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A STUDY OF LONGITUDINAL CONTROL PROBLEMS AT LOW AND NEGATIVE DAMPING AND STABILITY WITH EMPHASIS ON EFFECTS OF MOTION CUES

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SUMMARY

As part of a general investigation to determine the effects of simulator motions on pilot opinion and task performance over a wide range of vehicle longitudinal dynamics, a cooperative NASA-AMAL program was conducted on the centrifuge at Johnsville, Pennsylvania. The test parameters and measurements for this program duplicated those of earlier studies made at Ames Research Center with a variable-stability airplane and with a pitch-roll chair flight simulator. Particular emphasis was placed on the minimum basic damping and stability the pilots would accept and on the minimum dynamics they considered controllable in the event of stability-augmentation system failure.

Results of the centrifuge-simulator program indicated that small positive damping was required by the pilots over most of the frequency range covered for configurations rated acceptable for emergency conditions only (e.g., failure of a pitch damper). It was shown that the pilot's tolerance for unstable dynamics was dependent primarily on the value of damping. For configurations rated acceptable for emergency operation only, the allowable instability and damping corresponded to a divergence time to double amplitude of about 1 second.

Comparisons were made of centrifuge, pitch-chair and fixed-cockpit simulator tests with flight tests. Pilot ratings indicated that the effects of incomplete or spurious motion cues provided by these three modes of simulation were important only for high-frequency, lightly damped dynamics or unstable, moderately damped dynamics. The pitch-chair simulation, which provided accurate angular-acceleration cues to the pilot, compared most favorably with flight. For the centrifuge simulation, which furnished accurate normal accelerations but spurious pitching and longitudinal accelerations, there was a deterioration of pilots' opinion relative to flight results.

Results of simulator studies with an analog pilot replacing the human pilot illustrated the adaptive capability of human pilots in coping with the wide range of vehicle dynamics and the control problems covered

in this study. It was shown that pilot-response characteristics, deduced by the analog-pilot method, could be related to pilot opinion. Possible application of these results for predicting flight-control problems was illustrated by means of an example control-problem analysis.

The results of a brief evaluation of a pencil-type side-arm controller in the centrifuge showed a considerable improvement in the pilots' ability to cope with high-frequency, low-damping dynamics, compared to results obtained with the center stick. This improvement with the pencil controller was attributed primarily to a marked reduction in the adverse effects of large and exaggerated pitching and longitudinal accelerations on pilot control precision.

INTRODUCTION

A number of flight and simulator studies have investigated the range of vehicle dynamics which pilots consider desirable and the range they can cope with in the event of stability-augmenter failure (e.g., refs. 1 to 7). However, relatively little systematic work has been done in correlating these results in order to determine the accuracy with which simulator studies of advanced vehicle control problems can be extrapolated to flight. Some information bearing on this problem is provided in references 8 to 13.

As part of a general study of the adequacy of ground-based flight simulators, a cooperative NASA-AMAL program was conducted on the centrifuge at the Naval Air Development Center, Johnsville, Pennsylvania, to determine the effects of centrifuge motions on task performance and pilots' opinions of a wide range of vehicle longitudinal short-period dynamics. The range of vehicle dynamics corresponded to that of earlier studies made at Ames Research Center with a variable-stability airplane and with a pitch-roll chair flight simulator. Most of the centrifuge program was conducted with a conventional center stick similar to that used in the previous flight and pitch-chair studies; however, a brief evaluation of a pencil-type side-arm controller was also made to determine for certain problem areas the control improvement that might be realized with this type of controller.

The present study has three main objectives: First, the centrifuge flight-simulator results are examined to identify major longitudinal-control problems in terms of vehicle dynamics and pilots' task performance and to define the minimum damping and stability the pilots will accept in the event of failure of the stability augmenter. Second, the effects of incomplete or spurious kinesthetic or vestibular motion cues on control problem simulation are shown by comparing centrifuge, pitch-chair, and fixed-cockpit results with flight-test results. Third, simulator results with a linear analog model replacing the human pilot are analyzed to determine whether pilot-response characteristics deduced by this method can be related to pilot opinion, thereby making it feasible to predict flight control problems analytically.

SYMBOLS

A_N	vehicle normal acceleration factor (ratio of accelerating force to weight), g
ΔA_N	perturbations in vehicle normal acceleration factor relative to trim or bias g, g
A_X	vehicle longitudinal acceleration factor, g
A_Y	vehicle lateral acceleration factor, g
$\bar{c}$	wing mean aerodynamic chord of test vehicle
C_{o_q}	numerator constant in pitch transfer function, $1/\text{sec}^3$
C_{1_q}	numerator constant in pitch transfer function, $1/\text{sec}^2$
F_s	pilot stick force, lb
g	acceleration of gravity, $1\ g = 32.2\ \text{ft/sec}^2$
K_p	pilot-analog static gain, lb/deg
K_c	control-system static gain, δ_s/F_s, deg/lb
K_n	numerator constant in normal acceleration transfer function, $1/\text{sec}^2$
L	centrifuge arm length, ft
P	centrifuge inner gimbal (pitch) angle
R	centrifuge outer gimbal (roll) angle
s	Laplace transform variable
t	time, sec
T_c	control-system first-order lag, sec
T_I	pilot-analog first-order lag representing smoothing of error, sec
T_L	pilot-analog first-order lead, sec
T_N	pilot-analog first-order-lag approximation to neuromuscular lag, sec

δ_s	stabilizer deflection, deg
ϵ	tracking error, deg
ω_n	vehicle undamped short-period natural frequency in pitch, radian/sec
ω	angular velocity of centrifuge arm, radian/sec
$\dot{\omega}$	angular acceleration of centrifuge arm, radian/sec^2
τ	pilot-analog visual reaction time, sec
ζ	vehicle short-period damping ratio in pitch
θ	vehicle pitch attitude, deg
θ_i	target motion, deg

CENTRIFUGE FLIGHT SIMULATOR SETUP

General Description

A block diagram of the closed-loop simulator setup used for the AMAL centrifuge portion of the program is shown in figure 1. As indicated, the tracking task, control-system dynamics, aircraft dynamics, and the coordinate conversion system were set up on the analog computer. The stick force applied by the pilot was converted to normal-acceleration perturbations (ΔA_N) and pitch angle through the transfer-function relationships shown. The computed normal accelerations were then transformed by the coordinate conversion analog into centrifuge commands. (A detailed discussion of the centrifuge operation and capabilities is provided in refs. 14 to 17.) The centrifuge cab included a contoured seat with restraint for the pilot, a force-command center stick similar to that used in the flight study, and a display presenting conventional pitch-attitude information to the pilot, as well as simulated target motion. The bungee used to restrain the stick provided about 10 pounds stick force per inch of stick deflection. Maximum stick deflection was about ±4 inches. The pilot-restraint system was not critical for this study, since the accelerations encountered were in the relatively low range of 2g to 4g. The system used was a portion of that described in detail in reference 18. A photograph of the interior of the cab as modified for the present study is shown in figure 2.

Coordinate Conversion System

During the initial phases of the centrifuge program, considerable effort was expended in optimizing the coordinate conversion system for this study. What was desired was accurate reproduction of the normal-acceleration perturbations with minimum introduction of spurious rolling, longitudinal, and lateral accelerations. A total of 16 different schemes were tried and the system finally selected was a compromise between accurate reproduction of normal acceleration, pilots' impressions of the realism of the simulation, and minimization of longitudinal and lateral linear accelerations and rolling angular accelerations. In order to minimize these extraneous motions, the work was conducted at a bias trim normal acceleration of 3g. That is, the normal-acceleration pertubations were referred to 3g rather than 1g to avoid the disorienting effects on the pilot characteristics of centrifuge operation at lower g levels. The pilots generally felt that this bias g had little effect on their ability to evaluate a given set of dynamics.

Some of the results obtained during the coordinate conversion evaluation and a detailed description of two of the coordinate conversion analogs tested are presented in appendix A.

TESTS AND PROCEDURE

Since one of the primary purposes of the centrifuge program was to compare the results with those of a previous flight study, the control system and airframe dynamics were matched to those of the aircraft for the particular test conditions of the flight investigation. Specifically, the invariant constants in the pitch-transfer function C_{0q} and C_{1q} (see fig. 1) were set at 25 and the control system time constant T_c was fixed at 0.1 second to correspond to the airplane values. Variations in ω_n^2 from 1 to 36 and in $2\zeta\omega_n$ from 10 to -1 were evaluated with the stick force per g held constant at 8 pounds per g. This was accomplished both in the airplane and simulator tests by varying the control-system gain K_c as ω_n^2 was varied. Tests were also conducted for values of ω_n^2 from -1 to -10 (corresponding to negative maneuver margins of -1 percent to -13 percent $\bar{c}$) for damping $2\zeta\omega_n$ of 0.5, 4, and 8. For these latter tests, the control-system gain was fixed at 0.14° per pound. Most of these tests were conducted with a force-command center stick similar to that used in the flight tests. However, a brief evaluation of a pencil-type side-arm controller was also made. Photographs of the pencil-controller installation and the pilot arm restraint used for this portion of the program are shown in figures 3(a) and 3(b), respectively.

The test conditions described were evaluated by six experienced test pilots, including four from the NASA, and one each from the Naval and Air Force Flight Test Centers. Both static and dynamic evaluation runs were made for each set of airframe dynamics. The evaluation procedure used by the pilots was to "feel out" the pitch attitude and normal-acceleration response to stick-force commands. When the pilot considered himself familiar with the particular test condition, he was asked to perform pitch-angle and normal-acceleration transitions of about 3° and 1g, respectively, as abruptly as possible consistent with the vehicle dynamics being evaluated. He was then given a tracking task of one minute duration which simulated tracking the horizon in turbulent air with a fixed sight. The target motion comprised the sum of four sine waves to provide a random-appearing motion to the pilot. The pilot's tracking score was computed from the relationship $100[1-(\int\epsilon^2 dt/\int\theta_i{}^2 dt)]$ and is a measure of the pilot's ability to minimize the mean square error relative to the mean square target motion. For this study the mean square target motion was about $(0.6^{\circ})^2$ with maximum excursions of about 2°. Additional details of the tracking task used are presented in reference 10. The pilot was then asked to assign a numerical rating on the over-all controllability and tracking characteristics of the simulated airplane, assuming a mission typical of a current operational fighter.

RESULTS AND DISCUSSION OF CENTRIFUGE TESTS

Pilot's Evaluations of Vehicle Longitudinal Dynamics

Basic data from the centrifuge tests showing the variation of pilots' ratings with damping at several constant values of $\omega_n{}^2$ and with $\omega_n{}^2$ at several constant values of damping are presented in figures 4(a) and 5(a), respectively. Results are presented both for constant stick force per g of about 8 pounds per g (fig. 4) and for a constant control gain K_c of 0.14° per pound (fig. 5). The pilot rating schedule (table I) is a standard system used at Ames Research Center for the past several years and is described in detail in reference 19. The scatter of about two rating points for "good dynamics" is the normal variability between pilots or between repeat runs for the same pilot. These basic data for the six participating test pilots were averaged, faired, and replotted to define regions of constant pilot opinion in terms of vehicle longitudinal dynamics.

Stable dynamics.- The faired results for stable dynamics (positive $\omega_n{}^2$) are presented in figure 6. Shown are regions of satisfactory, unsatisfactory, and unacceptable dynamics expressed in terms of $\omega_n{}^2$, the square of the vehicle undamped natural frequency in pitch, and the damping, $2\zeta\omega_n$. For a given aircraft, $\omega_n{}^2$ is proportional to the degree of stability or to the maneuver margin. In the ensuing discussion, therefore, it is considered appropriate to use these terms (i.e., $\omega_n{}^2$, stability and maneuver margin) interchangeably. The damping $2\zeta\omega_n$ is inversely proportional to the subsidence time to one-half amplitude of the short-period oscillation. These parameters are those of the characteristic second-order equation used to describe the vehicle motions (see fig. 1). For positive ω_n^2, the motion is either oscillatory or pure subsidence. For the negative ω_n^2 case, to be considered shortly, the vehicle motion is a pure divergence.

It may be seen in figure 6 that the pilots are sensitive primarily to the amount of damping. The minimum damping the pilots considered acceptable for emergency operation (e.g., failure of a pitch damper) corresponds to maximum acceptable subsidence times to one-half amplitude of about 2 to 4 seconds.

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Region I was considered by the pilots to be the most acceptable area. Region II was characterized by a control sensitivity problem; that is, the pilots felt that the stick forces required to maneuver near trim and to track were extremely light, and they found it difficult to avoid inducing continual oscillations. It should be noted that this problem was undoubtedly aggravated by the effects on control precision of the exaggerated fore and aft accelerations impressed on the pilots at the higher frequencies because of deficiencies in the coordinate-conversion analog. (See appendix A.) Region III was characterized both by moderately sensitive control response and by a tendency to overcontrol and exceed the desired response considerably. In region IV, large stick forces were required to maneuver near trim and to track, and an overcontrol tendency was noted. Typical transient-response characteristics for these four regions of vehicle dynamics are presented in figure 7 in terms of the normal-acceleration response from trim for step stick-force commands of 8 pounds.

Since the pilots indicated that with the arm properly restrained, a side-arm controller might be used to advantage in coping with the control sensitivity problem (region II), a pencil-type side-arm controller (fig. 3) was evaluated for the higher frequencies. The results of this study are presented and compared with similar results for the center stick in appendix B.

Unstable dynamics.- Figure 8 presents the faired results of pilots' evaluation of vehicle dynamics extending well into the unstable region (negative ω_n^2). In this case the control-system gain was held constant, since it is obviously not possible to maintain constant stick force per g as the stability is decreased through zero. The particular value of gain selected ($K_c = 0.14^\circ$ per pound)[1] was the same as that used in the previous flight study where the gain was optimized for regions of low and negative static stability and for moderate damping.

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[1] It is interesting to note that the resulting control-power gradient of about 0.5 radian per second^2 per inch of stick travel falls well within the optimum range defined in reference 20 for atmosphere-entry type vehicles.

Comparison of the results in figure 8 with those for constant stick force per g (fig. 6) shows that the pilots will tolerate somewhat lower values of stability if the control gain is increased. For example, the boundaries for pilot ratings of 3.5 and 5 are shifted to near zero stability and to low negative stability at the higher damping levels. (For $\omega_n^2 = 1$, the control power gradient for $K_c = 0.14$ is approximately 10 times that for constant stick force per g.) The results also show the powerful effects of damping on the degree of instability the pilots would tolerate. For damping less than 1, any instability was considered unacceptable while for values of damping of about 4, instability corresponding to negative maneuver margins of up to 4 percent $\bar{c}$ were considered acceptable for emergency operation (e.g., failure of a stability augmenter).[2] Computed transient responses for three sets of vehicle dynamics located on or beyond the boundary between acceptable and unacceptable dynamics are shown in figure 9. These results are indicative of the control problem encountered; that is, the magnitude and rate of divergence of the normal-acceleration response to very small step stick forces ($F_s = 1$ lb), as compared to the results shown in figure 7 for stable dynamics for step stick-force commands of 8 pounds. The increase in negative stability with damping along constant pilot opinion contours (fig. 8) corresponds to essentially constant divergence times to double amplitude over most of the damping range. This is shown more clearly in figure 10 where contours of constant pilot opinion are plotted as a function of damping and of the reciprocal of time to double amplitude. These results suggest that pilot opinion is related to divergence time rather than to the degree of instability.

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Effects of Vehicle Dynamics on Pilots' Task Performance

The pilots were asked to perform two evaluation tasks during each test run. One task was to perform pitch-angle and normal-acceleration transitions, and the other was the simulated long-range tracking task. Since the tracking task was generally considered more difficult than the transition task, the pilots' ability to perform the former over the complete range of short-period dynamics covered in this study will be examined.

Basic results showing the effects of vehicle longitudinal dynamics on the tracking-task performance of the participating pilots are presented in figures 4 and 5. The results for constant stick force per g are shown in figure 4 and those for constant control gain are given in figure 5. These results indicate that the pilots were able to maintain

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[2] Maneuver margin can be related to ω_n^2 only for a specific airplane and for a specific flight condition. For the particular vehicle and flight conditions simulated in this study, the maneuver margin, in percent $\bar{c}$, is approximately 1.25 ω_n^2.

reasonably high tracking-performance levels over a wide range of vehicle dynamics because of their adaptive capability (i.e., their ability to compensate for variations in vehicle dynamics by varying their response characteristics appropriately to maintain good closed-loop performance of the pilot-airframe system). For extremely poor dynamics, however, the tracking score shows both a marked reduction and a large increase in variability between pilots and between repeat runs for the same pilot relative to the results for good dynamics. This is evident at very low damping, particularly at the higher short-period frequencies (fig. 4) and at low and negative stability (fig. 5). These results indicate that the pilots were able to adapt or to compensate only partially for very poor vehicle dynamics.[3]

Figure 11 was prepared to illustrate more clearly the relative deterioration in task performance in the several regions discussed in the previous section for stable and unstable dynamics. Comparative average tracking scores are shown for the six pilots for regions I, II, III, and IV for stable dynamics, and for lightly damped and moderately damped unstable configurations. It is apparent that the greatest reductions in tracking efficiency occur for region II (low damping, high frequency) and for lightly damped, unstable dynamics. An appreciation of the pilots' problem in performing the tracking task with reasonable proficiency may be gained by referring back to the associated transient-response characteristics (figs. 7 and 9). It is clear that the initial abrupt g response, followed by rapid, lightly damped oscillations (region II, fig. 7), and the magnitude and rate of divergence of the g response for very small control inputs for lightly damped, unstable dynamics (fig. 9) preclude the precise control required to track well. As pointed out in appendix B, the use of a pencil-type controller minimized the reduction in task performance observed for region II.

Since the pilots base their opinion, at least in part, on their ability to perform the tracking task, it is reasonable to assume that some interdependence between pilot opinion and task performance exists. To obtain a measure of this correlation, the basic data in figures 4 and 5 were replotted in figure 12. Although the results show that pilot opinion is roughly related to tracking score, the correlation is considered fairly poor. The poor correlation is typical of previous efforts made to correlate pilot performance with pilot opinion (refs. 3 and 10) and is attributable to the fact that this type of correlation does not account for the pilot effort or pilot response required to obtain a given level of task performance.

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[3] There is also some evidence provided in reference 21 which indicates that the pilots' ability to compensate for poor vehicle dynamics was further impaired as the steady-state acceleration field exceeded the 3g level of the present tests.

COMPARISON OF FLIGHT AND SIMULATOR RESULTS

The previous sections of this paper identified some of the major longitudinal-control problems in terms of pilots' evaluations and task performance. In this section corresponding data from three different simulators are compared with flight-test results to study the effects of the various incomplete or spurious motion inputs or cues supplied to the pilot. Since only one pilot, pilot B of Ames Research Center, participated in all simulator programs, as well as in the flight study, comparisons are available only for this one pilot. However, since his evaluations during the centrifuge program agreed fairly well with the average for all six participating pilots, the following results may be considered fairly general. Two of the regions where significant differences in the pilots' evaluations were observed will be considered first since this is where the selection of simulators for research will be the most critical.

Pilot Opinion

In figure 13, the flight-test results are compared with three stages of motion simulation. The particular centrifuge used has three degrees of freedom - two angular rotations and linear translation in a circle. The desired linear normal accelerations were matched with flight, but this had to be done at the expense of exaggerated angular accelerations in pitch and spurious fore-and-aft accelerations. The pitch-roll chair has two rotational degrees of freedom to match the angular accelerations in flight, but no linear motion. The fixed cockpit, of course, furnishes no motion inputs and the pilot has only the visual instrument display.

In figure 13(a) the four sets of pilot-opinion data are compared as functions of damping (at high short-period frequency) or stability. The first thing to be noted is that all of the curves show fairly good general agreement. However, at low damping where the pilot has difficulty, the centrifuge and fixed-cockpit simulator become somewhat more difficult to control and are rated worse than flight or the pitch-roll chair. This result was unexpected since it was felt that motion inputs would generally have an adverse effect on pilots' ability to control a lightly damped vehicle. Apparently, the correct angular accelerations provided by the pitch-roll chair and in flight are beneficial, while the masking of the correct normal accelerations by spurious centrifuge motions precludes an assessment of the importance of normal-acceleration feedback to the pilot in this particular control problem.

Figure 13(b) shows, for moderate damping, the comparisons of pilot's ratings of stability from various simulators. Again the curves are in general agreement, but the angular acceleration cues in flight and on the pitch-roll chair appear to be beneficial for moderately unstable dynamics. In the region of low positive stability, the simulator results appear somewhat optimistic.

Figure 14 presents a "broad-brush" treatment of the over-all correspondence between simulator and flight results over the complete range of dynamics covered in this study. Centrifuge and pitch-chair pilot ratings are compared with the corresponding flight-test evaluations. (Fixed-cockpit simulator results fall somewhere between these two sets of data.) The correlation is fairly good, indicating that the results of all three modes of simulation extrapolate reasonably well to the flight case. However, a closer look shows somewhat more scatter for the centrifuge correlation, and for extremely poor dynamics (the higher pilot ratings), the centrifuge simulation tends to amplify the flight control problem. This point was considered in detail in figure 13(a). It would appear, for the particular control problems studied, that angular acceleration cues are more important than linear accelerations for accurate simulator evaluations of flight control problems. However, it may be of interest to point out that for this particular study pilots with considerable experience in centrifuge, pitch-chair, and fixed-cockpit simulators preferred the centrifuge because they considered it more realistic; that is, they felt the control technique in the centrifuge more closely approximated that which they used in flight and they were more appreciative and respectful of the major control problems. It is probable that the over-all favorable reaction of the pilots to the centrifuge simulation was primarily due to the effort expended in optimizing the coordinate conversion analog for this investigation. It is clear from the results presented in appendix A that the use of a nonoptimum coordinate-conversion scheme or a lower bias g level would have resulted in somewhat less favorable pilots' impressions and correlation with flight results.

Aside from the favorable subjective impression of the pilots to the centrifuge simulation, the results indicate that for routine studies of flight control problems, where sustained high levels of acceleration are not expected, the use of a fixed-cockpit simulator or a relatively uncomplicated, inexpensive, angular motion simulator, such as the Ames pitch-roll chair, provides an adequate simulation. For a realistic assessment of piloting control problems for unusual flight environments, such as for sustained high g levels during orbital injection and re-entry (e.g., see refs. 21 and 22) or for extended low-level flights in turbulence, the use of a centrifuge or other g producing flight simulator is indicated.

Pilot Tracking Performance

Illustrated in figure 15 are the effects of simulator motions on a pilot's ability to perform the tracking task for the two regions of vehicle dynamics where appreciable differences in pilots' ratings and task performance were observed (i.e., high frequency, low damping, and unstable, moderately damped dynamics). Unfortunately, results are not available for the flight case, since the tracking task was not performed in flight. Briefly, the results in figure 15 show very little effect of motion cues on pilots' task performance over a wide range of damping and stability. However, for very low damping at high frequency, it may be noted that the motion cues provided by the pitch chair were favorable and those supplied by the centrifuge were adverse. The adverse effects of centrifuge motion on pilots' evaluations and task performance for this case were discussed previously. The reason for the favorable effect on task performance of the pitching motions provided by the pitch chair is not readily apparent, since it might be expected that any motion feedback to the pilot would have an adverse effect on control precision for this case. One possible explanation is that small phase lags (due to pitch-chair dynamics) of the order 20° or 30° would tend to increase the system damping with the pilot in the loop.

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For moderately damped, unstable dynamics (fig. 15), the motion cues provided by both the centrifuge and pitch-chair simulators had a favorable effect on task performance. This may be attributable either to greater pilot motivation when motion cues are supplied, or to the additional information provided the pilot, which he is able to use to advantage in this case.

One conclusion to be drawn from these results is that in the selection of simulators for evaluating effects of vehicle dynamics on the pilots' ability to perform a specific control task, much can be accomplished with a static simulator, that is, a simulator which provides only visual cues. However, for accurate assessment of pilot control in critical areas (e.g., failure of dampers or stability-augmentation system), realistic motion cues are necessary but care must be taken to insure that spurious or unrealistic cues do not compromise the results obtained.

ANALOG PILOT STUDIES

The final section of this paper is concerned with studies of a mathematical model of the human pilot. The human pilot is of course a remarkably adaptive controller who constantly changes his response characteristics in order to maintain good performance as his task or the dynamics problem becomes more difficult. His changes can be represented mathematically by the terms of an equation expressing his output or control force as a function of his input, the tracking error signal. If the terms of the equation, or analog pilot, can be related to the dynamics of the airplane and its controls and to the pilot opinions of the dynamics just presented, then it should be possible to use the analog pilot to predict adverse pilot opinions or control problems on a purely analytical basis.

Analog Pilot Model

With this in mind, figure 16 shows the simulator setup with the analog pilot replacing the human pilot. The expression for the analog pilot contains five parameters: a gain K_p, a reaction time τ, a first-order lead term T_L, and two first-order lag terms, T_N, which approximates the human actuator lag, and T_I, a smoothing term. Of these, the reaction time τ and the actuator lag T_N are relatively unalterable by the human pilot and were fixed at 0.2 and 0.1 second as shown. The other three parameters then are presumed to be those that express the changes in the pilot behavior as he copes with changes in the vehicle dynamics, tracking task, and so forth. In this particular study, it was found that the human pilot could be approximated fairly well by changing only the gain and the lead terms; therefore, the smoothing term T_I was fixed at 0.1 second.

Analysis of Pilot-Response Characteristics

The procedure was to present the analog pilot with the same tracking task given the human pilots during the simulator studies. The two variables, the gain and the lead, were then adjusted on the analog computer until the tracking performance matched that of the human pilot.[4] To determine specific values of gain and lead, it was assumed the human pilot optimizes his tracking performance with minimum introduction of lead and for maximum gain consistent with stability considerations of the closed-loop, pilot-aircraft combination. The procedure is illustrated in figure 17, which presents two typical variations of analog pilot tracking performance with gain, at constant values of the lead term. Plots are shown for region I, the best dynamics tested, and for one problem area (region II, high stability and low damping). For the good set of dynamics there is a broad range of gain where fairly good tracking is obtained and the human pilots' performance can be matched with a gain of 5 pounds of control force per degree of tracking error and no lead at all. In contrast, for the poor region where the human pilots complained of control sensitivity, the gain must be reduced to about 1 pound per degree, which is only 2 percent of the total control available. The gain adjustment must be fairly precise if either unstable

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[4] In the present study, the average tracking performance for all pilots during test runs with the centrifuge cab fixed was used as the reference human-pilot tracking level.

operation of the controls or poor tracking scores is to be avoided. Also, a small increase in lead still further reduces the allowable gain variation and the tracking score. The latter result is characteristic of configurations with control-sensitivity problems and is fairly indicative of the information provided by this method of analysis.

The above procedure was applied to the complete range of dynamics covered in the first part of this paper and the results are summarized in figure 18. The range of gain and the lead required to match the human-pilot tracking scores are shown with boundaries to indicate the corresponding human-pilot opinion of the vehicle dynamics. The major control problem areas are identified as in figure 6; that is, region I, good dynamics; region II, high frequency, low damping; region III, low frequency, low damping; and region IV, low frequency, moderate damping. It can be seen that a reasonable general correlation is established between pilots' ratings of satisfactory, unsatisfactory, and unacceptable dynamics and the values of pilot gain and lead required to cope with these dynamics. For example, satisfactory ratings correspond to gain variations of about 3 to 12 pounds per degree of error (about 6 to 25 percent of the total available control) and leads of less than 0.4 second. The small leads the pilots will tolerate for satisfactory ratings indicate that the pilots prefer to operate primarily as a simple gain changer, within the limits noted. On the basis of the general correlation established in figure 18 between pilot rating and pilot-response characteristics, it appears feasible to predict control-problem areas analytically before extensive pilot-operated simulator studies are available. It may be pertinent to point out that the work reported on in reference 23 also deals with the problem of correlating pilot-response data with conventional handling-qualities research results, typified by the data presented in the first section of this paper. In general, the results of the present study and those presented in reference 23 show substantial areas of agreement.

Example Control-Problem Analysis

As an example illustrating possible application of the analog-pilot results for predicting flight-control problems, a longitudinal-control problem recently encountered during the landing approach of a high-performance airplane is examined. For this particular flight, the pitch damper was inoperative and the problem encountered was one of large, apparently pilot-induced, pitch oscillations just prior to touchdown. With the short-period dynamics adjusted to those of the airplane, the tracking performance of the analog pilot was examined with the results shown in figure 19. The results are both for the pitch damper inoperative and operative. The human pilots' averaged tracking scores from fixed-cockpit simulator evaluations are again included for reference. In this case, the human pilots' tracking scores cannot be utilized to predict the gains and leads required. However, use can be made of the fact that the human pilots' tracking performance was found to correspond roughly to the maximum performance of the analog pilot. In the present example, this maximum performance is approximately that shown, that is, about 70 and 85 percent. For the case with the pitch damper off, these results would indicate that the pilots would be required to employ very low gains (of the order of 0.5 pound of control force per degree of tracking error) and considerable lead (of the order of 0.8 second) to attain the predicted level of performance. With the pitch damper on, the allowable gain is increased to about 2 pounds per degree and the required lead reduced to about 0.2 second, both favorable changes. These results are identified in figure 18 as regions A and B. The predicted pilots' ratings (from fig. 18) would be about 6 and 4.5, respectively. Figure 20 presents actual results of pilots' evaluations and tracking performances in a fixed-cockpit simulator for the example control problem. It can be seen that the predicted ratings of about 6 and 4.5 agree reasonably well with the actual ratings of about 5.5 for the pitch damper off and 4 for the pitch damper on. In addition to the obvious advantage of keeping the pitch damper on, the results in figure 18 suggest that further improvement could be obtained by reducing the control-system gain. For example, halving the control gain (which is roughly equivalent to doubling the allowable pilot gain) would move configuration B into the satisfactory region and would improve slightly configuration A to a rating of about 5.

SUMMARY OF RESULTS

Results of centrifuge flight-simulator evaluations over a wide range of aircraft longitudinal dynamics were used to identify major control problems and to define the minimum damping and stability the pilots will accept in the event of stability-augmenter malfunction.

Comparisons of centrifuge, pitch-chair, and fixed-cockpit results with flight-test results indicated:

1. The effects of incomplete or spurious motion cues, of the seat-of-the-pants or vestibular type, on control-problem simulation were important only for high-frequency, lightly damped dynamics or moderately damped, unstable dynamics.

2. Of the three modes of simulation studied, the pitch-chair simulation, which provided accurate angular acceleration cues to the pilot, compared most favorably with flight. For centrifuge simulation, which supplied accurate normal accelerations at the expense of introducing spurious pitching and longitudinal accelerations, there was a deterioration of pilot's opinion relative to flight-test results.

3. Over all, however, the results of all three modes of simulation could be extrapolated to flight with a fair degree of accuracy.

Results of simulator studies with an analog pilot replacing the human pilot were presented illustrating the adaptive capability of human pilots in coping with the wide range of dynamics and the major control problems covered in this study. It was shown that pilot's response characteristics deduced by this method could be related to pilot's opinion, thereby making it feasible to predict flight-control problems analytically.

Comparison of results obtained from a brief evaluation of a pencil-type side-arm controller in the centrifuge with those obtained for the conventional center stick showed a substantial improvement in control with the pencil controller for high-frequency, lightly damped vehicle dynamics. It was shown that the use of the pencil controller minimized the adverse effects of large pitching and longitudinal accelerations on the pilot's ability to apply the precise control inputs required.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., Aug. 29, 1960

APPENDIX A

DESCRIPTION OF CENTRIFUGE COORDINATE-CONVERSION ANALOGS

As indicated in figure 1, the purpose of the coordinate-conversion analog was to transform the computed linear accelerations, as determined by the analog computer from the appropriate aircraft transfer functions, into centrifuge commands. These commands were in the form of inner (pitch) and outer (roll) gimbal positions and arm angular rate. The two gimbal commands were used to position the centrifuge gondola so that the pilot would be subjected to linear accelerations similar in magnitude and direction to those he would experience in flight. However, this was ordinarily accomplished at the expense of spurious pitching and rolling accelerations.

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The standard coordinate-conversion analog, which was devised by the Aeronautical Computer Laboratory Group at NADC, Johnsville, for closed-loop operation of the centrifuge, solved the following system of equations:

$$A^2 = A_X{}^2 + A_Y{}^2 + A_N{}^2 \qquad (1)$$

$$A^2 = \left(\frac{\dot{\omega}L}{g}\right)^2 + \left(\frac{\omega^2 L}{g}\right)^2 + 1 \qquad (2)$$

$$\dot{\omega} = \left[A^2\left(\frac{g^2}{L^2}\right) - \frac{g^2}{L^2} - \omega^4\right]^{1/2} \qquad (3)$$

$$\omega = \int_0^t \dot{\omega}\, dt \qquad (4)$$

$$0 = \sin R - \frac{\omega^2 L}{g} \cos R + A_Y \qquad (5)$$

$$0 = \gamma \sin P - \frac{\dot{\omega}L}{g} \cos P - A_X \qquad (6)$$

$$\gamma = \frac{\omega^2 L}{g} \sin R + \cos R \qquad (7)$$

Most of the previous closed-loop centrifuge programs utilized this standard coordinate-conversion analog. In general, it was found in these previous studies (e.g., ref. 24) that the pilots were not appreciably distracted or disoriented by the spurious angular motions at the higher linear accelerations of interest.

For the purpose of the present study, where it was desired to reproduce accurately the normal acceleration perturbations with minimum introduction of spurious angular and linear accelerations, the standard coordinate-conversion system was found inadequate. This was due to both poor reproduction of the normal accelerations and to excessive rolling motions of the cab. Therefore, a number of different coordinate-conversion analogs were evaluated to arrive at a system adequate for this study. Of the 16 systems evaluated, pilot-opinion results for 7 will be presented, and the coordinate conversion schemes for 2 will be described in detail.

Pilots' evaluations.- Figure 21 presents the results of the evaluations for seven of the coordinate-conversion analogs tested. The various symbols represent the four pilots who participated in this phase of the program. The particular set of airframe dynamics chosen for this evaluation (i.e., $\omega_n^2 = 16$, and $2\zeta\omega_n = 2$) was intended to be just poor enough to indicate deficiencies in the coordinate-conversion system. The results show an appreciable effect of the coordinate-conversion system on pilots' evaluations and corresponding effects on their tracking scores. Pilots' observations and a study of the centrifuge records indicated that for the poorer systems (e.g., A, B, C) the centrifuge motions which were considered unrealistic and exaggerated were the longitudinal linear and pitching angular accelerations and, to a lesser extent, the lateral linear and rolling angular accelerations. System F, the best system tested, was a compromise between accurate reproduction of normal acceleration and minimization of the spurious centrifuge motions. Most of the evaluations were conducted with a bias g of 3; however a brief study was made of the effects of bias g level on pilot opinion and tracking score for one pilot, and the results are presented in figure 22. The results are for the best coordinate conversion analog tested and for good vehicle dynamics, $\omega_n^2 = 16$ and $2\zeta\omega_n = 8$. It can be seen that as the bias g was reduced below 2, the pilot's opinion rapidly deteriorated. With the bias g set at 1.5, the pilot stated that he became extremely disoriented because of the extreme rolling motions of the cab, and it was necessary to terminate the run to enable the pilot to regain his bearings. It was found that though the pilot was disoriented, his tracking score suffered only mildly at the lower bias g levels, in this case. On the basis of these results, the main portion of the centrifuge program was conducted with the optimized coordinate conversion system F and with the bias g set at 3.

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Mode B.- This mode was essentially the standard coordinate conversion with the addition of an arm equalizing filter and an additional input to the inner gimbal command in the form of a filtered pitch-rate signal. The purpose of the arm equalizing filter was to minimize the sizable time lag of the centrifuge arm response so that better correspondence between computed and measured normal-acceleration perturbations would be obtained. Adding the filtered pitch-rate signal to the inner gimbal command was intended as the best compromise between matching pitching accelerations and normal accelerations simultaneously. The inner gimbal command was then

$$P_c = P + \dot{\theta}^*$$

where

$$\dot{\theta}^* = \frac{KT_1T_2s\dot{\theta}}{(T_1s+1)(T_2s+1)}$$

The values used for this mode were: $K = 3$, $T_1 = 1$ second, $T_2 = 0.5$ second. In addition, the $\dot{\omega}$ contribution to the inner gimbal command was modified by a first-order lag of 0.5 second. Evaluation of this coordinate-conversion analog for relatively poor dynamics ($\omega_n^2 = 16$, $2\zeta\omega_n = 2$) in terms of pilot's rating and task performance (fig. 21) indicated mode B was one of the worst tested. The pilot observed that the motions of the cab following rapid control inputs were unrealistic, and practically uncontrollable. Results in figure 23, which compare the command linear accelerations with the actual values, indicate that part of the problem was due to the large, oscillating longitudinal accelerations A_X and, to a lesser extent, the lateral accelerations, A_Y. It should be pointed out that the commanded values of both A_X and A_Y were zero for this investigation. The fairly good correspondence observed in figure 23 between the commanded and actual values of A_N results from the favorable effects of the arm equalizing filter.

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Mode F.- This mode, which was considered the best of the 16 modes evaluated, consisted of the standard coordinate-conversion analog, the arm equalization filter and reductions in both the command to the outer gimbal and in the $\dot{\omega}$ contribution to the inner gimbal of one-half. The results provided in figure 24 indicate good reproduction of the desired, or commanded, normal accelerations with relatively small introduction of spurious longitudinal and lateral accelerations. Pilots' comments for this mode indicated that the centrifuge response to control inputs was fairly realistic and that the objectionable rolling motions and fore and aft accelerations were barely apparent, even for rapid control inputs.

Although this particular coordinate-conversion analog was found adequate over most of the range of aircraft short-period dynamics studied, deficiencies appeared, particularly at the highest short-period frequencies and at very low damping levels. For these dynamics, spurious fore and aft and lateral accelerations were introduced which had an adverse effect on the pilots' ability to control. Typical results illustrating these effects are presented in figure 25.

APPENDIX B

PENCIL-TYPE SIDE-ARM CONTROLLER RESULTS

Brief tests with the pencil-type side-arm controller (fig. 3) were conducted to assess the effects on pilots' ratings and task performance of minimizing inadvertent control inputs due to centrifuge motions. Since results of the main portion of this program with the center stick indicated that inadvertent control was a problem only at the higher short-period frequencies, the pencil-controller tests were confined mainly to values of ω_n^2 of 16 and 36 radians^2 per second^2. (A few check runs for unstable dynamics indicated no substantial control improvement compared to results obtained with the center stick.) The basic results for the four pilots who participated in this phase of the program are presented in figure 26. The pilot-opinion data in this figure were averaged and replotted to obtain lines of constant pilot opinion as a function of short-period frequency and damping.

The faired results are presented in figure 27 where they are compared with similar data obtained for the center stick. The shift in the pilot opinion lines to considerably lower damping levels shown for the pencil controller results is attributable to two factors. First, the use of the pencil controller appears to have minimized inadvertent control inputs and consequent tendencies toward pilot-airplane instability, since no significant difference was noted between dynamic simulation (fig. 27) and static-simulation results (not shown). This is verified, in a more quantitative fashion, in figure 28 which presents comparative averaged tracking scores for both the center stick and the pencil controller for region II ($\omega_n^2 \approx 36$; $2\zeta\omega_n \approx 0.5$). It is apparent that very little reduction in task performance, due to centrifuge motions, occurred with the pencil controller, while a marked decrease in performance resulted with the center stick. Second, the pilots indicated a preference for the pencil controller for the static as well as dynamic mode of centrifuge operation. They generally agreed that the pencil controller not only improved their ability to cope with high-frequency, low-damping regions, but also was a better control than the center stick for relatively good dynamics. One pilot went so far as to assign a rating of 1-1/2 for region I dynamics (fig. 26), which approaches the optimum rating of 1 as closely as possible without the pilot actually admitting the ultimate in control response had been attained. This improvement was probably due to the pilot's ability to apply smoother, more precise control inputs with a finger-manipulated control than with the conventional center stick, which requires hand and arm motions. It is of interest to point out that in previous fixed-cockpit and centrifuge studies, which compared the pilots' ability to control with various types of side-arm controllers, including the pencil type (refs. 21 and 25), it was generally found that the pilots could cope with lower levels of airframe damping with the pencil controller than with the more conventional hand-grip types.

It should be pointed out that the results of the present study were obtained with the pilots in a "shirt-sleeve" environment. It is possible that the improvement in control observed for the pencil controller might not have been so striking if the comparative evaluation had been made with the pilots wearing full pressure suits and gloves.

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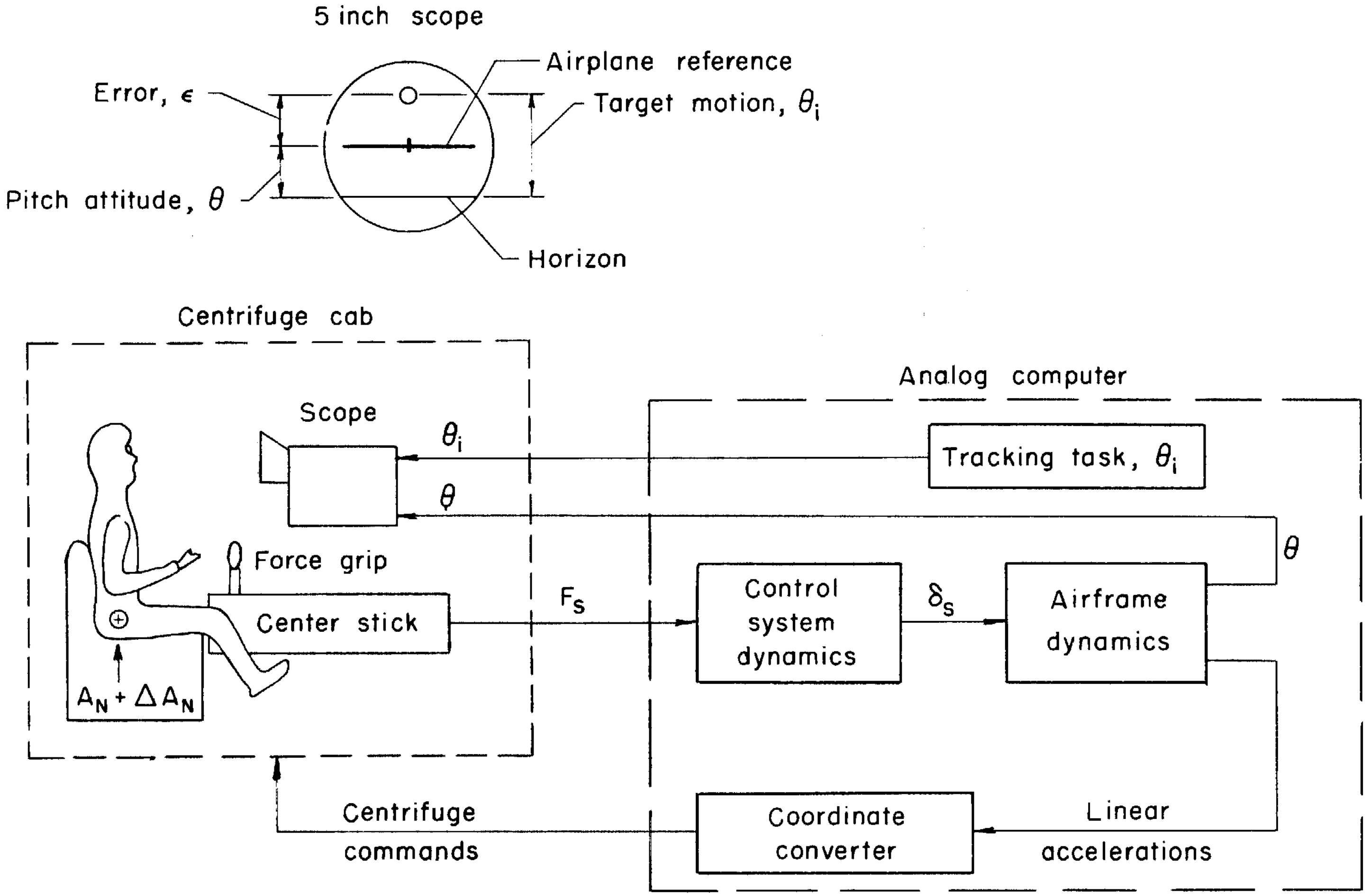

$$\frac{\delta_s}{F_s} = \frac{K_c}{1 + T_c s}, \quad \frac{\theta}{\delta_s} = \frac{C_{o_q} + C_{1_q} s}{s(s^2 + 2\zeta\omega_n s + \omega_n^2)}, \quad \frac{\Delta A_N}{F_s} = \frac{K_c K_n}{(1 + T_c s)(s^2 + 2\zeta\omega_n s + \omega_n^2)}$$

Figure 1.- Block diagram of centrifuge flight-simulator setup.

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Figure 2.- Photograph of interior of centrifuge cab as modified for present study.

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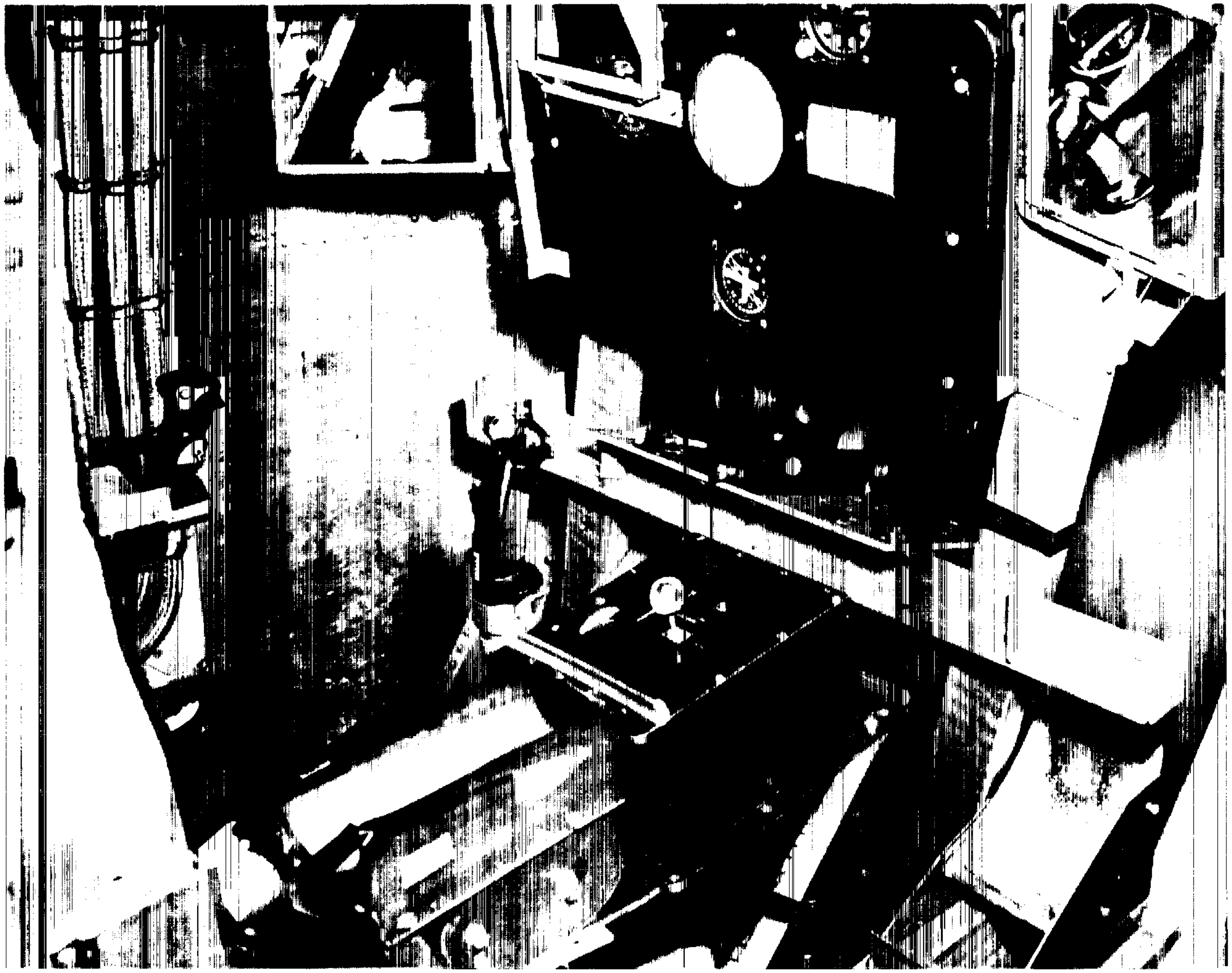

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(a) General view of controller and arm-support installation.

Figure 3.- Views of pencil type side-arm controller in centrifuge.

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(b) View of arm-restraint system.

Figure 3.- Concluded.

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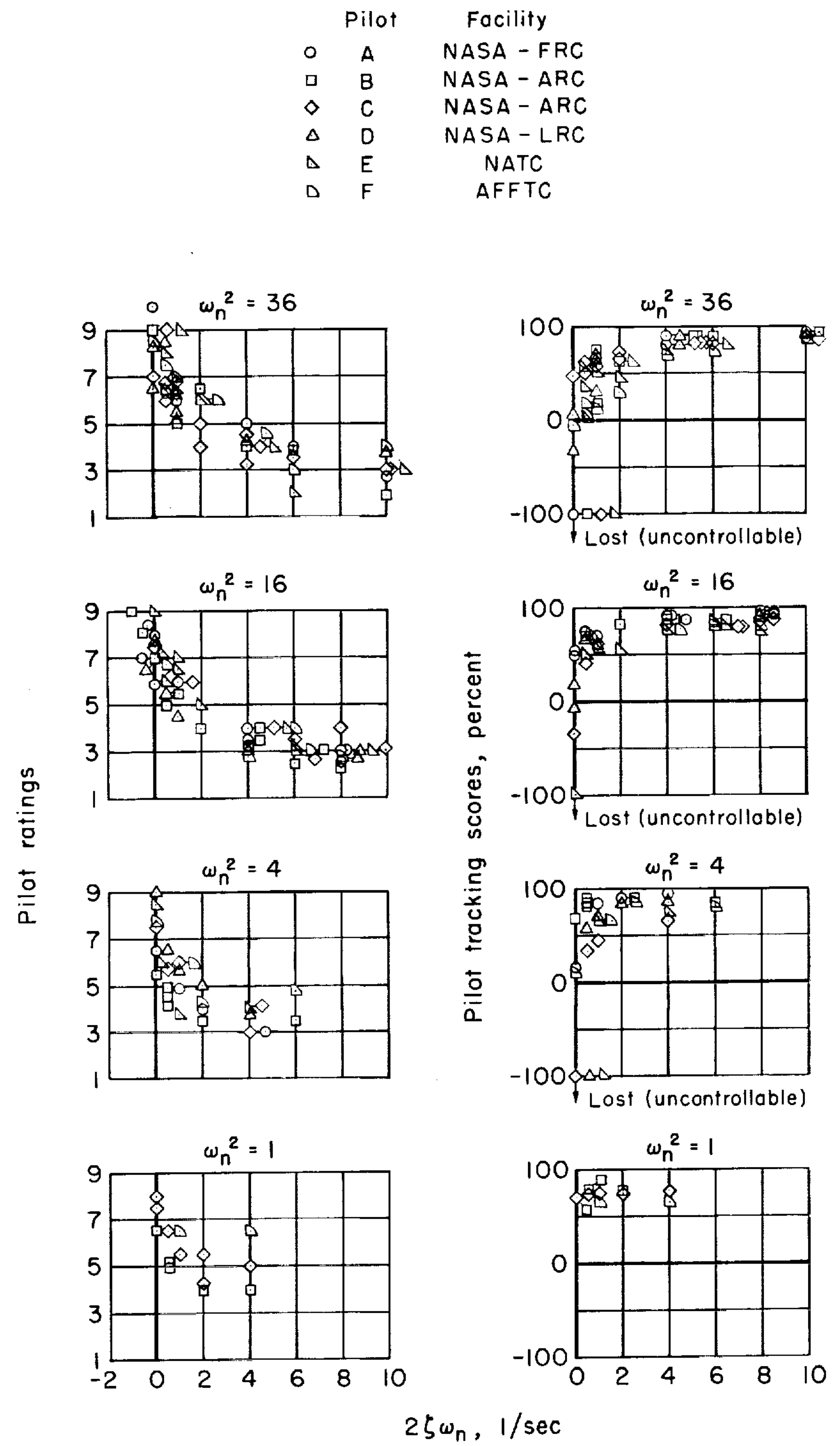
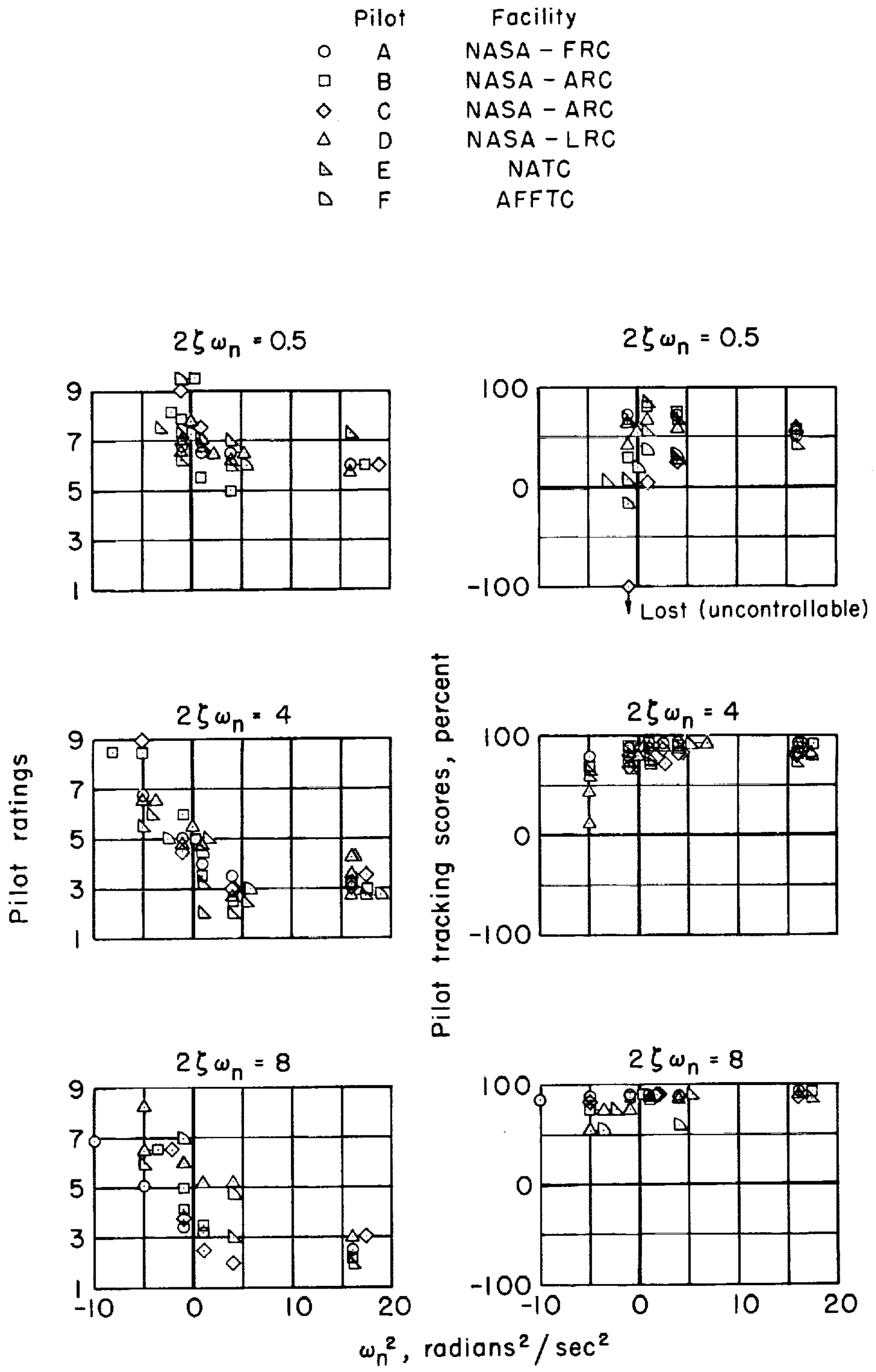


(a) Pilots' ratings. (b) Pilots' tracking scores.

Figure 4.- Basic data, constant stick force per g ($F_s/g = 8$).



(a) Pilots' ratings. (b) Pilots' tracking scores.

Figure 5.- Basic data, constant control gain ($K_c = 0.14^\circ$ per pound).

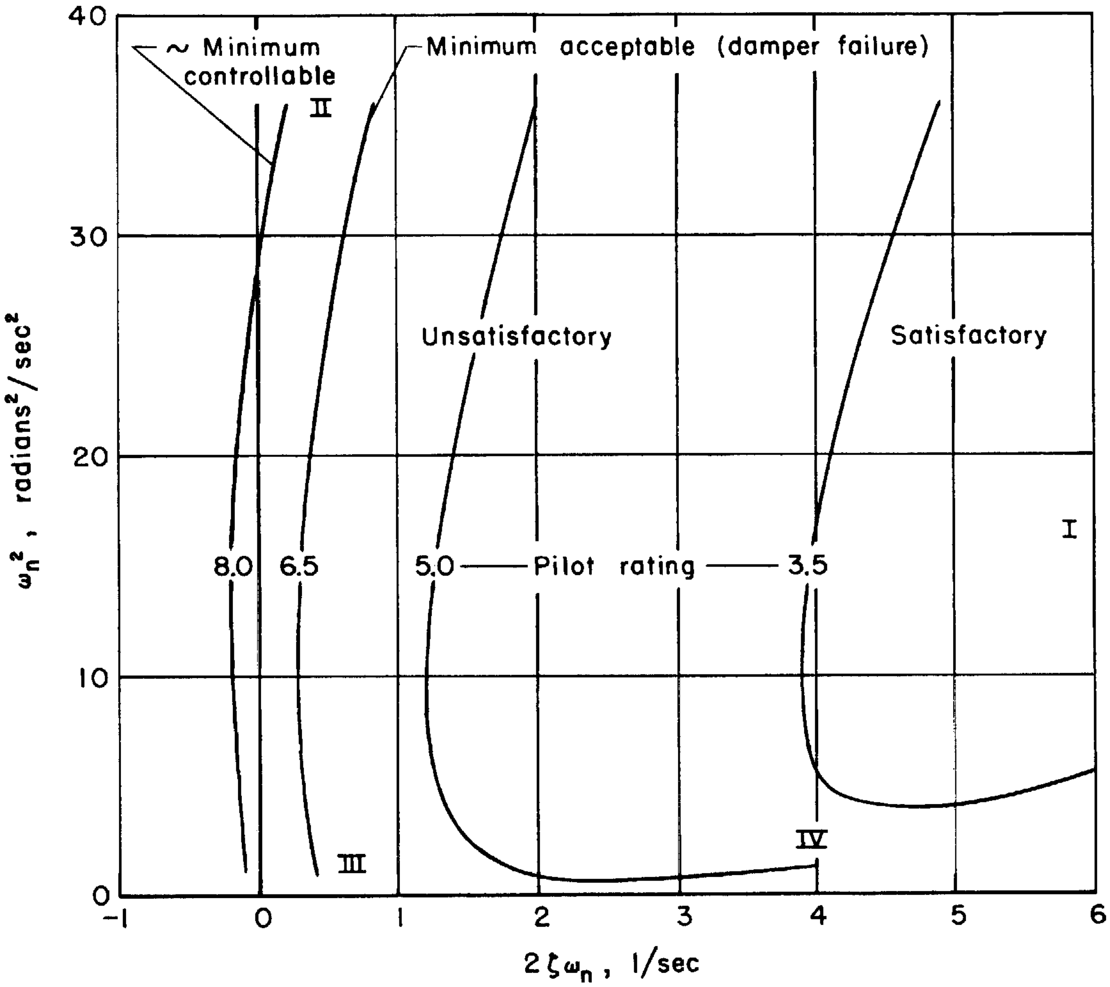


Figure 6.- Pilots' evaluations of stable short-period dynamics in centrifuge ($F_s/g = 8$).

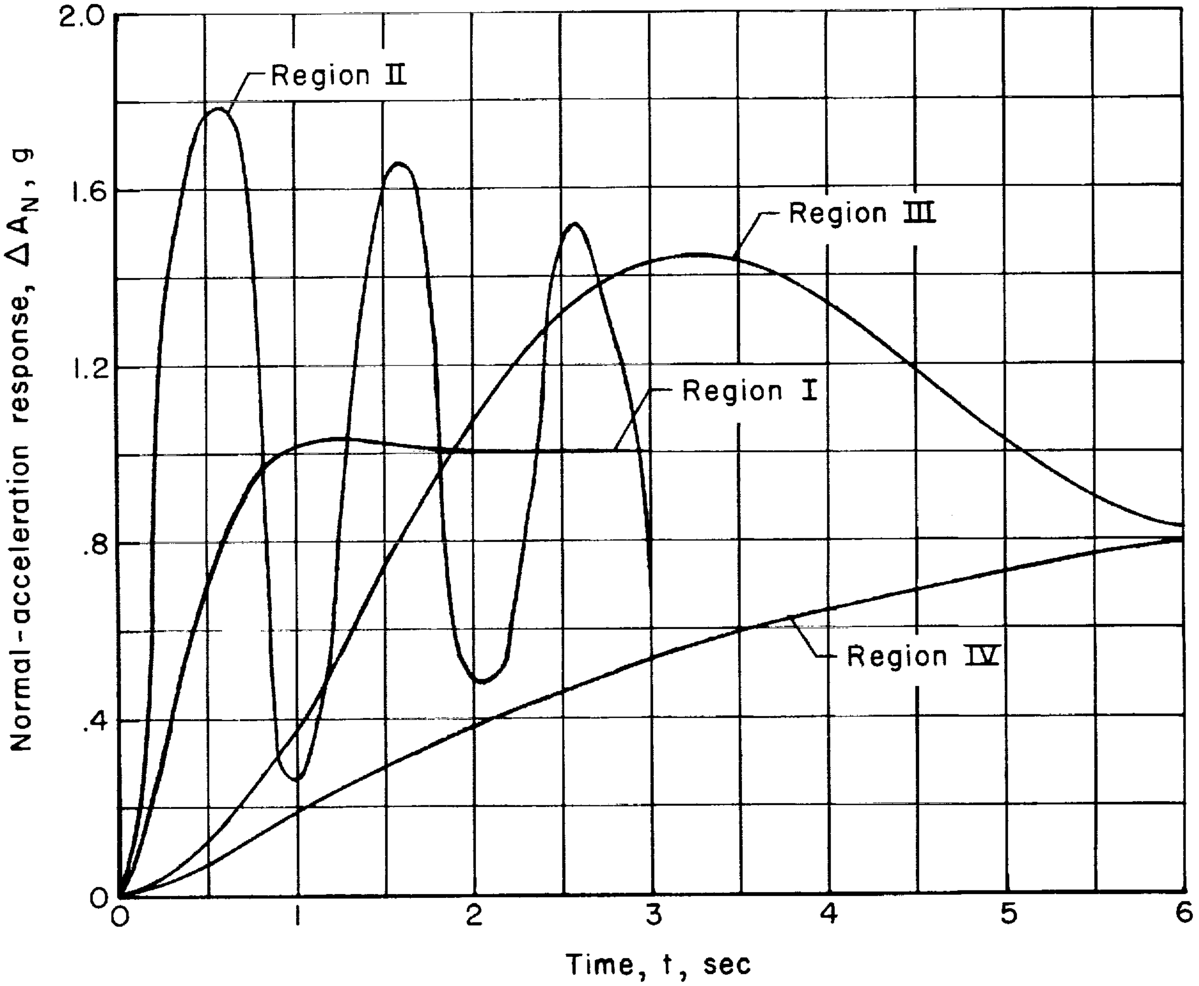


Figure 7.- Normal-acceleration step response from trim computed for a stick-force command of 8 pounds for regions designated in figure 6.

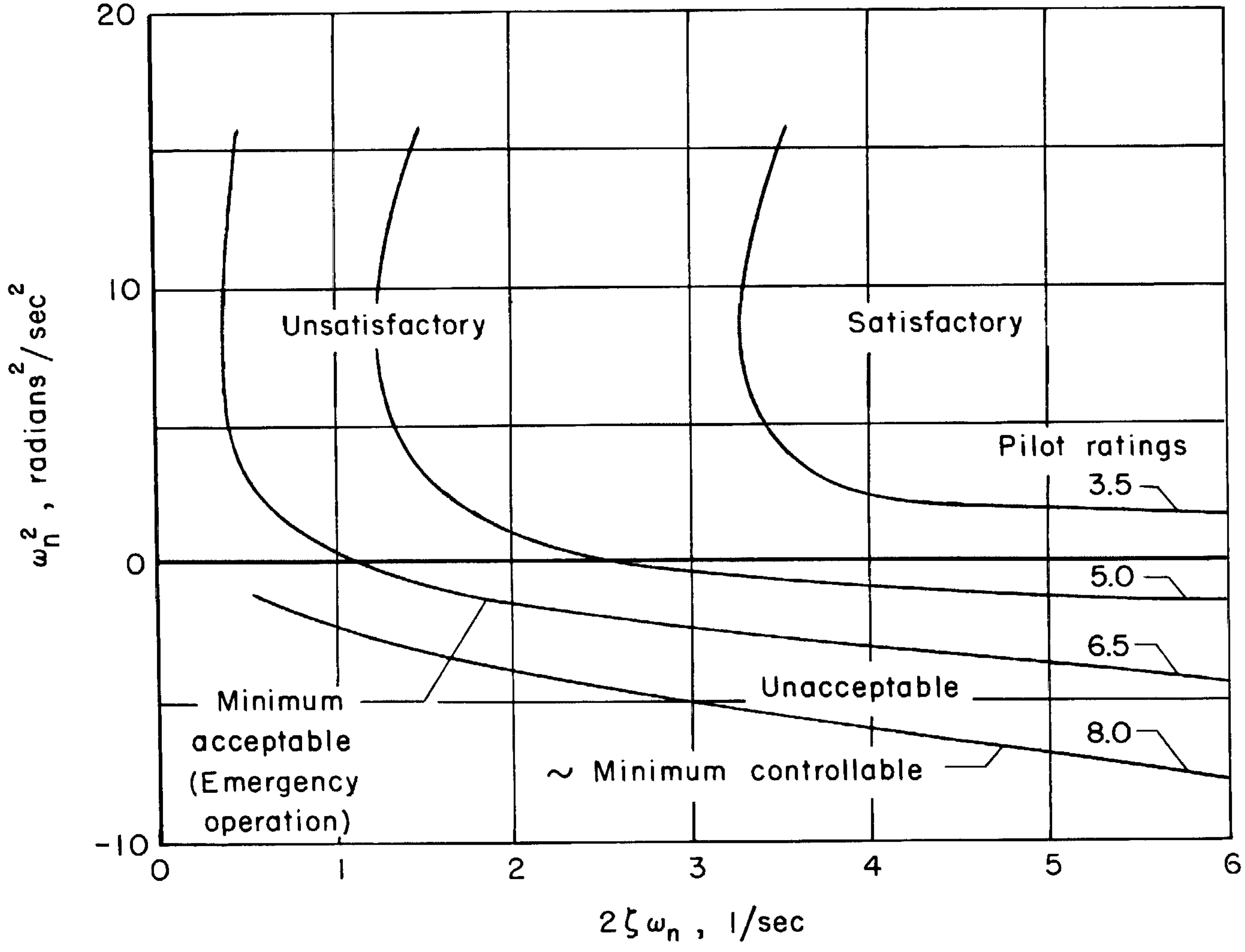


Figure 8.- Pilots' evaluations of unstable dynamics with centrifuge ($K_c = 0.14$).

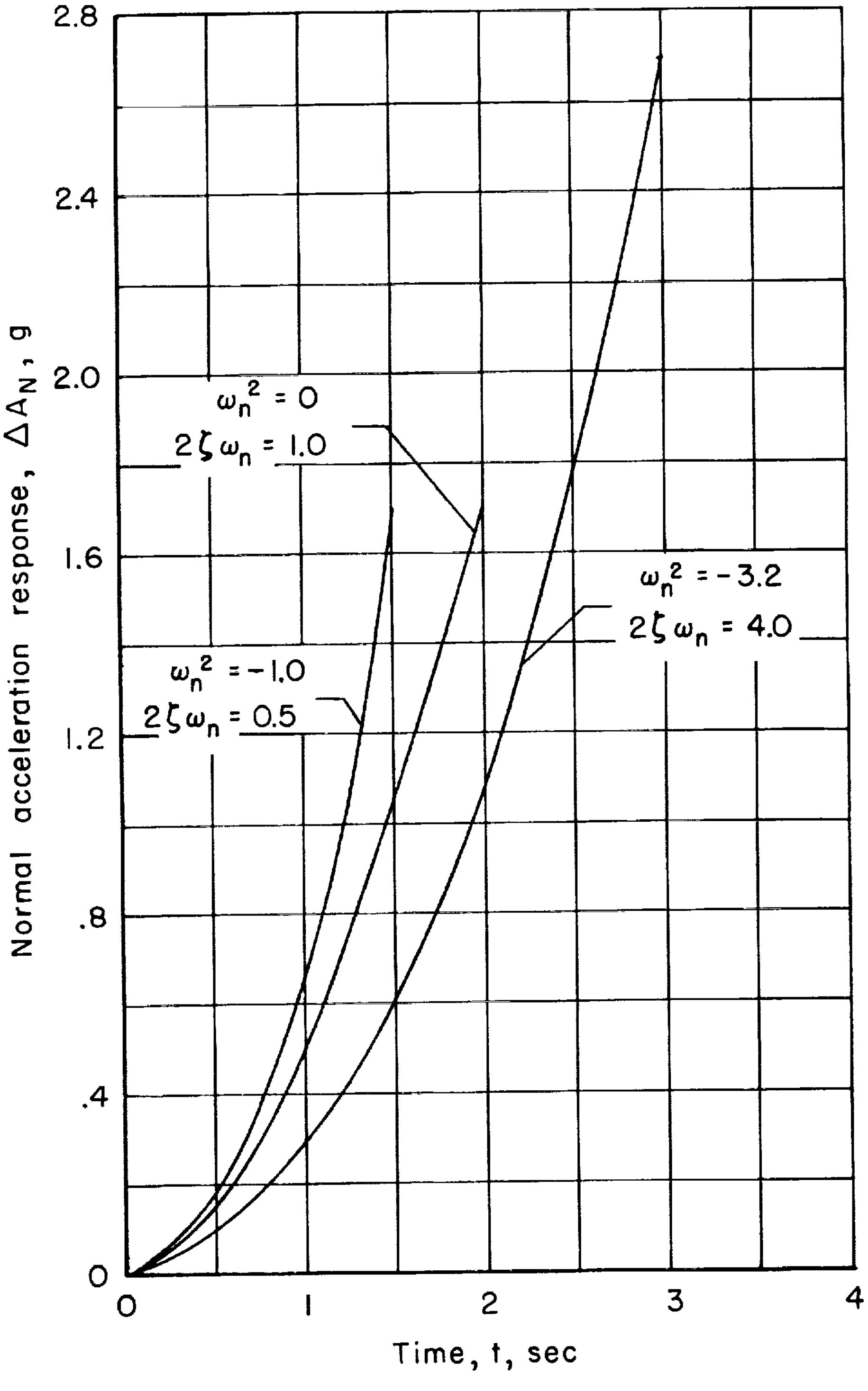


Figure 9.- Normal-acceleration step response from trim computed for a stick-force command of 1 pound for unstable dynamics.

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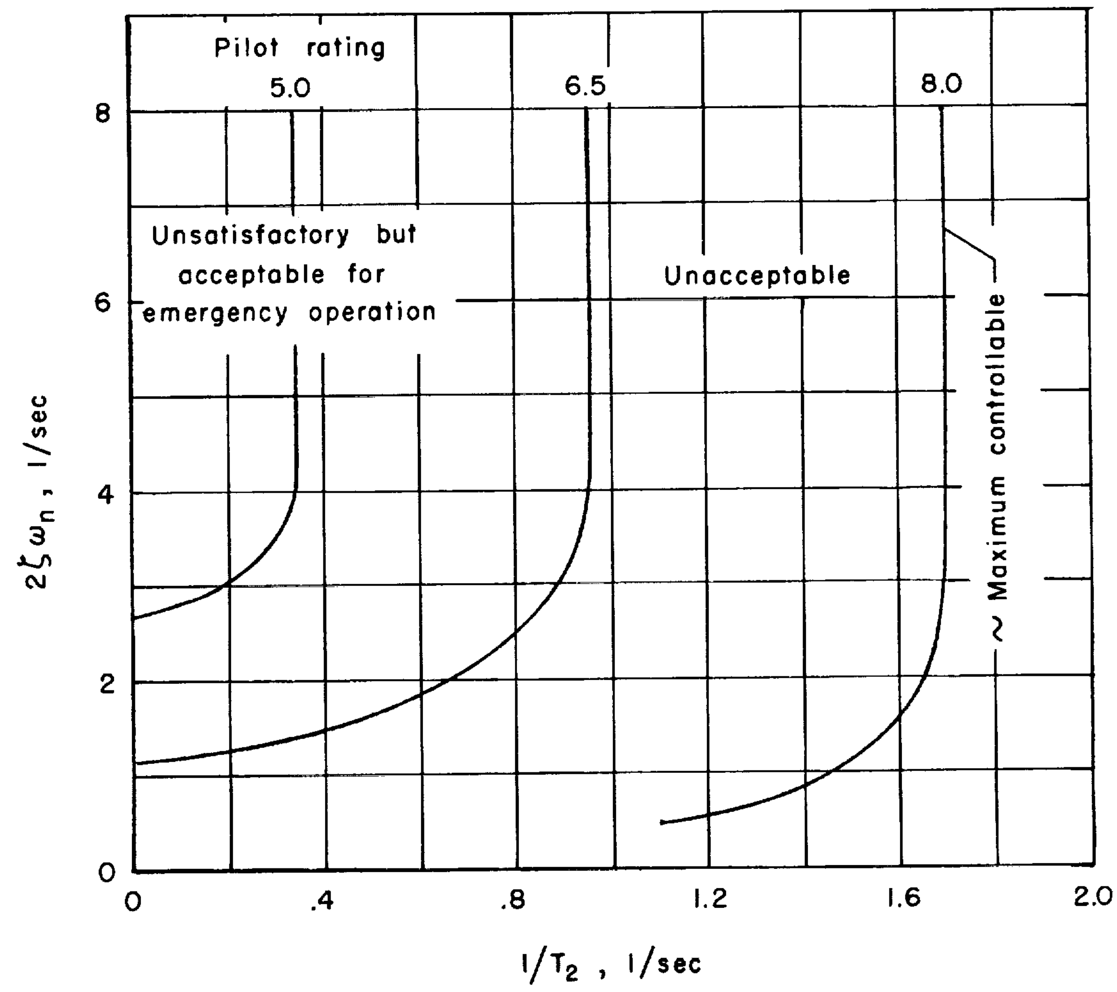
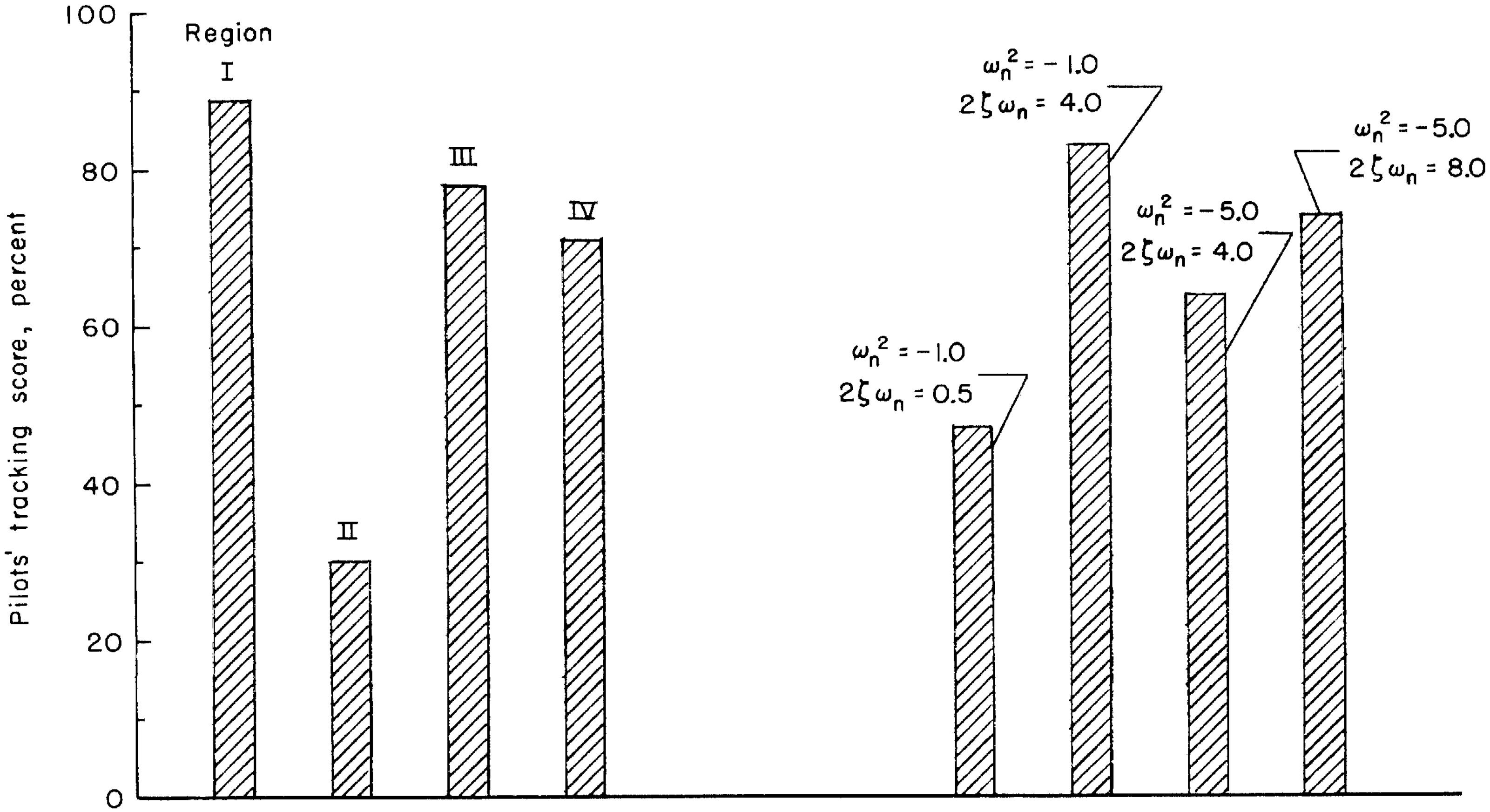


Figure 10.- Contours of constant pilot opinion as a function of damping and the reciprocal of time to double amplitude for unstable dynamics (K_c = 0.14).



(a) Stable dynamics
($F_s/g = 8$)

(b) Unstable dynamics
($K_c = 0.14$)

Figure 11.- Comparative average tracking scores for several sets of stable and unstable vehicle short-period dynamics.

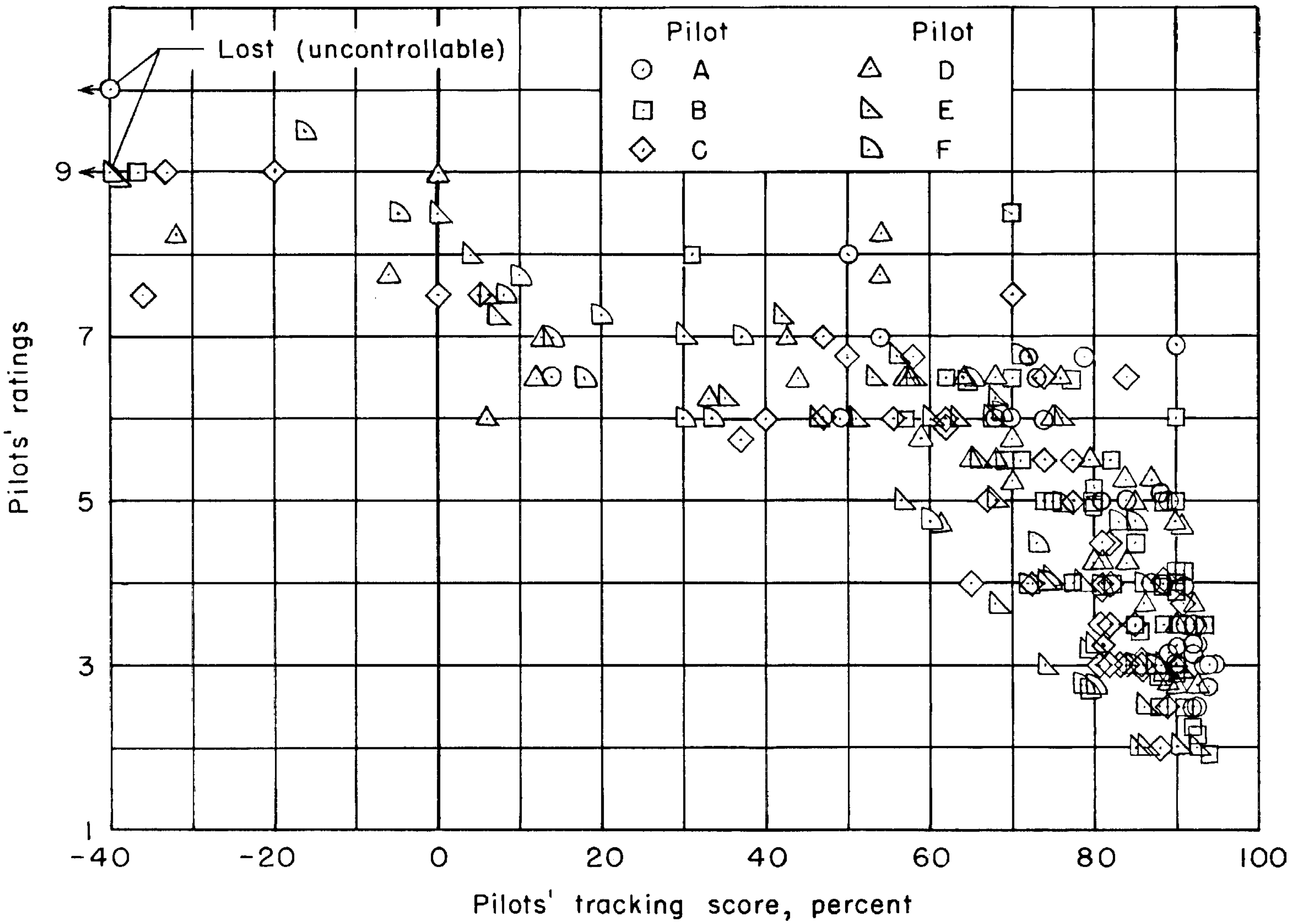
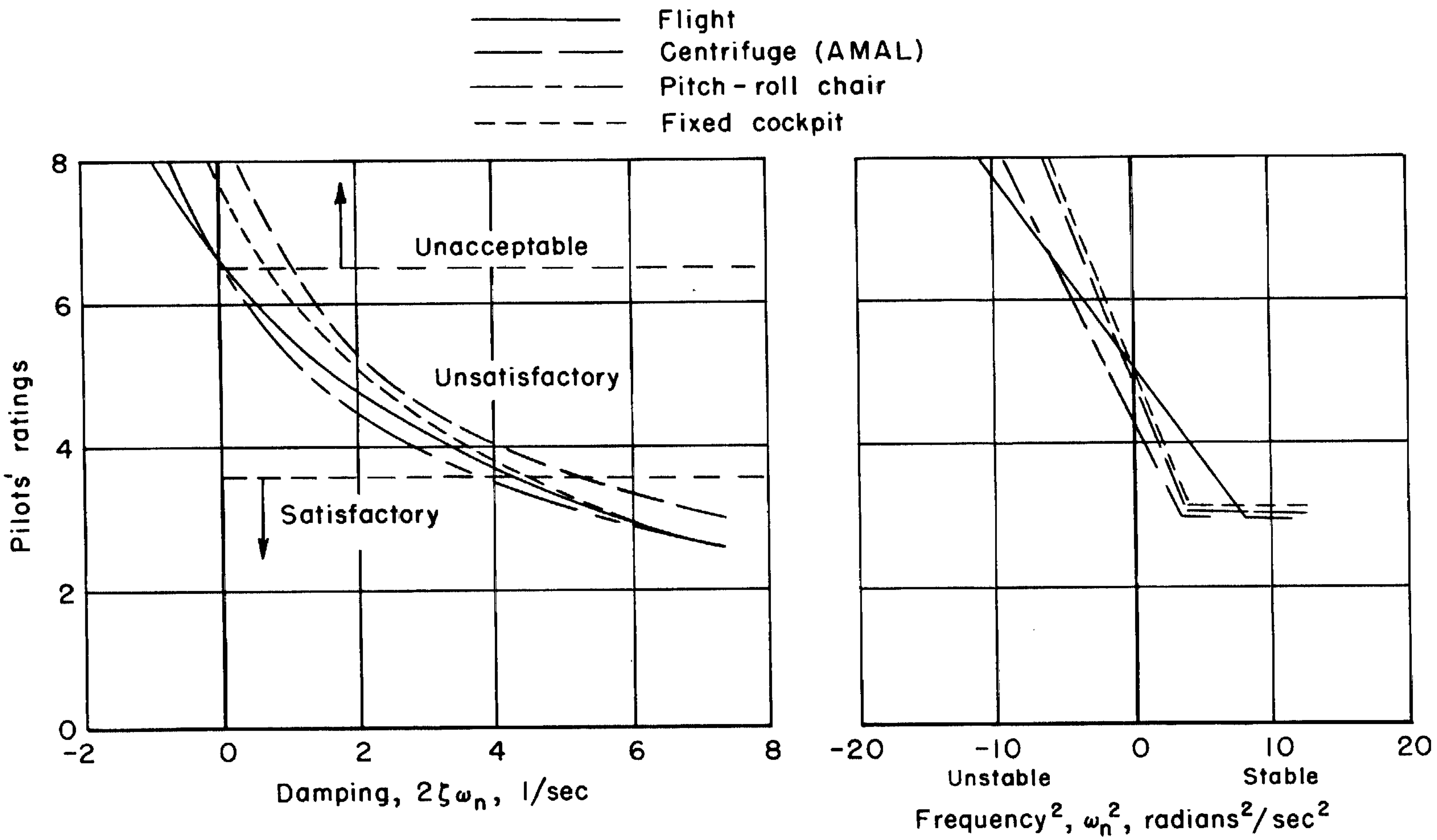


Figure 12.- Interdependence of pilots' tracking performance and pilots' opinion.



(a) High frequency ($\omega_n^2 = 36$).

(b) Moderate damping ($2\zeta\omega_n = 4$).

Figure 13.- Comparison of pilot-opinion data from three different simulators with flight-test results; pilot B.

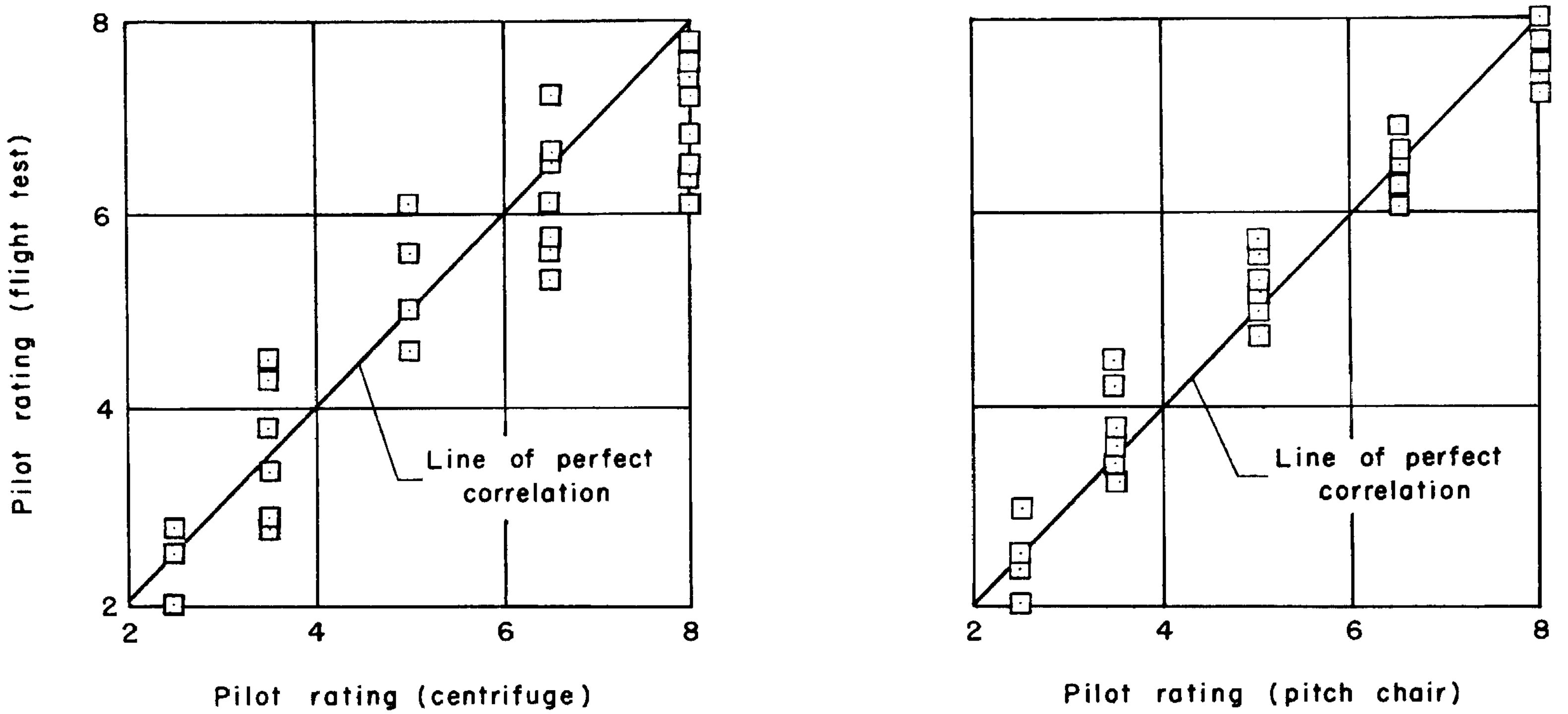


Figure 14.- Over-all correlation between centrifuge, pitch chair, and flight results; pilot B.

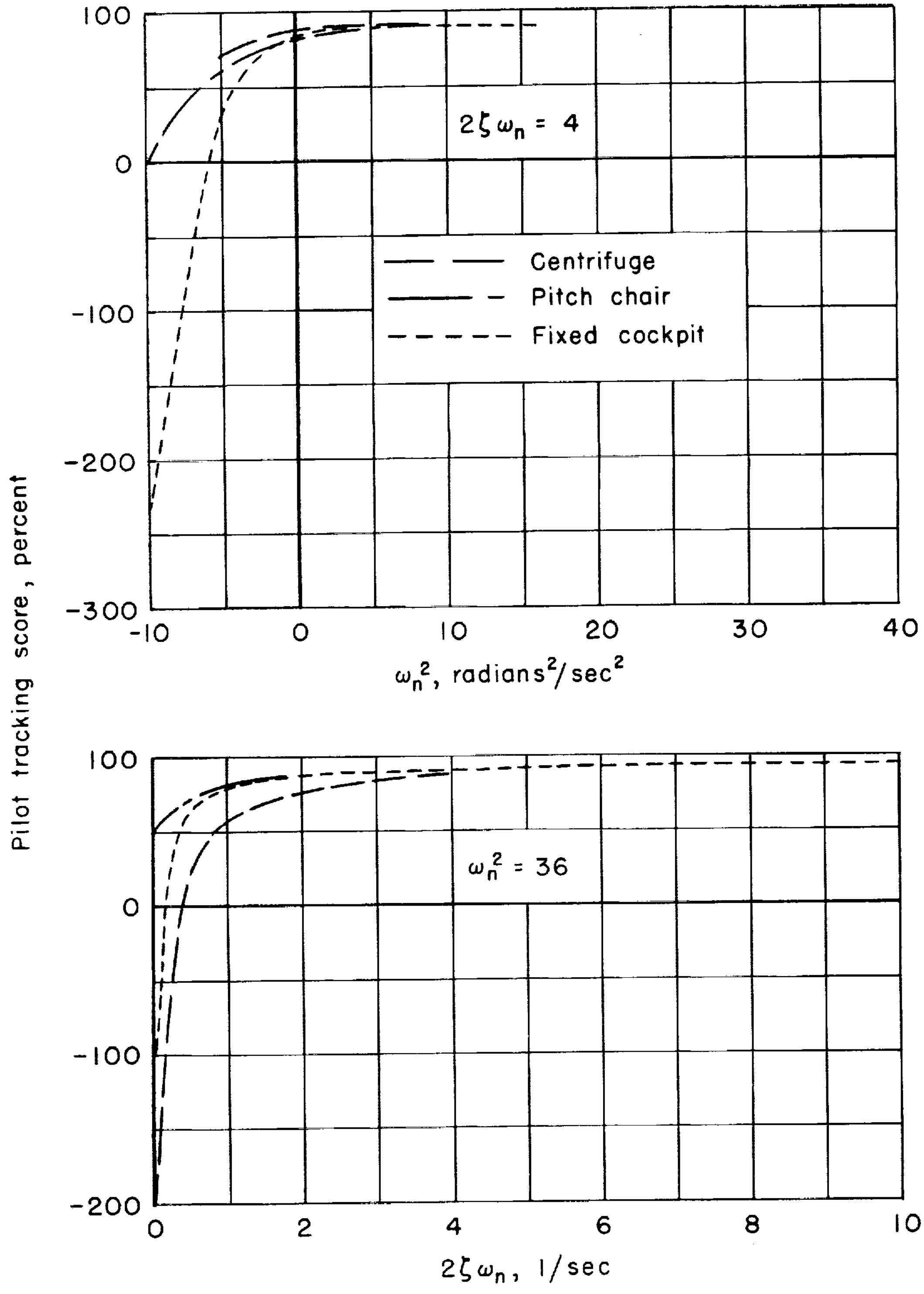
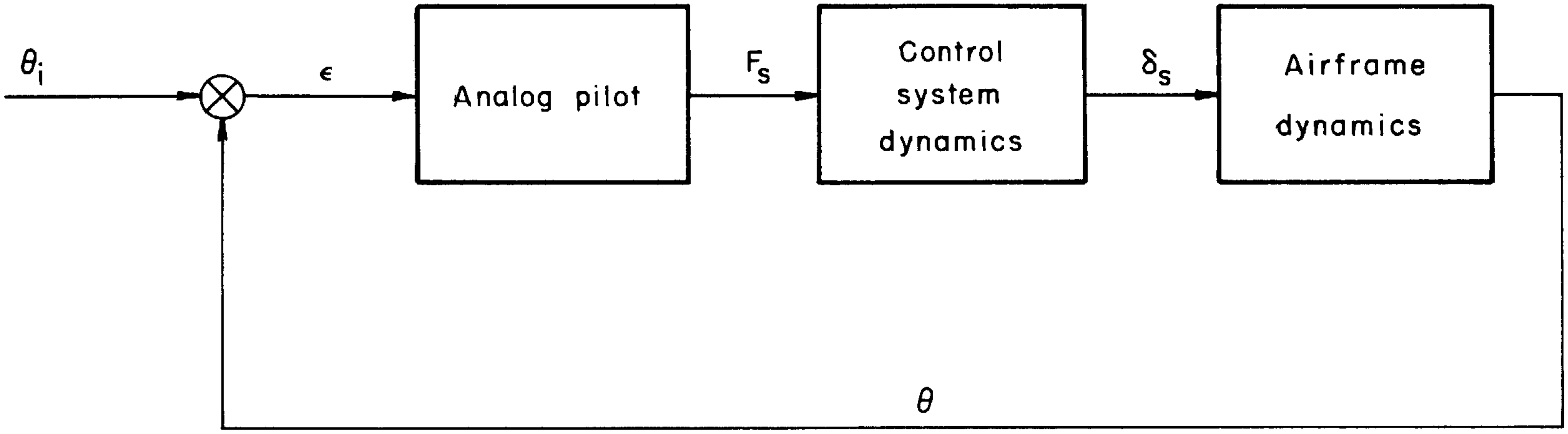


Figure 15.- Effects of simulator motions on pilot's tracking performance; pilot B.



$$\frac{F_s}{\epsilon} = \frac{K_p e^{-\tau s}(1+T_L s)}{(1+T_I s)(1+T_N s)} = \frac{K_p e^{-.2s}(1+T_L s)}{(1+.1s)(1+.1s)}$$

Figure 16.- Block diagram of simulator setup with analog pilot.

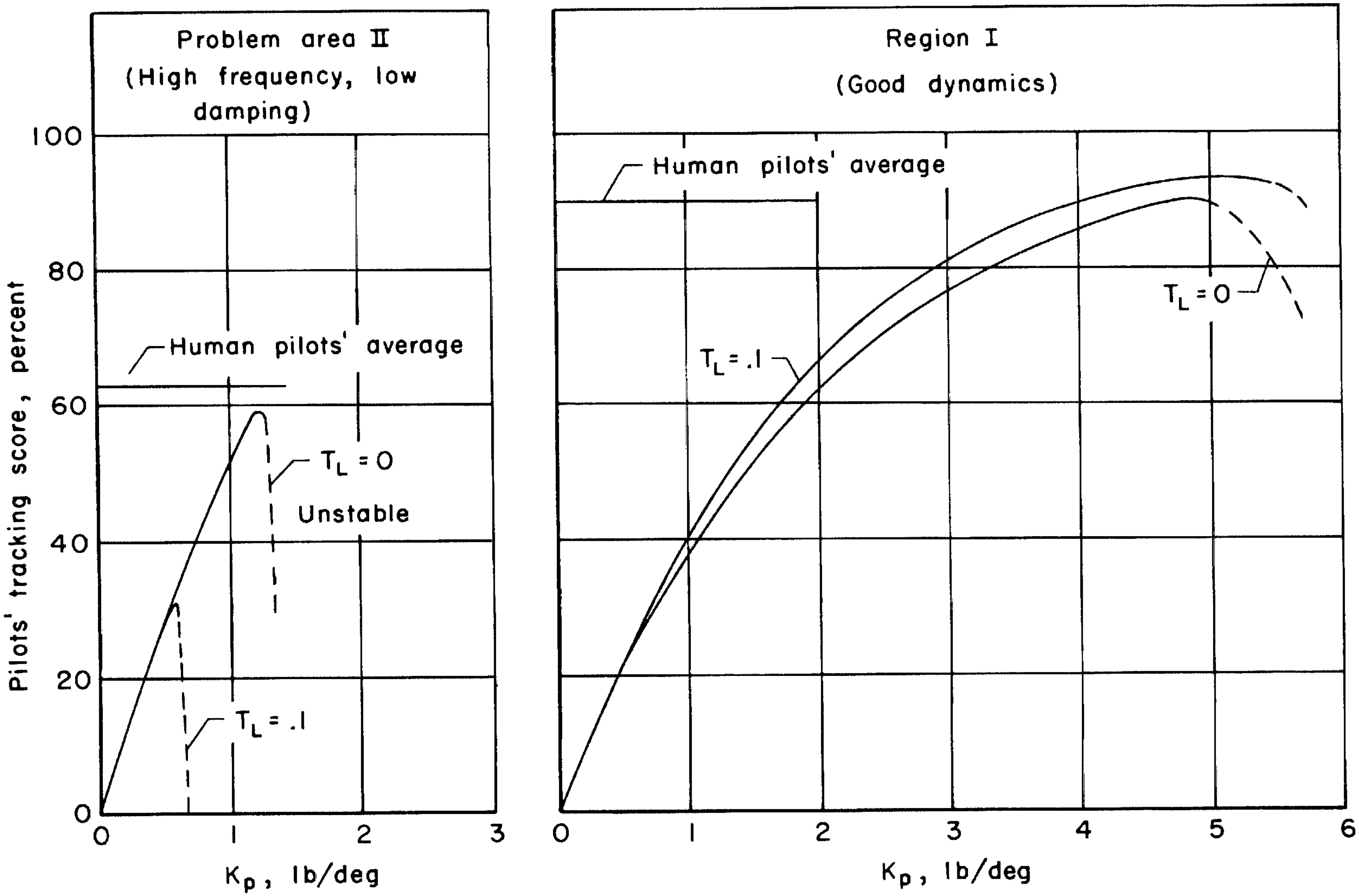


Figure 17.- Typical effects of vehicle short-period dynamics on analog pilot.

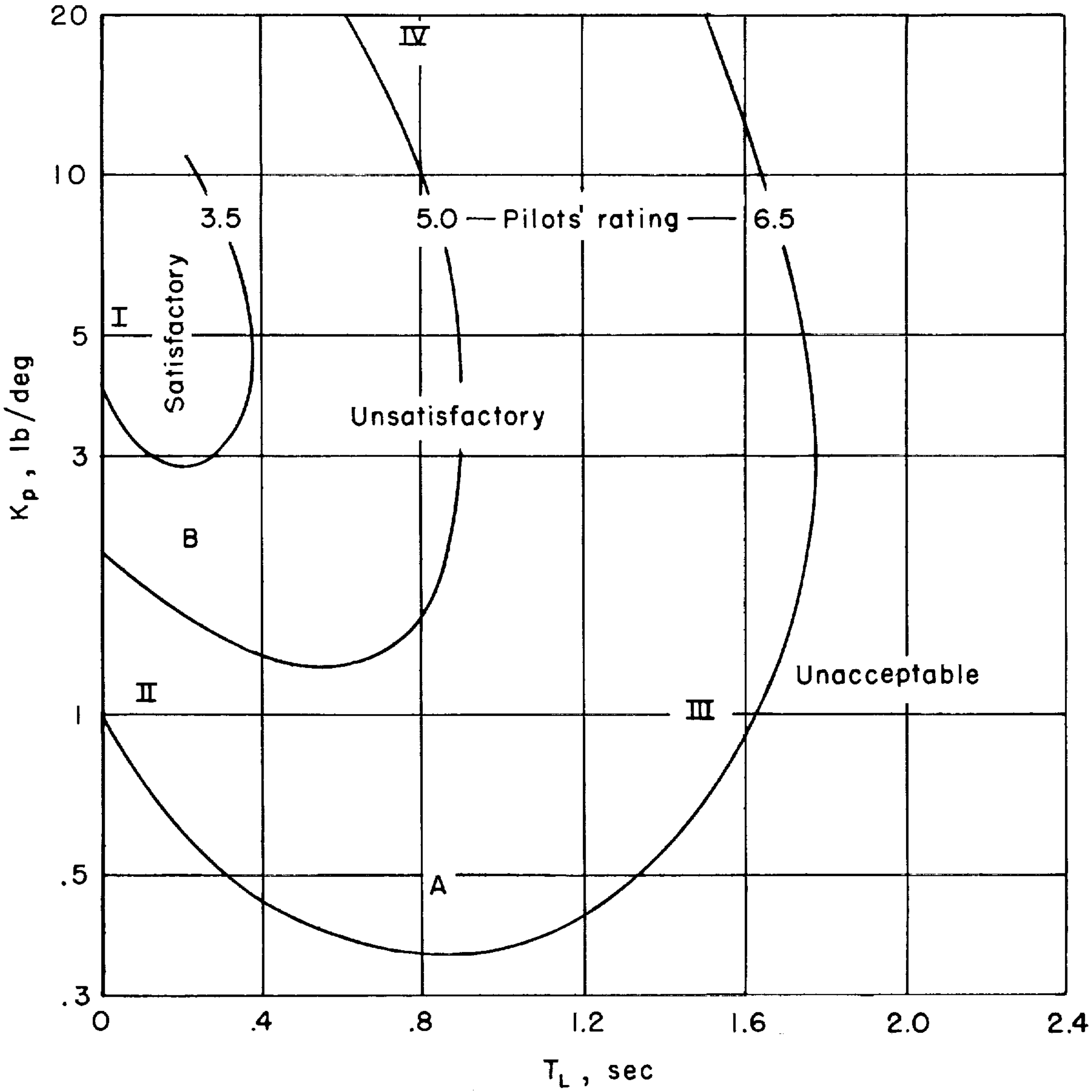
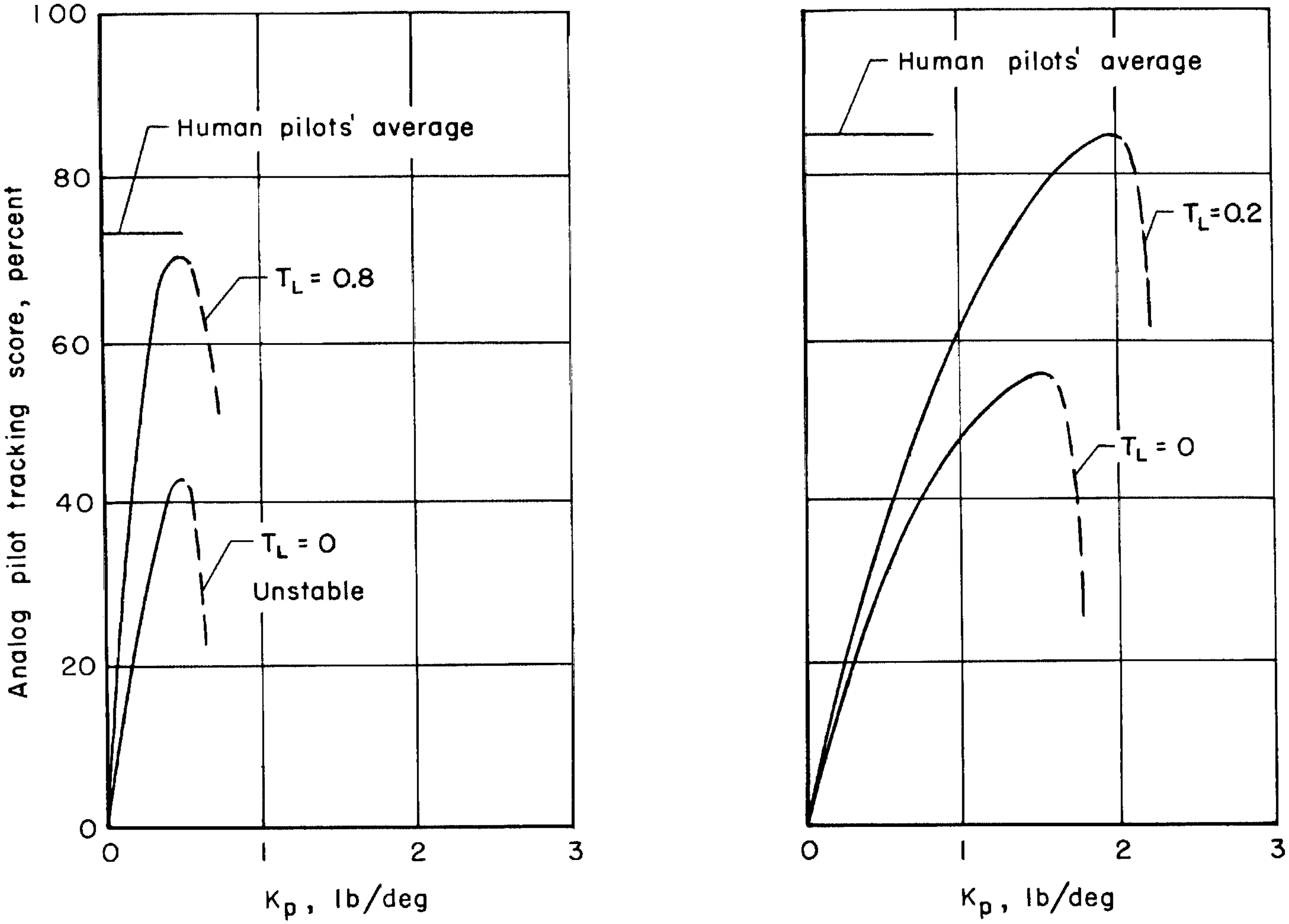


Figure 18.- Summary of pilot response characteristics defined by the use of the analog pilot.



(a) Pitch damper off.

(b) Pitch damper on.

Figure 19.- Analog pilot tracking characteristics for example control problem.

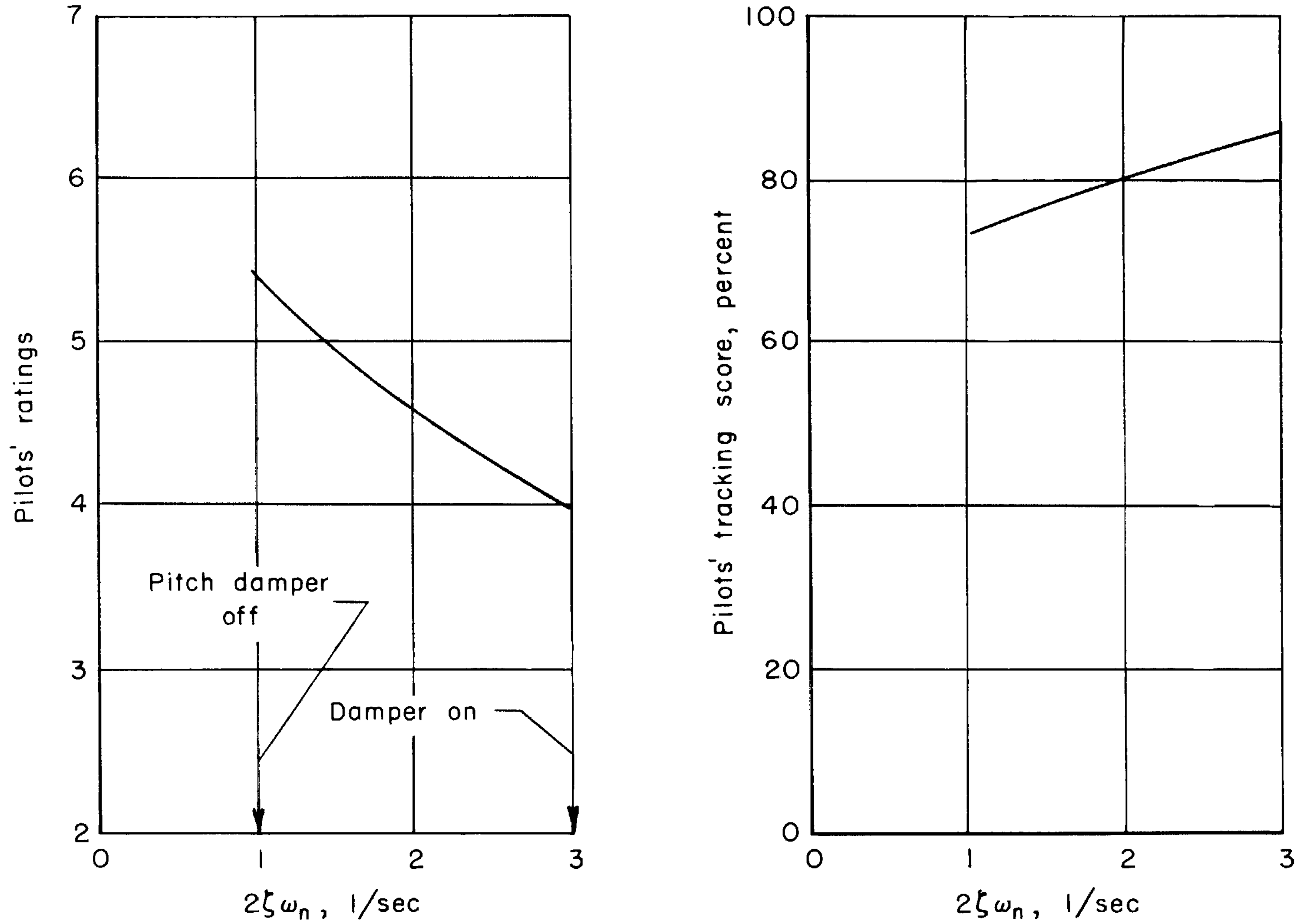
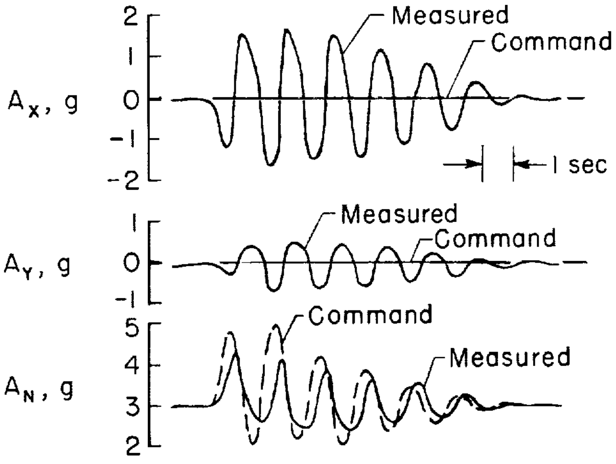
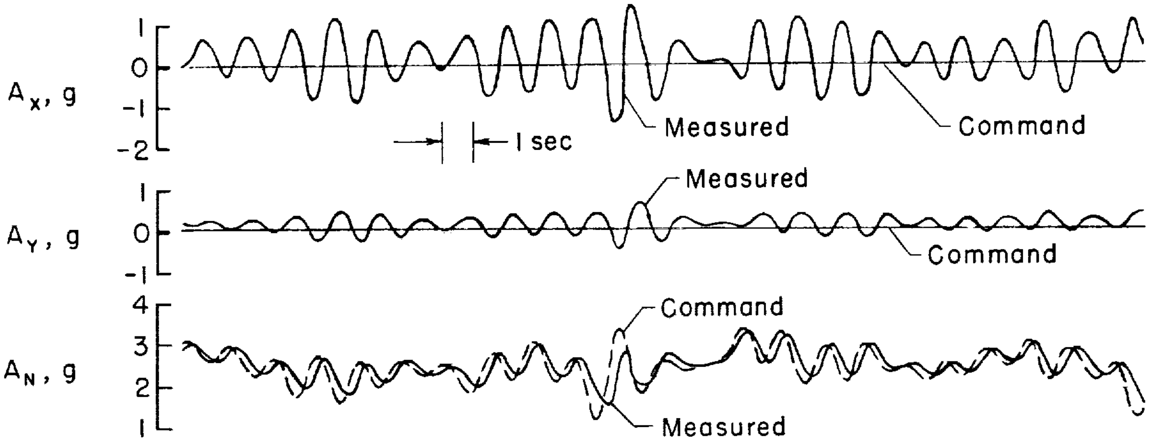


Figure 20.- Example control problem evaluation by human pilots.

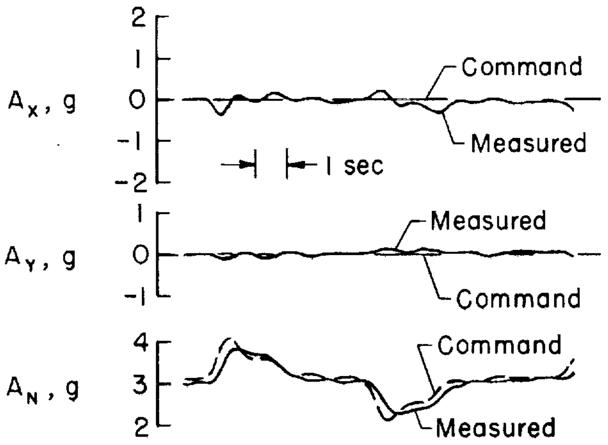


(a) Pulse response.

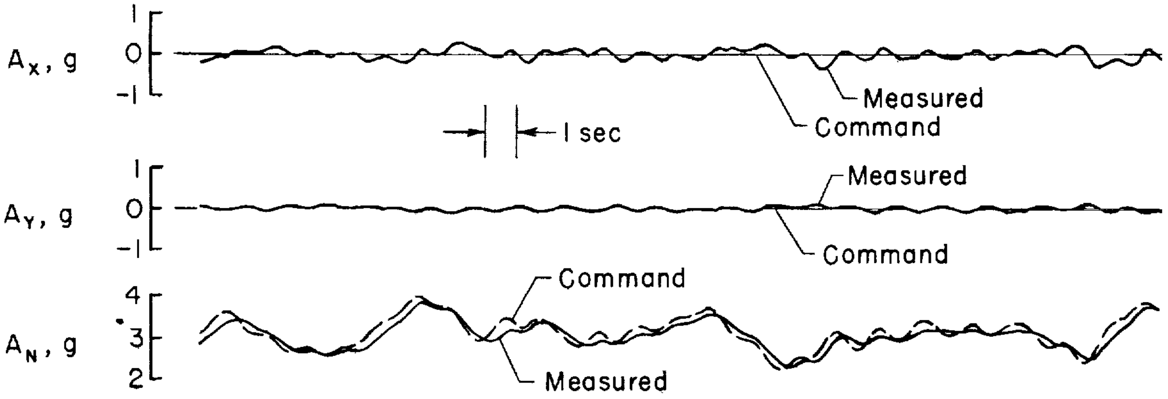


(b) Tracking.

Figure 23.- Comparisons of commanded and actual linear accelerations in centrifuge for coordinate conversion; mode B; pilot A; $\omega_n^2 = 16$; $2\zeta\omega_n = 2$.



(a) Step response.



(b) Tracking.

Figure 24.- Comparisons of commanded and actual linear accelerations in centrifuge for best coordinate conversion analog tested; mode F; pilot B; $\omega_n^2 = 16$; $2\zeta\omega_n = 2$.

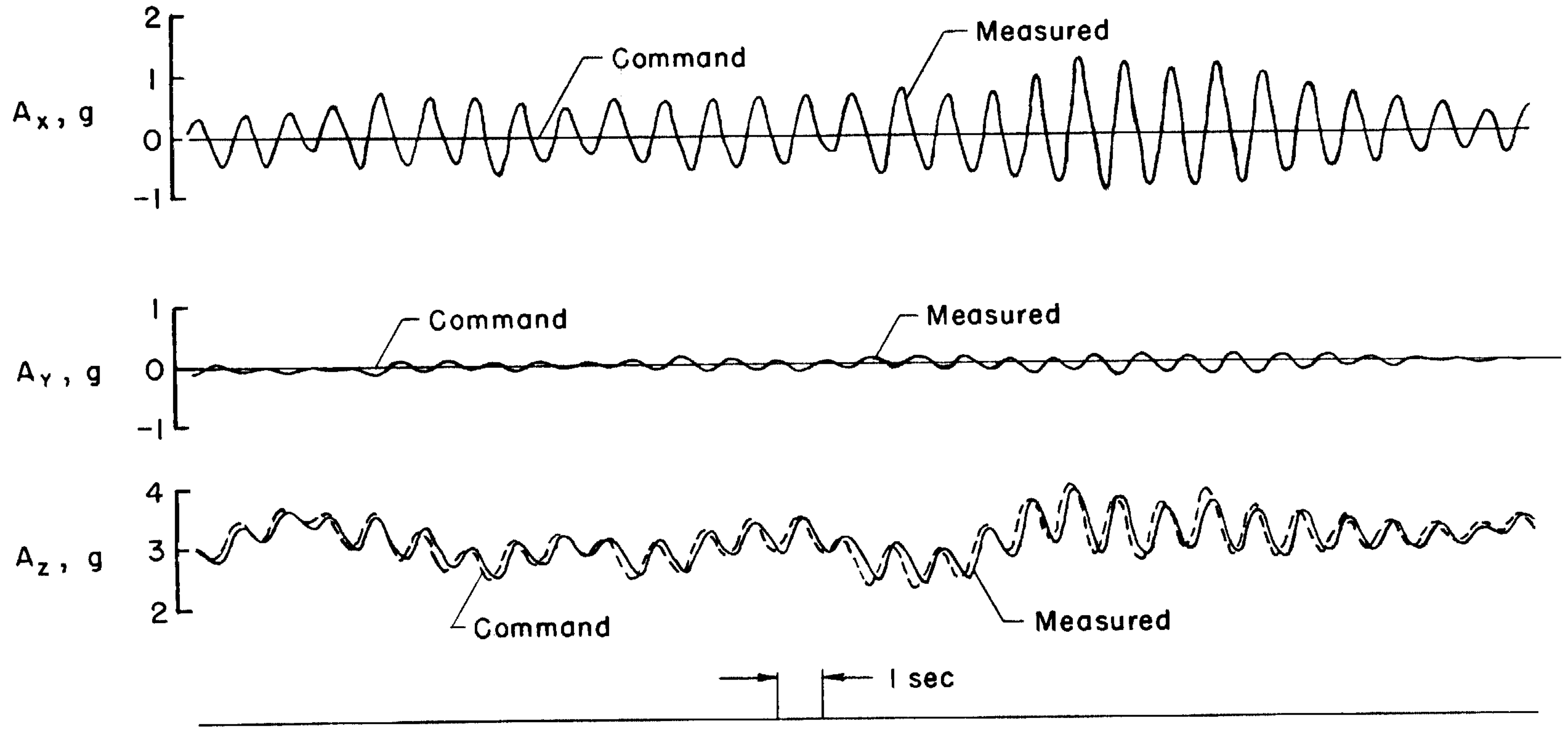


Figure 25.- Comparison of commanded and actual linear accelerations in centrifuge for coordinate-conversion mode F; pilot D; $\omega_n^2 = 36$; $2\zeta\omega_n = 0.5$.

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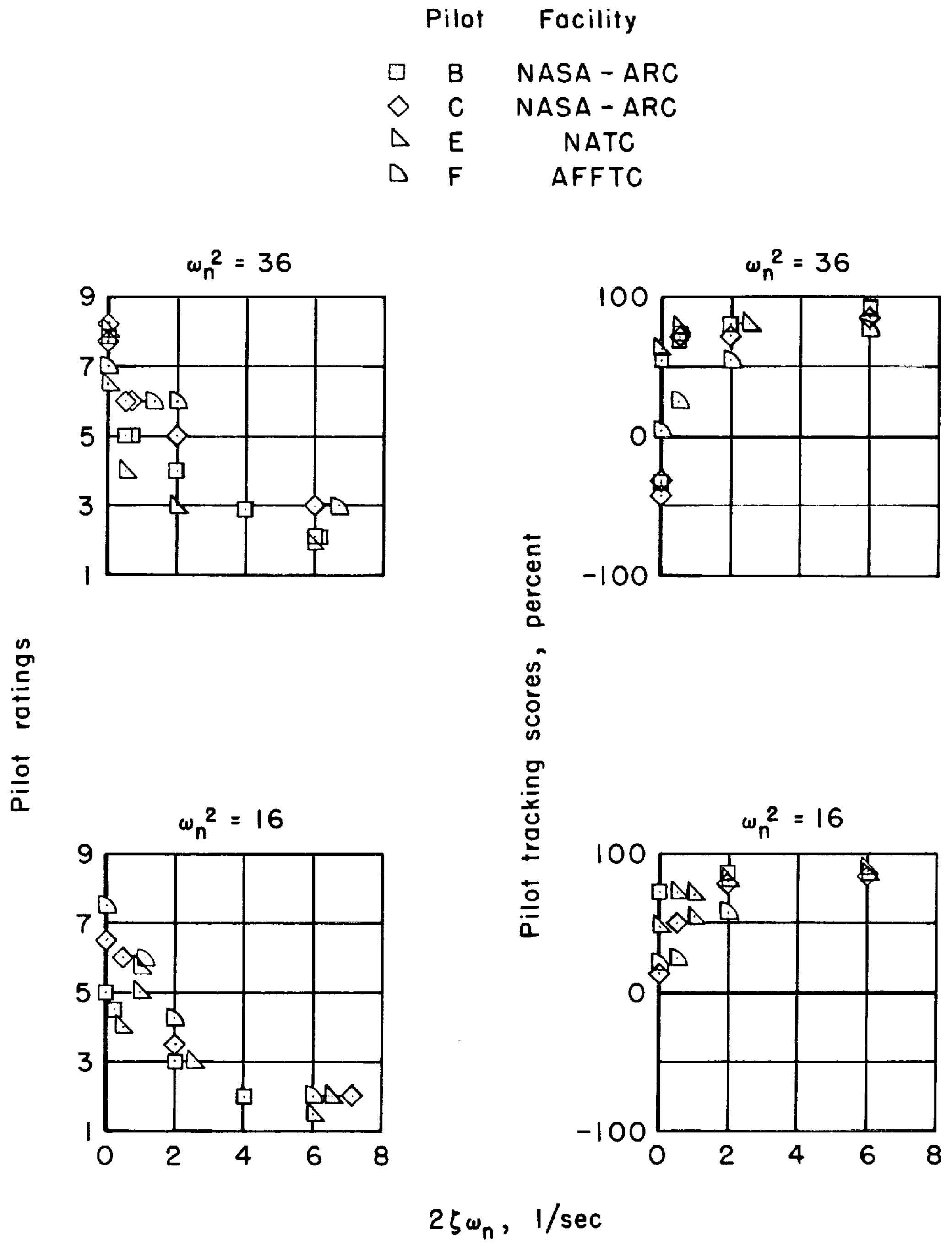

(a) Pilot ratings.

(b) Pilot tracking scores.

Figure 26.- Basic data, pencil-type side-arm controller. (Maximum control power about same as for center stick for constant stick-force per g tests.)

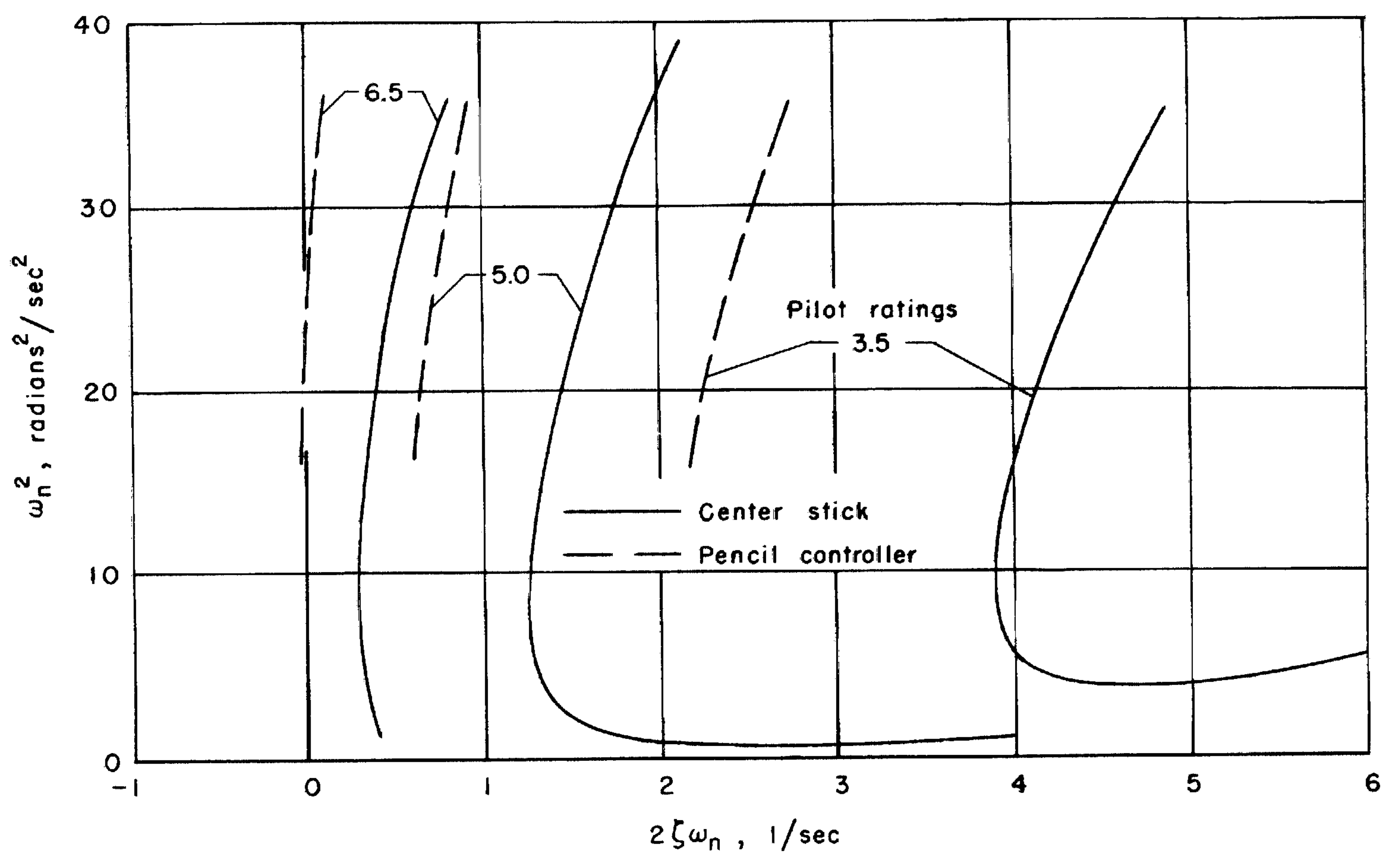

Figure 27.- Comparative evaluations of pencil-type side-arm controller and conventional center stick.

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4
3
5

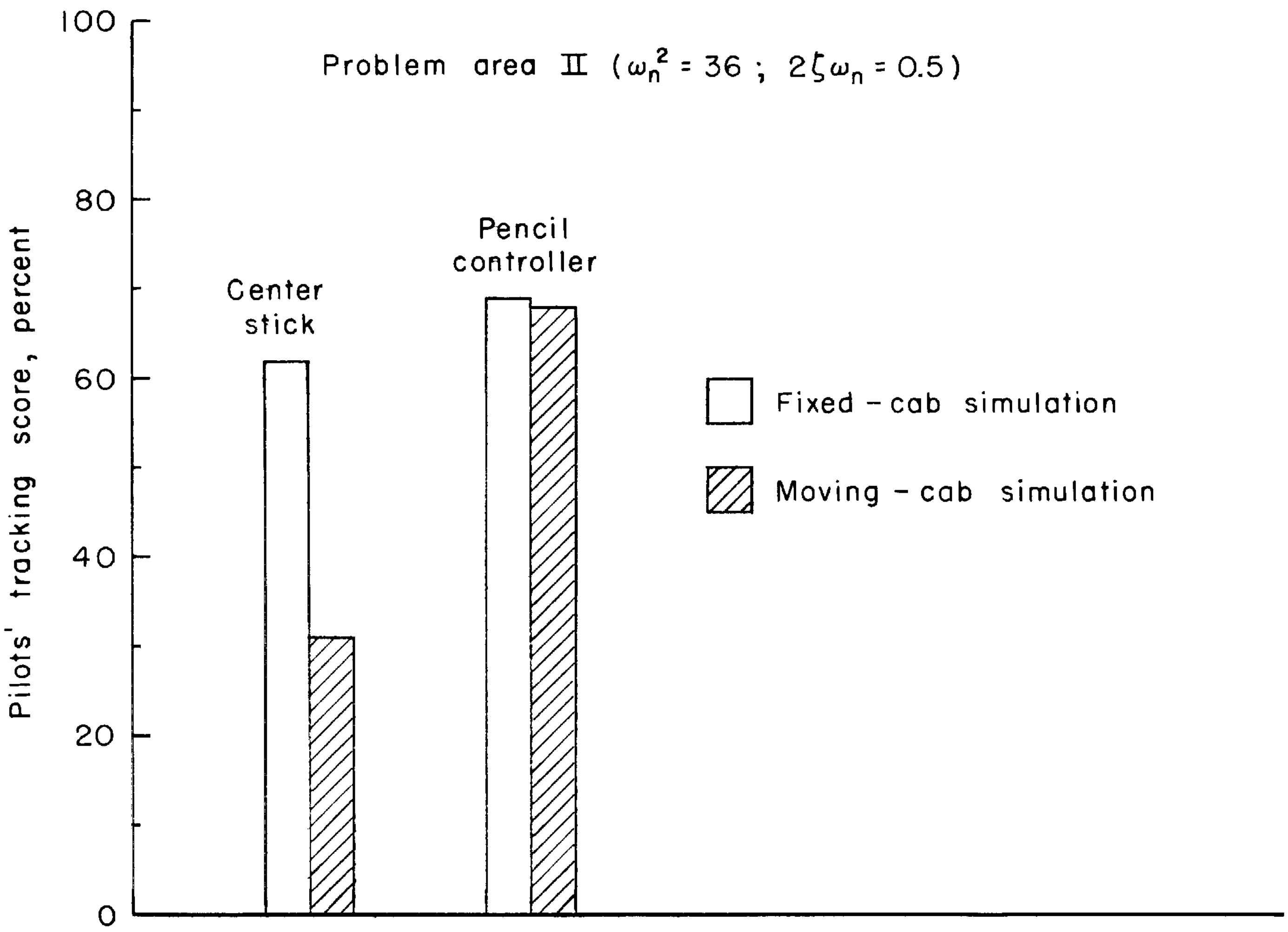

Figure 28.- Comparative averaged tracking scores for the pencil controller and the center stick for problem area II.