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CENTRIFUGE STUDY OF PILOT TOLERANCE TO ACCELERATION AND THE EFFECTS OF ACCELERATION ON PILOT PERFORMANCE

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SUMMARY

A research program, the general objective of which was to measure the effects of various sustained accelerations on the control performance of pilots, was carried out on the Aviation Medical Acceleration Laboratory centrifuge, U. S. Naval Air Development Center, Johnsville, Pa. The experimental setup consisted of a flight simulator with the centrifuge in the control loop. The pilot performed his control tasks while being subjected to acceleration fields such as might be encountered by a forward-facing pilot flying an atmosphere entry vehicle. The study was divided into three phases.

In one phase of the program, the pilots were subjected to a variety of sustained linear acceleration forces while controlling vehicles with several different sets of longitudinal dynamics. Here, a randomly moving target was displayed to the pilot on a cathode-ray tube. For each combination of acceleration field and vehicle dynamics, pilot tracking accuracy was measured and pilot opinion of the stability and control characteristics was recorded. Thus, information was obtained on the combined effects of complexity of control task and magnitude and direction of acceleration forces on pilot performance. These tests showed that the pilot's tracking performance deteriorated markedly at accelerations greater than about 4g when controlling a lightly damped vehicle. The tentative conclusion was also reached that regardless of the airframe dynamics involved, the pilot feels that in order to have the same level of control over the vehicle, an increase in the vehicle dynamic stability was required with increases in the magnitudes of the acceleration impressed upon the pilot.

In another phase, boundaries of human tolerance of acceleration were established for acceleration fields such as might be encountered by a pilot flying an orbital vehicle. A special pilot restraint system was developed to increase human tolerance to longitudinal decelerations. The results of the tests showed that human tolerance of longitudinal deceleration forces was considerably improved through use of the special restraint system.

A comparative evaluation was made, in another phase of the investigation, of the three-axis type of side-arm controller and the two-axis type in combination with toe pedals for yaw control. During the tests, the difficulty of blending and applying three control inputs with one hand using the three-axis controllers was repeatedly pointed out by the evaluation pilots; as a result, they were unanimous in their preference of the two-axis toe-pedal class of controllers.

INTRODUCTION

There have been numerous research investigations conducted on the effects of acceleration forces on man. These experiments were focused principally upon the medical aspects of man's tolerance to acceleration forces with only secondary interest in assessing the influence of acceleration forces on the human's ability to perform a task (refs. 1 through 13). The results of these research studies have been of great value in the initial design studies of man-carrying orbital vehicles. However, it appears that man will eventually be called upon to assume manual control of an orbital vehicle. This may come about because of a failure in the automatic control system or it may be a routine piloting task. It appears, therefore, that much more information is needed on the influence of acceleration on man's ability to perform a complex control task.

In addition, most of the studies on man's tolerance to sustained accelerations were made using nonpilot test subjects. It is probable that only highly motivated test pilots will be used to man the orbital or near orbital vehicles. The fairly large differences in time tolerance to acceleration for pilot and nonpilot subjects were demonstrated in reference 12. It is generally accepted that the pilot's performance in and tolerance to acceleration fields are critically dependent upon the pilot's restraint system. The restraint systems used in many of the past studies were of course not representative of the current state of the art. It would therefore appear that additional tests are required, using test pilot subjects and representative restraint systems, to define pilot tolerance to sustained accelerations.

Recent work conducted by the National Aeronautics and Space Administration was focused directly on the problems of a pilot flying a vehicle during launch, or along an atmosphere entry trajectory (refs. 14 through 16). In these studies the principal objective was assessing the pilot's ability to control the vehicle while flying in an elevated g field. However, these studies were rather specific in nature.

As part of the general NASA program, a study was conducted by the Ames Research Center (during Sept. 1959) on the Aviation Medical Acceleration Laboratory centrifuge, Naval Air Development Center, Johnsville, Pa.

For this experiment, which was fairly general, the flight simulator experimental setup utilized the centrifuge in the control loop. The subject pilots were seated in the gondola of the centrifuge and were confronted with a fairly complex task which involved flying a simulated orbital vehicle entering the atmosphere. This study was split into three phases. The objectives of each phase were as follows:

(1) To obtain information on the combined effects of magnitude and direction of the applied acceleration force and of control task complexity on the pilot's performance.

(2) To establish some meaningful tolerance to acceleration times for the direction of acceleration fields encountered by a pilot in a forward-facing position flying along an atmosphere entry trajectory. A special anterior restraint system was developed in an attempt to increase human tolerance to longitudinal decelerations. Time tolerance to acceleration runs were also made for other directions of acceleration fields.

(3) A preliminary centrifuge investigation was conducted wherein several side-arm controllers were evaluated. One objective was to compare three-axis controllers with the two-axis, toe-pedal-type airplane controls. The toe-pedal-type control used was designed to minimize the effects of acceleration on the pilot's yaw control inputs.

This study was brief and of an exploratory nature. Nevertheless, it is believed that the results will be of value to the orbital-vehicle design engineer. In this paper, the vernacular of the test pilot has been used to describe the direction of the applied acceleration force. The terms "eyeballs in," "eyeballs out," and "eyeballs down" correspond to acceleration fields A_X, $-A_X$, and A_N, respectively, where A_X, $-A_X$, and A_N refer to the direction of acceleration forces measured in the conventional airplane body-axis coordinate system.

NOTATION

A_N acceleration factor, ratio of acceleration force to weight, positive when directed upward along spinal axis (i.e., from seat to head)

A_X acceleration factor, ratio of acceleration force to weight, positive when directed forward transverse to spinal axis (i.e., from back to chest)

$\bar{c}$ wing reference chord, ft

$C_{m_{\delta_e}}$ variation of pitching-moment coefficient with δ_e, per radian

g acceleration of gravity, ft/sec^2

I_Y moment of inertia about vehicle Y axis, slug-ft^2

M_{δ_e} $\frac{\bar{q}S\bar{c}}{I_Y} C_{m_{\delta_e}}$, per sec^2

$\bar{q}$ dynamic pressure, lb/sq ft

S reference wing area, sq ft

δ_e elevator deflection, radians

δ_p pilot stick deflection, deg

ζ damping ratio of longitudinal oscillatory mode of motion

ω_n natural frequency of longitudinal oscillatory mode of motion, per sec

APPARATUS AND TEST PROCEDURES

With regard to apparatus used in this test, the centrifuge at Johnsville, Pa., has received extensive coverage in the nation's magazines and technical journals and it will be assumed that everyone is generally familiar with this device. For a fairly detailed description of the centrifuge see references 17 and 18.

The pilot's restraint system used in the centrifuge tests is shown in figure 1. For protection against eyeballs-in accelerations it was felt that a pilot's couch similar to the type used in the Project Mercury capsule would be adequate for this study. Individual molds were made for each pilot. In figure 1, the pilot was essentially in a sitting position, with his upper body and head held at an angle of 85° to 90° with reference to the thigh position. The lower end of the leg mold in the vicinity of the ankles and the feet was cut off to permit the installation of the toe pedals for yaw control. The pilot's feet were restrained by strapping them in the toe-pedal devices. It might be noted that the toe pedals were actuated by differential rotation of the feet about the ankle joint. Thus, no movement of the leg was required and the entire leg could be firmly restrained. The head restraint, which is a critical item for eyeballs-out accelerations, was incorporated in the helmet system. The helmet was secured into the mold by nylon straps which were attached on each side of the helmet. Face pieces, which were used to restrain the head in the helmet, were individually molded from plaster cast impressions of each pilot's face. They were designed so that the major portion of the load would be taken over the prominences of the malar bones of the face. The chin cup was included in this restraint system, but only as a minor component since the chin is an unstable support point and its tolerance to large loadings is poor. The face plates were attached to the helmet by adjustable nylon straps fitted into a standard oxygen mask assembly.

The upper half of the torso was restrained by a bib fabricated of straps crossed over the upper portion of the chest so that most of the loading was taken over the upper rib cage. The rather snug fitting bib restricted the expansion of the upper chest. Therefore, the frontal area over the abdomen and lower chest was left essentially unsupported to allow excursion of the diaphragm and movement of the lower rib cage during the normal breathing process. Another separate component was fabricated for the pelvis. This consisted of two slightly crossed straps which were positioned to carry the loading over the pelvic bones and the upper thighs.

The limb restraints were constructed of nylon netting. All anterior restraints were extended through the mold and secured to the structure which supported the styrofoam couches. A more detailed description of the pilot's restraint system is given in reference 19. It should be noted that anti-g suits were worn by all test subjects.

The pilots instrument display is shown in figure 2. A cathode-ray tube in the instrument panel was used to display a randomly driven doughnut-shaped target. The dashed line on the display was drawn to illustrate that the target motion always remained on a line which passed through the center of the airplane reference and was perpendicular to the horizon. The vehicle roll and pitch attitude were displayed on the scope in the same fashion as they appear on a normal gyro horizon indicator. The sideslip angle was presented on the scope by the lateral displacement of the short vertical line away from the center index.

For all phases of the investigation, except the evaluation phase of the side-arm controllers, the pilot controls consisted of a finger operated two-axis side-arm controller and toe pedals. A description of the finger operated side-arm controller and of the toe-pedal controls is given in the last section of this report.

With regard to test conditions and procedures, the pilot flew the centrifuge as a closed-loop system; that is, for acceleration fields greater than 1 g, the centrifuge was driven in response to the pilot control inputs in such a fashion that the impressed linear accelerations varied in the same manner as the linear accelerations computed from the aircraft equations of motion. A detailed description of the closed-loop centrifuge operation is given in reference 14. The test setup was arranged so that the total g field impressed on the pilot consisted of two separate components; to a specified constant (biased) g field was added the computed perturbations in normal and side acceleration which resulted from the vehicle maneuvering about a given trim condition. The perturbations in side and normal accelerations were generally not greater than ±0.5g. In this experiment, the aircraft equations of motion described five degrees of freedom with the vehicle forward velocity assumed constant.

EFFECTS OF ACCELERATION AND CONTROL TASK ON PILOT PERFORMANCE

In this phase of the experiment, six different acceleration fields were investigated. The maximum accelerations investigated were 6g in an eyeballs-in direction, 6g in an eyeballs-down direction, and 7g in an eyeballs-out direction. A number of runs were made in each accelera- A436
tion field with the complexity of the control task as the variable. The complexity of the control task was varied by changing the damping and frequency of the vehicle longitudinal short-period oscillation. The dynamic characteristics of the roll and yaw modes of airframe motion were held constant. Table I presents the lateral-directional and the longitudinal airframe dynamics used in this phase of the study.

A qualitative measure of pilot performance was obtained by having the pilot give a numerical rating on the controllability of the simulated vehicle by using the pilot opinion rating schedule presented in table II. This pilot opinion schedule is essentially that presented in reference 20. In order to obtain a quantitative measure of the pilot's performance, a tracking task was utilized. The pilot's tracking score, which was the quantitative index of pilot performance, was calculated as the accumulated tracking error compared with the accumulated excursions of the target as expressed in the following equation:

$$\text{Pilot tracking score} = \frac{\int_0^T \theta_i^2 dt - \int_0^T e^2 dt}{\int_0^T \theta_i^2 dt}$$

where

θ_i^2 the square of the target excursions

e^2 the square of the tracking error excursions

T time interval of the tracking task

A detailed description of this tracking task is presented in reference 21. The length of the centrifuge tasks was 2-1/2 minutes. Approximately 1-1/2 minutes were devoted to the pilot's assessing the controllability of the system, the last minute being devoted to the tracking task. It might be noted that during the latter part of the 1-minute tracking task, the integrated pilot tracking score was still fairly sensitive to the pilot's instantaneous tracking error.

Figure 3 presents the tracking scores obtained from these tests for one of the subject pilots. This particular pilot was experienced in riding the centrifuge and was thoroughly familiar with the tracking task, and the data obtained from his test runs were believed to be representative of a well-trained pilot preconditioned to the effects of acceleration forces. His tracking score is plotted against the magnitude of the g force. Data for the eyeballs-down, eyeballs-out, and eyeballs-in accelerations are given for well-damped vehicle motions and for lightly damped vehicle motions. The well-damped case corresponds to a fairly easy control task and the lightly damped case corresponds to a fairly difficult control task. Certain tentative conclusions may be drawn from these data. To a first approximation, it appears that any decrement in pilot's tracking score is independent of the direction of the applied acceleration investigated in this program. Pilot's tracking score deteriorated markedly at accelerations greater than about 4g for the lightly damped dynamic situation. Finally, it appears that the more difficult control task greatly magnifies any deficiencies in the pilot's performance.

The results of the pilot's ratings on the longitudinal handling qualities of the vehicle obtained from these same performance runs are shown in figure 4. Pilot opinion boundaries which define satisfactory, unsatisfactory, and unacceptable regions of controllability of an entry vehicle are shown in terms of the period and damping ratio of the longitudinal oscillatory mode of motion. The pilot ratings which defined the various boundaries have been labeled in figure 4 and were as follows:

satisfactory-unsatisfactory = pilot rating 3-1/2
unsatisfactory-unacceptable = pilot rating 6-1/2

A curve corresponding to a pilot rating of 5 has been included since this boundary defines the region of "unacceptable for normal operation." The solid-line boundaries to the left of the shaded regions were derived from a moving cockpit flight simulator investigation (see ref. 22), wherein the pilots were exposed to the earth's constant gravitational field. The dashed-line boundaries to the right of the shaded regions were obtained from the centrifuge tests wherein the pilots were immersed in acceleration fields of approximately 6g to 7g. Thus, an increase in the acceleration field results in a corresponding shift in the pilot-opinion boundaries. This shift is from the solid-line boundary toward the dashed-line boundary. The tentative conclusion is reached that regardless of the region of airframe dynamics involved, the pilot feels that in order to have the same level of control over the vehicle, an increase in the longitudinal dynamic stability, as shown by the shaded area, is required with increases in the magnitudes of the acceleration impressed upon the pilot. There is some logic to the above results. The pilots often noted that more physical effort was required to control the simulated vehicle under the higher g loadings; consequently, they applied control very cautiously. It is well known that a reduction in manual dexterity and visual acuity may result with increases in the accelerations impressed upon the pilot.

TIME TOLERANCE TO ACCELERATION

In the study to establish some meaningful tolerance to acceleration times, a single set of airframe dynamics was used. A description of these vehicle dynamics is given in table I. The pilot was faced with a fairly difficult task when controlling this set of dynamics. The magnitudes of the accelerations investigated ranged from 6g to 8-1/2 g and the directions of the accelerations investigated were eyeballs in, eyeballs down, and eyeballs out; a diagonal acceleration vector was also investigated which consisted of a combination eyeballs-out and eyeballs-down direction.

During the tolerance runs the pilot was required to fly the simulated airplane and, to the best of his ability, track the randomly driven target. He was instructed to terminate the run if bodily pain became excessive, if he became so fatigued that he could no longer continue the run, if his vision markedly deteriorated, or if anything else of an untoward nature occurred. The project medical doctor monitored the pilot's electrocardiogram and respiratory recordings and terminated the run at his discretion. The project engineer monitored the tracings of pilot tracking score and terminated the run if the pilot's tracking score deteriorated markedly. A time history of a typical eyeballs-out endurance run is presented in figure 5. Only the most pertinent traces are presented in this figure; namely, the pilot's tracking score, the pilot's elevator deflection, and a recording of the acceleration trace. The beginning point for measuring tolerance time was taken when the acceleration value was within about 10 percent of that desired. It can be seen from figure 5 that after the initial starting transients in tracking score have subsided, the pilot's tracking efficiency remained essentially constant during the remainder of the run. This characteristic was typical of nearly all test runs. These results were somewhat surprising in view of the fact that the pilot became more fatigued and his vision deteriorated as the run progressed.

A brief survey of existing data on time tolerance to sustained accelerations was made. These data were then amalgamated with the results of the present investigation in an attempt to arrive at tolerance to acceleration boundaries which are meaningful to the orbital vehicle design engineer. In presenting these data, the currently accepted boundaries of time tolerance to acceleration are shown for comparison with the newly established boundaries. A brief description is given of the test conditions, procedures, and pilot's restraint system for each experiment which contributed data on time tolerance to acceleration to give the reader some insight on the degree of confidence that can be placed in the new proposed tolerance boundaries. In addition, the presentation of this information should provide the reader with a better understanding of the differences between the currently accepted and the proposed tolerance to acceleration boundaries.

The data obtained from the literature survey and the data obtained from the Ames investigation are presented in figures 6 through 9. For the tolerance to acceleration times obtained from the literature, it was attempted to use values wherein the subject was within about 10 percent of the specified acceleration value, rather than to measure the tolerance time from the beginning of onset of the acceleration force to the removal of the acceleration force. It should be noted, however, that in many of the reference reports, no exact definition of tolerance time was given and, hence, the listed tolerance time values may have been the total length of the run. The currently accepted boundaries defining human tolerance to sustained acceleration for the eyeballs-out, eyeballs-down, and eyeballs-in inertial force directions are presented as dashed lines in figures 6, 7, and 8, respectively. The data points on which the dashed-line boundaries are based were obtained by averaging the measured tolerance times for several test runs of nonpilot subjects. It is felt that the dashed-line boundaries are conservative. In contrast, the data points on which the new tolerance boundaries are based were obtained from runs by test pilots who were preconditioned to the effects of acceleration forces or from maximum tolerance-time runs completed by members of a group of nonpilot test subjects. These data points were in some cases the result of a single test run. It is therefore anticipated that the proposed new boundaries apply only to a fairly select group of which test pilots are members.

Eyeballs-Out Case

Figure 6 presents the available data for time tolerance to sustained accelerations for the eyeballs-out case.

Perhaps the most consistent and complete tests on tolerance to eyeballs-out acceleration were conducted by Clarke and Bondurant (ref. 3). The boundary obtained from this investigation is shown by the dashed line in figure 6. In these tests the subjects were in an essentially normal seated position. The anterior torso and extremity restraint system was somewhat similar to the restraint system used in the Ames tests. The head-restraint system for the Clarke tests, however, was arranged so that most of the weight of the head was taken across the subject's forehead. It should be noted that nonpilot subjects were used in this test.

The data obtained from the tests conducted in the present study are plotted as circular test points in figure 6. In a comparison of the tolerance time to acceleration values for the Ames and Clarke tests, it can be seen that a roughly sixfold increase in tolerance times to 7g eyeballs-out acceleration fields was demonstrated in the Ames tests. The Clarke data show a tolerance time of about 0.6 minute at 7g whereas the subjects in the Ames data show a tolerance time of 4 to 5 minutes at 7g. This increase in tolerance is attributed mainly to an improved restraint system and the use of highly motivated test pilots as centrifuge subjects.

The work by Ballinger and Dempsey (ref. 4) is shown by the triangular A
test points. In these tests the restraint system consisted of a semi- 4
prone nylon-net bed. The restraint system, although not designed for 3
operational use in an airborne vehicle, appeared to afford protection 6
to eyeballs-out accelerations nearly comparable to that offered by the system used in the Ames studies. It might be noted that nonpilot subjects were used in the Ballinger tests; however, only a small percentage of the centrifuge test group subjects completed the runs shown. The subjects completing the runs were, of course, those who were most highly motivated and who were physically able to tolerate the fatigue and pain associated with the endurance test trials.

A centrifuge investigation on human tolerance to eyeballs-out accelerations was conducted by Gauer and Ruff in reference 1. The test subjects were supported by a foam-rubber mattress 15 cm thick. The vision of the test subjects was checked during the run by having them read from a lighted chart placed about 30 cm from the eyes. A measure of manual dexterity was obtained by having the subjects write on a blackboard during the test trials. In this experiment the subjects were able to tolerate acceleration forces of 3g for as long as 38 seconds and 10g for as long as 16 seconds. By resting their wrists on the blackboard the test subjects were able to write numbers while immersed in a 10g field. During the high g runs there was some deterioration in vision which improved after blinking the eyes. This reduction in visual acuity was attributed by Gauer and Ruff to the tear fluids accumulating over the lenses of the eyes.

A 12g run for 15 seconds was reported in reference 23. The reference report indicates that these data were obtained from unpublished work conducted by the University of Southern California. No additional information was available regarding the test conditions for this program.

A 12g run for 1-minute was conducted by Ruff (ref. 6). In this case the subject was in the prone position. The original report by Ruff was not available; however, references to his work by other investigators would lead one to believe the subject was uninjured.

The work conducted by Duane and others (ref. 5) showed that a pilot in a seated position can tolerate backward accelerations up to and including 15g for 5 seconds. Duane employed a restraint system of padded barriers in the front of the lower face, chest, and legs. Here again, nonpilot subjects were used, and only the hardiest of subjects apparently completed the 15g run.

The single data point shown in the impact acceleration region was the much publicized run of Stapp (ref. 7) wherein he endured 25g eyeballs-out force for about 1 second. It has been included in figure 6 to show the voluntary endpoint of human exposure to eyeballs-out accelerations. Stapp was injured in this run; however, his injuries were apparently not permanent in nature. It should be noted that Stapp's head was not restrained during this run. From a pure tolerance to acceleration standpoint, it would appear that a healthy, highly motivated male, as exemplified by a test pilot, can withstand acceleration fields for the times indicated by the solid-line boundary in figure 6, provided he is suitably restrained.

A
4
3
6

Eyeballs-Down Case

A procedure similar to the one outlined for the eyeballs-out acceleration direction was also made for the eyeballs-down acceleration direction. Figure 7 presents the available time-tolerance data for this g field direction. For all the data points presented in this figure the test subjects were wearing anti-g suits.

The most complete set of data on tolerance to eyeballs-down acceleration forces was obtained by Miller, et al. (ref. 10). Nonpilot subjects were used in this investigation. For the tolerance tests the subjects were apparently in a normal seated position. Signal lights were used to determine visual loss. Acceleration forces from 3 to 6g were investigated in this research program. Exposures as long as an hour at 3g were tolerated by the test subjects; however, these data do not appear on figure 7 because of the limited time scale. The dashed line in figure 7 illustrates the time tolerance to eyeballs-down acceleration boundary derived from this set of data.

Human tolerance to 9g for 15 seconds was reported in reference 23. There is little information available on this data point. The reference report indicates that these data were obtained from unpublished work conducted by the University of Southern California and that the centrifuge subjects were wearing g protective equipment.

Acceleration force levels of 7g for 30 seconds were investigated by Dorman, et al. (ref. 12). In these tests the centrifuge test subjects consisted of nonpilot laboratory personnel and active duty fleet pilots selected at random from the operating squadrons. The test subjects were seated in the normal position and were secured by a lap belt and shoulder harness. Deterioration of peripheral vision was assessed by having the subject turn off peripheral lights through a push-button arrangement. Only 3 out of 24 pilot subjects successfully withstood the 30 second run at 7g without anti-g suits; however, with anti-g suits, 16 out of 24 pilot subjects withstood the prescribed g stress. None of the nonpilot personnel were able to tolerate the prescribed test run.

The triangular symbols indicate human tolerance times of about 1.2 minutes to normal acceleration values of 6.6g. These data were obtained from unpublished centrifuge time histories obtained from the Langley Research Center of NASA. The subjects used in the Langley tests were experienced test pilots. For these test runs the pilots were seated in a contoured couch similar to that used in the Ames tests. The pilot task consisted in controlling a simulated vehicle along an atmosphere entry trajectory.

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The data obtained from the Ames tests are plotted as circles on figure 7. The Ames data show that the test pilot subjects could withstand 6g in an eyeballs-down direction for as long as 6-1/2 minutes. The subjects reported that at the beginning of the run there were no physiological problems other than a momentary blurring and dimming of vision. As the run progressed, the pilot's vision grew dimmer. During the last 1-1/2 minutes of the run the pilot indicated he was having considerable trouble locating the target on the scope. The run was terminated when the pilot could no longer tell exactly the position of the target. Other than breathing becoming more labored there were no adverse physiological effects. There was no feeling of pooling of blood in the extremities and no pain.

As can be seen there is a scarcity of data on which to base any new tolerance to acceleration boundary for the eyeballs-down g field direction. However, on the basis of the existing information, a tentative boundary has been drawn and is shown by the solid line in figure 7. It is believed this boundary is valid for a test pilot subject wearing an anti-g suit.

Eyeballs-In Case

Figure 8 presents a summary of the available data on human tolerance to sustained accelerations for the eyeballs-in g field direction.

The dashed line boundary in the figure was derived from the research program of reference 3. It is believed the data from this program represent the most complete set of results on human tolerance to this g field direction. Nonpilot subjects were used in this experiment. Loss of vision, inability to breathe, or pain sufficient to interfere with judgment or performance were considered valid end points to the test run. The test subjects were positioned so that their legs were sharply flexed, with the trunks and heads tilted 25° in the direction of the acceleration. Reference 3 considered this to be the position for maximum tolerance to eyeballs-in accelerations. In this position blackout was not observed below 10g and substernal pain was minimum. An average tolerance time of 5 seconds at 12g was demonstrated in this program. It might be noted, however, that one of the test subjects tolerated 12g for 14 seconds.

Reference 5 reports on a centrifuge investigation conducted by Duane, et al. Nonpilot subjects were seated in a standard ejection seat from a Navy jet fighter airplane. Conventional lap belts and shoulder harnesses were used to restrain the subject in the seat. The task, required of the test subjects, consisted in turning off center and peripheral lights through a finger switch arrangement. In this study the subjects were exposed to an acceleration force of 15g for 5 seconds. It was noted in the reference report that as soon as the g stress was removed, the subject was not debilitated. This means that if voluntarily or involuntarily caught in this position, a pilot could recover instantly and perform intricate movements which might be life saving after removal of the inertial force.

In unpublished work by the AMAL, NADC, Johnsville, Pa., a nonpilot test subject was immersed in an acceleration field greater than or equal to 15g for a period of approximately 18 seconds. The subject was restrained by a molded couch contoured to fit the posterior shape of the body with the subject positioned in the couch so that his upper torso and head were held at an angle of approximately 10° with the horizontal. The knees were propped up so they were near the same level as the chest. The subjects reported blurring of vision at the higher g levels; however, a side-arm controller could be manipulated by the test subject.

Reference 2 gives some results obtained by the investigator Buehrlen. The subjects used in this investigation consisted mostly of junior surgeons of a German military academy. The subjects were essentially in a normal sitting position with their backs supported by an upholstered board. In this study, peak accelerations of 17g were investigated. The results of the investigation showed that the subjects could withstand 10 to 12g without difficulty; however, above 14g the subjects reported their vision had deteriorated and they could only see dark clouds with stars, etc. Most of the tabulated data presented in this reference indicates only the total length of the centrifuge run and does not show the period of time the subject was at or above a given g level. A single time history of a tolerance run is presented in reference 2, which shows that the test subjects were held at or in excess of 12g for 0.72 minutes. This single data point has been plotted in figure 8.

Reference 4 reports on a series of centrifuge tests of subjects in a semisupine position. The body was flexed at the hips so that the head, chest, and abdomen were raised to make an angle of approximately 20° with the horizontal. The knees were propped up so they were at the same level as the head. Nonpilot subjects were used in these tests with many of the subjects having no prior centrifuge experience. During these test trials the subjects were required to turn off center and peripheral lights through a three-switch arrangement situated on a hand grip. The subjects were also required to read word lists and perform a memory association test. Certain subjects were able to tolerate 10g for as long as 2 minutes. An opinion, expressed in reference 4, was that 2 minutes did not represent the maximum time tolerance to 10g.

The results of the Ames tolerance investigation are shown as circles in figure 8. In this case the subjects tolerated 6g eyeballs-in for approximately 6 minutes. It might be noted that in these tests the pilots were not seated in a position for maximum tolerance to eyeballs-in acceleration. It was surmised that had they been positioned differently, their tolerance time to this magnitude and direction of acceleration force would have been somewhat greater.

From the data in figure 8 a new tolerance boundary to eyeballs-in acceleration has been drawn. It is believed that the tolerance boundary represented by the solid line is valid for a test pilot subject suitably restrained in a near sitting position or in a semisupine position.

The data of time tolerance to acceleration obtained in the diagonal g field direction of eyeballs down and out is presented in figure 9. In this case it can be seen that a maximum g level of 8.4 was tolerated for as long as 20 seconds. This g field direction was particularly uncomfortable for the pilot because of the pain associated with blood pooling in the extremities. A tentative boundary to this direction of applied g is shown by the solid line faired through the data points. It might be noted that no additional time tolerance data were available for this diagonal g field direction.

In the Ames tests of tolerance to acceleration, post run comments by the test pilot subjects portray realistically the physical sensations encountered during the test trials. These comments are on file at the Ames Research Center.

A summary plot showing the derived time tolerance to acceleration boundaries for the principal g field directions of eyeballs down, eyeballs in, and eyeballs out is presented as figure 10. It is well known that the pilot cannot tolerate g forces applied in the normal direction as well as he can tolerate g forces applied in the transverse direction. It had been speculated by several investigators (refs. 3 and 9) that man's tolerance to eyeballs-out accelerations was equal to his tolerance to eyeballs-in accelerations. The results shown in figure 10 would tend to confirm these speculations. The tolerance boundaries to eyeballs-in and eyeballs-out accelerations are shown as being one and the same. One of the major physiological problems encountered by a person immersed in a high acceleration field is his inability to breathe properly (ref. 4). With the pilot positioned for optimum tolerance to the applied acceleration force, indications are that breathing is considerably easier during eyeballs-out than during eyeballs-in accelerations. An explanation for this was offered by Gauer and Ruff in reference 1 A word of caution should be inserted here regarding the use of the derived tolerance boundaries. The pilot of an orbital vehicle will be in a weightless state for extended periods of time before the entry phase of the mission. It is speculated these extended periods of weightlessness may alter his tolerance to high accelerations.

There is a paucity of data from which to draw conclusions on man's ability to perform a control task when he is immersed in an elevated acceleration field. From an extrapolation of the results of the Ames tests and the results of other tests, it would appear that the pilot's
A ability to perform a manual control task has markedly deteriorated when
4 he is exposed to eyeballs-out or eyeballs-in accelerations greater than
3 12g. It has been stated by Duane and others (ref. 5) that, between 12g
6 and 15g, the pilot is capable of simple manual switching operations
using the hands and fingers, and the study by Clark and others (ref. 8) has indicated that forearm, hand, finger, and ankle movements were not impaired at 12g. Above 15g there is the possibility of injury to the subject and less possibility that the pilot could assume primary control of the vehicle after removal of the acceleration stresses. In figure 10, the shaded area denotes the region of reduced pilot performance for the eyeballs-in and eyeballs-out acceleration forces. From the results of the Ames study and the study of reference 15, it would appear that the pilots' vision was greying out and they were on the verge of blackout for normal acceleration forces greater than about 6 to 7g. It is probable that because of this visual impairment pilot control performance deteriorates above 6 to 7g for the normal g field direction. The shaded area in figure 10 shows a tentative region of reduced pilot performance for the eyeballs-down g field direction.

The dashed curve in figure 10 labeled "Entry from parabolic velocity" was computed for a drag-modulated vehicle flying along a ballistic entry trajectory with the vehicle initial velocity taken as parabolic. Each point of the curve represents a different atmosphere entry trajectory starting from a different initial entry angle. The curve shows, for example, that by proper drag modulation the maximum acceleration which the vehicle would encounter during an entry could be 8g and this level of acceleration must be endured for about 1-2/3 minutes. It has been presumed that structures are currently available which will withstand the heating dictated by the entry conditions making up this curve. On the return from a lunar mission, the depth of the entry corridor, which must be acquired in order to effect a landing on the earth, increases as the allowable entry accelerations increase (ref. 24). Thus it is desirable to enter at the high g portion of this curve, since this reduces the accuracy demanded of the midcourse navigation and guidance system. The conclusion is reached that for the re-entering manned lunar vehicle, man is still the weakest link in the chain. The presence of man would probably prevent the vehicle from flying at the sustained accelerations for which it can be made structurally safe and which would allow an attendant reduction in the accuracies demanded of the navigation system.

The curve for the entry from circular velocities is presented in figure 10 to show the maximum acceleration and length of time which must be endured by an occupant of a drag-modulated ballistic vehicle entering the earth's atmosphere from a circular orbit. Each point of the curve represents a different atmosphere-entry trajectory; however, each point of the curve is computed for an initial entry angle of -5°. This curve shows the severest acceleration stress which man would probably be required to endure on a controlled, drag-modulated, ballistic re-entry from a circular orbit. As can be seen from the figure, man, if properly restrained, is apparently capable of withstanding these stresses.

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EVALUATION OF SIDE-ARM CONTROLLERS

An additional item which can strongly influence the performance and efficiency with which a pilot can fly a vehicle in an elevated g field is the design of the pilot's side-arm controller. In an attempt to negate the effects of acceleration forces on the ability of a pilot to control a vehicle, various side-arm controllers have been proposed. It appears, as of the present time, that three-axis side-arm controllers are receiving the most serious consideration. With this type, the pilot's legs can be firmly restrained and they are not used to make control inputs. An alternate class is the two-axis side-arm controller. It is similar to the three-axis class, except the yaw control is obtained through movement of the feet or legs. The argument as to which class of controller is better hinges (1) upon whether the high acceleration forces would render the legs useless for making control inputs, and (2) upon the ability of the pilot to blend and apply three (instead of two) different control inputs with one hand. An additional objective of the side-arm-controller study was to determine the best side-arm controller from configurations which represent the present state of the art.

The procedure for evaluating the side-arm controllers was very similar to that used in the rest of the study. To each test controller the pilot assigned numerical ratings on vehicle controllability. After each run, the pilot was thoroughly interrogated on the desirability of certain controller characteristics, such as breakout force, force gradients, and axes of control rotations.

Each controller was tested in the earth's gravitational field (static run) and in two elevated accleration fields, and two to three different sets of airframe dynamics were utilized. The two elevated test accelerations were as follows:

$$A_X = 6g,\ A_N = 0g \quad \text{and} \quad A_X = -2g,\ A_N = 4g$$

These accelerations were chosen as typical of those which might be encountered during the launch and entry phases of an orbital mission. The vehicle longitudinal and lateral-directional airframe dynamic characteristics, which are shown in table III, ranged from a well-damped system with moderate control-moment cross coupling (i.e., application of the ailerons produced both rolling and yawing moments) to a lightly damped system with heavy control-moment cross coupling. The parameter $100C_{l_\beta}C_{n_{\delta_a}}/C_{n_\beta}C_{l_{\delta_a}}$, which is discussed in reference 22, was used as a measure of the control-moment cross coupling. It was believed that the lightly damped heavily cross-coupled dynamic situation would emphasize existing deficiencies in the various controller configurations.

Figure 11 shows the input axes of rotations for the various test controllers in this investigation. The axis running parallel to the forearm should be regarded as being essentially the center line of the forearm. Sketch F is intended to show that the toe pedals were actuated by differential rotation of the feet about the ankle joint. Photographs of the various test controllers and a photograph showing the lower leg restraints and the toe-pedal installation is presented as figure 12. The controllers were designated A, B, C, D, E, and toe pedals. Controllers A and B were in the three-axis class. Controllers C, D, and E were in the two-axis class. The three-axis side stick controller A was converted into a two-axis controller by freezing the yaw control axis. As a two-axis controller it was labeled controller C. Note that controller E is held by the fingers (fig. 11).

The force characteristics of each controller, as measured in the earth's constant 1g field, are shown in figure 13. The control forces presented in this figure were measured at approximately the mid-point of the stick grip. Fairly complete descriptions of the mechanical features of controllers A and E are given in references 25 and 26, respectively. No published references are available giving the design details of the remaining side-arm controllers or toe-pedal controls; however, the mechanical design of these latter items was reasonably straightforward. In general, the force gradients of these controllers were obtained by a coiled spring arrangement with a mechanical feature which allowed some adjustment in the controller breakout forces.

When the controllers were operated in the earth's 1g field, the consensus of the pilots was that side-arm controller, toe-pedal force gradients, and breakout forces were acceptable for normal operation; however, the following specific criticisms were offered:

<u>Controller A</u>: The breakout force and force gradient for the directional axis of control were higher than desired. The roll-axis breakout force was high and the roll-axis force gradient was too low.

Controller B: The breakout forces about all axes for this controller were high; in addition, the roll-axis breakout forces for right stick deflection were considerably higher than those for left stick deflection.

Controller D: A more positive stick centering force for the roll-axis of control was desired.

Controller E and toe pedal controls: No specific criticism.

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For the controllers used in these tests the pilot control input was transmitted through a mechanical linkage to electric potentiometers. This mechanical linkage usually consisted of a small number of links with a minimum of backlash and friction at each connecting point, with the consequence, that the damping forces present in the controllers were fairly small for some of the controllers tested. An indication of the damping forces present in the linkage system of the various controllers was obtained by measuring the cycles to damp to half amplitude ($C_{1/2}$) of the free oscillations about each axis of each controller. The natural frequency in terms of the period of the free oscillation and the damping in terms of $C_{1/2}$ about each axis of each controller is presented in table IV.

It was pointed out in reference 22 that pilot opinion of the longitudinal handling qualities of an atmosphere entry vehicle is a function, among other things, of the gearing between the pilot's stick and the vehicle pitch-control power (pitch-control power gradient) expressed as $(M_{\delta_e}\delta_e/\delta_p)/\omega_n^2$. The value of pitch-control power gradient desired by the pilots is, in turn, a function of the type of controller (i.e., center-stick, side-arm controller, etc.) as well as a function of the vehicle longitudinal period and damping. The desired values of pitch-control power gradient for a conventional center control stick were presented in reference 22. A brief investigation was conducted to determine the desired values of pitch-control power gradient for side-arm controllers D and E. These two controllers were chosen for this phase of the study since they represented two distinctly different types, namely, hand-held and finger-held. This portion of the study was conducted on a fixed simulator in the same manner as described in reference 22. The results of the present study are shown in figure 14. In this figure are shown optimum regions of pitch-control power gradient for a vehicle with high damping, $2\delta\omega_n \approx 2$, and for a vehicle with low damping, $2\delta\omega_n \approx 0$. It is interesting to note that in this figure the hand controller (controller D) exhibits a broad area of acceptable pitch-control power gradients; whereas the finger-held controller (controller E) has a more limited range of acceptable pitch-control gradients. The information in figure 14 was used to select the value of pitch-control power gradient for the various controllers used in the side-arm controller evaluation tests. The value of pitch-control power gradients used for all handgrip side-arm controllers (i.e., controllers A, B, C, and D) and for the finger-held controller (E) is shown in figures 14(a) and 14(b), respectively.

Figure 15 is a summary plot obtained by averaging each pilot's ratings on vehicle controllability for all the acceleration fields of this investigation and then averaging this average rating for all the pilots (for a given set of airframe dynamics and for a specified controller). Pilot comments from these tests indicated a unanimous preference for a two-axis controller, toe-pedal combination. The difficulty in blending and applying three control inputs through one hand was repeatedly pointed out by the evaluation pilots; this difficulty, however, was not reflected in the pilots' numerical ratings when they used a controller to fly the well-damped configuration. The preference for the two-axis controllers was much stronger for controlling the lightly damped configuration than for controlling the well-damped dynamic one. This was verified by the pilots' numerical rating on vehicle controllability presented in figure 15. An approximately 1-3/4 rating point preference of the two-axis class of controllers is indicated for controlling the lightly damped, heavily cross-coupled vehicle.

Quantitative data as well as subjective pilot comments obtained during the tests did not indicate a clear-cut superiority of any particular two-axis controller over the others. At a roundtable discussion following the tests, participants expressed a general preference for controller E; however, this preference was not a strong one. Arguments in favor of the finger-held controller were as follows: There were some indications that for short-period oscillations the pilot could control a lower level of airframe damping with this type of controller as opposed to the heavier handgrip type of two-axis controllers. Because the finger-held controller differed from the conventional center stick (i.e., held with fingers, inertia very low, light-force gradients, etc.), some pilots noted that they had less tendency to handle it like a conventional center stick and this reduced their tendency to revert back to center-stick control patterns when faced with a "clutch" situation. The pilots noted that with the heavier controllers and in the higher g fields, there was an apparent increase in the inertia of the controller and hand. As a result more effort was required to deflect the controller, and the pilots' control inputs were smaller and were made very cautiously; this effect was apparently reduced to some extent when the light pencil controller was used. Arguments not in favor of the finger-held controller were that positioning of the hand on the controller was critical and, as a result, fore-and-aft displacement of the hand and arm relative to the stick, due to high $\pm A_X$ accelerations, caused some downgrading of the controller in the opinion of the pilots. Pilots also indicated a vague feeling of the controller being somewhat feathery, being "tender" to use, requiring no work, etc.

As for the axes of control rotations for the handgrip controllers, the pilots expressed a unanimous preference for the roll axis of rotation to be below and to run essentially parallel to the longitudinal axis of the lower arm, and for the pitch axis of rotation to be perpendicular to the roll axis and to pass through the nominal wrist pivot point. Side-arm controllers B and D exemplify the desired positioning of the roll and pitch axes of rotation. Agreement on the desirable positioning of the yaw axes of rotation for the three-axis controllers was not reached.

The toe pedals, used in conjunction with the two-axis controllers, were considered quite usable. The majority of pilots who used them stated there was no tendency toward inadvertent inputs, and good coordination of the yaw input with the roll input was possible after some practice. No marked reduction in their usefulness was noted for the pure eyeballs-out or eyeballs-in acceleration (maximum values of $A_X = -7g$ and $A_X = 6g$ were tested for periods as long as 5 minutes). For the combination eyeballs-out and eyeballs-down accelerations ($A_X = -5g$, $A_N = 5g$ and $A_X = -6g$, $A_N = 6g$), the usefulness of the toe pedals was diminished. Blood pooling in the lower extremities caused numbness and pain which precluded precise yaw control inputs with the rudder pedals. Indications were that the acceleration fields in which the toe pedals could be successfully used could be extended appreciably if an improved lower leg g protection system were used and if the lower leg were positioned so that its long or tibial axis was always perpendicular to the applied acceleration vector.

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Interrogation of the pilots after each centrifuge run indicated that for nearly all controllers tested, there was an apparent change in friction levels, stick-force gradients, breakout forces, etc., with different levels of the impressed acceleration field. According to pilot opinion, these stick-force changes were usually to the detriment of the controller. It appeared that the variation in stick-force characteristics with impressed accelerations was partly due to mass unbalance of the controllers and, in part, to deflections in the structure of the stick, which tend to bend the movable parts with an increase in the friction levels, etc. It is recognized that these changes may also be partly imagined as a result of physiological or psychological effects of the impressed accelerations on the pilot. It seemed that the controllers exhibiting the largest apparent changes in force characteristics were of the high inertia, high weight, bulky type which required considerable design effort to attain some semblance of mass balance. It would seem from the experience gained in these tests that a prime consideration in the design of controllers should be to keep them light in weight with low inertia about the control axes.

CONCLUDING REMARKS

The centrifuge study showed there could be marked decreases in pilot tracking performance with increases in the magnitude of the impressed accelerations. Pilot comments indicated that in order to have the same level of control over the vehicle, an increase in the vehicle dynamic stability is required with increases in the magnitude of the acceleration impressed on the pilot. It appears that a great deal of additional research work is warranted in investigating the effects of sustained accelerations on the pilot performance.

The study indicated quite clearly the improvement in tolerance to acceleration times which can be realized through relatively minor improvements in the pilot's restraint system. It would appear that with a suitable restraint, the pilot's tolerance to eyeballs-out accelerations can be made equal to his tolerance to eyeballs-in accelerations. It is suggested in this study that more meaningful tolerance to acceleration times may be obtained by using highly trained and highly motivated test subjects, as exemplified by the test pilot.

Finally, pilot comments indicated a unanimous preference for the two-axis class of side controller over the three-axis class. The pedal controls used in this study resulted in effective yaw control for most acceleration fields of this investigation.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., April 12, 1960

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TABLE I.- VEHICLE DYNAMIC CHARACTERISTICS FOR PERFORMANCE TESTS

Vehicle dynamic parameters	Combination 1	2	3	4	5
Dutch roll damping ratio	0.344[a]	Constant →			
Dutch roll period, sec	2[a]	Constant →			
Roll time constant, sec	1[a]	Constant →			
Cross-coupling parameter, $\frac{100 C_{l_\beta} C_{n_{\delta_a}}}{C_{n_\beta} C_{l_{\delta_a}}}$, percent	50[a]	Constant →			
Longitudinal damping ratio	.34	0.11[a]	0.02	0.02	0.02
Longitudinal period, sec	2	2[a]	2	1	6

[a]Indicates vehicle dynamic characteristics for tolerance to acceleration tests.

TABLE II.- PILOT OPINION RATING SYSTEM FOR UNIVERSAL USE

	Adjective rating	Numerical rating	Description	Primary mission accomplished	Can be landed
Normal operation	Satisfactory	1	Excellent, includes optimum	Yes	Yes
		2	Good, pleasant to fly	Yes	Yes
		3	Satisfactory, but with some mildly unpleasant characteristics	Yes	Yes
Emergency operation	Unsatisfactory	4	Acceptable, but with unpleasant characteristics	Yes	Yes
		5	Unacceptable for normal operation	Doubtful	Yes
		6	Acceptable for emergency condition only*	Doubtful	Yes
No operation	Unacceptable	7	Unacceptable even for emergency condition *	No	Doubtful
		8	Unacceptable - dangerous	No	No
		9	Unacceptable - uncontrollable	No	No
	Catastrophic	10	Motions possibly violent enough to prevent pilot escape	No	No

*(Failure of a stability augmenter)

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TABLE III.- VEHICLE DYNAMIC CHARACTERISTICS FOR SIDE-ARM CONTROLLER EVALUATION TESTS

Vehicle dynamic parameters	Lightly damped, heavily cross-coupled vehicle	Intermediately damped, intermediately cross-coupled vehicle	Well-damped, moderately cross-coupled vehicle
Dutch roll damping ratio	0.11	0.344	0.344
Dutch roll period, sec	2	2	2
Roll time constant, sec	2	1	1
Cross-coupling parameter, $\frac{100C_{l_\beta}C_{n_{\delta_a}}}{C_{n_\beta}C_{l_{\delta_a}}}$, percent	75	50	25
Longitudinal damping ratio	0.11	0.344	0.5
Longitudinal period, sec	2	2	2

TABLE IV.- PERIOD AND $C_{1/2}$ OF FREE OSCILLATION

Controller	Axis	$C_{1/2}$	Period, sec
A and C	Pitch	3/4	1/4
	Roll	1/2	1/3
	Yaw	1/2	3/4
B	Pitch	1	1/2
	Roll	2	3/4
	Yaw	1-1/2	1/15
D	Pitch	1	3/4
	Roll	1	1/2
E	Pitch	3	1/10
	Roll	3	1/6
Toe pedals	Yaw	1/2	1/5

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Figure 1.- Pilot's restraint system.

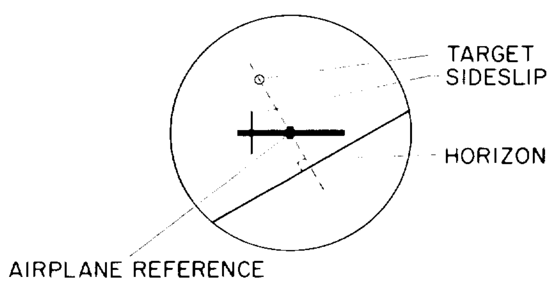
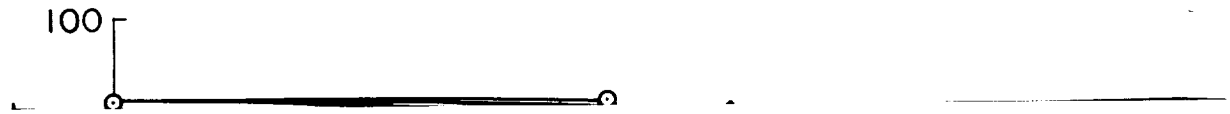


Figure 2.- Pilot's instrument display.

Figure 6.- Summary of tolerance to eyeballs-out acceleration.

28



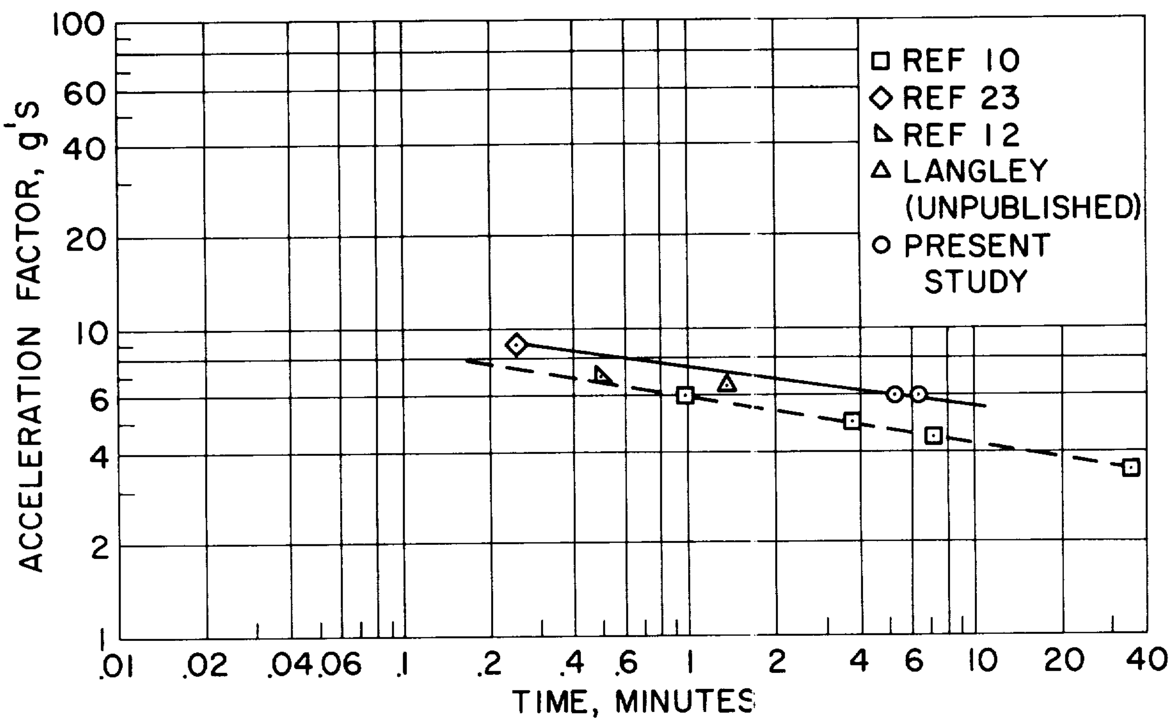


Figure 7.- Summary of tolerance to eyeballs-down acceleration.

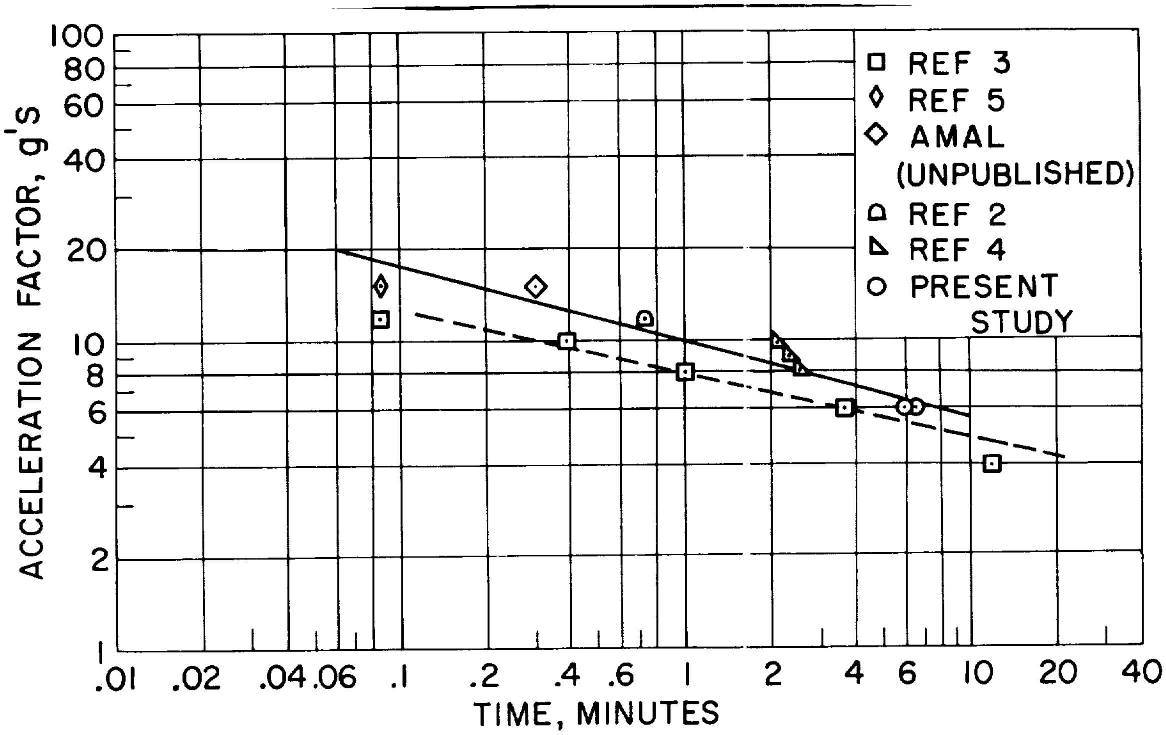


Figure 8.- Summary of tolerance to eyeballs-in acceleration.

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A
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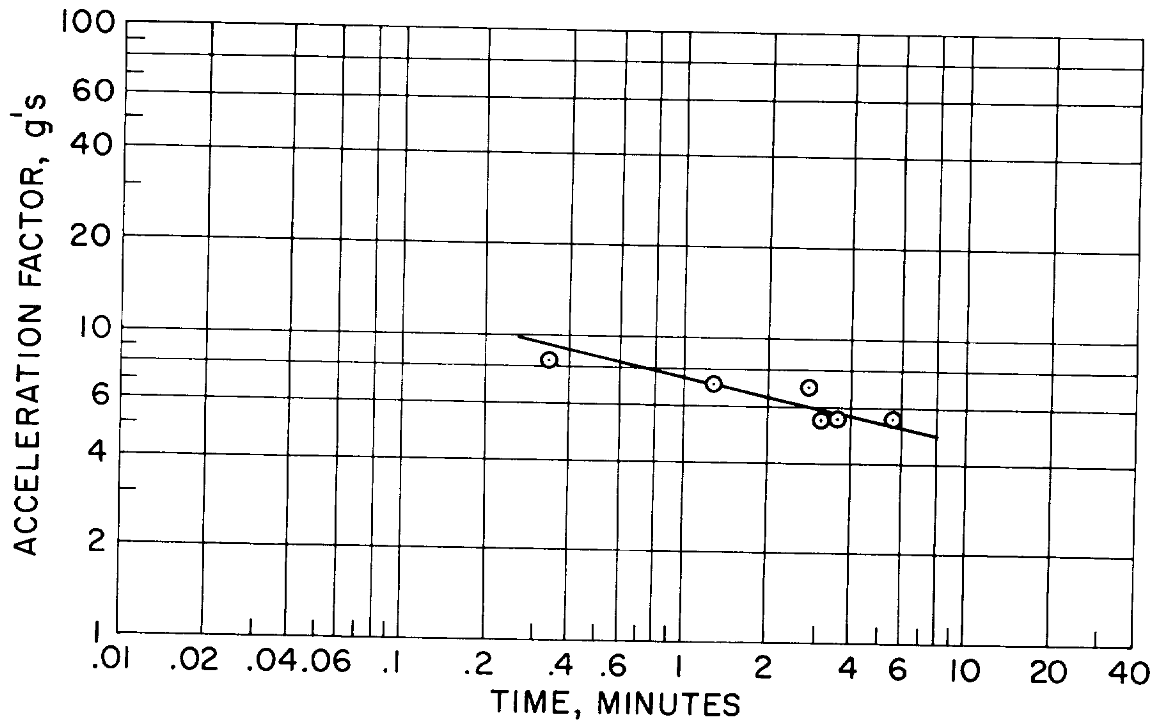

Figure 9.- Summary of tolerance to eyeballs-down and -out acceleration.

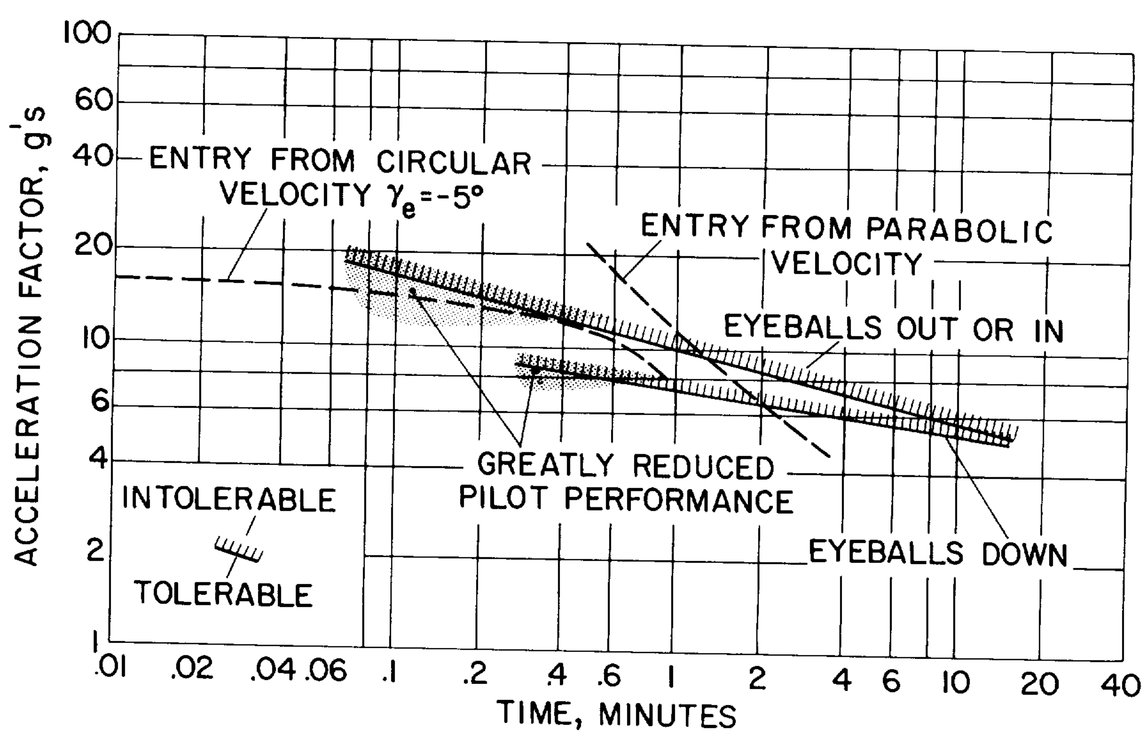

Figure 10.- Time tolerance to acceleration boundaries.

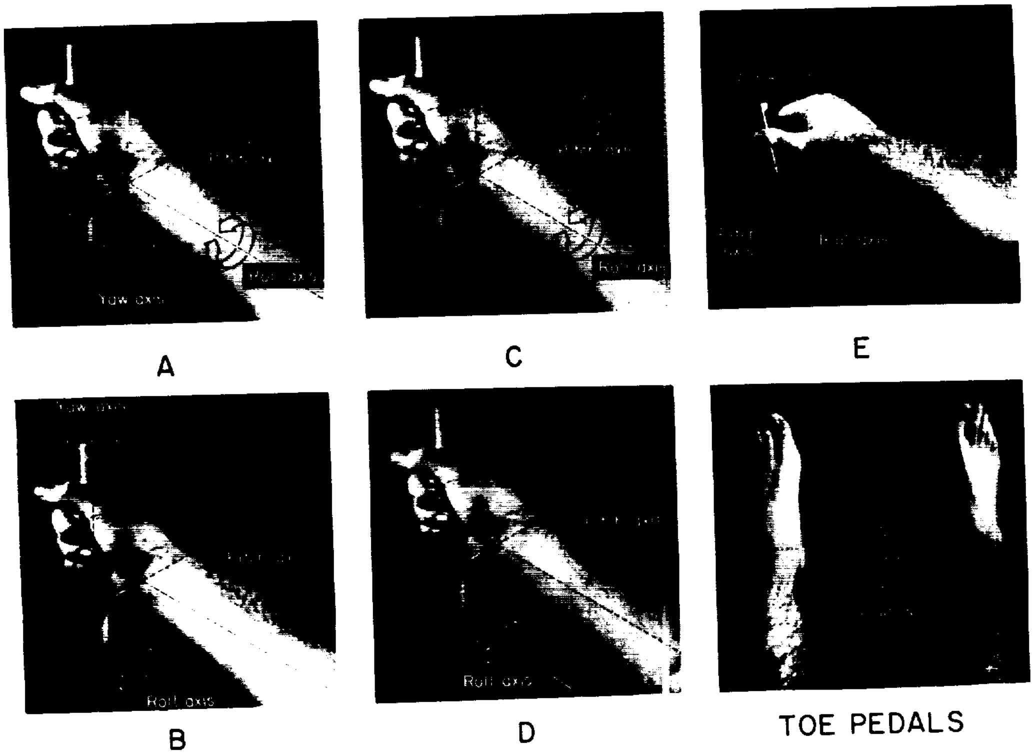

Figure 11.- Axes of rotation for test controllers.

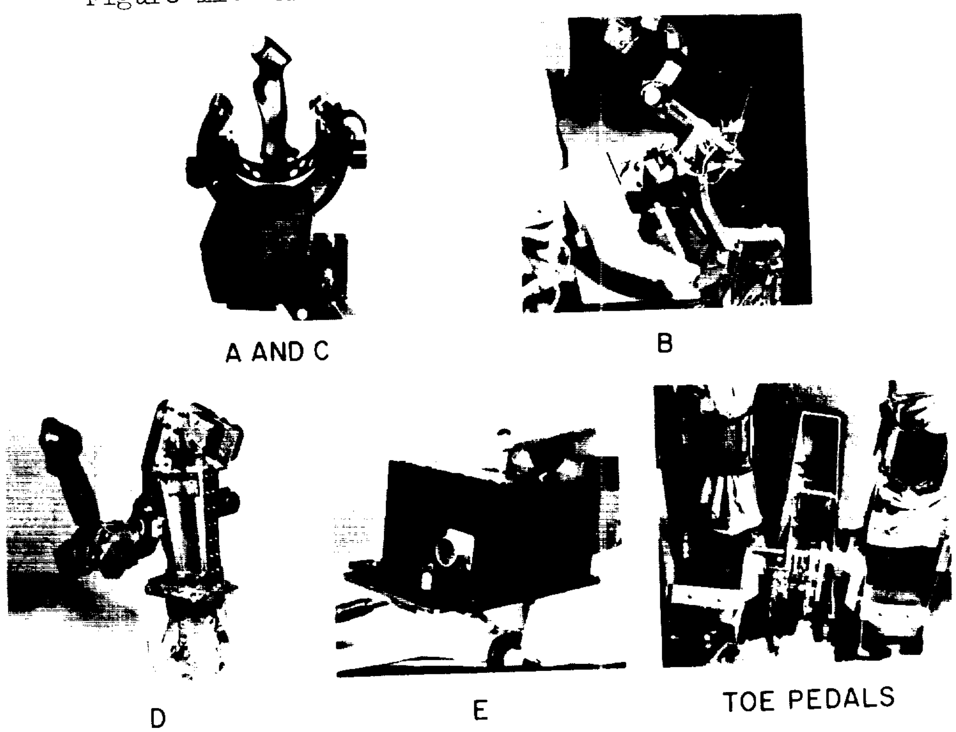

Figure 12.- Test controllers.

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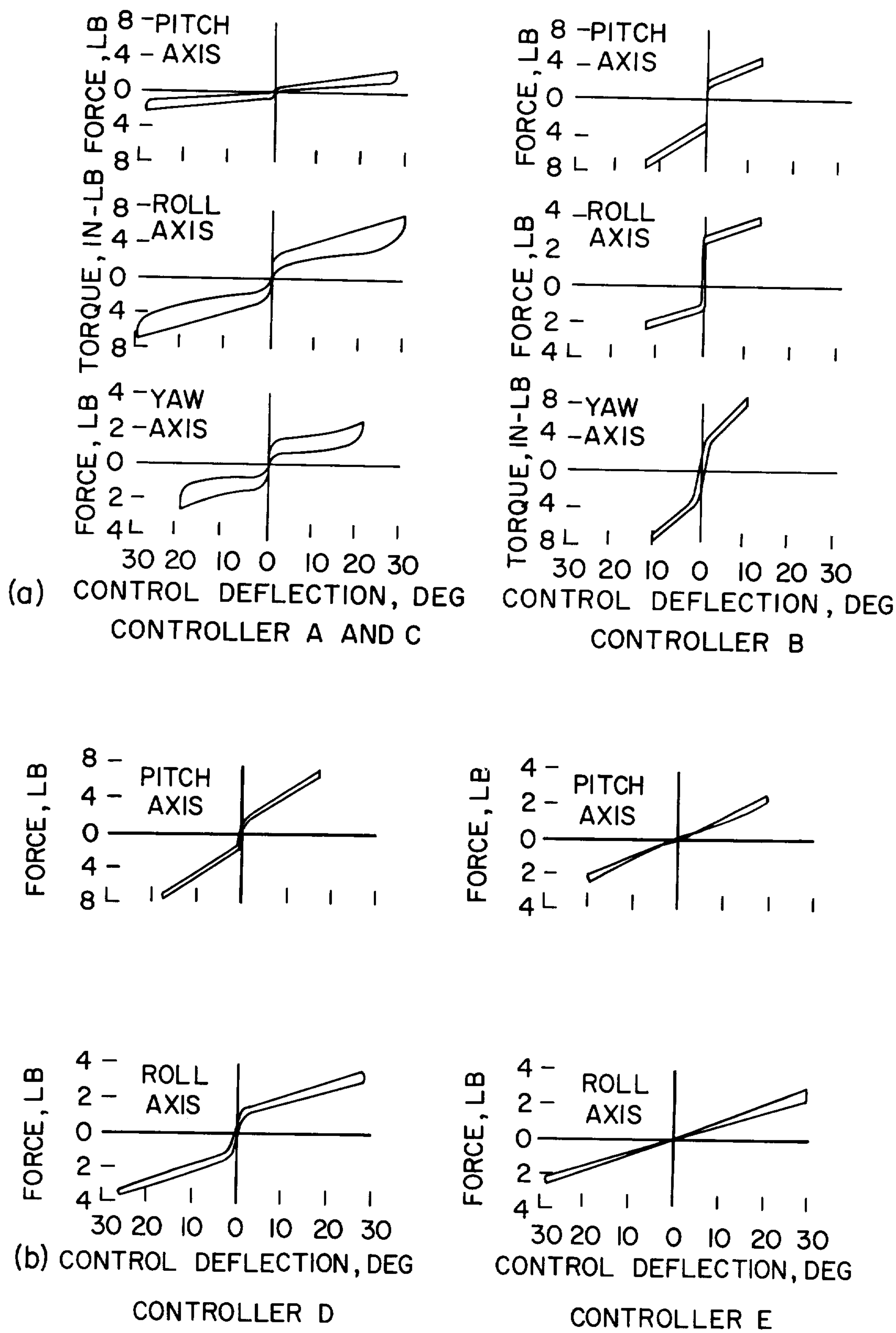


Figure 13.- Control force characteristics.

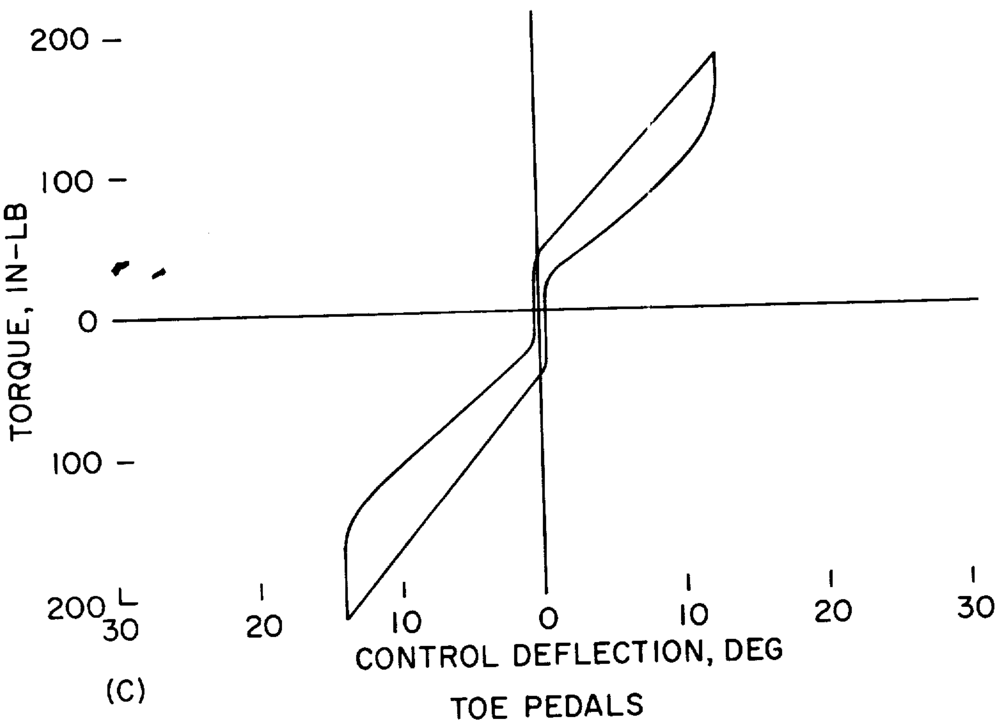


Figure 13.- Concluded.

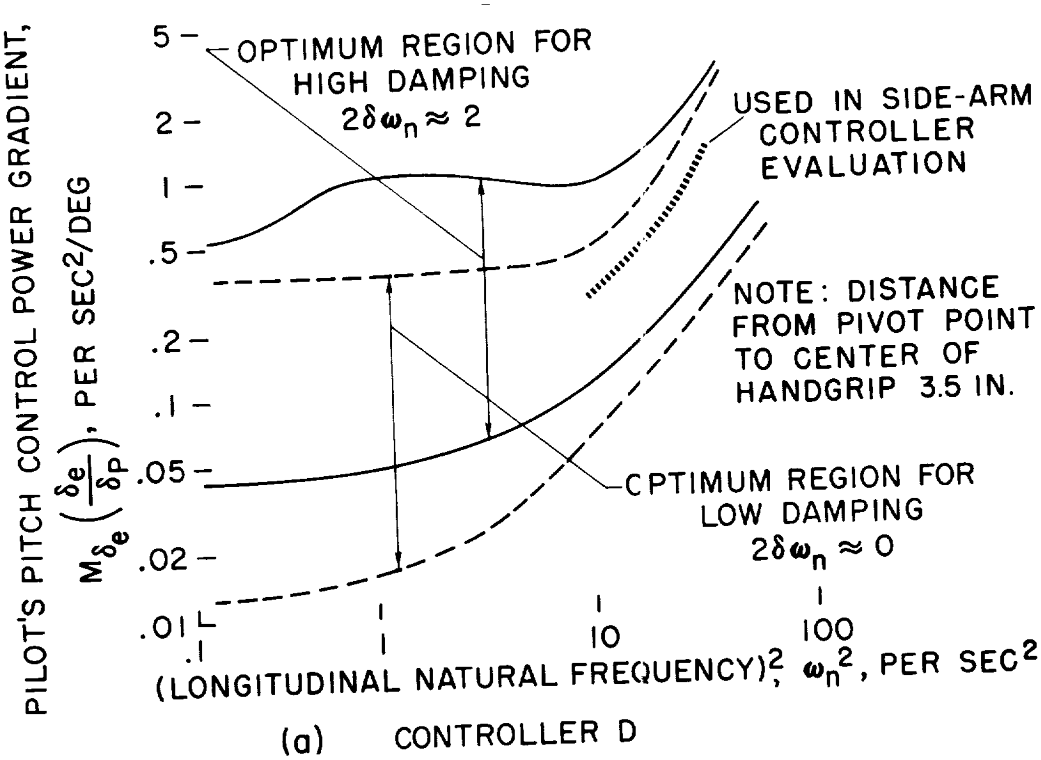
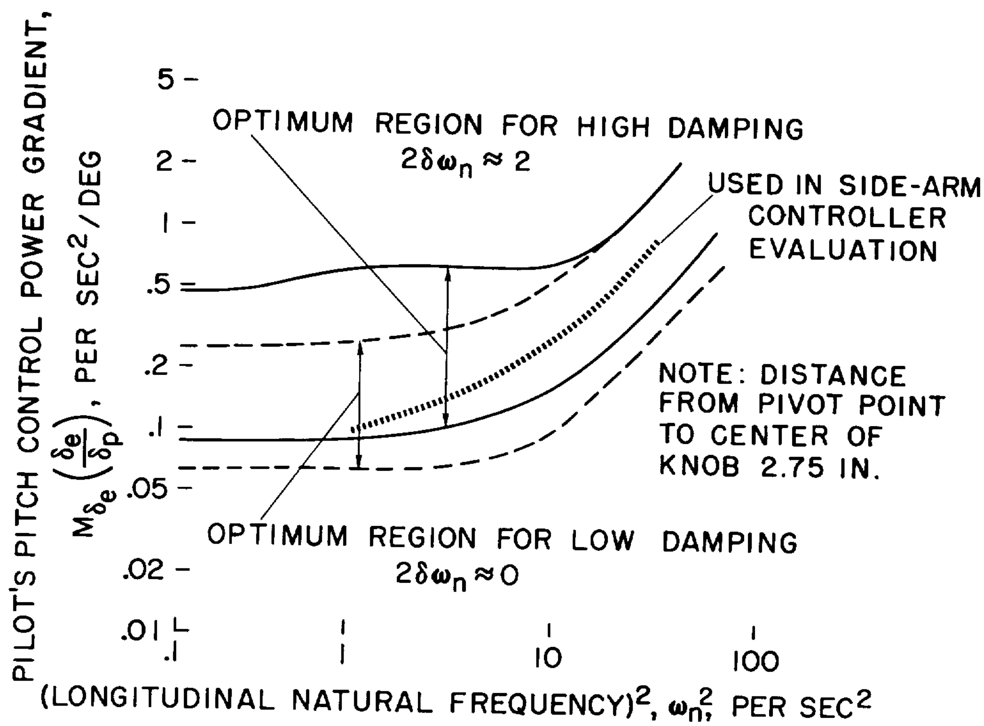


Figure 14.- Optimum pitch control power gradient.



(b) CONTROLLER E

Figure 14.- Concluded.

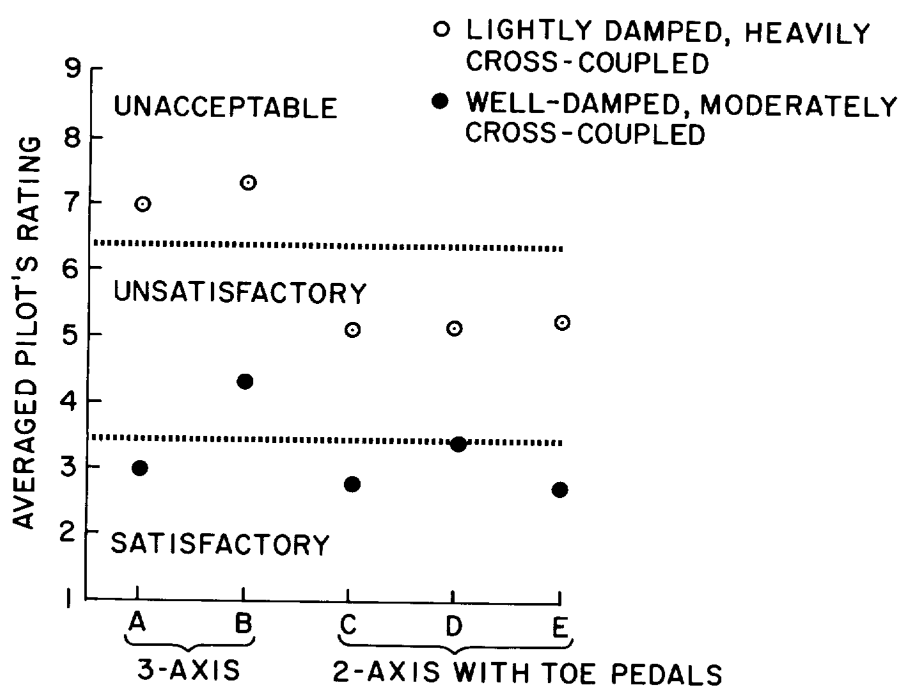


Figure 15.- Pilot rating on vehicle controllability using test controllers.

NASA TN D-337
National Aeronautics and Space Administration.
CENTRIFUGE STUDY OF PILOT TOLERANCE TO ACCELERATION AND THE EFFECTS OF ACCELERATION ON PILOT PERFORMANCE. Brent Y. Creer, Harald A. Smedal, and Rodney C. Wingrove. November 1960. 35p. OTS price, $1.00. (NASA TECHNICAL NOTE D-337)

The experimental setup consisted of a flight simulator with a centrifuge in the control loop. The pilot performed his control tasks while being subjected to acceleration fields such as might be encountered by a forward-facing pilot flying an atmosphere entry vehicle. Information was obtained on the combined effects of complexity of control task and magnitude and direction of acceleration forces on pilot performance. Boundaries of human tolerance to acceleration were established. A comparative evaluation was made of the three-axis type of side-arm controller and the two-axis type in combination with toe pedals for yaw control.

I. Creer, Brent Y.
II. Smedal, Harald A.
III. Wingrove, Rodney C.
IV. NASA TN D-337

(Initial NASA distribution: 5, Atmospheric entry; 8, Behavioral studies; 34, Piloting.)

NASA

NASA TN D-337
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III. Wingrove, Rodney C.
IV. NASA TN D-337

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