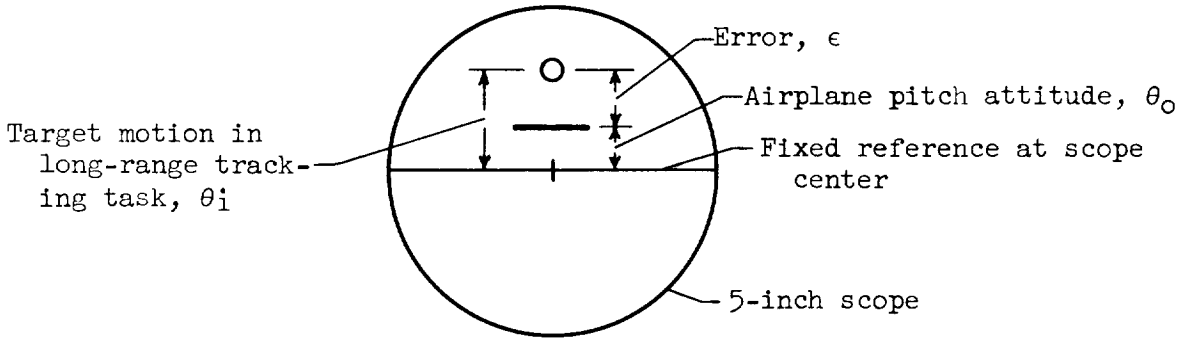
(These tasks are essentially the same as those used in the study of reference 5 where the effects of three input band widths on human operator characteristics were assessed.)

During preliminary tests, tasks 2 and 3 were presented to the pilots, but they indicated that the resulting tracking situation was unrealistic. Presenting the pilots with the low-frequency target inputs (task 1) proved satisfactory, however, and has been used as the primary task on the ground simulator. The pertinent features of task 1 are shown in figure 6. Figure 6(a) presents a portion of the time history of the target motion. In figures 6(b) and 6(c), the autocorrelation function and the power spectrum of the target motion at the four selected frequencies are shown and compared with equivalent-noise values to indicate the degree of correspondence of the target motion to a purely random function.

Scope presentation.- Two types of scope presentation were investigated. Initially, the so-called Compensatory Display, wherein only the error signal was presented to the pilots, was used. This display is shown in the following sketch:



The pilots objected to this type of display because they found it difficult to monitor the effects of their control motions on the error signal. This was remedied by providing the pilot with an indication of pitch attitude as well as the target input motion. This display, commonly referred to as a Pure Pursuit Display, is shown in the sketch below:



The problem was scaled on the analog computer so that 1 cm on the scope represented $1/2^{\circ}$ (8.75 mils) of either target motion or airplane pitch attitude.

Measurement of pilot tracking efficiency.- The measurement of pilot tracking efficiency on the simulator was considered desirable in order to determine (1) whether a correlation exists between pilot opinion of a particular control-system configuration and pilot tracking efficiency, and (2) to provide a reference for adjusting the pilot-analog model.

The pilot efficiency, P.E., during a tracking run is given in percent as

$$\frac{100 \int (\theta_i^2 - \epsilon^2) dt}{\int \theta_i^2 dt}$$

The rms target input is

$$\sqrt{\frac{1}{T}\int \theta_i{}^2 dt}$$

and is equal to 13.4 mils for a tracking run of 90 seconds. The rms error in mils is related to P.E. by the expression

$$\sqrt{\frac{1}{T}\int \epsilon^2 dt} = 13.4\sqrt{\frac{100\text{-P.E.}}{100}}$$

A plot of rms error in mils as a function of pilot efficiency is given in figure 7.

TESTS AND PROCEDURE

Flight Tests

For the flight tests, the pilots were instructed to determine the best available, the maximum acceptable, and the minimum acceptable values of control-system time constant T_c for several constant values of control-system gain K_c, corresponding to values of F_s/g of 2, 5, and 10 pounds per g. The system T_c was adjustable over a range of 0.15 to about 3.4 seconds. In addition to the basic tests with zero deadband F_{s_D}, a value of ±1 pound was also investigated. All the flight tests were conducted at 0.80 Mach number at 35,000 feet. For these flight conditions, the pertinent parameters defining the longitudinal short-period dynamics were determined, from an analysis of pulse-response data, to be:

$$K_{\dot{\theta}} = 2.36/\text{sec}$$
$$T_{\dot{\theta}} = 0.56 \text{ sec}$$
$$\omega_n = 3.63 \text{ radians/sec}$$
$$\zeta = 0.20$$

The values of ω_n and ζ listed above were rated unacceptable by the pilot in the flight study summarized in reference 2.

Simulator Tests

For the fixed-base simulator tests, the computer was adjusted to provide a specified value of F_s/g and F_{s_D}. The control-system T_c was then varied by the computer operator in discrete steps of about 0.2 second, and values of $T_{c_{min}}$, $T_{c_{BA}}$, and $T_{c_{max}}$ were determined from the pilot's

observations during the tests. For each control-system configuration, the pilot was allowed to "feel out" the simulator by noting on the display the airplane pitch response to control-force inputs. Tracking runs of about 60- to 90-seconds duration were then obtained, and the pilot's performance was recorded. For these tests, values of F_s/g of 2, 5, and 10 pounds per g, and values of system deadband of 0, ±1, ±2, ±3.5, and ±5 pounds were investigated; T_c was variable over a range of about 0.01 to 10 seconds.

Most of the simulator tests were conducted for the unacceptable airframe dynamics characteristic of the test airplane at 0.80 Mach number and 35,000 feet altitude listed in the preceding section. However, for one tracking run, the F-94A airplane of reference 2 was simulated in a region of good airframe dynamics (ω_n = 3.26 radians/sec; ζ = 0.70). For this case, the control-system gain was adjusted to provide, a stick force per g of 8.6 and a time constant of 0.05 second to correspond closely to values used for the major portion of the reference 2 study.

RESULTS

Although both the variable control-feel airplane and fixed-base simulator were provided with means for commanding stabilizer position by stick position as well as by stick force, this report presents the results obtained only with the force-command system. It should be noted that for the force-command system, stick position per g varied directly with stick force per g, since the additional complication of a stick servo was not considered desirable during these initial tests.

Effects of Control-System Dynamics on Pilot Opinion

Effects of time constant.- The first-order control-system lag between application of stick force and stabilizer motion was utilized by the pilots, both in flight tests and on the ground simulator, to compensate for the poor airframe dynamics (ω_n = 3.63 radians/sec; ζ = 0.20) investigated in the present study. At low values of time constant, the pilots noted that the control system was too sensitive, and they had a tendency to overcontrol and induce oscillations. As the time constant was increased above certain values, the pilots observed that the aircraft response became too sluggish and the amount of "apparent damping" in the control system became excessive. The best available constants for the poor airplane dynamics considered were a compromise between these two limiting conditions.

In figure 8 the time constants selected by the pilots in flight and on the simulator are presented as a function of stick force per g. These results are given for zero deadband. Points identified as A, B, and C in

figure 8(a) are several problem areas discussed in a later section of this report. Pilot-opinion ratings, based on the rating schedule of table I, are presented in table II for the pilot-opinion boundaries established in figure 8. Flight ratings were provided by the pilots for only the best available boundary, while the simulator ratings were obtained for all three boundaries. It is interesting to note that the pilot was able to adjust the control-system dynamics to provide a satisfactory rating, that is, 2.5 to 3.5 for the best available T_c at a stick force per g of 10, even though the airframe dynamics correspond to the unacceptable pilot-opinion region established in reference 2. The results in table II also indicate that the pilots generally consider the minimum and maximum T_c boundaries on the simulator unsatisfactory and unacceptable for normal operation (i.e., a pilot rating of 5).

In connection with the results presented in figure 8, pilots' comments and duplicate runs on the ground simulator indicated that the boundaries shown should be more properly defined as bands rather than lines. This is attributable both to the pilots' difficulty in precisely selecting these time constants and to the pilots finding it difficult to repeat, precisely, an evaluation of the same control system after a lapse of several days. The simulator results shown in figure 8 were obtained from runs in which the entire stick force per g range was covered either in a single "flight" or in several consecutive flights the same day.

Effects of deadband.- Control-system deadband, or stabilizer breakout force is utilized by the pilots in a manner somewhat similar to system time constant. As the deadband is increased from zero pounds, lower values of time constant are generally selected by the pilots to obtain satisfactory airplane response. This is illustrated in figure 9 where the flight and simulator values of time constant selected by the pilots are presented as a function of deadband at several constant values of stick force per g.

An interesting observation in figure 9 for pilot A on the simulator for $F_s/g = 2$ is that decreasing values of time constant were selected as the deadband was increased from 0 to ±1 or ±2 pounds, while increasing values of time constant were selected with a further increase in deadband. This latter trend may be due to pilot A's requiring additional apparent damping to reduce the tendency toward overcontrolling at the higher values of deadband. The same trend was not noted for pilot B as the deadband was increased from ±2 to ±5 pounds.

The numerical pilot-opinion ratings the pilots assigned to the control system, including the effects of deadband, are presented in table III. These results show that the flight rating for pilot A was relatively insensitive to an increase in deadband from 0 to ±1 pound. On the simulator, both pilots A and B indicated a preference for small values of deadband of the order of ±1 or ±2 pounds; at higher values of deadband, the pilots' ratings tended toward unacceptable values due, primarily, to a tendency to overcontrol particularly at the lowest stick force per g.

Effects of Control-System Dynamics on Pilot Tracking Performance in Simulator

The effects of control-system dynamics on pilot tracking performance on the ground simulator are presented in figure 10. Correlation of pilot tracking efficiency with numerical pilot-opinion ratings is shown in figure 11. Although there is considerable scatter in the results shown in figure 10(a), it appears that the tracking performance decreases roughly 10 to 20 percent as the time constants are increased from best available values to the maximum values investigated. It may also be noted in figure 10(a), particularly for pilot A, that the tracking performance improves as the time constants are decreased from best available values. This trend may not be realized in flight, however. Flight results of the present study and in reference 1 indicate that in tracking runs of distant objects such as clouds, the airplane response became more oscillatory as T_c was reduced below best available values, particularly at the lower values of F_s/g. This tendency toward pilot-induced oscillations for these sensitive control systems would be expected to result in an increase in tracking errors in flight relative to those observed on the fixed-base ground simulator.

Figures 10(b) and 10(c) illustrate the effect of system deadband on pilot tracking performance. The control-system time constant was fixed at 0.2 second for the results in figure 10(b) and the best available values (fig. 9) were used for the results shown in figure 10(c). The results, though limited, indicate a deterioration in tracking performance results when the deadband is increased above about ±2 pounds.

The relationship of pilot tracking efficiency to numerical pilot-opinion ratings for a wide range of control-system configurations is presented in figure 11. In figure 11(a) the effects of T_c and F_s/g are shown, and in figure 11(b) the effects of variation in deadband and F_s/g are illustrated. It should be noted that the points shown in figure 11 are actually faired averages of the results presented in figure 10, where an average scatter in tracking performance of about ±5 and ±10 percent was observed for pilot A and pilot B, respectively. Where necessary, these average points were offset slightly from the ratings provided by the pilots to avoid merging and loss of identification of the symbols. Also shown in figure 11(a) is the tracking performance and pilot opinion associated with the simulated F-94A airplane in the "good" airframe dynamic region established in reference 2.

In general, the results in figure 11 indicate the tracking performance tends to decrease as pilot opinion becomes more unfavorable, due either to excessive T_c or F_{s_D}. It was observed previously that the relatively high levels of tracking performance in the fixed-base simulator tests for control systems rated too sensitive by the pilots (i.e., $T_{c_{min}}$ points in fig. 11(a)) would not generally be realized in flight tests.

DISCUSSION

Comparison of Flight- and Fixed-Base Simulator Results

Time constant and deadband.- The agreement between flight and simulator results in figure 8 and in table II showing the effects of time constant on pilot-opinion boundaries and numerical ratings is considered fairly good. The time constants selected by the pilots on the simulator compare favorably with the flight values and show substantially similar trends as stick force per g is varied. Certain discrepancies exist, however, which may be attributable to the lack of cockpit-motion feedback on the fixed-base ground simulator. It is planned in subsequent tests to examine this possibility on a pitch-roll chair which will duplicate the pitching motions imposed on the pilot. The large difference in the maximum time constants selected by pilot B at the lowest F_S/g is believed due to the limit of about 3.4 seconds imposed on the flight values of time constant by the control circuitry. The maximum T_c available on the simulator is 10 seconds.

The agreement shown between flight and simulator deadband results (fig. 9) is fair. Both show roughly the same order of decrease of time constant as the deadband was increased from 0 to ±1 pound. Unfortunately, the flight results were only obtained over this limited range of deadband.

Dynamic response.- The extent of the agreement between flight and simulator results can also be shown in terms of the over-all response characteristics of the best available control-system and airframe combination tested. Figure 12 presents amplitude-ratio plots of θ/F_S and n/F_S as a function of dimensionless frequency ω/ω_{n_1} for the best available time-constant boundaries selected by pilots A and B in flight and on the simulator. The assumed transfer functions for these plots are

$$\frac{\theta}{F_S} = \frac{K_{\dot{\theta}}K_c(1+T_{\dot{\theta}}s)}{s(1+T_cs)\left(\frac{s^2}{\omega_n^2} + \frac{2\zeta s}{\omega_n} + 1\right)}$$

and

$$\frac{n}{F_S} = \frac{(V/57.3g)K_{\dot{\theta}}K_c}{(1+T_cs)\left(\frac{s^2}{\omega_n^2} + \frac{2\zeta s}{\omega_n} + 1\right)}$$

Comparison of the flight and simulator results in figure 12 shows the pilots attenuate the short-period response peaks (by increasing system time constant) roughly the same amount, whether they are flying the

simulator or the airplane. This is perhaps illustrated more clearly in figure 13 where the n/F_S results from figure 12 and from other data not shown are plotted in the form

$$100\ \frac{\left[(n/F_S)_{\omega_n} - (n/F_S)_{\omega=0}\right]}{(n/F_S)_{\omega=0}}$$

which is the percent attenuation or amplification of $(n/F_S)_{\omega=0}$ at the short-period peak. These results, which are essentially the basic results in figure 8 considered in a slightly different form, show that the pilots will accept less apparent damping (i.e., attenuation of the short-period response peak) or a greater percent overshoot as the stick force per g is increased. A comparison in figure 13 between the results for pilots A and B, both in flight and on the simulator, shows that pilot B requires more apparent damping for satisfactory response than does pilot A. (If these results are compared with those for a second-order system, it can be shown for the best available T_c that pilot A requires an equivalent damping ratio ζ of about 1.5 at $F_S/g = 2$ and about 0.45 at $F_S/g = 10$.) The comparison in figure 13 also indicates, perhaps more clearly than does that shown in figure 8, that the simulator tests predict not only the trends with F_S/g for the individual pilots, but also the differences between pilots.

Step response.- In an earlier flight study on the YF-86D airplane (ref. 1), it was found that the pilot selected values of control-system time constant such that the n response in one second to a step F_S was essentially independent of F_S/g. For the best available control systems studied in reference 1, a value of n response in one second of about 0.09 g per pound was noted.

In this section, some of the results obtained in the present study are presented to provide a measure of the correlation between flight and simulator results and to show the correspondence with the results of the earlier tests.

Figure 14 presents the step-response characteristics for the best available time constants selected by pilots A and B in flight and on the simulator. From these results and from others not shown, the variation with F_S/g of the n response at one second for a 1-pound step in stick force are plotted in figure 15 for the minimum, best available, and maximum time-constant boundaries (fig. 8) selected by pilots A and B. The comparison shown in figure 15(a) for pilot A indicates the flight results of reference 1 fall generally below the flight results for the present study. The lower rates of response from the earlier flight tests may be due to an undesirable stabilizer feedback to the stick, characteristic of the system operation for rapid stick motions. (See ref. 1.) The

simulator results for pilot A compare favorably with the flight results with the possible exception of those for the minimum T_c boundary where a considerably higher rate of response is shown for the simulator results. An interesting observation in figure 15 for the results of the present study is that, over the range of F_s/g considered, the pilots will accept a more rapid response if it is accompanied by an increase in apparent damping (fig. 13).

Pilot-Analog Studies

Previous sections of this report were concerned with documenting and correlating the results of flight and simulator studies of the effects of variations in control-system dynamics on pilot opinion. Specifically, pilot-opinion boundaries were established which defined not only the best available control system (for the poor airframe dynamics considered), but also acceptable limits based on over-all response characteristics which were considered either too sensitive or too sluggish.

In this section, results of studies made with a linear analog model of the human pilot are presented in order to define the probable modes of pilot behavior, or pilot response characteristics, associated with the established pilot-opinion boundaries. The procedure used to define these modes of pilot behavior was to adjust the pilot-analog model to tracking performance levels comparable to those of one of the human pilots in the fixed-base simulator. The resulting pilot-analog characteristics were assumed to be those the human pilot generates for the particular system under consideration. Specific objectives of this study are to provide some information on (1) the preferred mode of pilot behavior, corresponding to systems rated good or optimum by the human pilot and (2) problem-area modes of pilot behavior, corresponding to systems rated unacceptable by the human pilots. The linear pilot analog is felt justified since, for the case of zero deadband, the control system was free of appreciable nonlinearities and, for the long-range tracking task used in the simulator studies, it was expected that most of the pilot's force-command signals were linearly related to his input signals.

The pilot-analog model.- Previous studies by Russell (ref. 5), McRuer and Krendel (ref. 6), and others have indicated that a linear analog model of the human pilot may be represented by the transfer function

$$\frac{F_s}{\epsilon} = \frac{K_p e^{-\tau_p s}(1+T_L s)}{(1+T_N s)(1+T_I s)}$$

where

K_p pilot-analog static gain, lb/deg

τ_p pilot-analog visual reaction time, sec

T_L pilot-analog lead representing utilization of error-rate information, sec

T_N pilot-analog neuromuscular lag, sec

T_I pilot-analog lag representing integration or smoothing of error, sec

s Laplace operator

For the present study, τ_p was assumed invariant at 0.2 second, and T_I and T_N were assumed invariant at 0.1 second.

A block diagram of the closed-loop system including the pilot-analog model is shown in figure 16. It should be pointed out that in order to reduce the number of variables to be considered, the pilot analog was presented only with an indication of error (compensatory-tracking task) while the human pilot was presented with a pursuit task in which target motion as well as error information was displayed (see fig. 5). There is no known experimental information for determining the effects of the differences in these two tasks on the results presented here. These effects are believed to be small, though it is indicated in reference 6 that smaller tracking errors may be obtained in a pursuit task if the pilot is able to utilize effectively the additional information available to him.

Preferred mode of pilot behavior as deduced from pilot analog.- Pilot-analog tracking-performance characteristics were evaluated by conducting tracking runs of about 60- to 90-seconds duration with the pilot analog and by systematically varying the analog gain and lead terms. Runs were made for several control-system configurations covering variations in F_s/g from 2 to 10 lb/g and variations in T_c corresponding to opinions provided by pilot A in the simulator of minimum acceptable, best available, and maximum acceptable values for the test airplane. A limited study was also made for the F-94A variable-stability airplane in the "good" airframe dynamics region. For the latter case, the control-system gain was adjusted to 8.6 lb/g and the system T_c was set at 0.05 second; the airframe frequency and damping ratio were adjusted to 3.26 radians per second and 0.7, respectively. Representative tracking-performance plots for the pilot analog are presented in figure 17. In figure 17(a) the variation of tracking performance with pilot-analog static gain for several constant values of lead is shown for the best control system evaluated on the simulated YF-86D airplane by pilot A, that is, $F_s/g = 10$ and $T_c = 0.6$. Figure 17(b)

presents similar results for the simulated F-94A airplane in the good airframe dynamics region; this configuration was rated 2 by pilot A, or better than the best system tested on the YF-86D airplane.

Several observations may be made from the results of figure 17. The fact that the pilot analog can be readily adjusted to tracking-performance levels which approach or encompass that of the human pilot implies that the linear pilot-analog model is a fairly good approximation of the human pilot. If this were not the case, appropriate changes in the form of the analog pilot or in the values of the assumed constant coefficients would have been required. It may also be noted, from figure 17, that the performance curves for both the optimum control system for the YF-86D airplane and for optimum airplane dynamics for the F-94A airplane are fairly similar in shape, particularly for zero or small lead. The shaping of these curves is such that fairly good levels of tracking performance are obtained over a broad range of gain before instability of the system is indicated; also the peak tracking performance is attained at moderate gain levels of 5 to 7 pounds per degree. These results also show that the tracking performance, both for the human and the analog pilot, is somewhat higher for the configuration with good airframe dynamics.

In order to determine the preferred pilot characteristics, specifically the gain and lead levels, from the results in figure 17, two assumptions are required. One is that the human pilot adjusts his characteristics to attain either a certain acceptable level of performance, or the maximum of which he is capable. The other is that he obtains this performance, if possible with minimum utilization of lead T_L or error-rate information.[1] The values of pilot-analog gain and minimum lead for which the peak analog tracking performance corresponds to that of the human pilot are those the human pilot generates for the particular task assumed in the present study. For example, from the results for the "optimum" control-system configuration in figure 17(a), it may be seen that the pilot must adjust his gain and lead to about 6 pounds per degree and 0.1 second, respectively, to attain the level of tracking performance shown. Figure 18 presents time histories, which compare the tracking of the analog pilot, with these values of gain and lead, with that of pilot A. Although the stick-force time history for the human pilot is slightly more irregular than that for the analog pilot, the generally good correspondence between the two sets of time histories in figure 18 lends some confidence in the above procedure for determining values of pilot gain and lead for the task considered in this study.

From figure 17 and from other pilot-analog performance plots not shown, the pilot response characteristics corresponding to the pilot-opinion boundaries established in figure 8 were determined by the

[1]This assumption implies that the pilot prefers to operate in an environment where he is required only to act as a simple gain changer to attain acceptable performance levels.

procedures outlined above, and the results are presented in the summary plot of figure 19 for pilot A. This plot shows clearly the trends in pilot response characteristics as the optimum control-system configuration for the test airplane (i.e., pilot A rating of 2.5) is approached. Also shown is the point for optimum airframe dynamics from reference 2. It is interesting to note that the preferred pilot characteristics, derived from two different studies, that is, optimization of the control-system dynamics in the present report and optimization of airframe dynamics (ref. 2) are roughly the same. These results suggest that the pilot apparently prefers an over-all system for which good performance can be obtained with gain levels of 6 or 7 pounds per degree and values of lead of 0.1 second or less.

Problem-area modes of pilot behavior as deduced from pilot analog.- Several specific problem areas isolated during the course of the present investigation are identified in figures 8 and 19. Generally, these problem areas fall into two main categories - exceedingly sensitive response and extremely sluggish response. The problem area denoted by point A in these figures is associated with pilots' observations of "severe pilot-induced oscillations" in flight and "extremely sensitive response" on the simulator. Points B and C correspond to problem areas where the pilots noted the "response was too sluggish with too much apparent damping in the control system."

The results in figure 19 show that, for variations in control-system dynamics from best available values, the sensitive-response boundary is approached along lines of decreasing gain and lead, and the sluggish-response boundary is approached along lines of increasing gain and lead (for constant F_s/g). The boundaries shown in figure 19 represent the range of acceptable pilot response characteristics for pilot A. It should be recognized that these limits are probably dependent on the particular pilot, the task he is required to perform, and the pilot environment, that is, fixed- or moving-base simulator or flight test.

With regard to the results for problem area A in figures 8 and 19, it may be seen that for very sensitive control systems (i.e., $F_s/g = 2$; $T_c = 0.2$), the pilot must adjust his gain to very low values of the order of 3/4 pound per degree of error for optimum tracking performance. The critical nature of the gain adjustment required of the pilot is shown more clearly in figure 20(a), where the analog-pilot tracking performance is plotted as a function of gain for several values of lead. The sharp peaking characteristic shown indicates that the pilot must adjust his gain within a very narrow band to avoid either poor performance or instability. The results on the fixed-base simulator indicate the pilot performs this adjustment satisfactorily, although he objects to the extremely sensitive response. In flight, however, motion-feedback effects preclude the fine gain adjustment required, and a severe pilot-induced oscillation results and persists until the pilot frees the stick. These results suggest that pilot-analog tracking-response characteristics, which exhibit a sharp

peak at relatively low values of gain, may provide a useful means for predicting tendencies toward pilot-induced oscillations in flight.

The pilot-analog response characteristics associated with the sluggish-response problem areas B and C (fig. 19) are shown in figures 20(b) and 20(c). These results, in contrast to those in figure 20(a), show extremely poor peak tracking performance for zero lead. With increase in lead, the peak tracking performance rapidly increases and approaches the human pilot level for values of lead 0.2 to 0.3 second. The results in figure 20(b), in particular, indicate that pilot A could have attained a higher level of tracking performance if he had utilized more lead, of the order of 0.4 to 0.8 second. Either the pilot is incapable of generating the increased lead required or, because of the increased difficulty of the tracking problem,[2] he operates in some fashion which is not amenable to a quantitative analysis by means of the linear analog. The former possibility does not seem probable, since values of T_L of 0.25 to 2.5 seconds have been observed in various studies (e.g., ref. 7). The second possibility, that is, where a significant portion of the pilot's output cannot be linearly correlated with his inputs, appears to be the probable explanation for the decreased tracking performance in the present case. Although this tends to cast some doubt on the acceptable limits of pilot behavior defined by the sluggish-response boundary in figure 19, the trends shown with variation in control-system dynamics are valid. If it is desired to define the limits of acceptable pilot characteristics with more precision, it would be necessary first to isolate that portion of the human pilot tracking error which results from pilot outputs not linearly correlated with his inputs. The remaining error might then be used as a reference for adjusting the gain and lead of the linear pilot analog.

CONCLUSIONS

The results of a fixed-base simulator evaluation of the effects of variable control-system dynamics on pilot opinion and comparison with flight-test data indicated the following:

1. With the exception of the problem of predicting regions of pilot-airplane instability, fixed-base simulator studies appear generally adequate in control-system design. Specifically, it was shown that:

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[2]In the present example, the extreme sluggishness of the control system increases the difficulty of the tracking task. Some information in reference 6 indicates that, as the task becomes more difficult, the pilot tends to become more variable and less precise in his response to the inputs presented him. As a consequence, the "remnant," or that portion of the pilot output not linearly correlated to the system inputs, increases and his tracking performance deteriorates.

(a) Fairly good correlation was obtained with flight results showing the effects of variations in stick force per g, in control-system time constant and in control-system deadband on pilot-opinion boundaries and on numerical ratings for two pilots.

(b) Differences between the results for the two pilots in flight were paralleled by similar differences on the fixed-base simulator.

2. In certain problem areas, for example, for sensitive control systems associated with pilot-induced oscillations in flight, fixed-base simulator results appear to be inadequate and it appears that tests in moving-base simulators are required.

Studies with a linear pilot-analog model concurrent with those with the human pilot on the fixed-base simulator showed:

1. The pilot-analog model was easily adjusted to provide tracking-performance levels which approached or encompassed those for the human pilot, implying the linear pilot-analog model is a fairly good approximation to the human pilot.

2. The pilot apparently prefers an over-all system for which good performance can be obtained with values of gain of 6 or 7 pounds per degree and values of lead of 0.1 second or less. Optimization of both control-system dynamics (for poor airframe dynamics) and of airframe dynamics showed roughly the same preferred values of gain and lead for the pilot.

3. Pilot-analog tracking-response characteristics for control-system configurations associated with pilot-induced oscillations in flight indicated the pilot must adjust his gain closely within a narrow band to avoid either poor performance or instability. While he performs this adjustment satisfactorily on the fixed-base simulator, adverse motion feedback effects in flight apparently preclude the fine gain adjustment required. It is suggested that the tracking-response characteristics of a simplified pilot-analog representation of the human, which exhibit a critical dependence on gain, may provide a useful means for predicting tendencies toward pilot-induced oscillations in flight due to sensitive control systems.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., July 18, 1958

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7. Anon.: Application of Human Response Data to Aircraft Design. Control Specialists, Inc., Memo. Rep. No. 69, June 7, 1956.

TABLE I.- PILOT-OPINION RATING SCALE USED IN SUBJECT PROGRAM

	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[1]	Doubtful	Yes
No operation	Unacceptable	7	Unacceptable even for emergency condition[1]	No	Doubtful
		8	Unacceptable - dangerous	No	No
		9	Unacceptable - uncontrollable	No	No

[1]Failure of a stability augmenter.

TABLE II.- PILOT NUMERICAL RATINGS CORRESPONDING TO THE PILOT-OPINION BOUNDARIES OF FIGURE 8; ZERO DEADBAND

Source		Pilot ratings								
		F_s/g = 2.0			F_s/g = 5.0			F_s/g = 10.0		
		Tc_{min}	Tc_{BA}	Tc_{max}	Tc_{min}	Tc_{BA}	Tc_{max}	Tc_{min}	Tc_{BA}	Tc_{max}
Flight simulator	Pilot A	--- 5.5	3 4	--- 5	--- 5	2.5 3.0	--- 5	--- 4.5	2.5 2.5	--- 5
Flight simulator	Pilot B	--- 5	4 4	--- 5	--- 5	3 3.5	--- 5	--- 5	2.5 3.5	--- 5

TABLE III.- EFFECT OF DEADBAND ON PILOT NUMERICAL RATINGS; BEST AVAILABLE CONTROL-SYSTEM TIME CONSTANT

Source		Pilot ratings														
		F_s/g = 2.0 lb/g					F_s/g = 5.0 lb/g					F_s/g = 10.0 lb/g				
		Deadband, lb					Deadband, lb					Deadband, lb				
		0	±1	±2	±3.5	±5	0	±1	±2	±3.5	±5	0	±1	±2	±3.5	±5
Flight simulator	Pilot A	3 4	3 3	--- 3.5	--- 5	--- ---	2.5 3	2.5 2.5	--- 2.5	--- 3.5	--- 4.5	2.5 2.5	3 2.5	--- 2.5	--- 3	--- 4
Flight simulator	Pilot B	4 4	3 3.5	--- 3.0	--- ---	--- 5.50	3 3.5	3 3	--- 3	--- ---	--- 4.5	2.5 3.5	2.5 3	--- 3	--- ---	--- 4.5

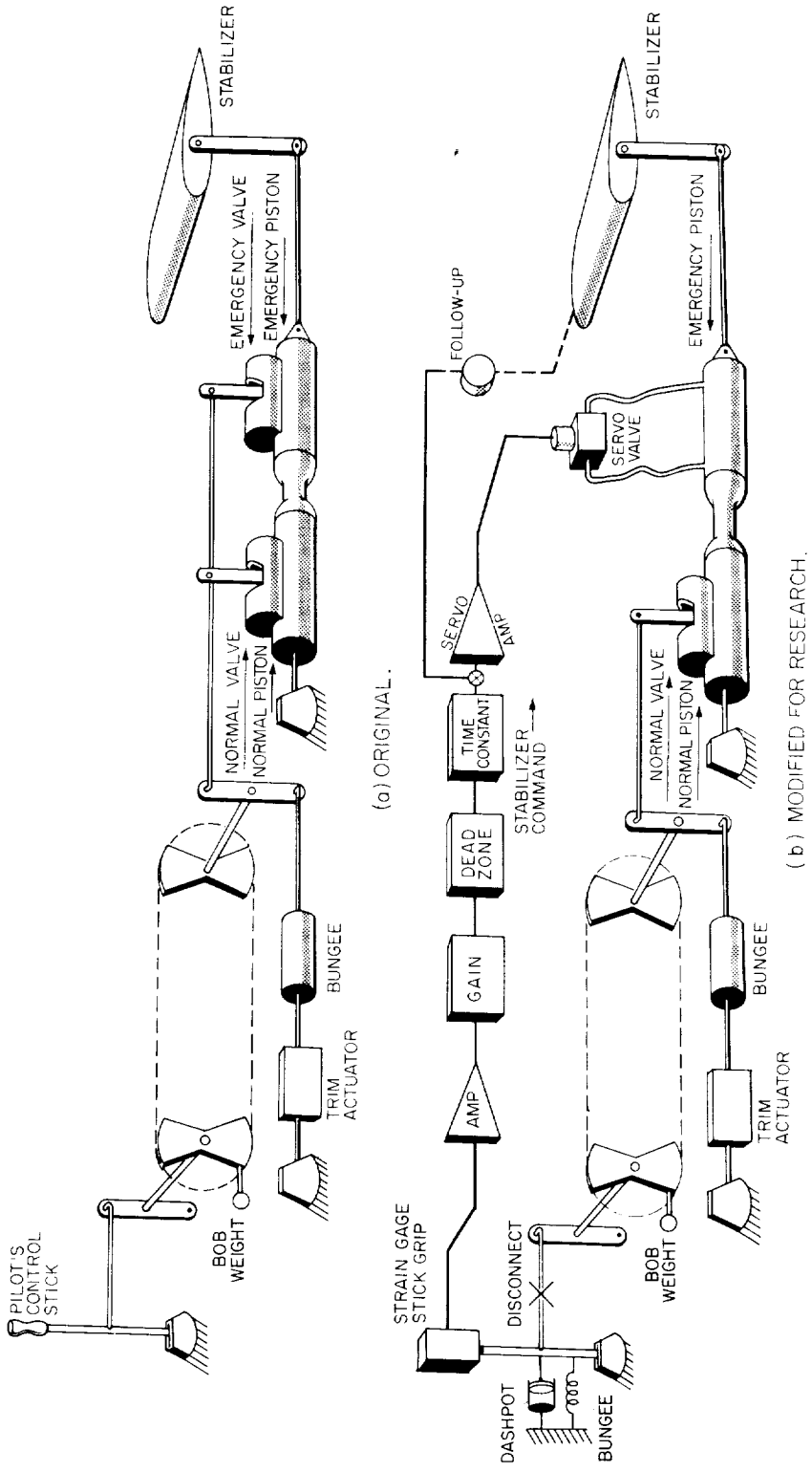


Figure 1.- Mechanical schematic diagrams of original and modified control systems used in flight tests.

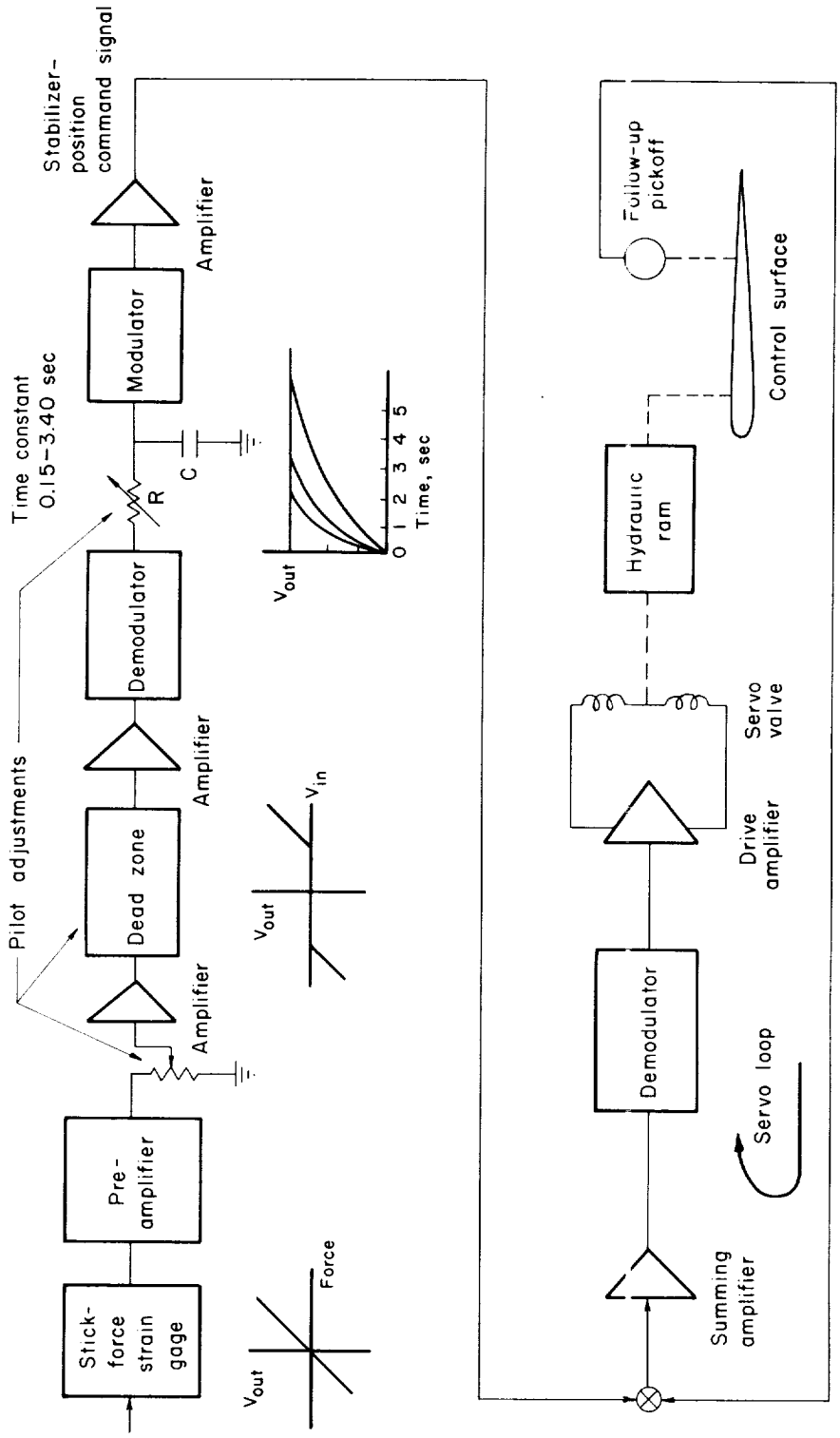


Figure 2.- Electrical schematic diagram of modified longitudinal control system.

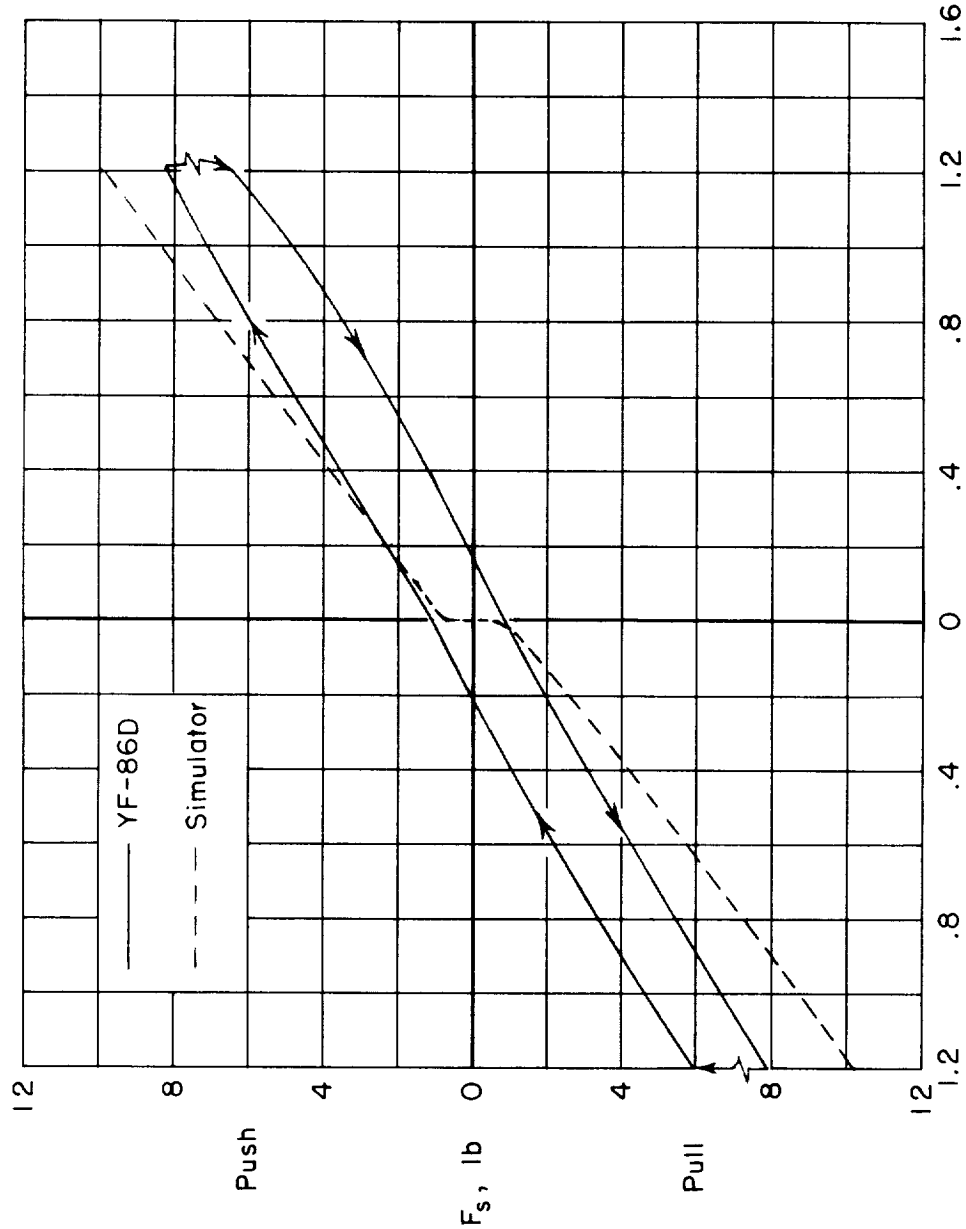
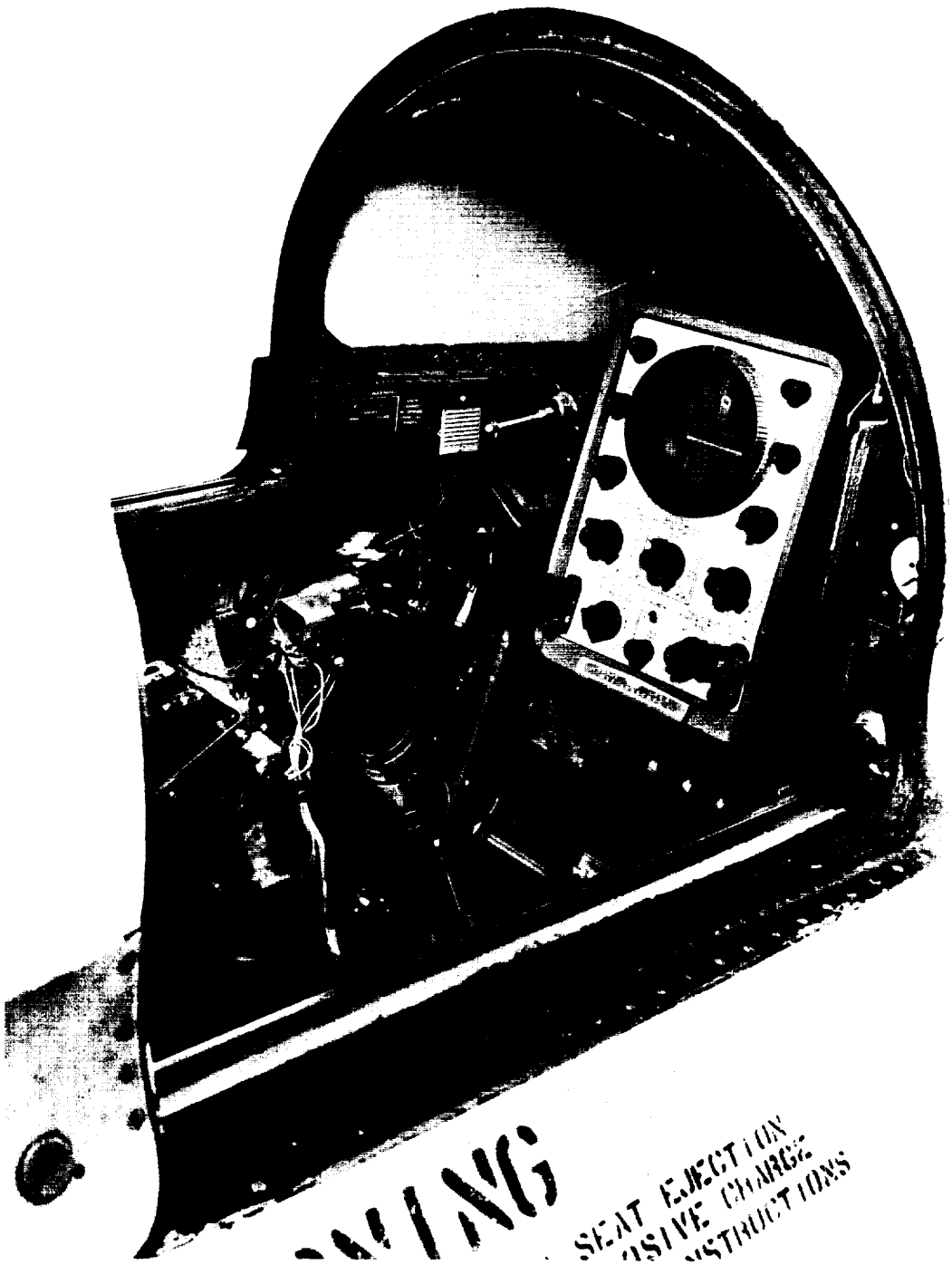


Figure 3.- Variation of stick force with stick position.

A-23881

(a) General view.

Figure 4.- Views of fixed-base cockpit.



(b) Detail view showing scope presentation. A-23883

Figure 4.- Concluded.

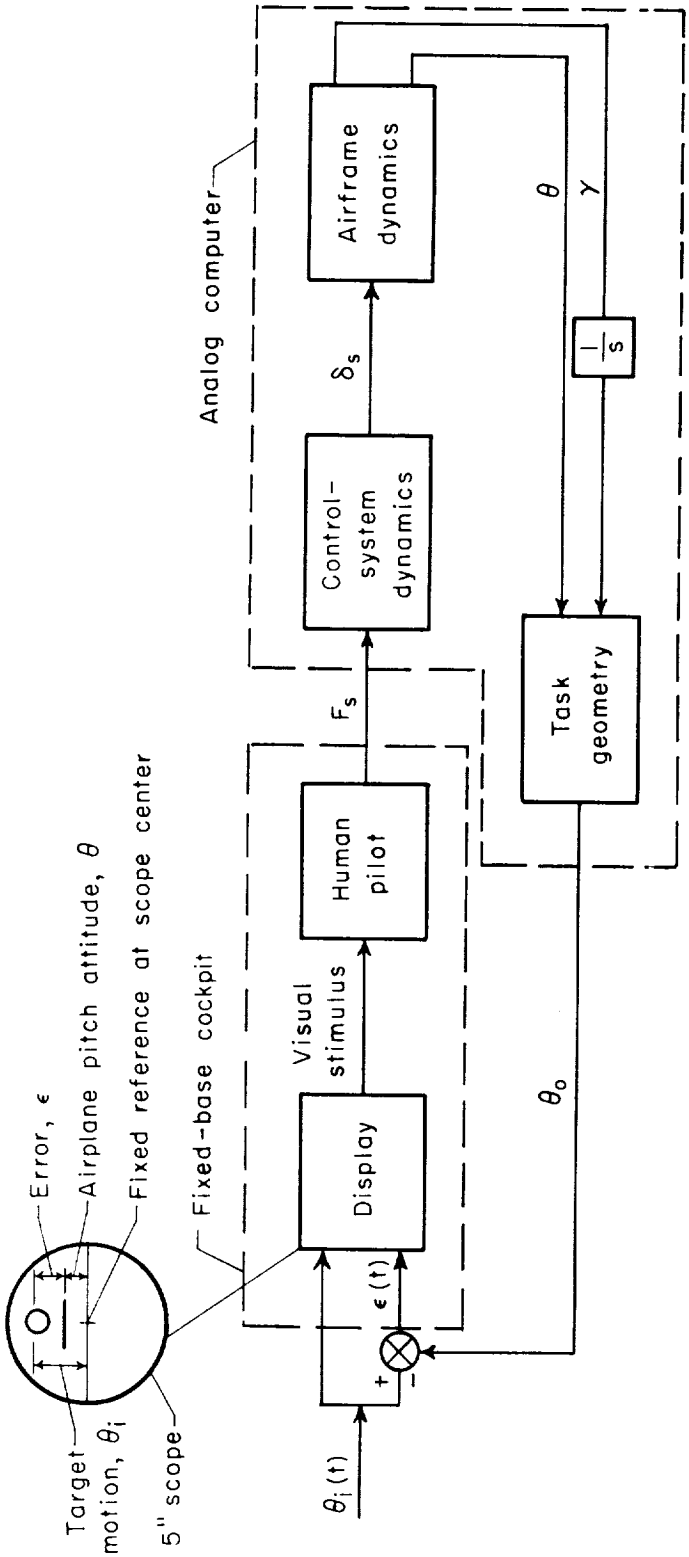
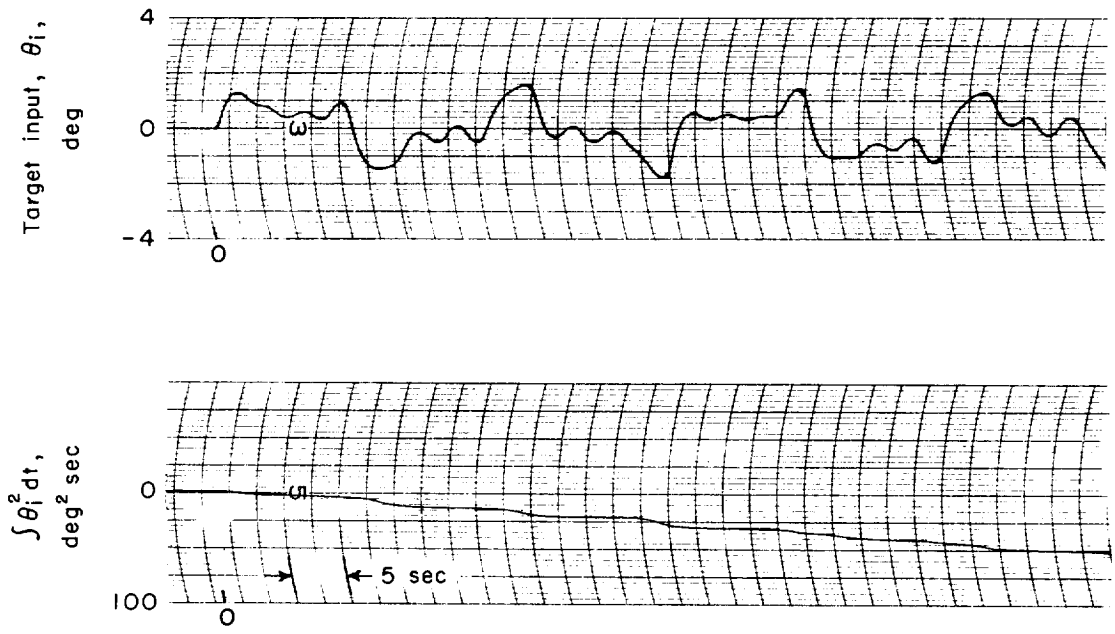
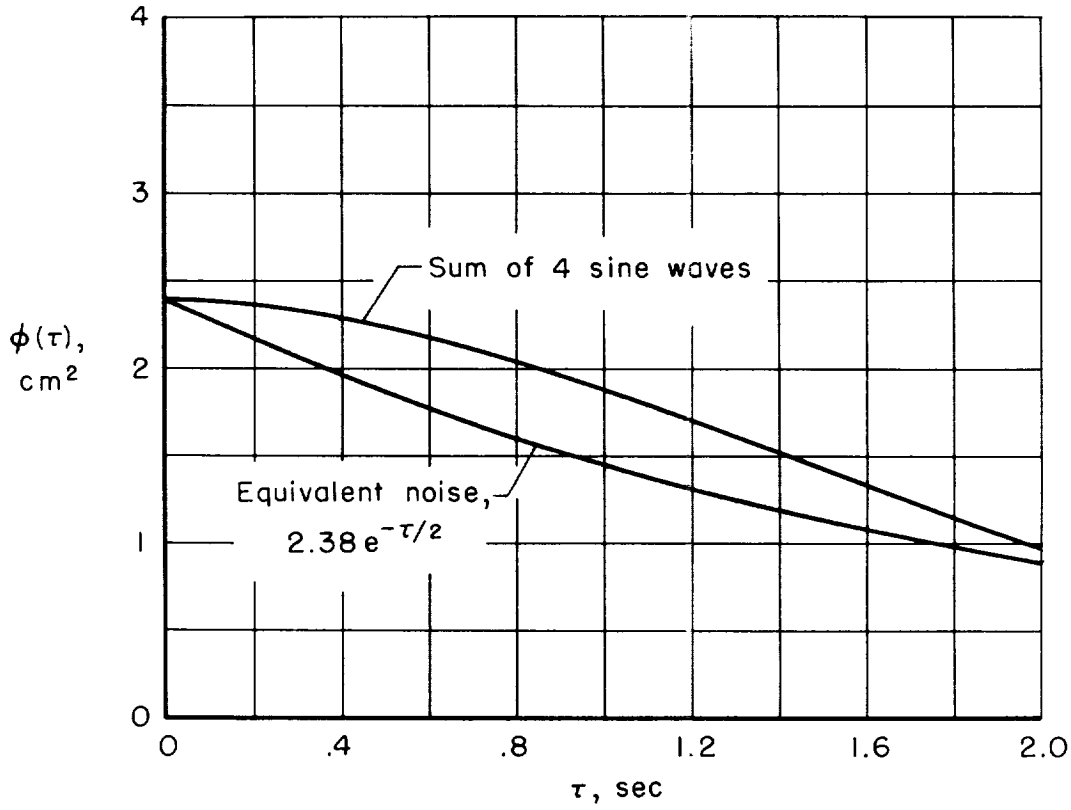


Figure 5.- Block diagram of simulator with human pilot.



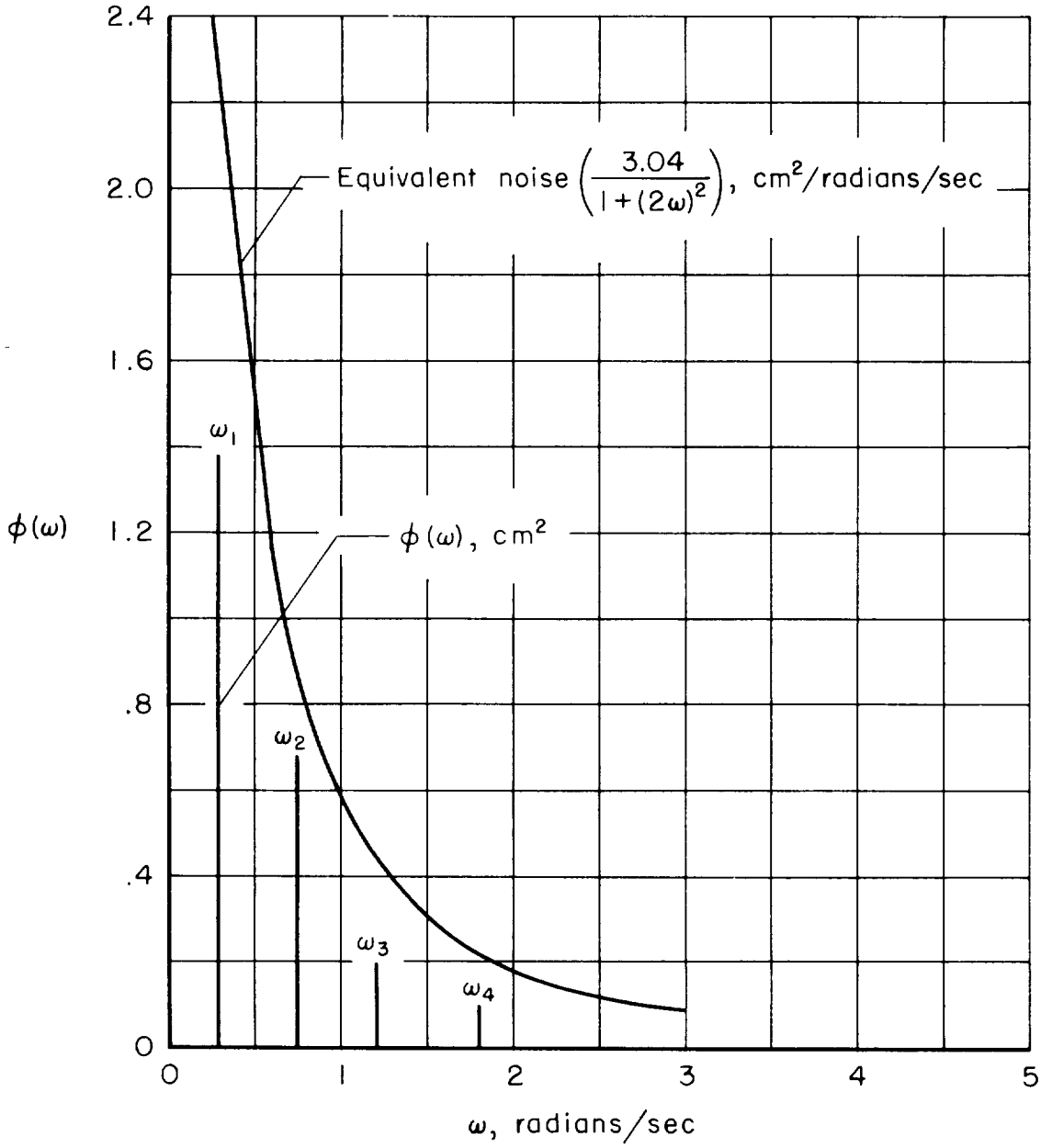
(a) Time history.

Figure 6.- Pertinent characteristics of task presented to pilots in simulator.



(b) Autocorrelation function.

Figure 6.- Continued.



(c) Power spectrum.

Figure 6.- Concluded.

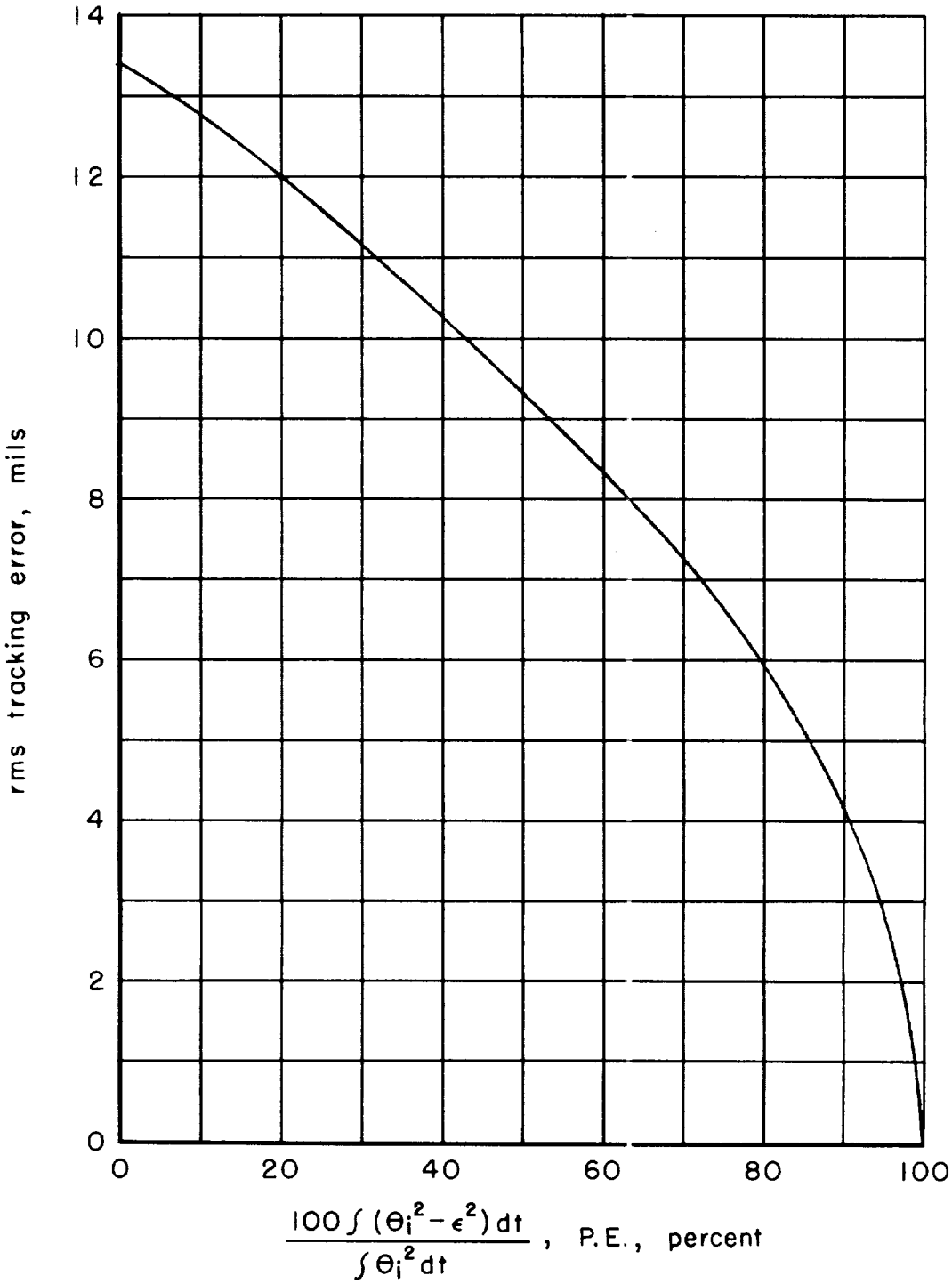
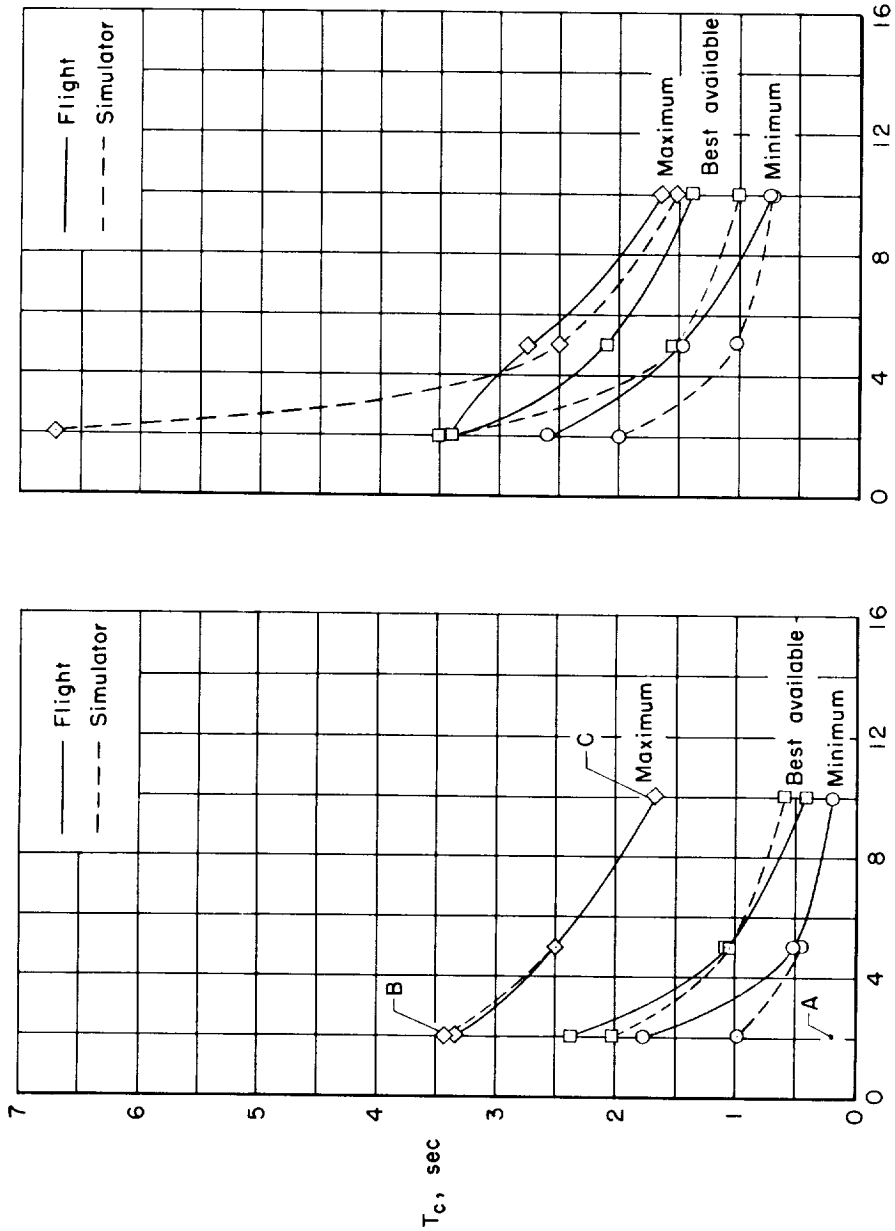


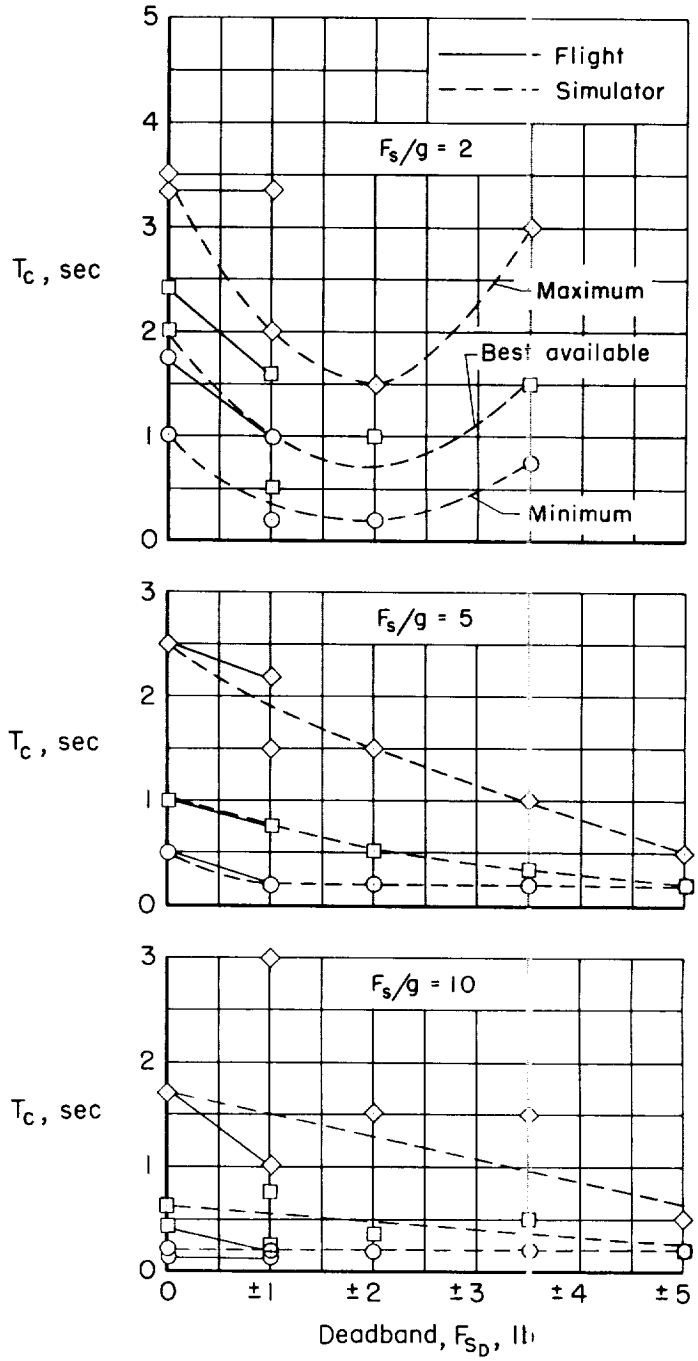
Figure 7.- Relationship of root-mean-square tracking error to pilot tracking efficiency.



(a) Pilot A.

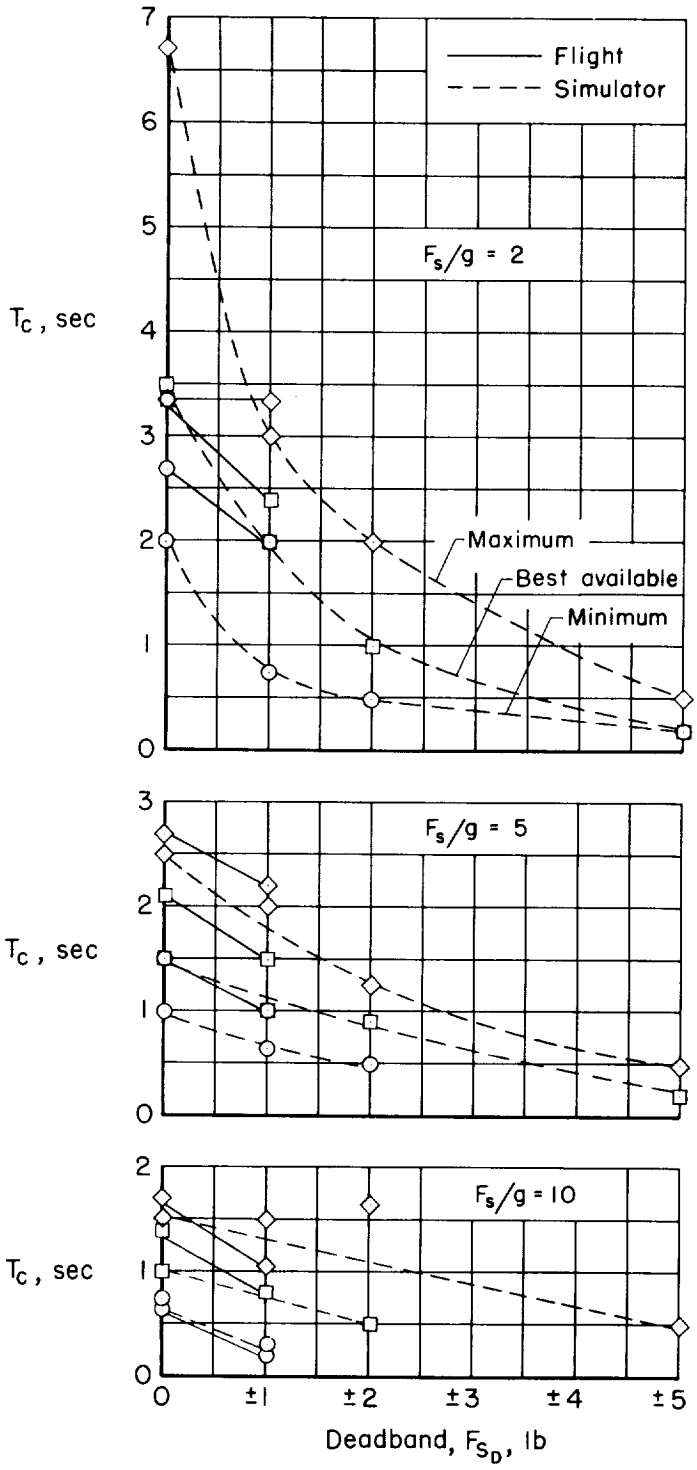
(b) Pilot B.

Figure 8.- Control-system time constant selected by pilots A and B in flight and on the ground simulator as a function of stick force per g, zero deadband.



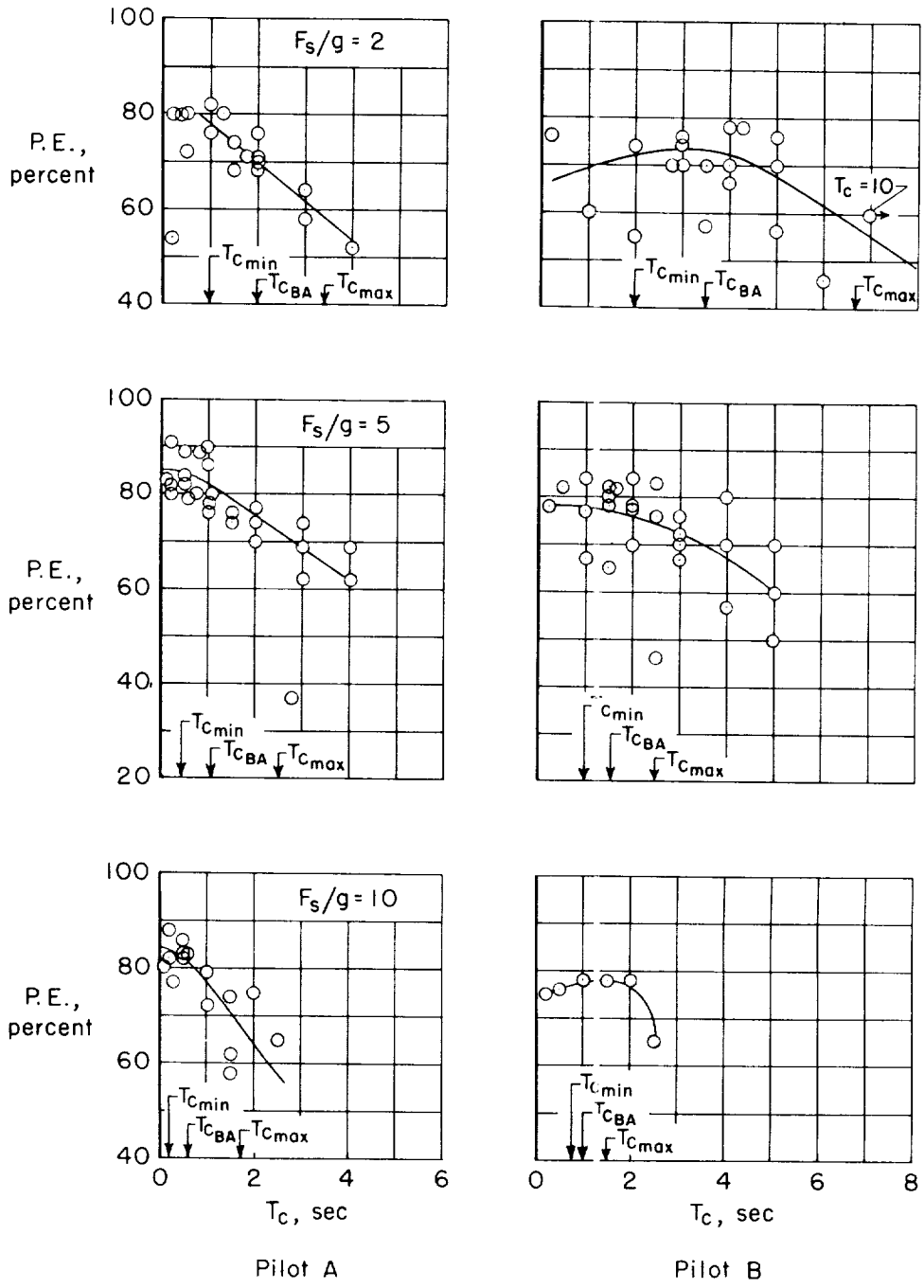
(a) Pilot A.

Figure 9.- Best available time constants selected by the pilots on the simulator for several values of deadband and comparison with flight-test results.



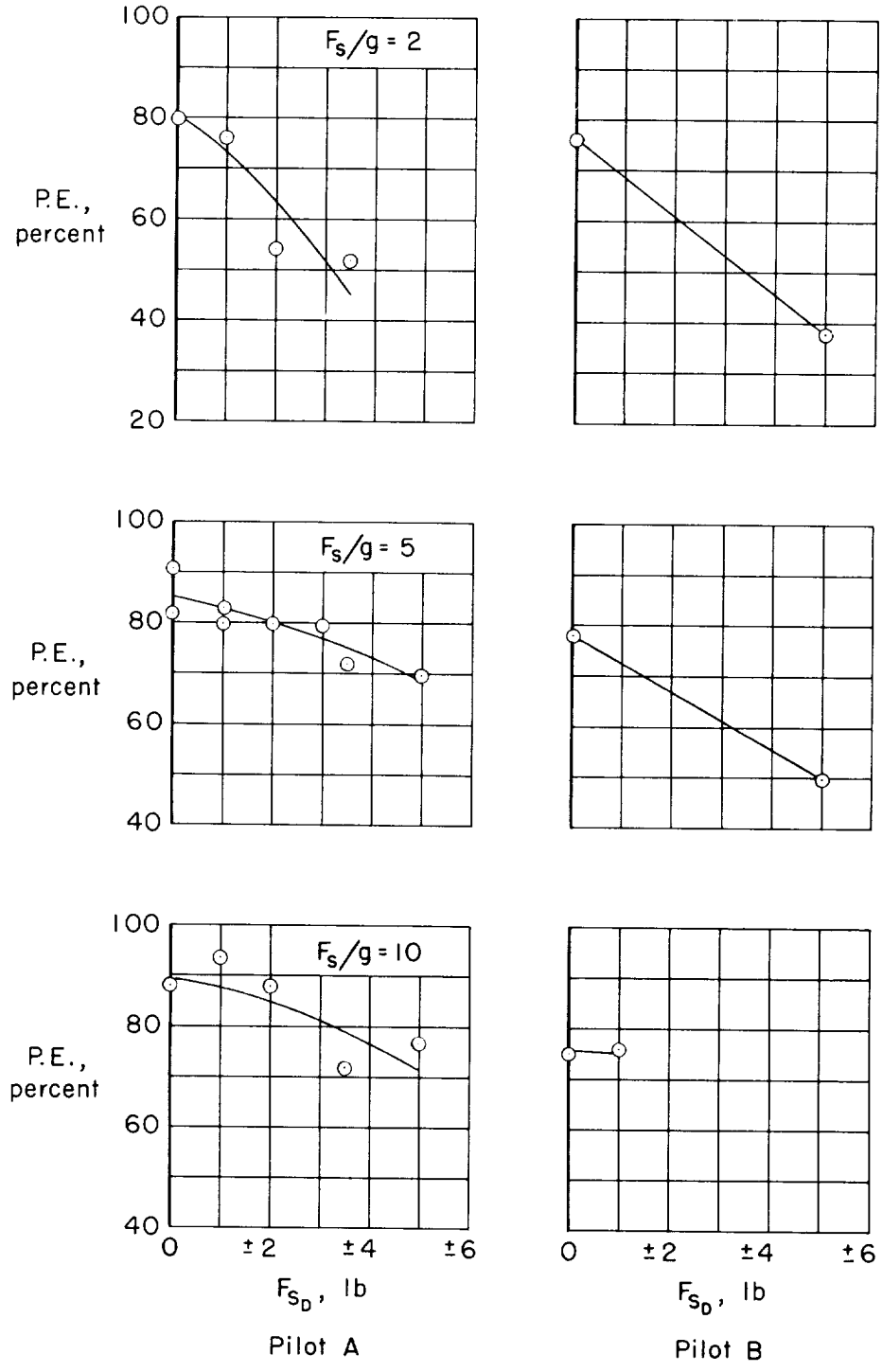
(b) Pilot B.

Figure 9.- Concluded.



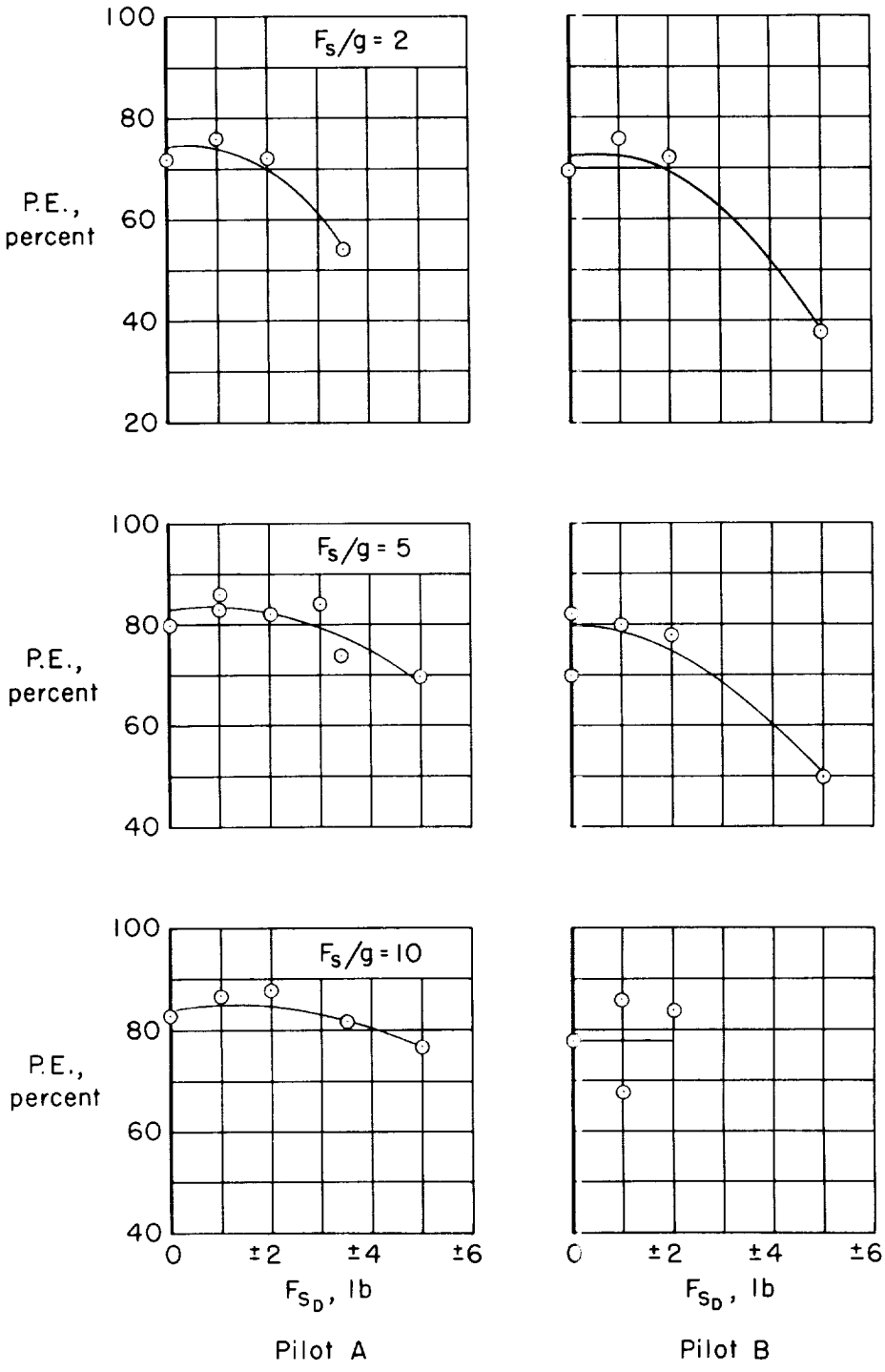
(a) Effect of T_c ($F_{s_D} = 0$).

Figure 10.- Effects of variations in control-system parameters on pilots' tracking efficiency in fixed-base simulator.



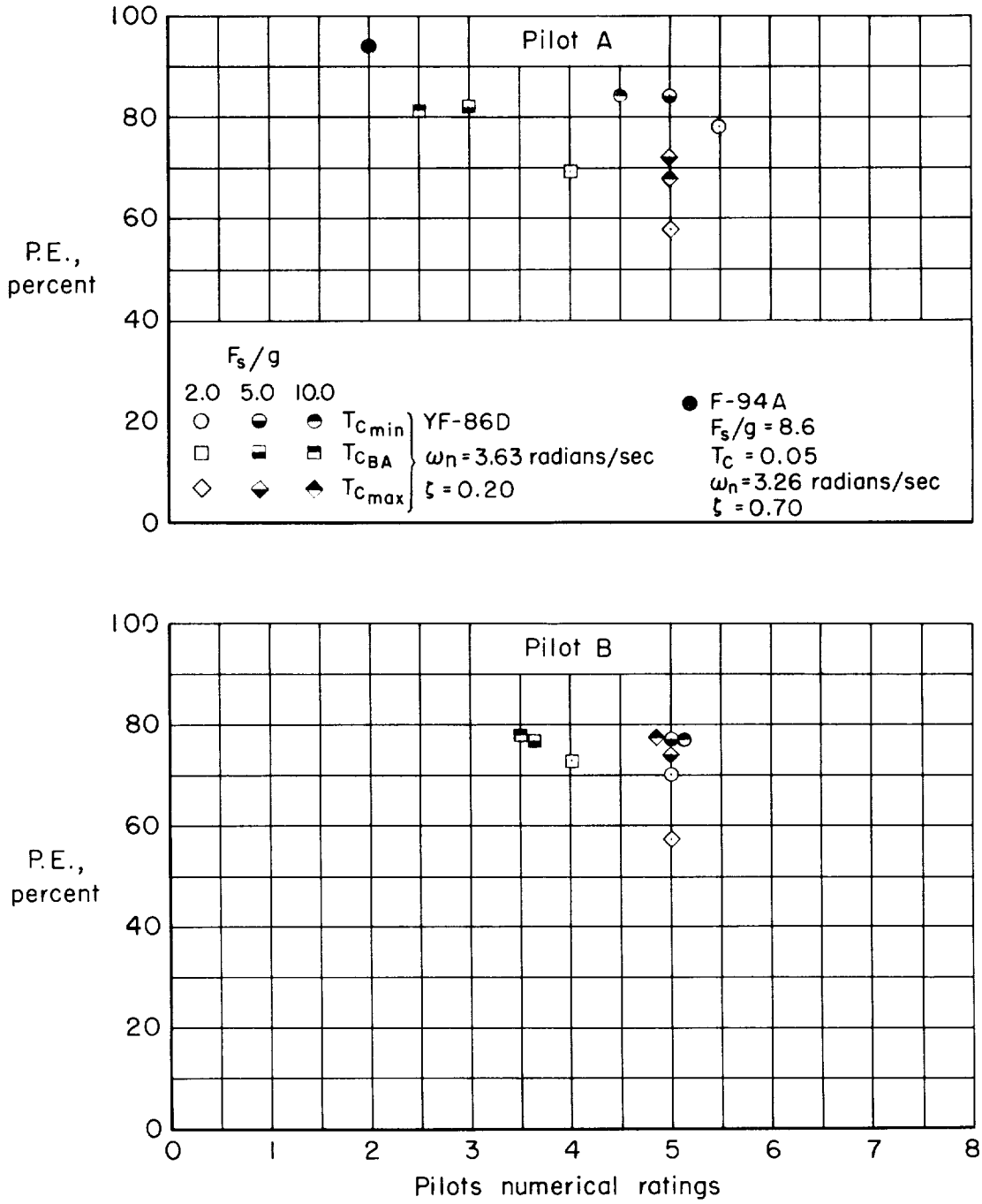
(b) Effect of deadband (T_C = 0.2 sec).

Figure 10.- Continued.



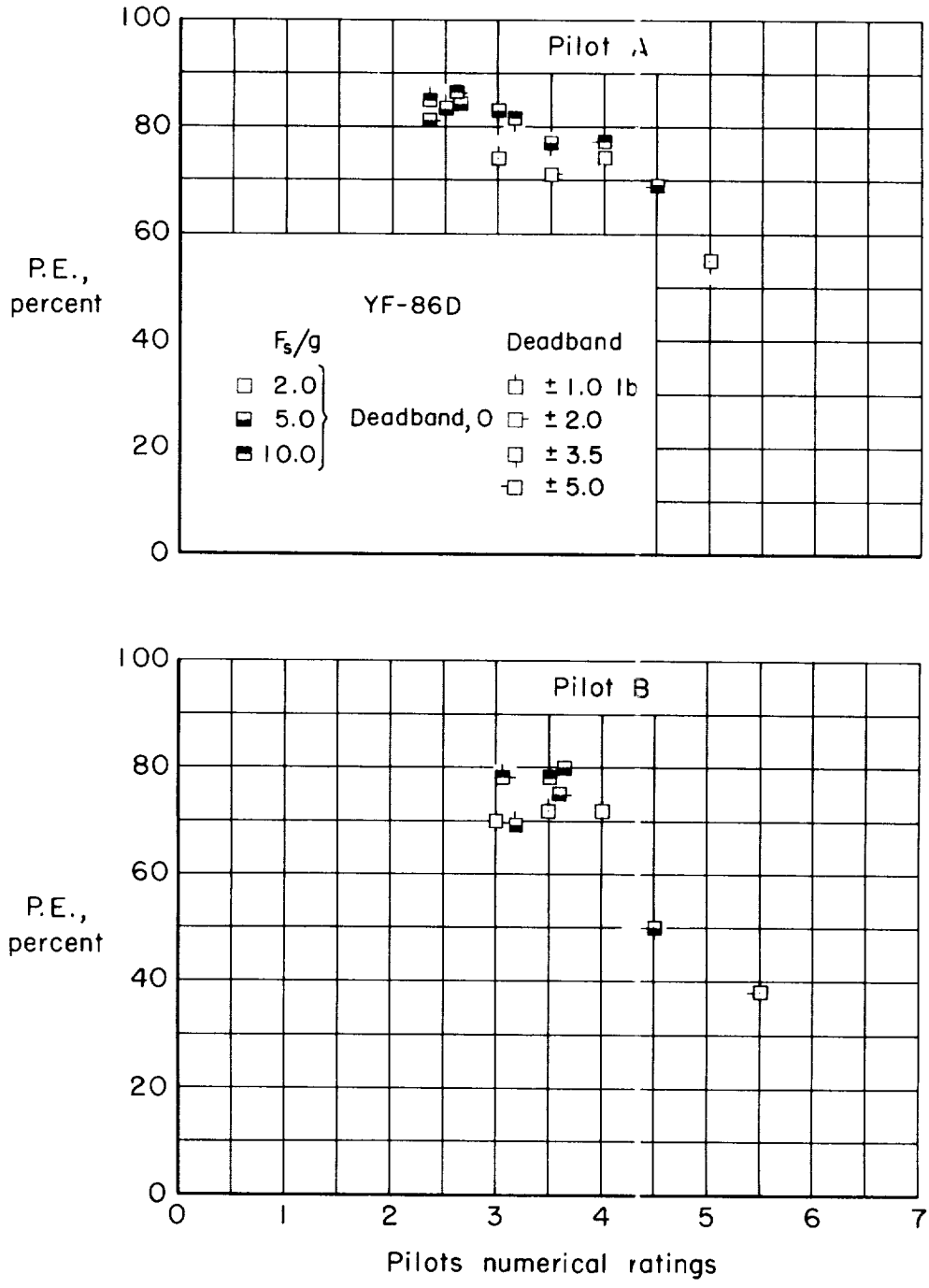
(c) Effect of deadband (best available T_c).

Figure 10.- Concluded.



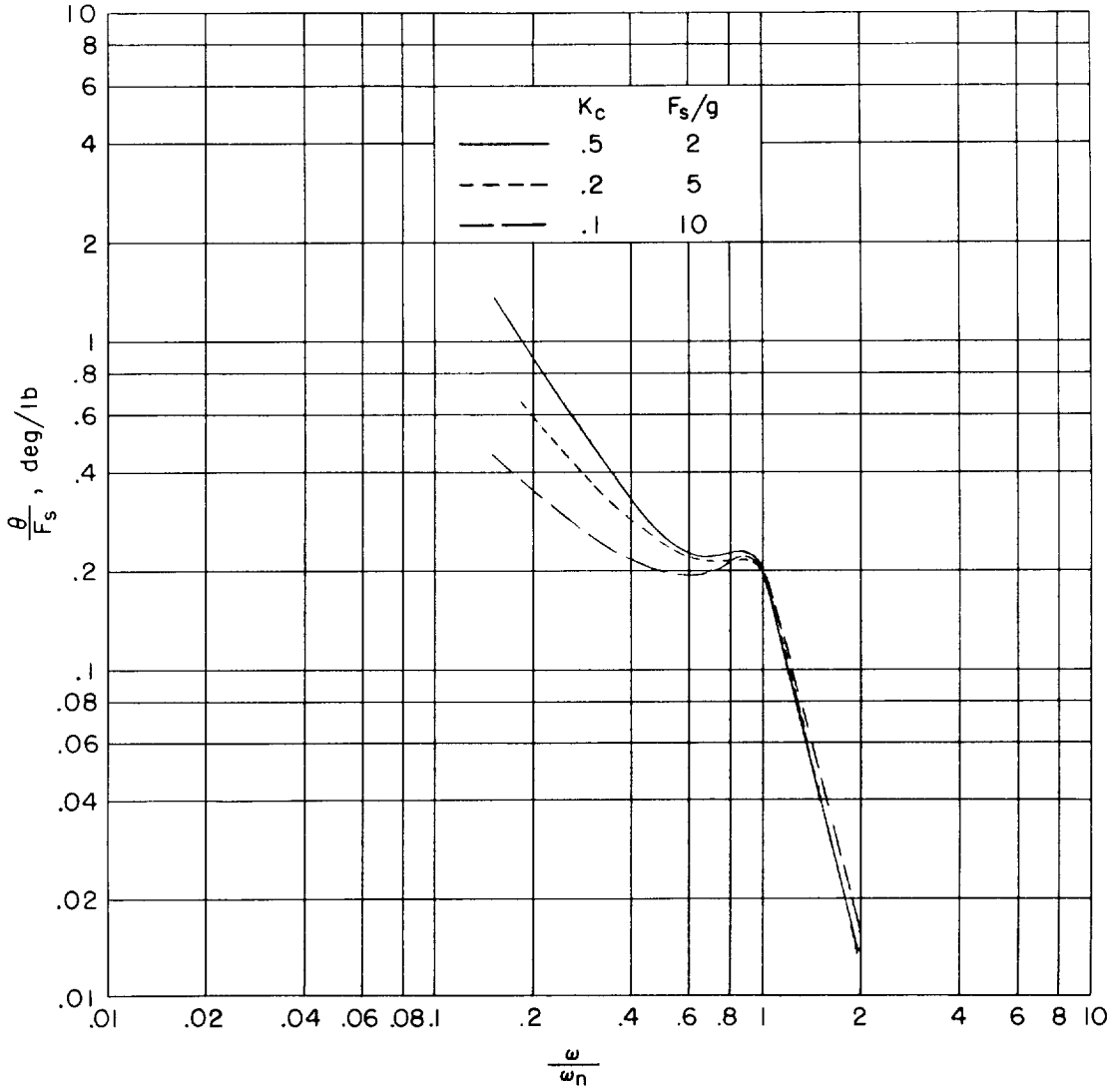
(a) Effect of T_C at several values of F_S/g (deadband, 0).

Figure 11.- Variation of pilots' tracking efficiency with pilot opinion, as determined from fixed-base simulator tests.



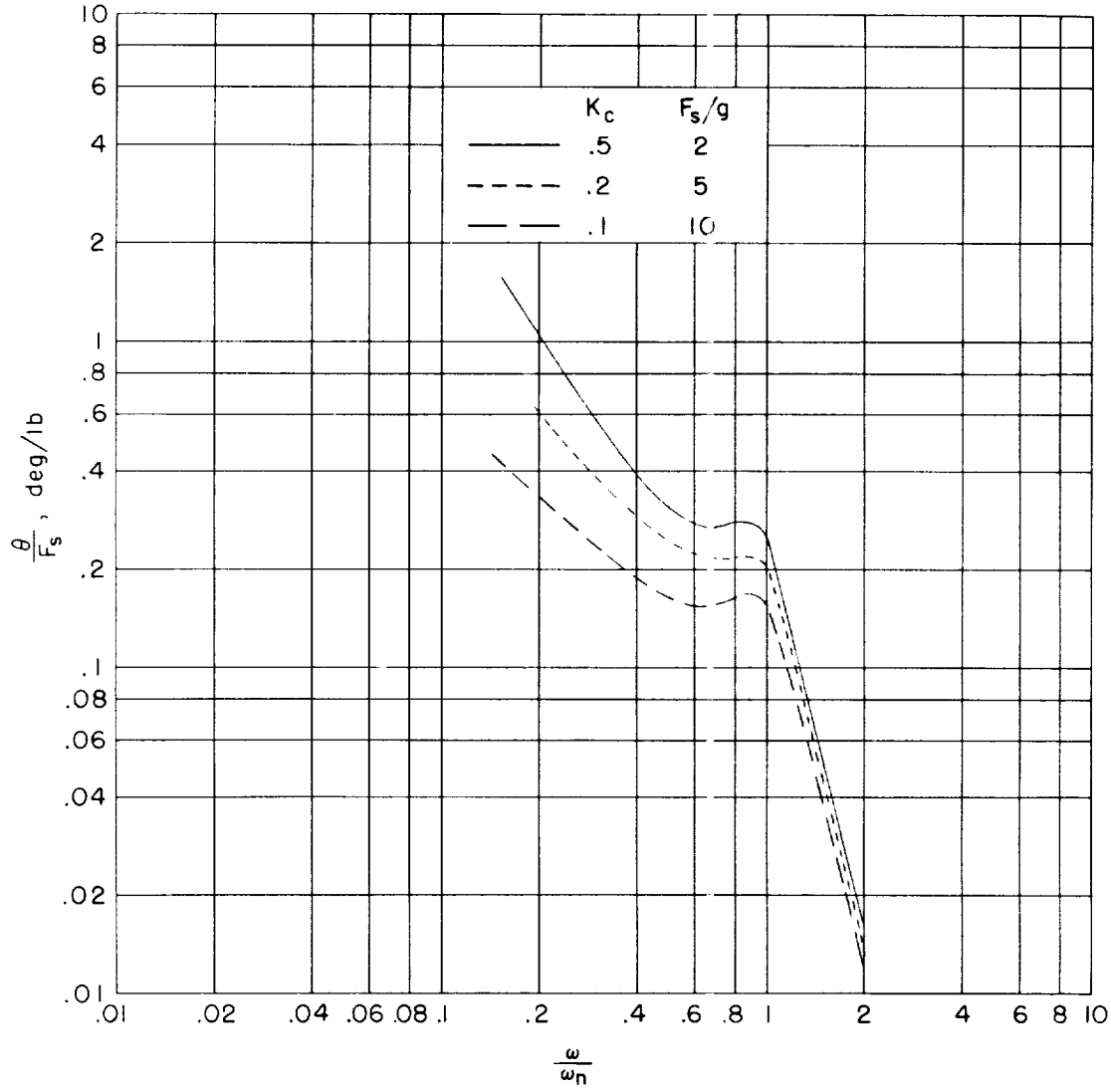
(b) Effect of deadband at several values of F_s/g (best available T_c).

Figure 11.- Concluded.



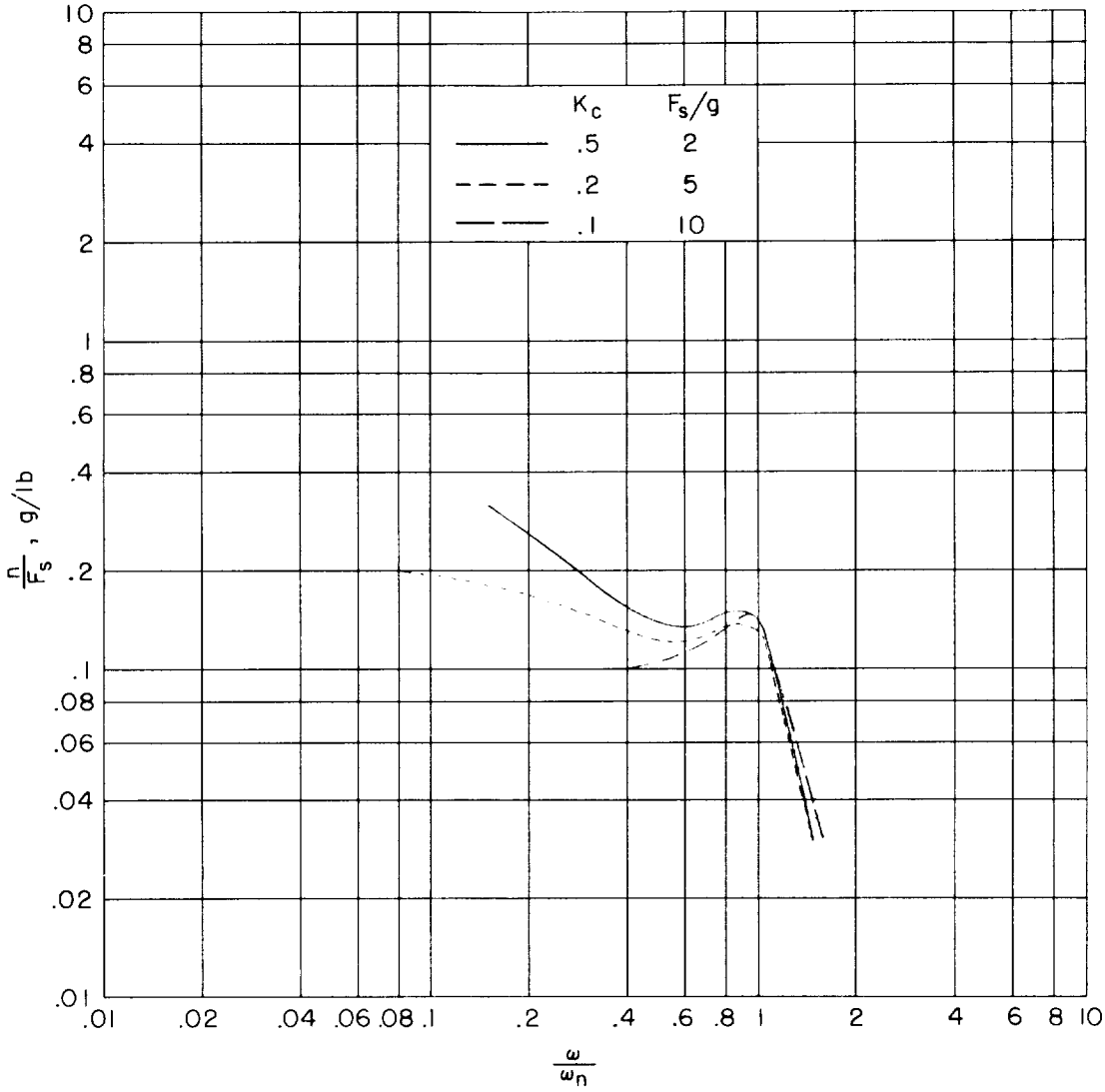
(a) Flight, pilot A; pitch response.

Figure 12.- Amplitude-ratio plots of θ/F_S and n/F_S as a function of dimensionless frequency parameter ω/ω_n for several values of F_S/g; best available time constants for pilots A and B, $F_{S_D} = 0$.



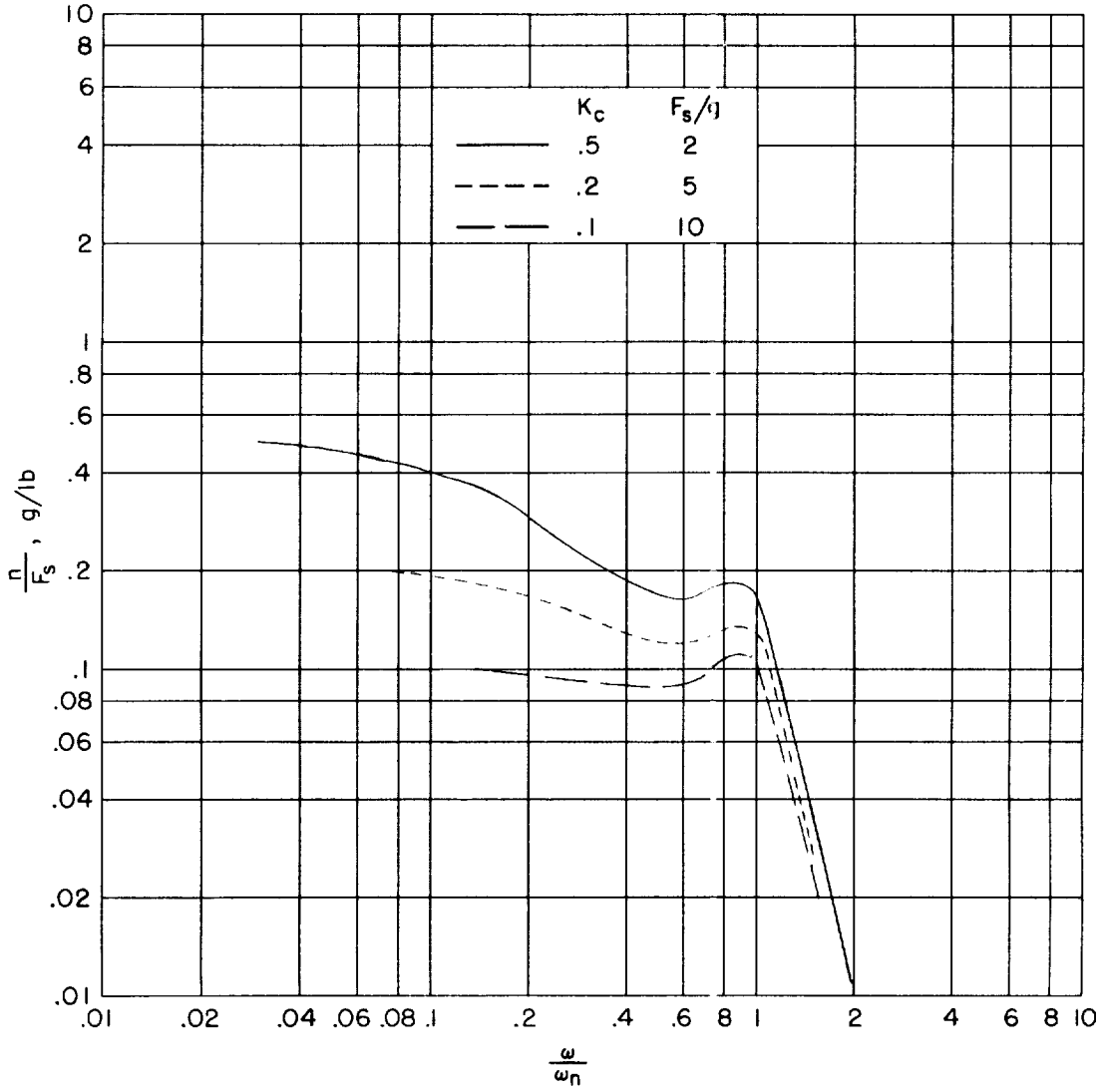
(b) Simulator, pilot A; pitch response.

Figure 12.- Continued.



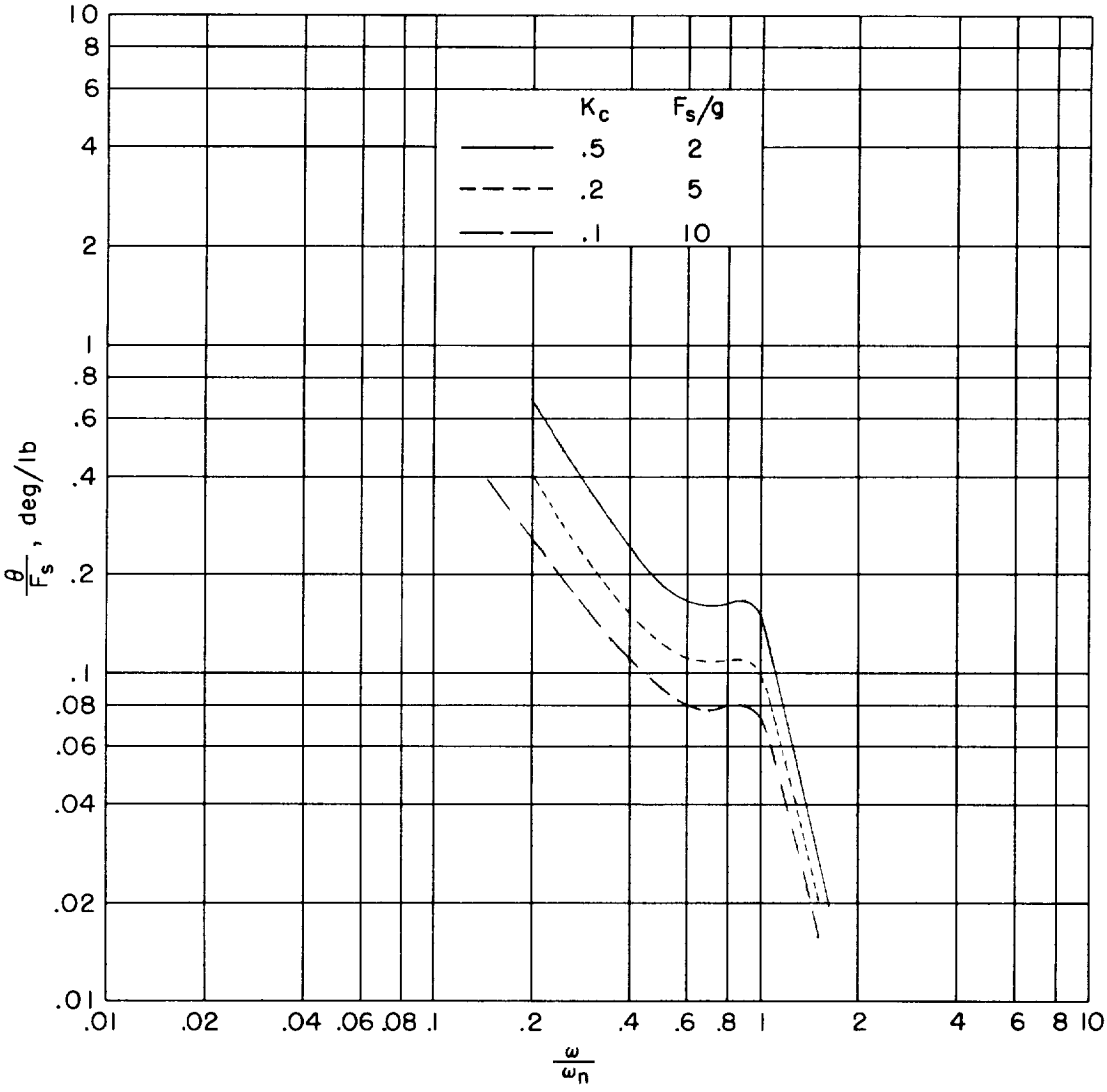
(c) Flight, pilot A; normal-acceleration response.

Figure 12.- Continued.



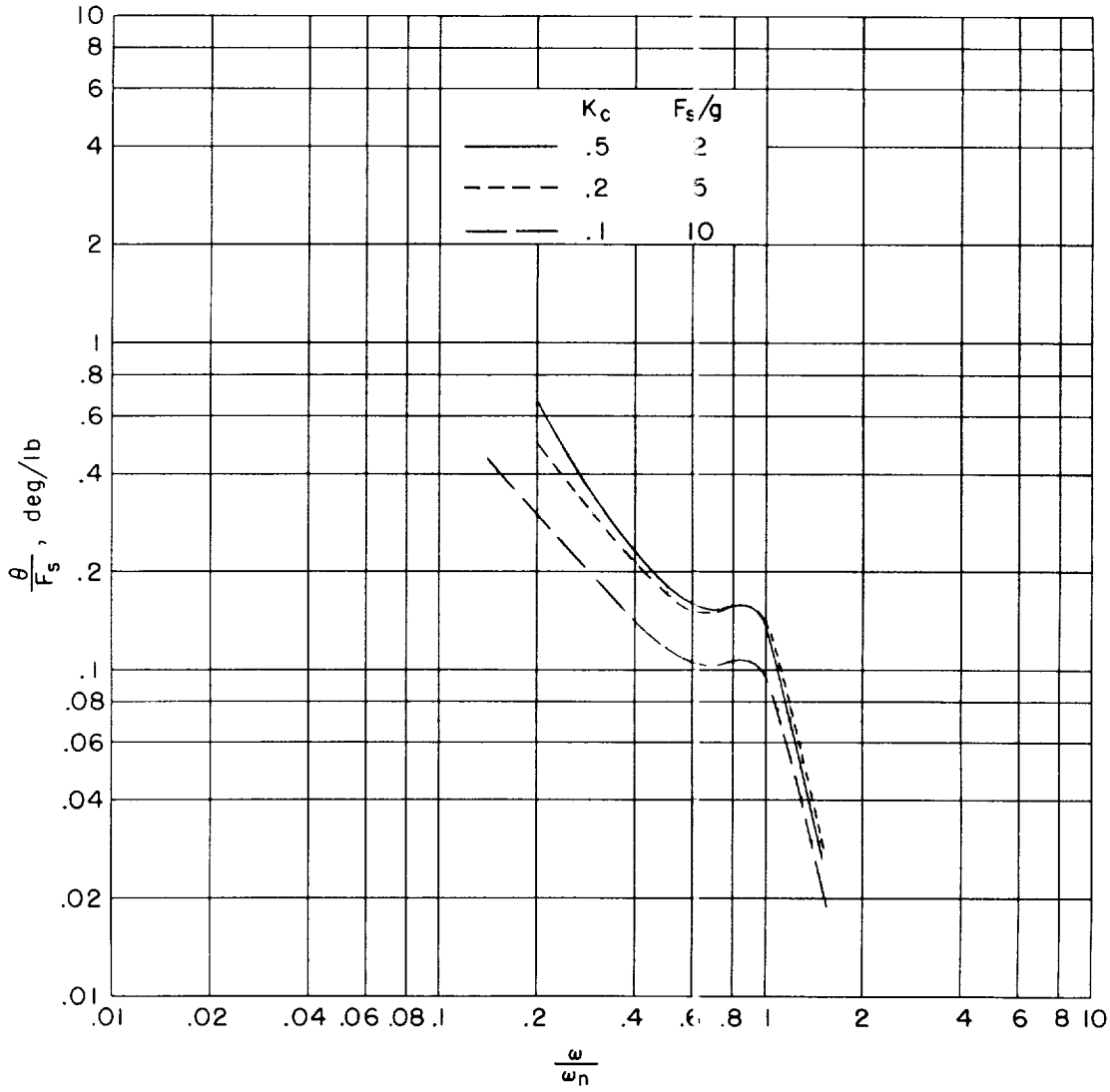
(d) Simulator, pilot A; normal-acceleration response.

Figure 12.- Continued.



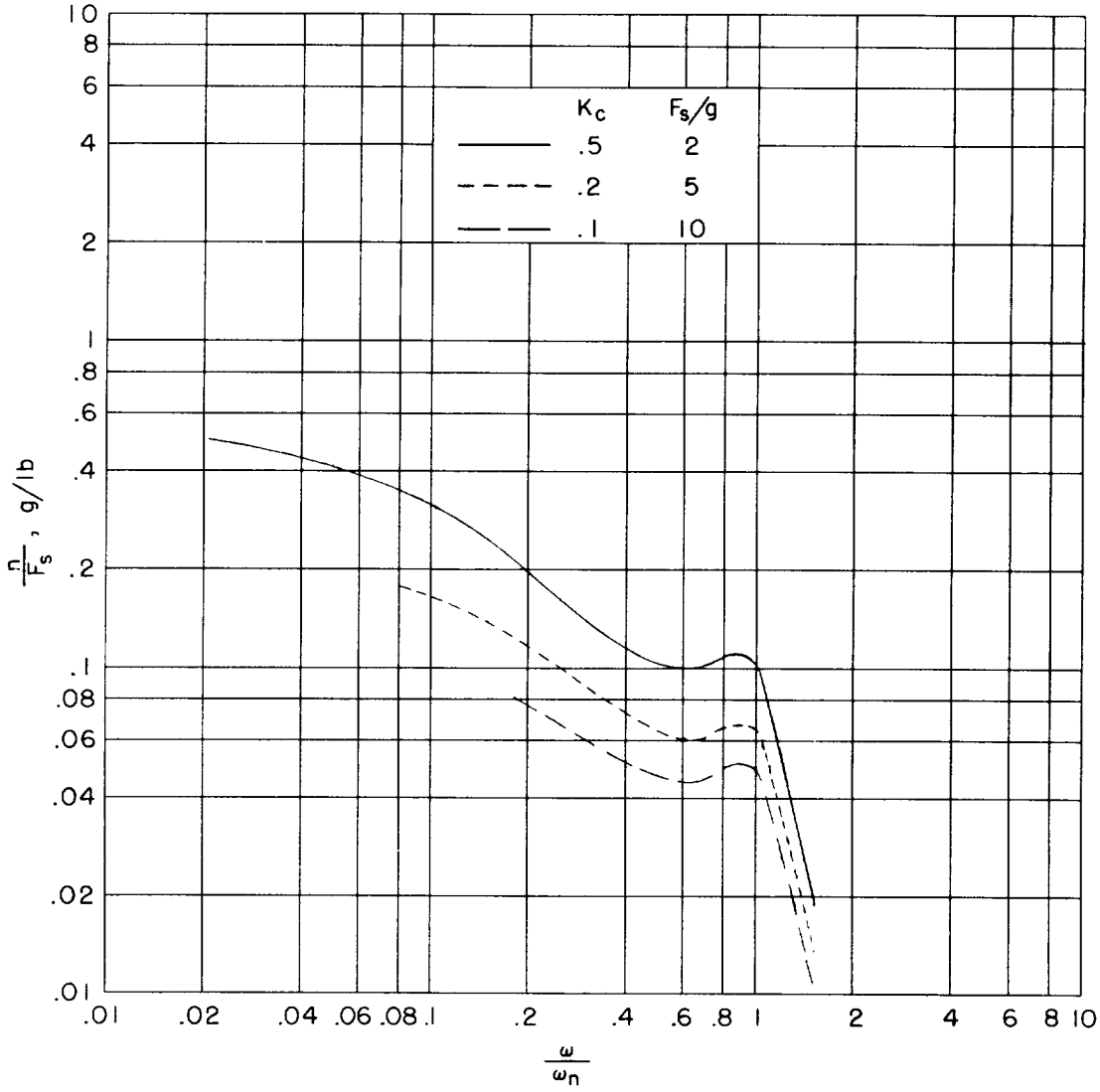
(e) Flight, pilot B; pitch response.

Figure 12.- Continued.



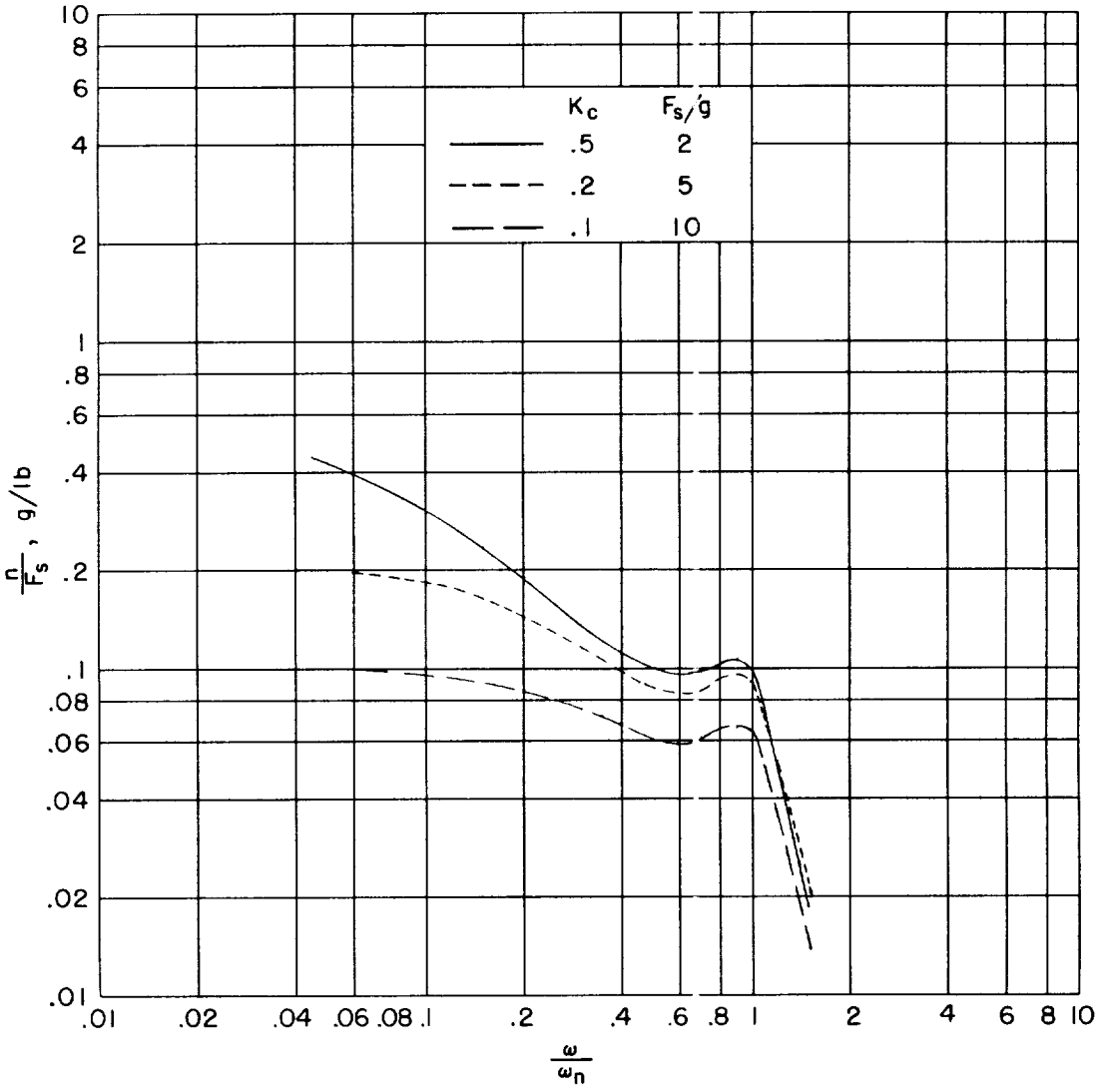
(f) Simulator, pilot B; pitch response.

Figure 12.- Continued.



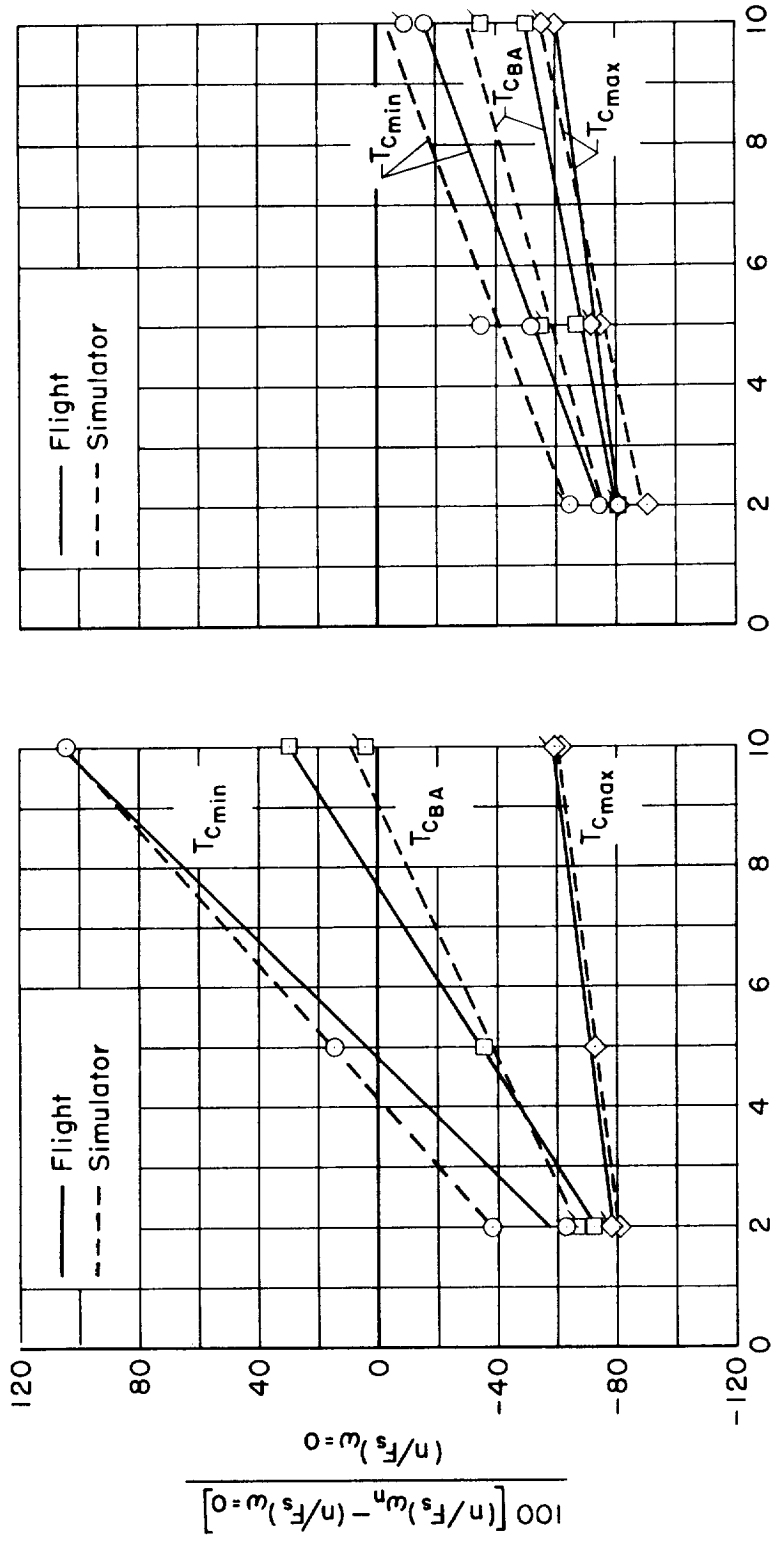
(g) Flight, pilot B; normal-acceleration response.

Figure 12.- Continued.



(h) Simulator, pilot B; normal-acceleration response.

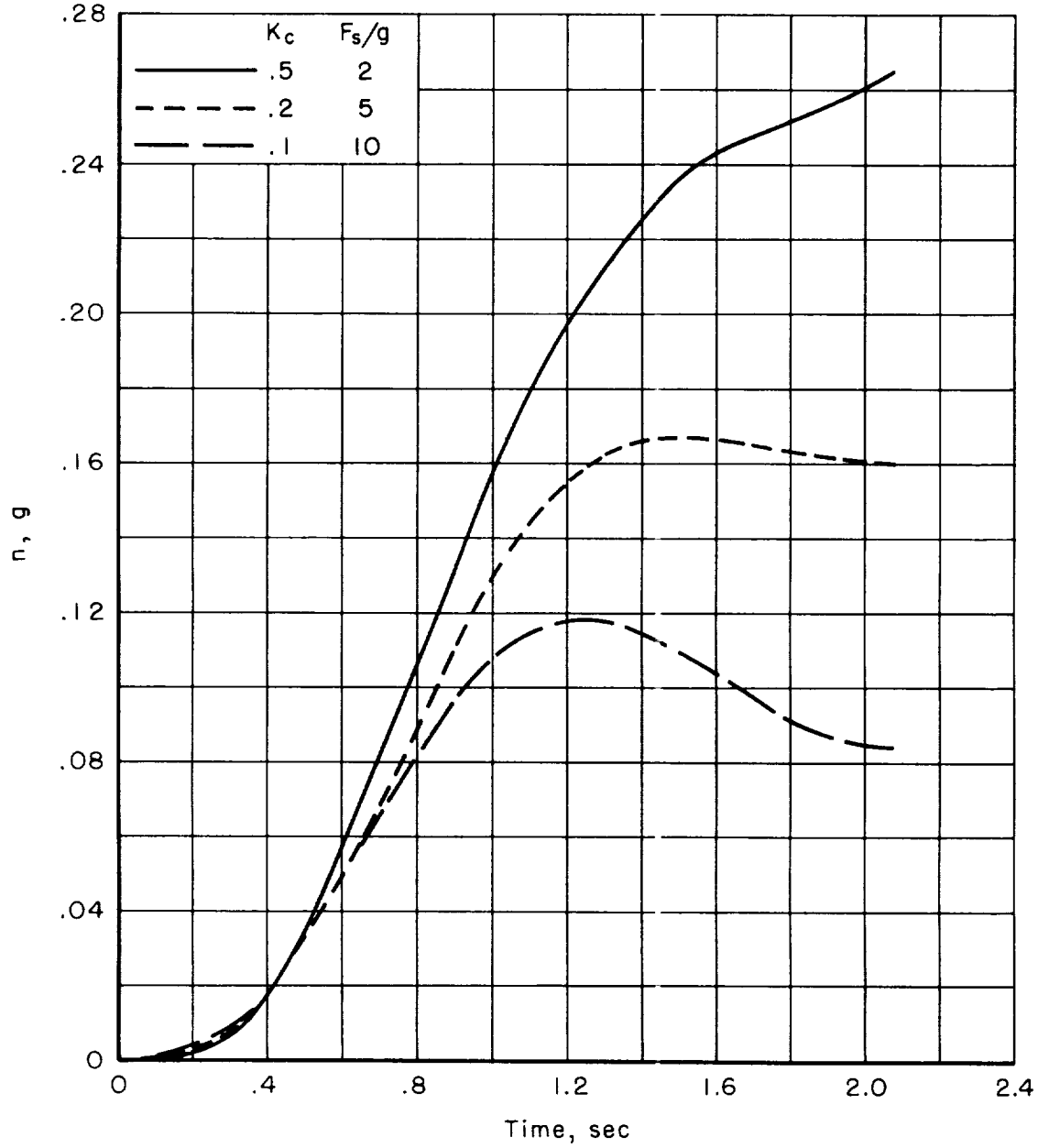
Figure 12.- Concluded.



(a) Pilot A.

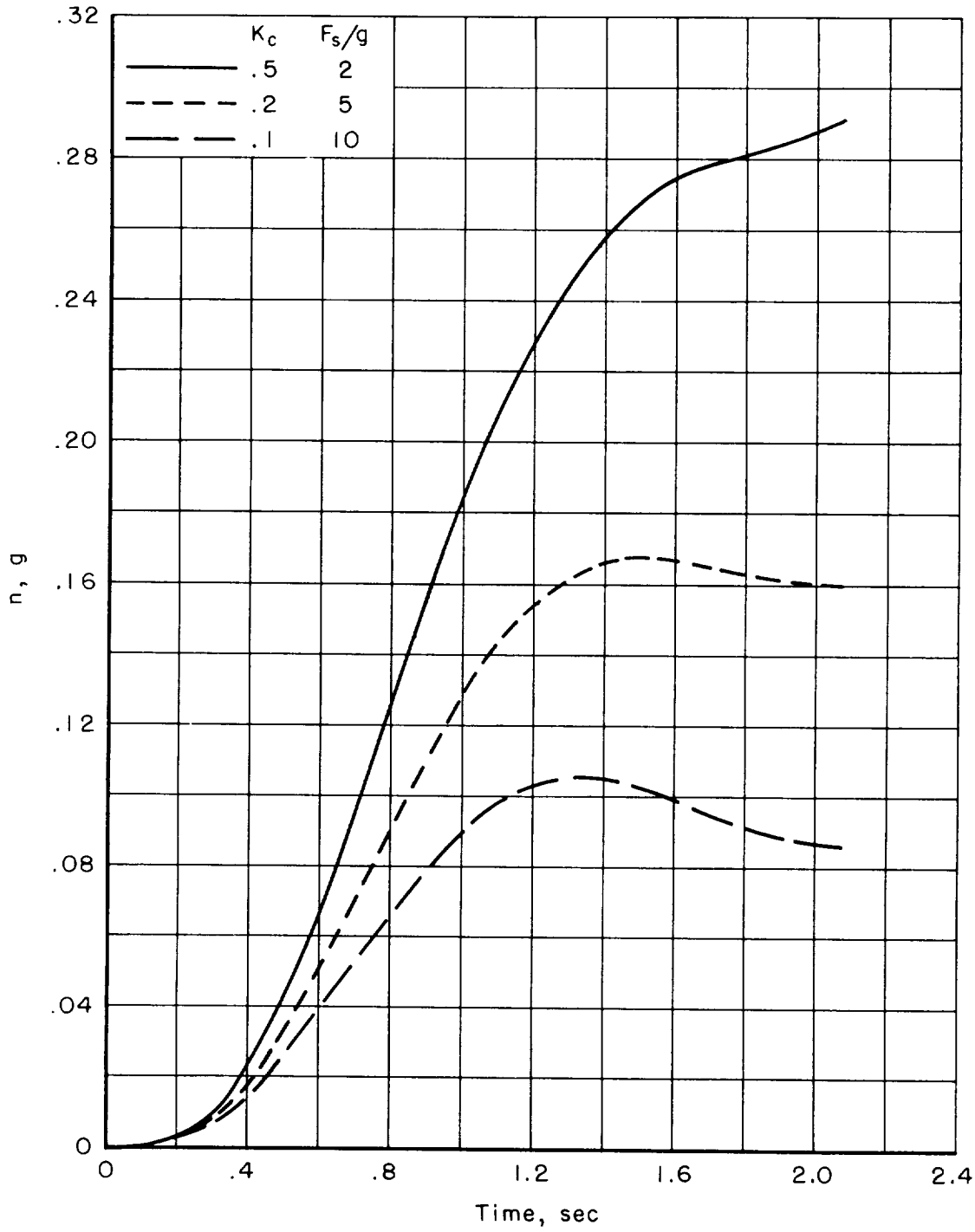
(b) Pilot B.

Figure 13.- Variation with stick force per g of the attenuation (or amplification) of the steady-state ($\omega/\omega_n = 0$) value of n/F_s at the short-period peak.



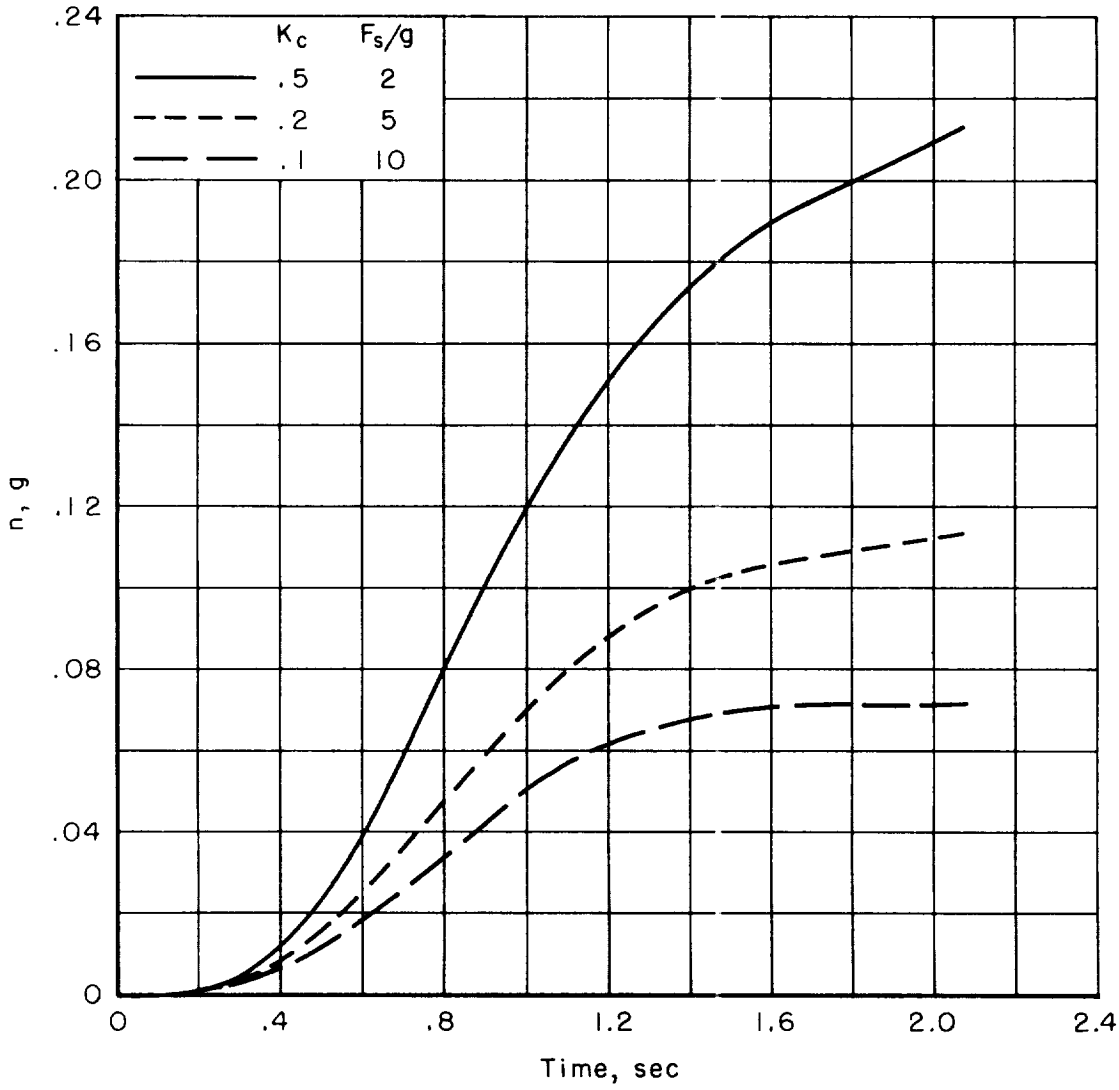
(a) Flight, pilot A.

Figure 14.- Normal-acceleration response to a 1-pound step in stick force for the best available time constants selected by pilots A and B.



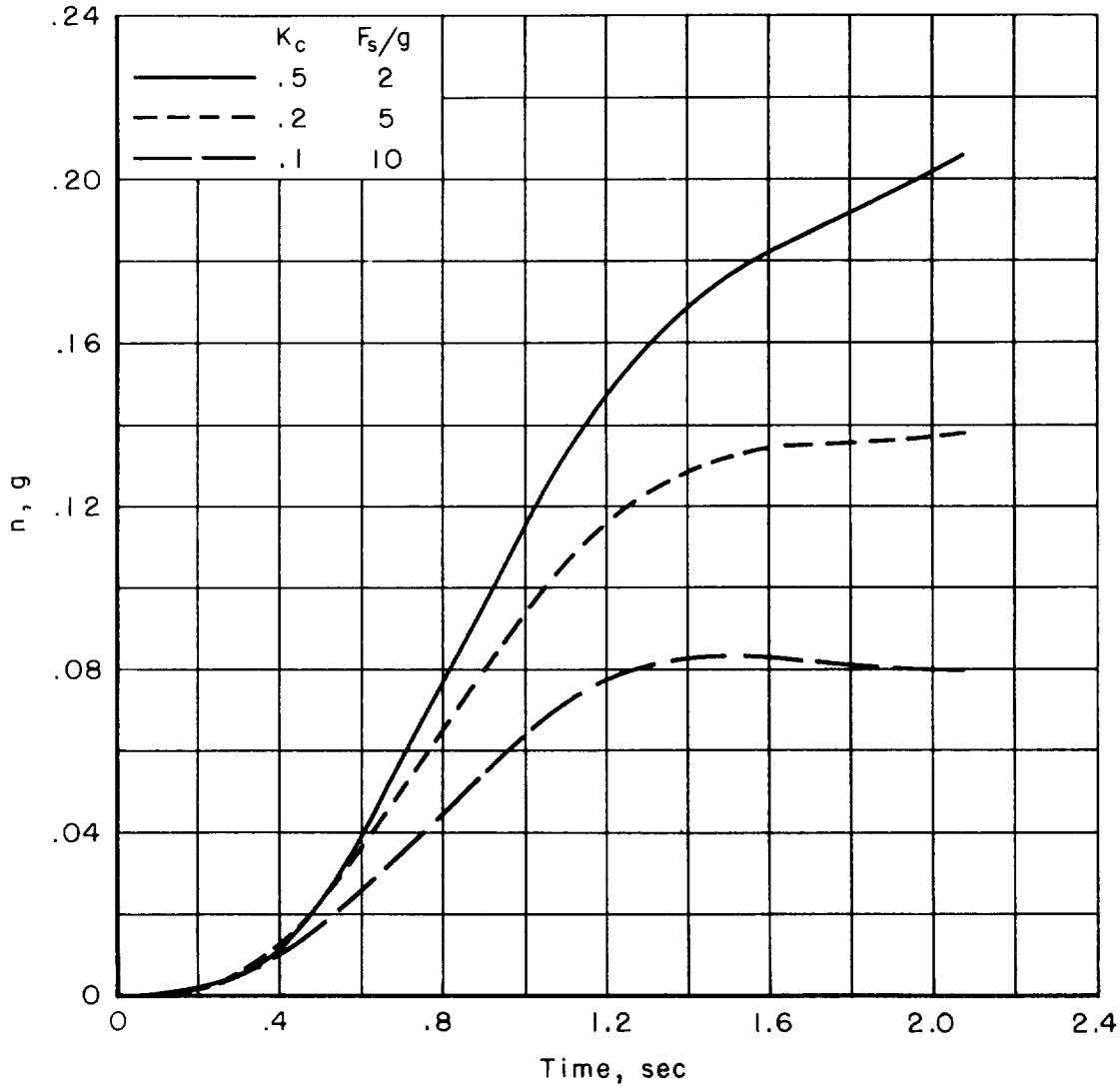
(b) Simulator, pilot A.

Figure 14.- Continued.



(c) Flight, pilot B.

Figure 14.- Continued.



(d) Simulator, pilot B.

Figure 14.- Concluded.

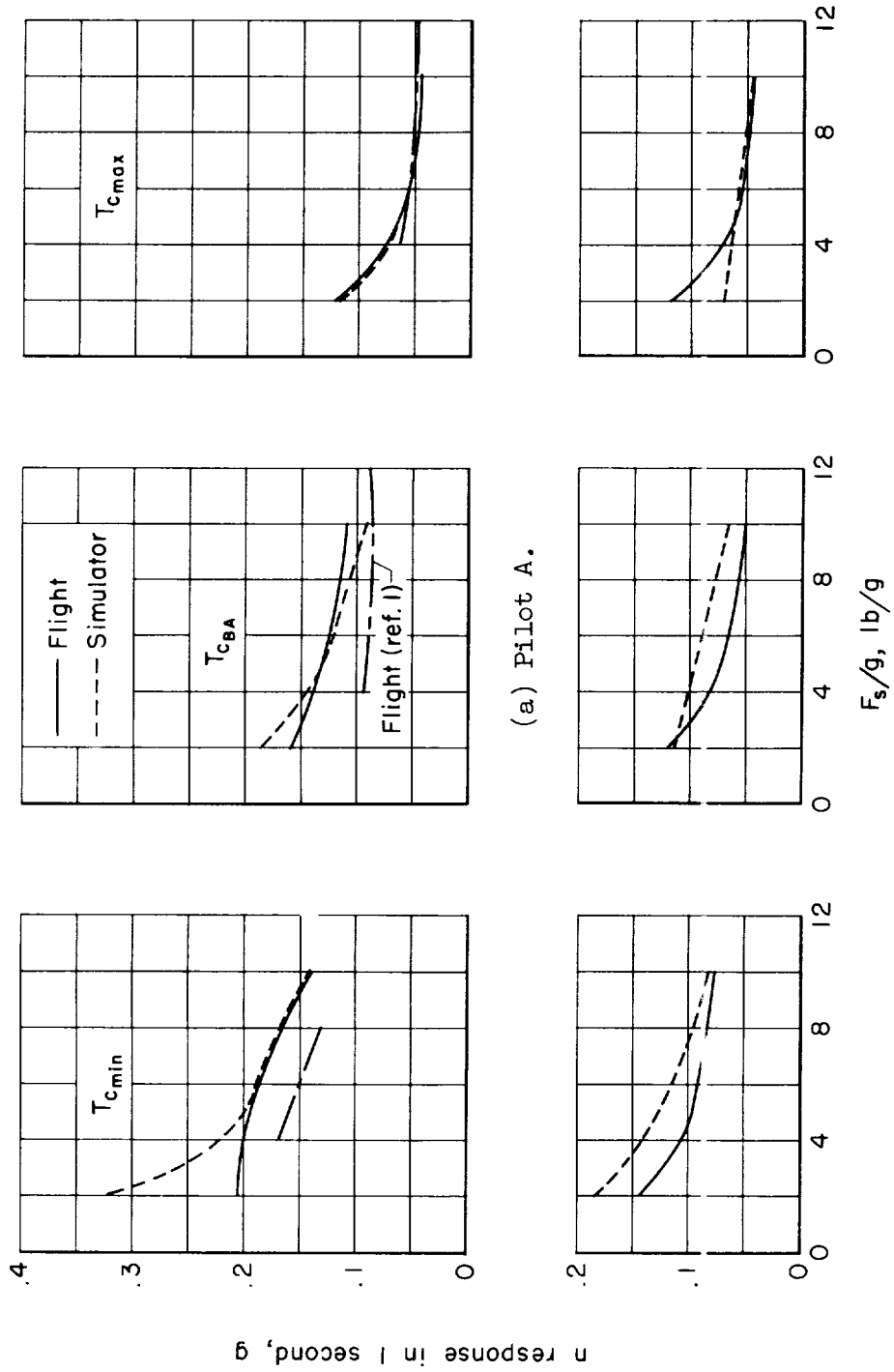
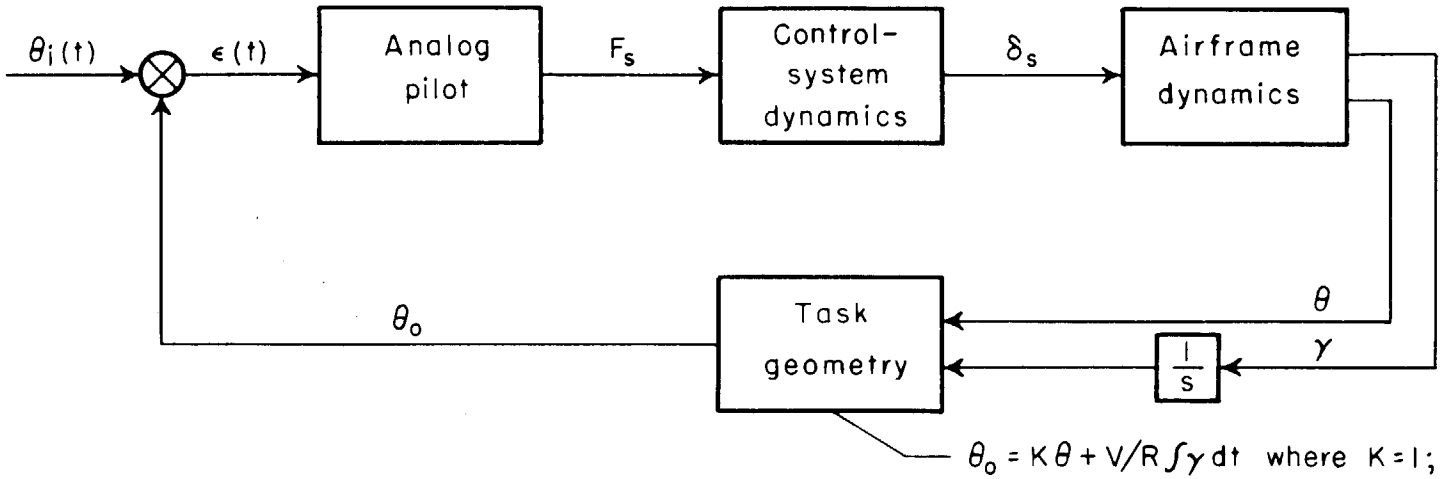


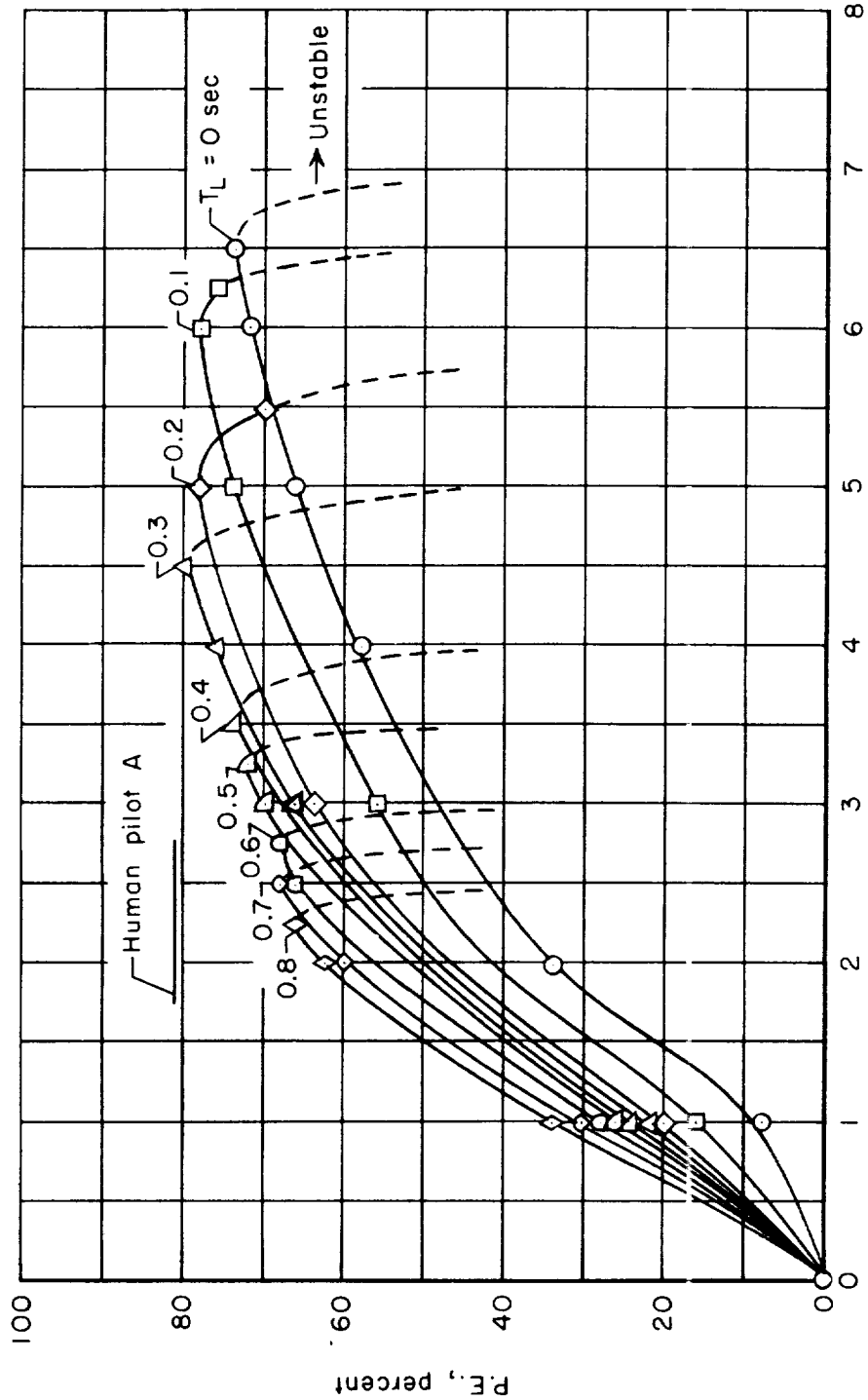
Figure 15.- Variation with F_s/g of the normal-acceleration response the first second to an applied stick-force step of 1 pound.



$$\frac{F_S}{\epsilon} = \frac{K_p e^{-\tau_p s}(1 + T_L s)}{(1 + T_I s)(1 + T_N s)} \quad ; \quad \frac{\delta_S}{(F_S - F_{S_D})} = \frac{K_c}{1 + T_c s} \quad ; \quad \frac{\theta}{\delta_S} = \frac{K_{\dot\theta}(1 + T_{\dot\theta} s)}{s\left(\frac{s^2}{\omega_n^2} + \frac{2\zeta s}{\omega_n} + 1\right)}$$

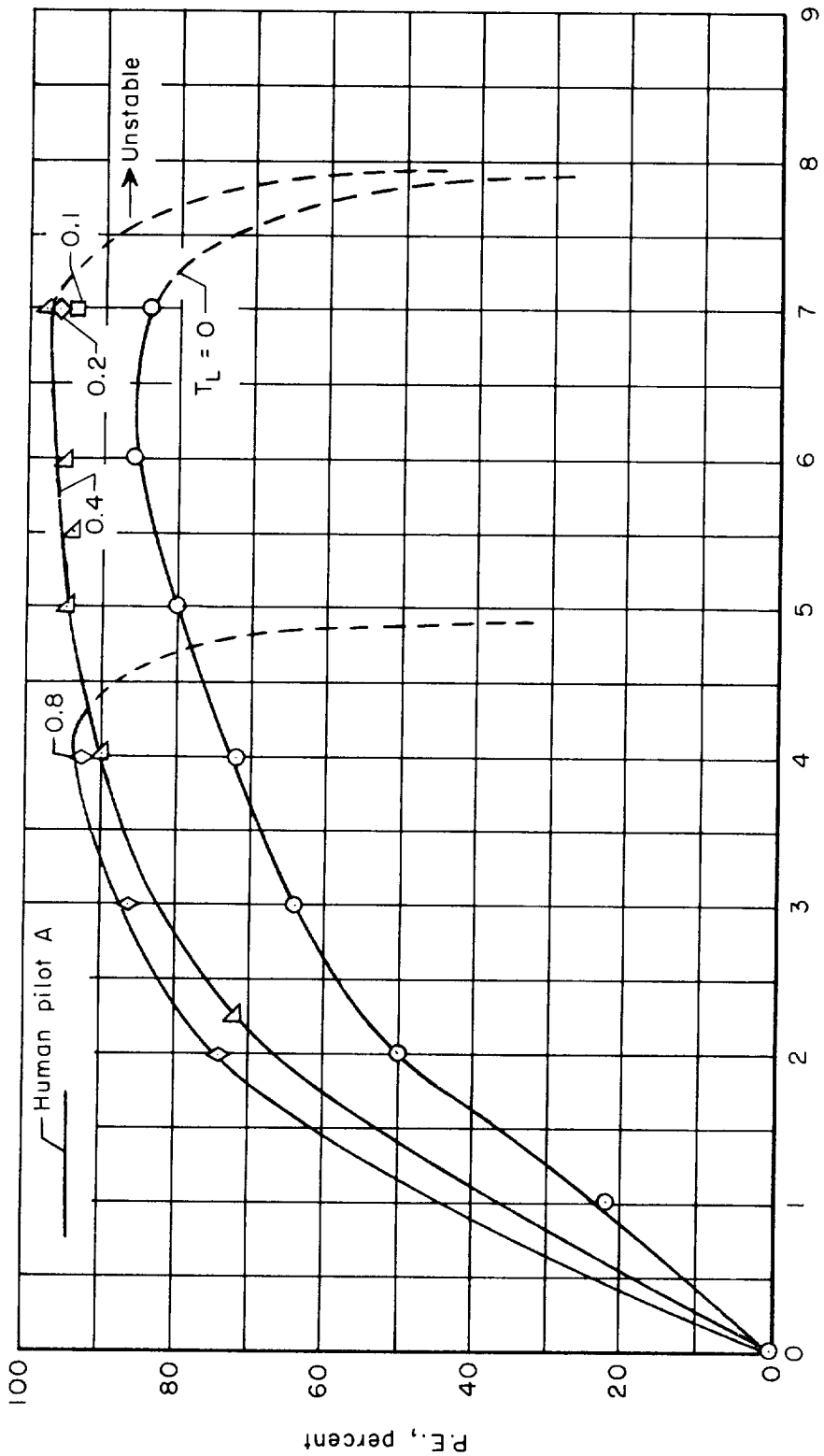
$$\left(e^{-\tau_p s} \approx \frac{\tau_p s^2 - 6\tau_p s + 12}{\tau_p s^2 + 6\tau_p s + 12}\right)$$

Figure 16.- Block diagram of variable control feel simulator with analog pilot.



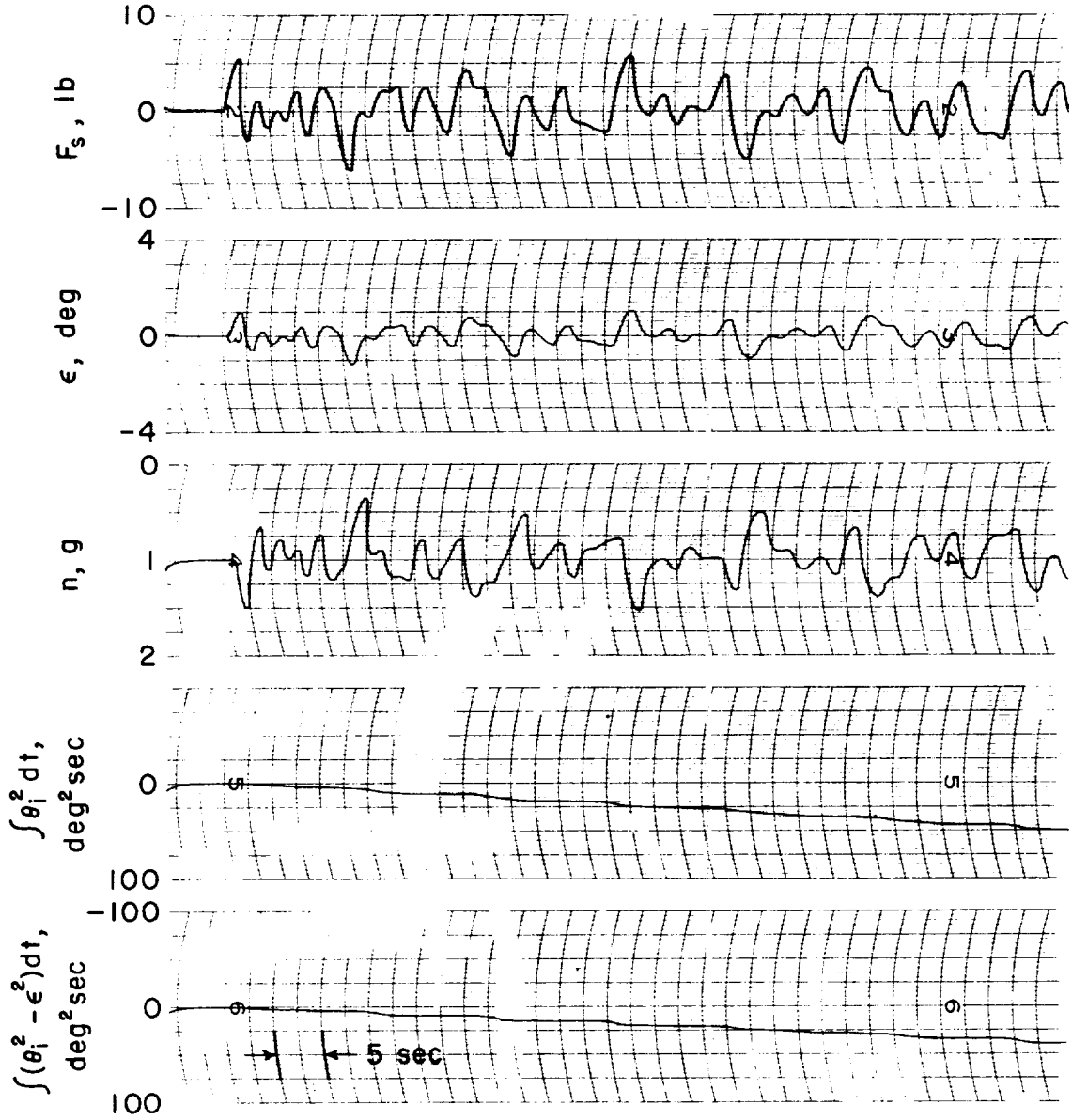
(a) YF-86D; F_s/g = 10; Tc_{BA} = 0.6; ω_n = 3.63 radians/sec; ζ = 0.20.

Figure 17.- Representative pilot-analog tracking-performance characteristics.



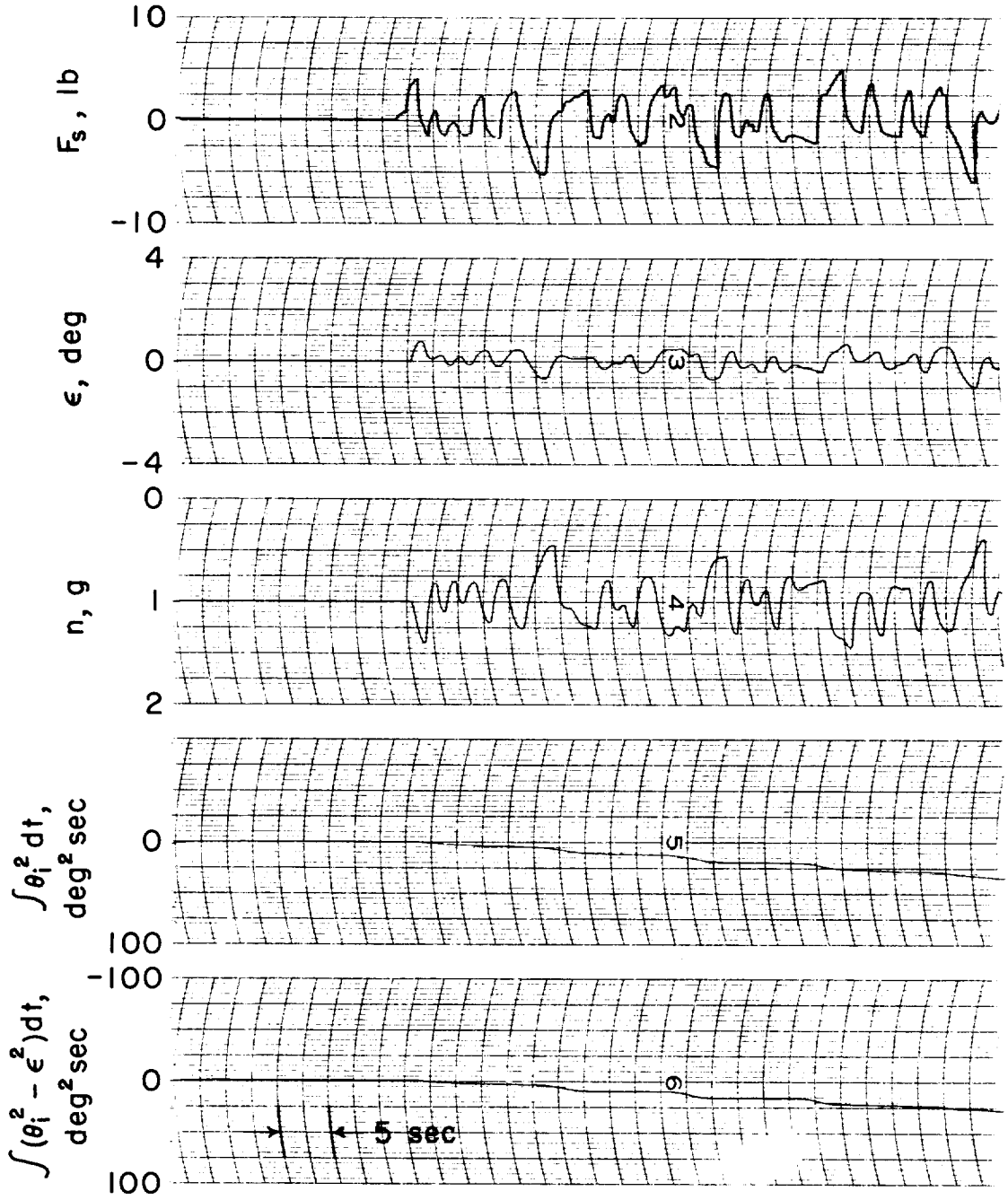
(b) F-94A; Fs/g = 8.6; Tc = 0.05; ω_n = 3.26 radians/sec; ζ = 0.70.

Figure 17.- Concluded.



(a) Pilot analog; K_p = 6 lbs/deg; T_L = 0.1 sec.

Figure 18.- Representative pilot-analog and human pilot tracking time histories for optimum control-system configuration; F_s/g = 10, $T_{C_{BA}}$ = 0.60.



(b) Pilot A.

Figure 18.- Concluded.

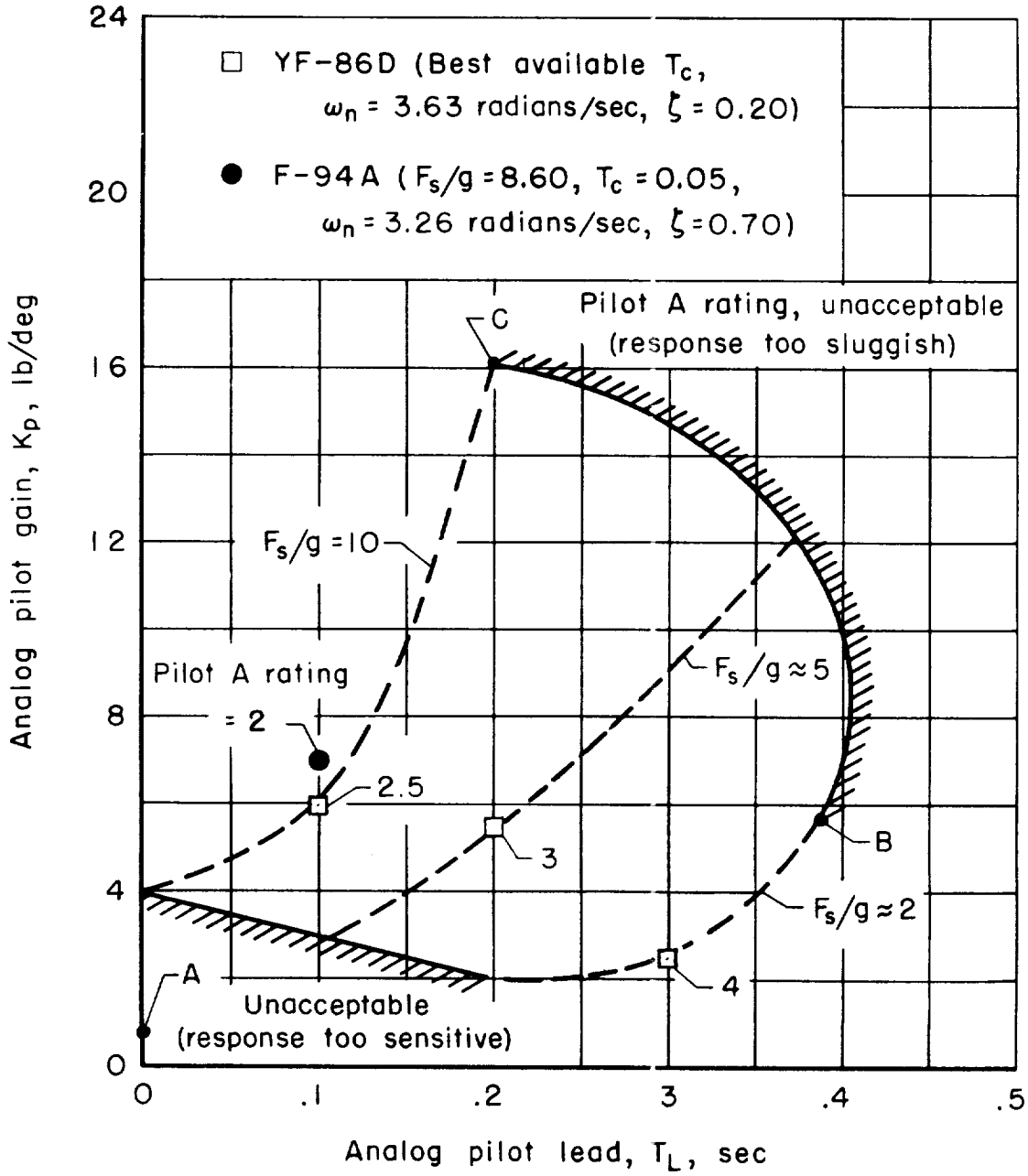
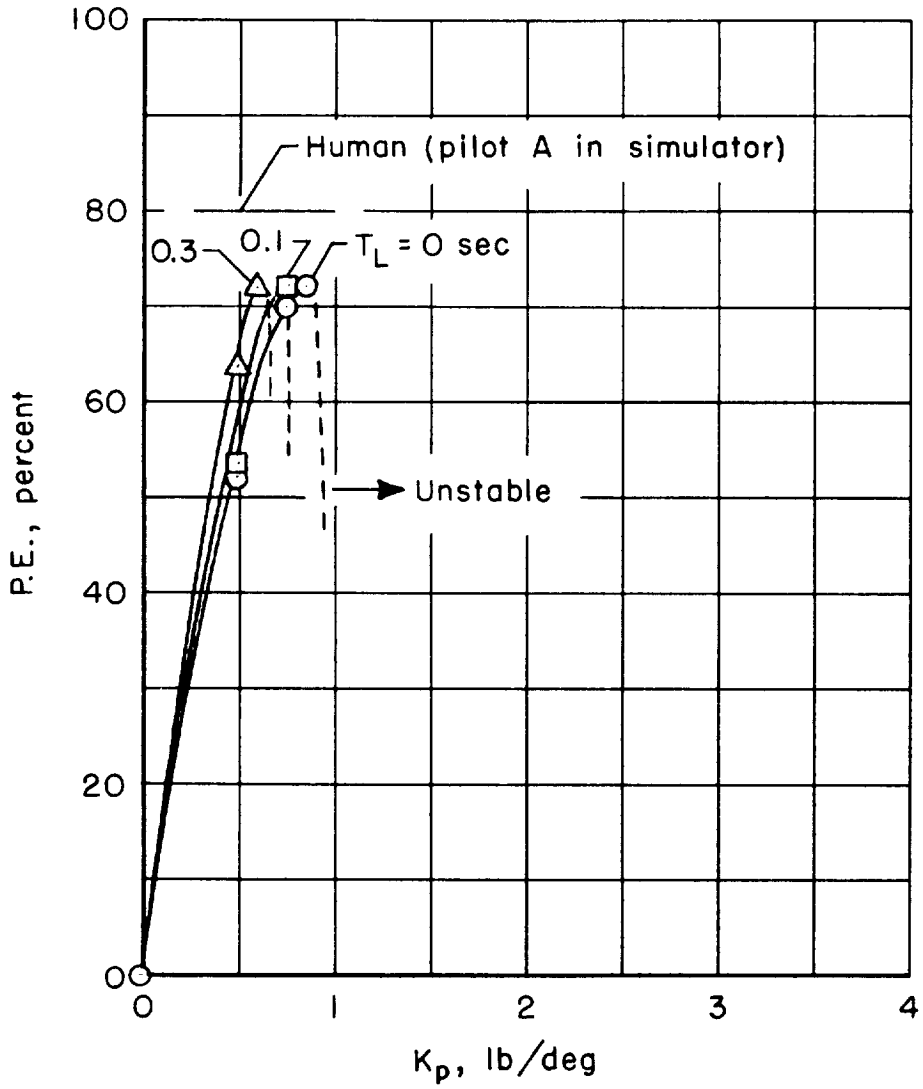
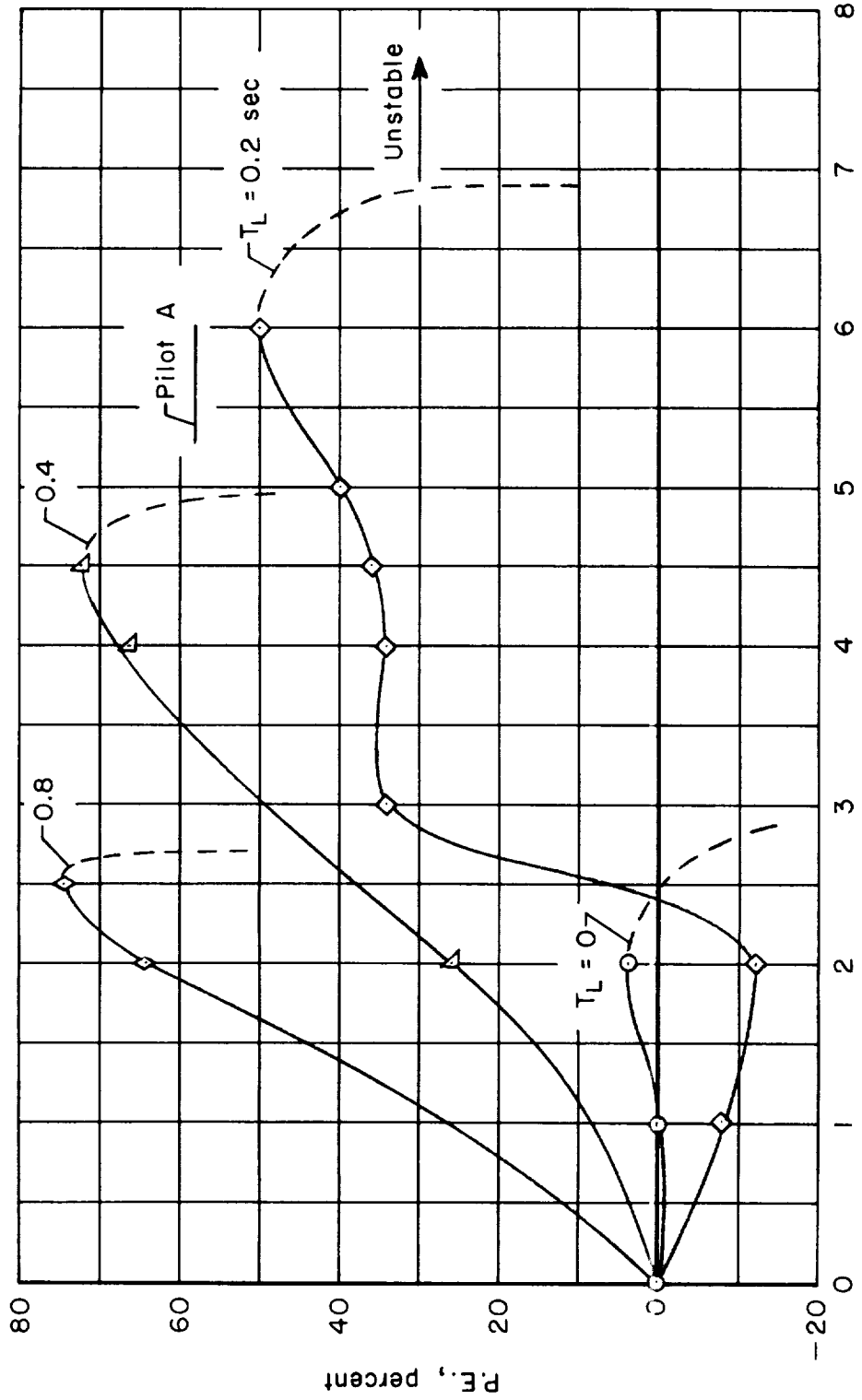


Figure 19.- Summary of pilot operator characteristics adjusted for analog-pilot tracking performance equivalent to that for pilot A.



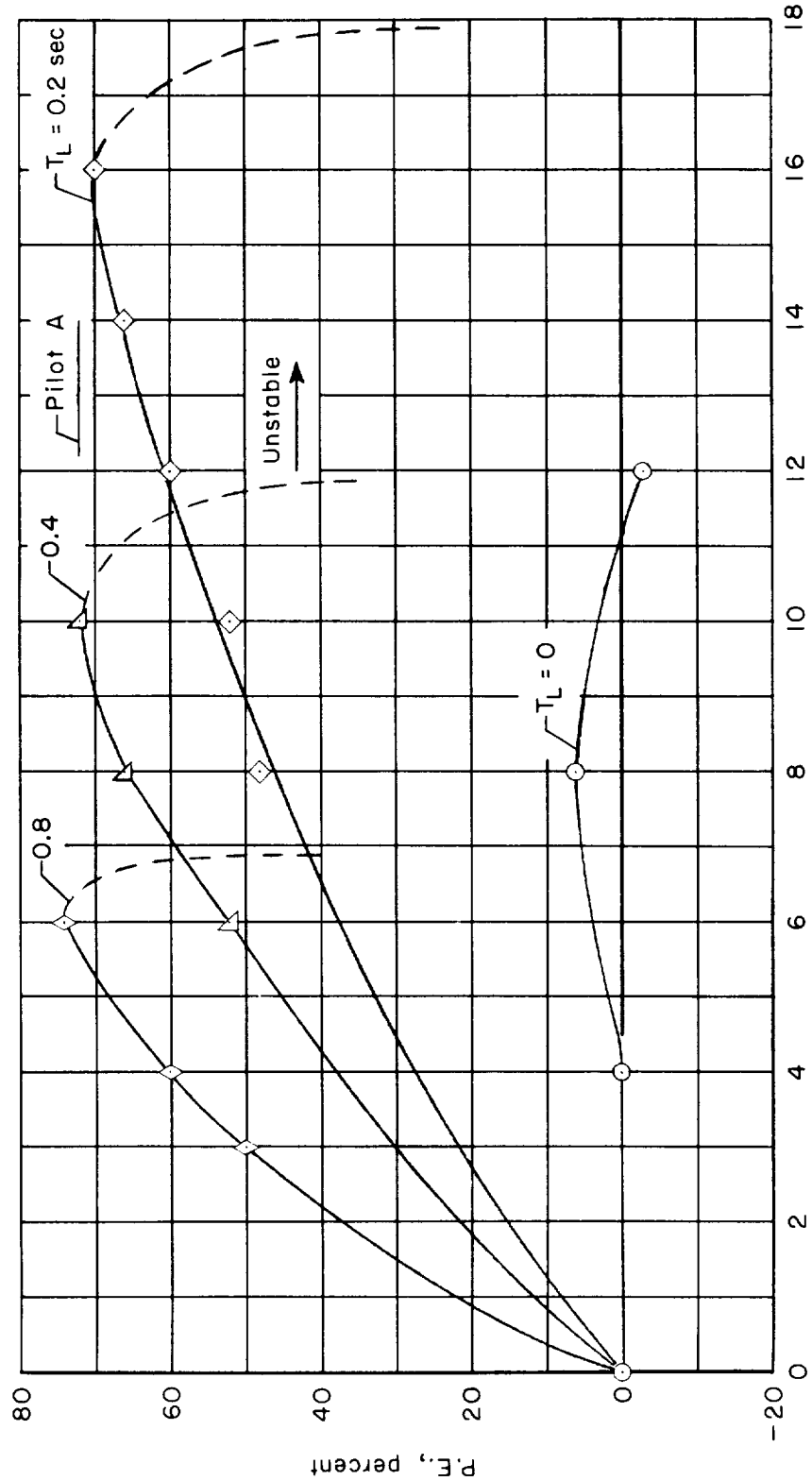
(a) Problem area A (extremely sensitive response in simulator; pilot-induced oscillations in flight; $F_s/g = 2.0$; $T_c = 0.2$).

Figure 20.- Pilot-analog response characteristics for several problem areas defined in flight and fixed-base simulator studies.



(b) Problem area B (sluggish response; $F_s/g = 2.0$; $T_{c_{max}} = 3.40$).

Figure 20.- Continued.



(c) Problem area C (sluggish response; F_s/g = 10.0; Tc_{max} = 1.70).

Figure 20.- Concluded.