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THE EFFECTS OF MOTION CUES AND MOTION SCALING ON ONE- AND TWO-AXIS COMPENSATORY CONTROL TASKS

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16. Abstract

One- and two-axis compensatory control tasks were performed both with and without motion inputs. Additional tests were made in which the motion input, compared with the visual input, was reduced in scale. Little or no difference in error measurements was observed in the single-axis-motion/no-motion tests. However, a decrease in normalized tracking error and an increase in the closed-loop system frequency were observed when motion was added to the two-axis tests. In the tests with reduced motion scale, the normalized tracking error remained constant for full, 1/2, and 1/4 motion scaling but increased with a further reduction in motion scaling. In general, the results show that motion may or may not be an aid in controlling a compensatory tracking task, depending on the difficulty of the task and on the requirements of the mission. Also it is shown that for cases in which motion is beneficial, it is not always necessary to supply full-scale motion cues.

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SUMMARY

Tests were made to determine the effects of angular motion on compensatory control tasks. The tests included one- and two-axis tasks with and without motion. Both full-scale motion and reduced-scale motion (tests in which the scale of motion, compared with the visual input, was reduced) were examined. The reduced-scale motion tests were performed to investigate the minimum requirements of motion inputs in those tests where motion was found to be beneficial.

Little or no difference in the error measurements was observed in the single-axis motion/no-motion tests. The two-axis tests, which consisted of pitch and yaw or pitch and roll, did however, produce a difference in the error measurements in the motion/no-motion comparisons. A decrease in normalized tracking error and an increase in the closed-loop system frequency were observed when motion was added.

The reduced-scale motion tests were made with the two-axis pitch and yaw task. These tests were performed in a sequence starting with no motion all the way to full-scale motion and back to no motion. Each motion scale condition (none, 1/16, 1/8, 1/4, 1/2, and full) constituted a test. The normalized tracking error remained constant for full, 1/2, and 1/4 motion scaling but increased with a further reduction in motion scaling.

The results show that motion may or may not be an aid in controlling a compensatory control task, depending on the difficulty of the task and on the requirements of the mission. In general, angular motion is helpful if (1) the characteristics of the plant dynamics are such that the subject can use the lead information inherent to motion to tighten the control loop, that is, increase the system frequency without decreasing the damping ratio, or (2) two or more variables are being controlled and the motion inputs allow the subject to be alert to changes in the variable or variables not being closely monitored visually at the time.

INTRODUCTION

With the present development of highly sophisticated vehicles, a better understanding of input requirements is needed in order to insure valid simulations. Of these requirements, motion appears to be one of the most important.

It is well known that motion is a factor in many simulations, but it is not well understood just what elements of motion are the most important. For this reason, many simulations use either no motion at all or full-scale motion, even though experience has shown that full-scale motion is very expensive in terms of equipment, power, and other factors. Full-scale motion requirements often demand motion inputs that are beyond the limitations of the simulator. Therefore, electrical limit circuits must be used to restrict these motion inputs. The addition of these circuits can lead to unacceptable discrepancies between the motion and visual inputs.

The study discussed herein was made to examine conditions for which motion is beneficial and to determine the particular requirements of these motion inputs. With this information it is possible to analyze the simulation to be performed and to incorporate only those motion inputs necessary to obtain valid simulation results. Previous works in this area, such as references 1 and 2, have examined some conditions for which motion is necessary. Related works, such as references 3 and 4, have explained how motion is perceived as an input.

The principal technique of this study is a simple concept of reducing the motion input requirements by direct motion scaling.

SYMBOLS

C	output of computer-generated dynamics, volts or degrees
I	system input, volts or degrees
K	gain or arbitrary value
K_1	model gain, volts
K_2	model lead coefficient, seconds
k_1	average measured value of K_1 for a particular run, volts
k_2	average measured value of K_2 for a particular run, seconds
N	filtered noise, volts or degrees
O	system output, volts or degrees
s	Laplace operator, second^{-1}

δ output of subject or model of subject, volts or degrees

ϵ system error (I - O), volts or degrees

τ lag break frequency, radians/second

τ_m average measured value of τ for a particular run, radians/second

DESCRIPTION OF APPARATUS

The tests were performed in a small one-man enclosure, which was mounted on a U-shaped frame. The U-shaped frame was mounted on a rigid platform. (See fig. 1.) This configuration allowed the enclosure to be rotated in two degrees of freedom. The inner axis was a rotation of the enclosure within the U-shaped frame and was always defined to be a rotation in pitch. The outer axis was a rotation of the frame on the

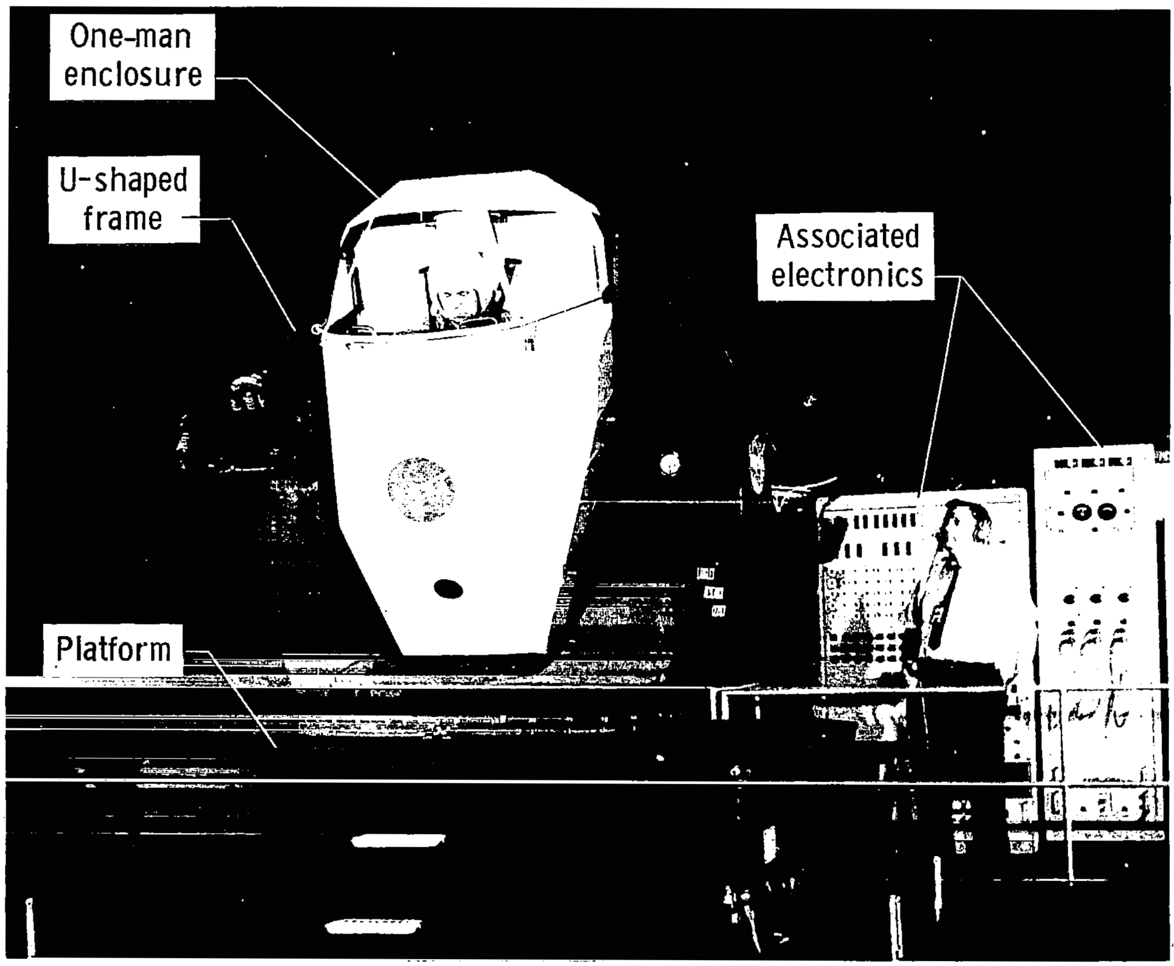

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Figure 1.- Photograph of simulator.

platform and was defined to be either yaw or roll, depending on the zero pitch orientation for the test. If the pitch attitude was such that the subject was in a sitting position, a rotation of the outer axis was defined to be yaw, and if the subject was in a supine position, a rotation of the outer axis was defined to be roll. (See fig. 2.) Both axes were capable of continuous rotation.

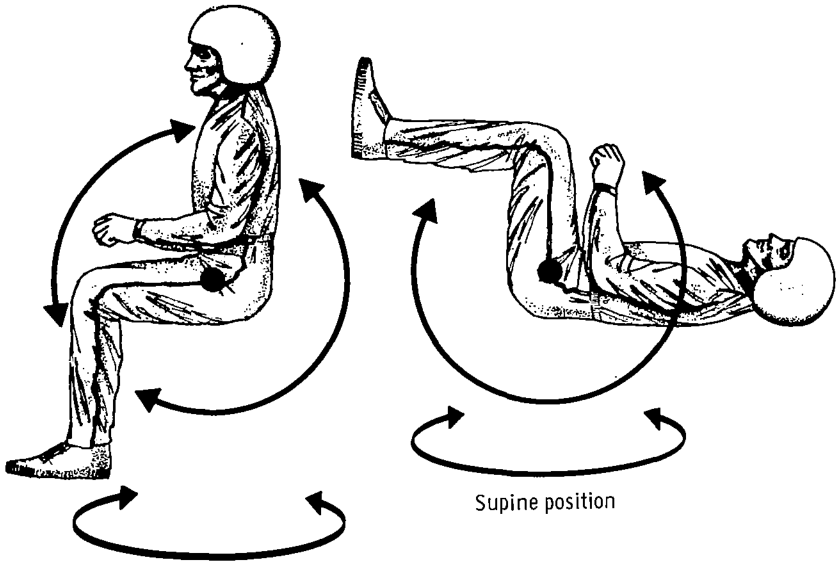

Figure 2.- Sketch of simulator motions.

The enclosure contained a molded couch with appropriate restraints, which allowed the subject to be rotated to any position without undue discomfort. An instrument panel was located directly in front of the subject 56 cm from the head rest, as shown in figure 3. Several instruments could be mounted on the panel, but for this study, only a three-axis attitude indicator (8-ball) was used. The 8-ball was 11 cm in diameter. Control was imparted to the system by a three-axis side-arm controller mounted on the right side of the subject. Fore and aft movement of the controller corresponded to pitch, side-to-side movement corresponded to roll, and a twisting motion through the center of the stick corresponded to yaw. The controller had a maximum freedom of movement of $\pm 26^{\circ}$, scaled to ± 10 volts, in each axis. All other scaling was 1/2 volt per degree. A more detailed explanation is presented in appendix A.

The dynamics used in the tests consisted of a combination of computer-generated dynamics and the actual dynamics of the simulator. It was necessary to incorporate the simulator dynamics into the tests, since the response of the simulator was not good enough to assume a one-to-one input-output correspondence. The linear representation of the simulator drive dynamics for both the inner and outer axes was $\frac{O}{C} = \frac{40}{s^2 + 11s + 40}$.

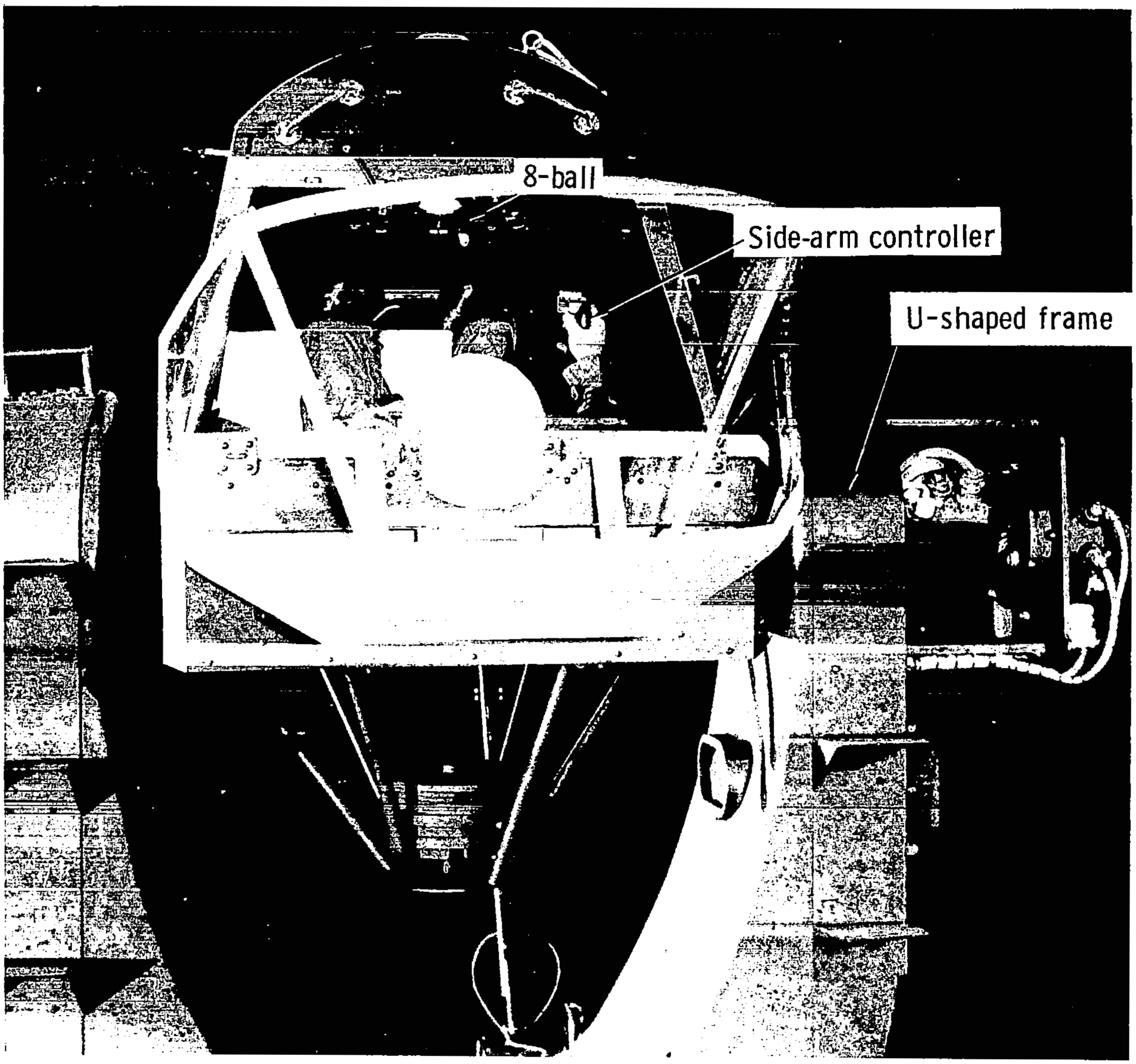

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Figure 3.- Photograph of subject and instrument panel (upper section of cab open).

The computer-generated dynamics were $\frac{C}{\delta} = \frac{K}{s}$ for both axes. The resultant plant dynamics became $\frac{O}{\delta} = \frac{40K}{s^2 + 11s^2 + 40s}$. Figure 4 shows the location of the dynamics in the control loop. The simulator dynamics were not completely linear and are further explained in appendix B.

A solid-state analog computer was used to drive the simulator and to generate the equations of motion. The forcing function, the control inputs, and the system error were obtained from the computer and recorded on magnetic tape for later analysis. This

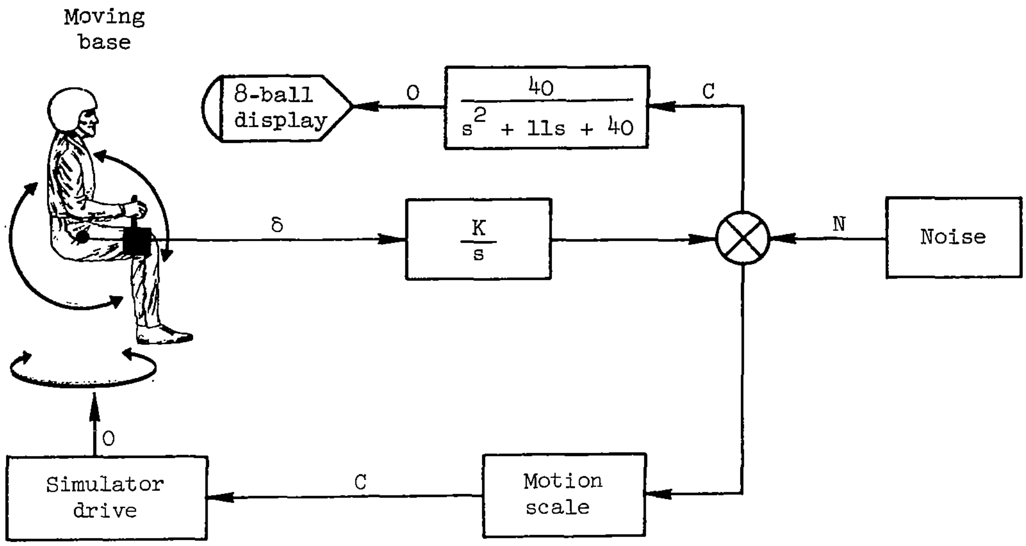


Figure 4.- Sketch of control loop.

analysis was accomplished by using the recorded data as inputs to appropriate analog circuits in order to obtain the mean square error, mean square stick output, and closed-loop system characteristics.

PROCEDURE

The task was a compensatory control task (that is, the subject attempted to hold zero attitude) which consisted of tracking a random disturbance function on an attitude indicator (8-ball). The plexiglass section of the enclosure was covered to prevent the pilot from receiving outside cues and/or from being distracted. The disturbance or forcing function was obtained by first passing the output of a Gaussian noise source through two first-order filters. Each filter was adjusted for a break frequency of 1 rad/sec. The amplitude was adjusted to produce a maximum peak-to-peak value of $\pm 25^{\circ}$ (± 12.5 volts) after filtering. This forcing function was used as an input to the simulator in the motion runs and was filtered by the equivalent simulator dynamics $\frac{O}{C} = \frac{40}{s^2 + 11s + 40}$ in the no-motion runs. Each axis had a different disturbance time history; however, to minimize the effects of the disturbance, the same time history was used from run to run for a particular axis by using prerecorded disturbance signals. A schematic of the control system for one axis is presented in figure 5. Both axes used the same control configuration.

The task consisted of controlling pitch, roll, and yaw in various combinations of one and two axes with and without full-scale motion. A second set of two-axis tests was

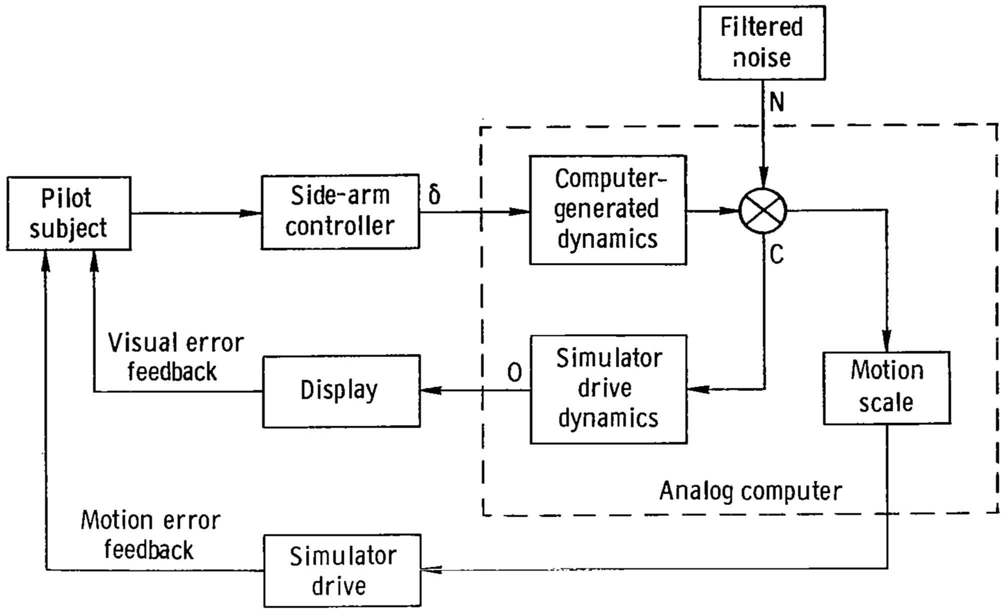


Figure 5.- Block diagram of control system for one axis.

performed in pitch and yaw only, with the scale of motion varied from run to run. Table I outlines all the tests performed.

Four NASA test pilots and four engineers experienced in tracking tasks were used as subjects. Prior to each test the subject was allowed to practice, first without the disturbance and then with the disturbance, for the particular task he was to perform. The length of the practice period was determined by the subject but rarely exceeded $1\frac{1}{2}$ minutes. He was then given a 3-minute data run. The testing sequence is presented in table I. A series of tests was never continued beyond 1 hour and was halted sooner if the subject became fatigued. Also, the subject could elect to rest for short periods between runs. In addition to the sequence in table I, two of the subjects were given tests in a random order.

ANALYSIS

The data analyzed were the normalized mean square of the error and stick and the closed-loop system characteristics. The characteristics were obtained with an automatic parameter-adjusting mathematical model. This model represented the human controller and is explained in reference 5. The method uses the model form $\frac{\text{Output}}{\text{Input}} = \frac{K_1\tau + K_1K_2s}{(\tau + s)^2}$ where the computer gains K_1, τ, and K_2 are allowed to adjust so that the model output produces the best fit of the subject output. The model is combined with the plant dynamics to obtain the closed-loop characteristics. (See fig. 6.) This technique is described in appendix B of reference 5.

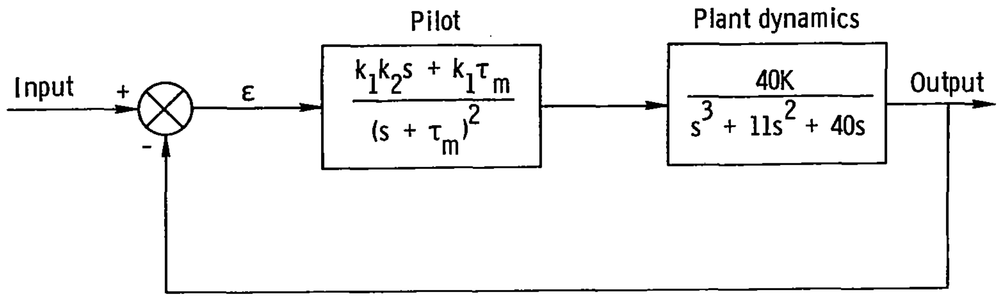


Figure 6.- Diagram of analog representation of control system.

RESULTS AND DISCUSSION

Of the data analyzed, the mean square error and closed-loop system frequency of the dominant mode were considered as two of the more important measurement criteria. A mean-square-error comparison of two similar tasks gives an indication of the relative difficulty of the tasks; the more difficult task has a larger mean square error. The computed closed-loop system frequency gives additional, more subtle information on task difficulty. The system frequency will change for a corresponding change in the pilot parameters (gain, lead, and lag). These parameters define to a large extent the control requirements, hence the difficulty, of the task. A reduction in system frequency generally implies that the task is more difficult.

The data obtained from the different tests are compiled and presented in figures 7 to 11. These data are the normalized mean square error and the closed-loop system frequency. In figures 7 to 9 the circles and triangles represent average values. The upper and lower bars on the graphs are maximum and minimum values obtained from the individual runs. (Note that the data in fig. 7 without minimum and maximum values are for individual runs only.) Group A shows the single-axis data, and groups B and C are the two-axis data. Group B shows the results when both axes either had or did not have motion, whereas group C represents two-axis runs in which motion was supplied to one axis but not the other, that is, when the pitch axis had motion, the yaw or roll axis did not, and vice versa. Figures 12 to 14 show typical time histories of some of the tests.

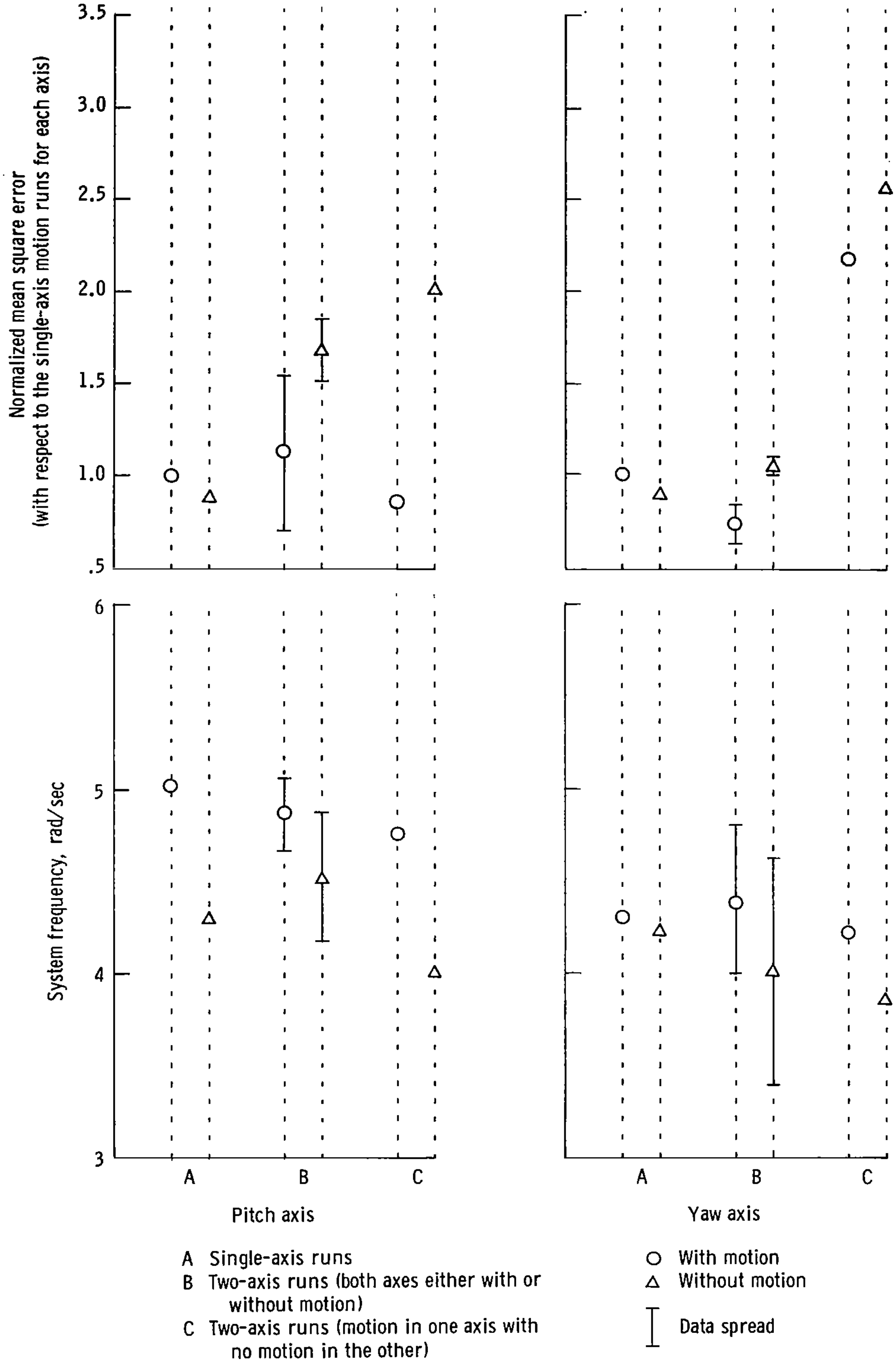


Figure 7.- One- and two-axis pitch and yaw data for one subject.

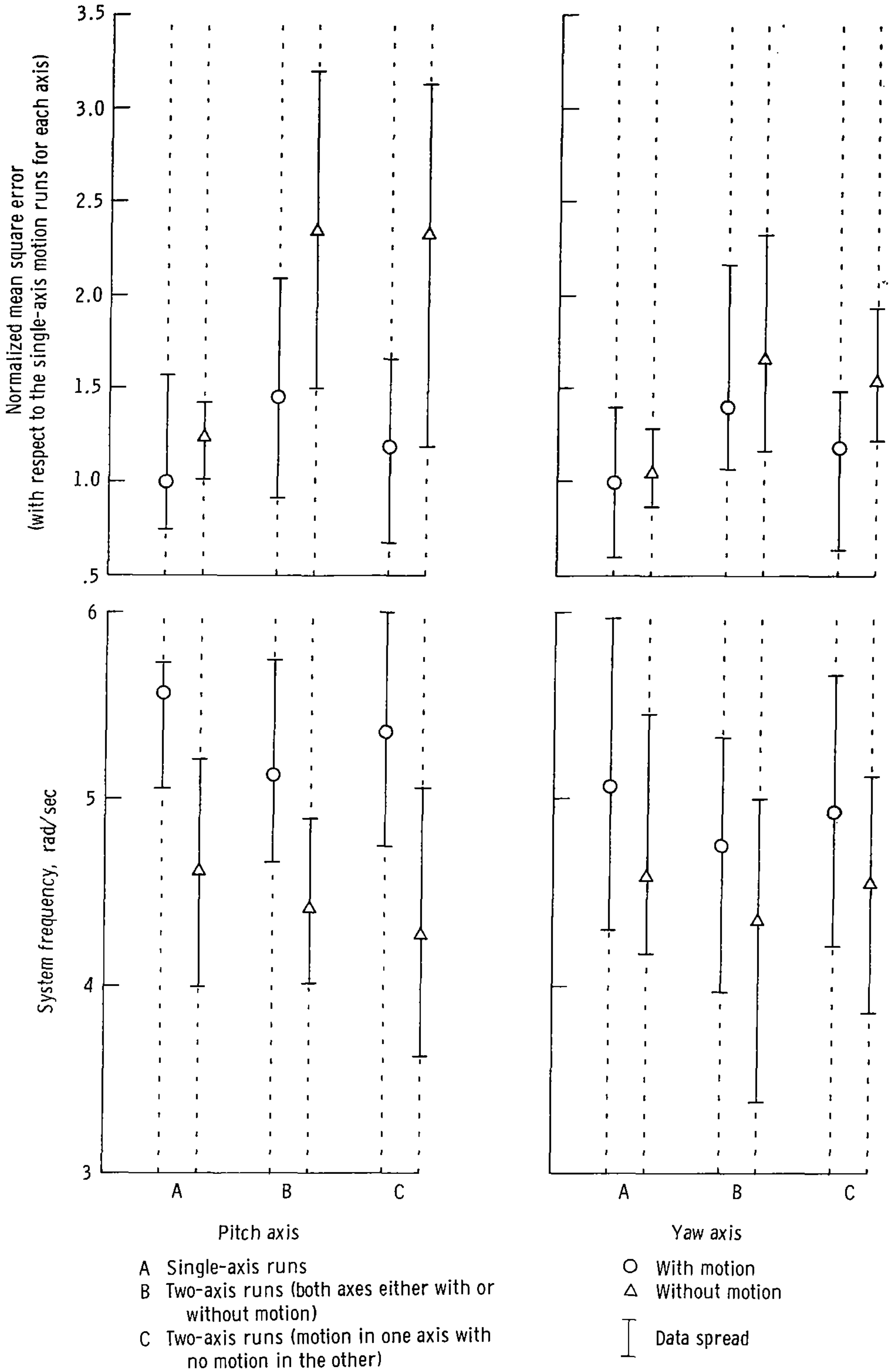


Figure 8.- One- and two-axis pitch and yaw data for all subjects.

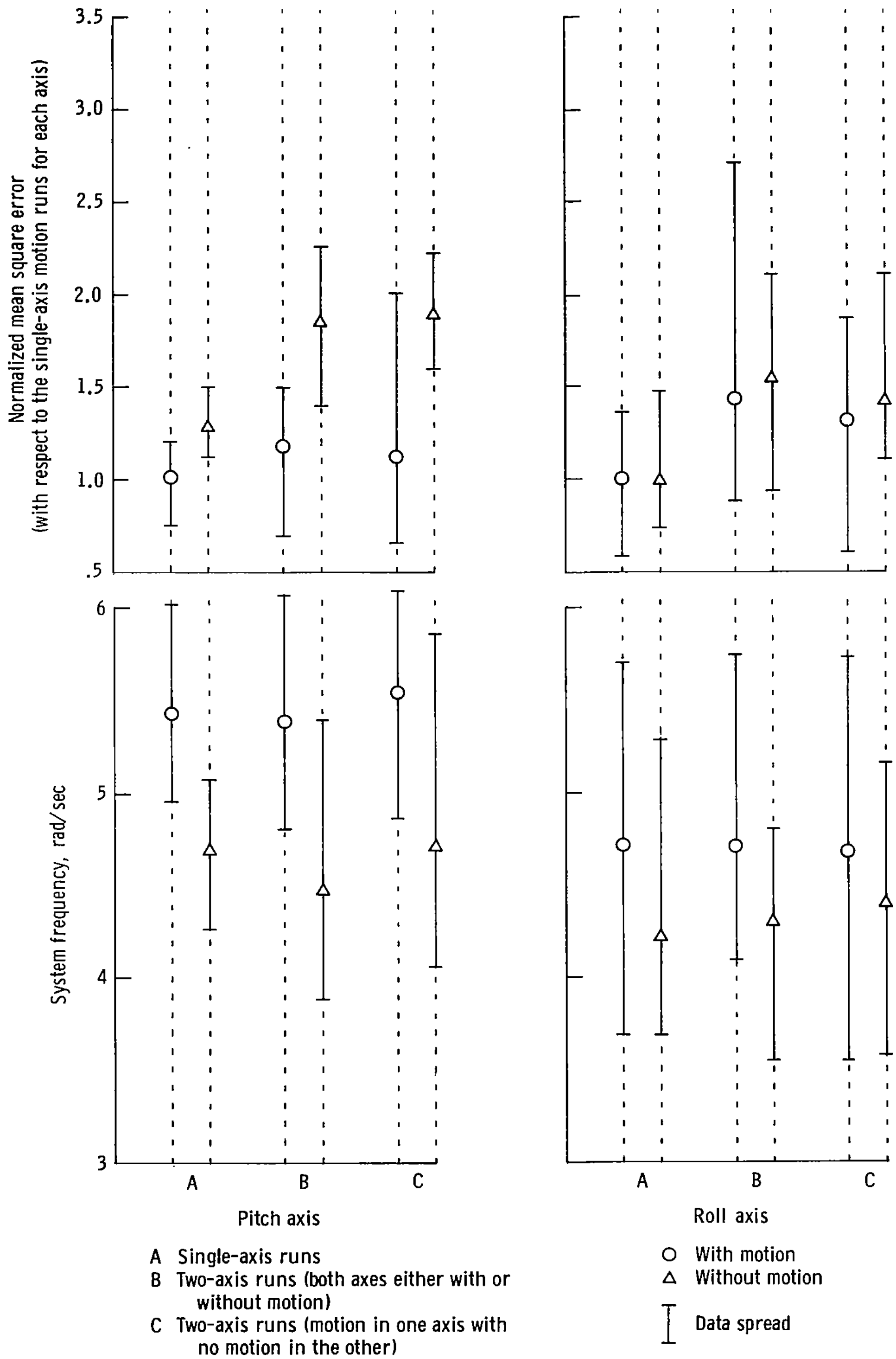


Figure 9.- One- and two-axis pitch and roll data for all subjects.

Single-Axis Tasks

Tests were made in all three axes of rotation (pitch, yaw, and roll) with and without full-scale motion. Two sets of conditions were tested in pitch, one in which the subject was in a seated position for zero pitch orientation and one in which the subject was in a supine position for zero pitch orientation. In the no-motion tests the only difference between the two conditions is body orientation and its associated physiological effects. In the motion tests the differences included slightly different proprioceptive cuing and a difference in the change of the gravity vector on the otolith. When the subject is in a seated position, the perceived gravity vector is a function of the sine of the given angle; whereas for a supine position, it is a function of the cosine. The effects on the semicircular canals should be the same for both positions. Tests results show no appreciable differences in either error or system frequency between the two axis orientations, either with or without motion.

When motion was compared with no motion, the mean square error did not change appreciably. (See the upper part of figs. 7, 8, and 9.) There was an increase in system frequency (lower part of figs. 7, 8, and 9) but a reduction in damping. Table II presents the average absolute values of the closed-loop system frequency and the damping for all the single-axis tests. These results may imply that the subjects were not able to take advantage of the lead information supplied by the motion inputs.

The yaw tests were conducted with the subject in a seated position. The primary motion sensing is from the semicircular canals and proprioceptive cues. For a pure yaw input, the otolith does not change in orientation with respect to gravity. As in pitch (fig. 7), the mean square error did not change when motion was added. Also similar to pitch, an increase in system frequency was measured when motion was added. However, this increase was not as pronounced as in the pitch tests, and in fact, some subjects showed no increase. (See lower part of fig. 7.) The yaw error was greater than that for pitch for any given test condition. However, in the present analysis the error for all single-axis motion runs was given a value of 1. Thereby, a comparison of the relative change in error between axes could be made.

The roll tests were conducted with the subject in a supine position. This is not the normal body position for roll maneuvers but was required because of the restrictions of the simulator axes of rotation. In a supine position, for roll, similar to yaw, the subject receives motion inputs from the semicircular canals and proprioceptive cues. The otoliths do not change orientation as they normally would in a conventional roll task. The single-axis roll results were directly comparable to the single-axis yaw results. This relation will also be shown in a later discussion of the two-axis tests. Most previous work has usually found that roll response was more closely related to pitch. A possible reason for these results could be the subject's body orientation in the present tests.

In general, little to no improvement was obtained in the single-axis tests when motion was added. Several things must be considered, however, in the analysis of these results. If the control dynamics are more difficult, the addition of motion is normally beneficial. (See ref. 2.) If a side task is added to the present control task, motion cues can also make a difference. In summary, it is believed that the addition of motion cues will be beneficial if the lead information that motion supplies is not redundant and can be used to maintain better control of the system. It appears that for the single-axis tasks tested under these conditions, motion does not supply any additional usable information.

Two-Axis Tasks

The two-axis task was pitch and yaw or pitch and roll. Because of the previously mentioned restrictions, the test for pitch and yaw was performed with the subject in a seated position and for pitch and roll with the subject in a supine position. The related motion cuing was the same as that for the single-axis tasks. The only difference would be due to the effects of cross coupling. However, as long as the error is sufficiently small, the cross-coupling effects can be considered negligible. Both sets of two-axis tests were controlled either with or without motion. To investigate further the effects of motion in two-axis control, additional tests were made in which one axis was supplied with motion and the other axis was not.

The two-axis pitch and yaw data are presented in figures 7 and 8. Somewhat different from the single-axis tasks, an appreciable decrease in the mean square error was measured for pitch when motion was added to the two-axis tasks. A decrease, not as large, was also observed for yaw. (See upper part of figs. 7 and 8.) Correspondingly, the system frequency increased when motion was added. (See lower part of figs. 7 and 8.) The system damping remained constant or decreased only slightly. The resultant implication is that for the conditions of the tests, the addition of motion supplies information that can be used to tighten the control loop. This addition is detected as an increase in system frequency and a reduction in mean square error.

Figures 7 and 8 also show results when motion was added to one axis of the two-axis pitch and yaw runs but not to the other. It was assumed that this test configuration would produce a much wider separation in the mean square error of the motion/no-motion comparisons of test configuration C in the upper part of figures 7, 8, and 9. This trend was present for two subjects (upper part of fig. 7) but proved not to be the general case for all subjects (upper part of fig. 8). The predominant feature that did occur was a slight decrease in mean square error, compared with the two-axis motion runs, in the axis which had motion, but the mean square error for the axis without motion was about the same as that for the two-axis no-motion test. That is, motion helps slightly more for the axis in which it is added, with respect to the two-axis motion runs, but does not change the no-motion axis with respect to the two-axis no-motion run.

Figure 9 includes the results for the two-axis pitch and roll tests. When figures 8 and 9 are compared, it can be seen that the results for pitch were the same regardless of pitch orientation – seated or supine. Also, the results for the roll and yaw tests were very similar. The very high maximum value of the mean square error in figure 9 in the roll axis of the two-axis motion tests is only one data point for one of the subjects and is not representative of all the tests. The reason for this high value is not known.

In general, the addition of motion did aid in the control of the two-axis tasks. The analysis shows that the lead information inherent to motion was used by the subjects to tighten the control loop. Also, motion supplied cues which assisted the subjects in monitoring and controlling the multiaxis task situation. This was detected in the model parameter variations and is discussed in a subsequent section. The data also showed that motion was more helpful in pitch and less helpful in yaw and roll.

Two-Axis Scaled-Motion Data

The scaled-motion tests were made with the two-axis pitch and yaw runs only. The tests were performed with the amplitude of motion, compared with the visual input, reduced in scale from run to run. This reduction is a direct scaling of the input signal to the motion base. Therefore, a reduction in motion scale implies a reduction in acceleration, velocity, and displacement. The tests incorporated six different conditions: full-scale motion, 1/2, 1/4, 1/8, 1/16, and no motion. The testing sequence is presented in table I. Figure 10 presents the average mean square error and system frequency for one subject, and figure 11 presents the same information for all subjects. The upper part of figure 10 shows the mean-square-error results. The mean square error remains about the same from full-scale motion down to 1/4-scale motion. As the scale of motion is further reduced, the mean square error begins to increase and continues until the condition of no motion is reached. Similarly, in the lower part of figure 10 the system frequency begins to decrease about the 1/4 motion scale condition. The mean-square-error results shown in figure 10 are representative of the other subjects. The only variation noted between subjects was a slight difference in motion scale value at which the error began to increase. The system frequency results however, showed an additional variation. Not only was there a slight difference in motion scale value at which the frequency began to decrease, but for about half the subjects, the decrease leveled off at about 1/8 motion scale or even began to increase again by the no-motion condition. The leveling phenomena could represent the point where a further reduction in motion no longer affects the system frequency. However, the tendency for the frequency to reverse and then slightly increase, measured for two of the subjects, for the no-motion condition cannot be explained.

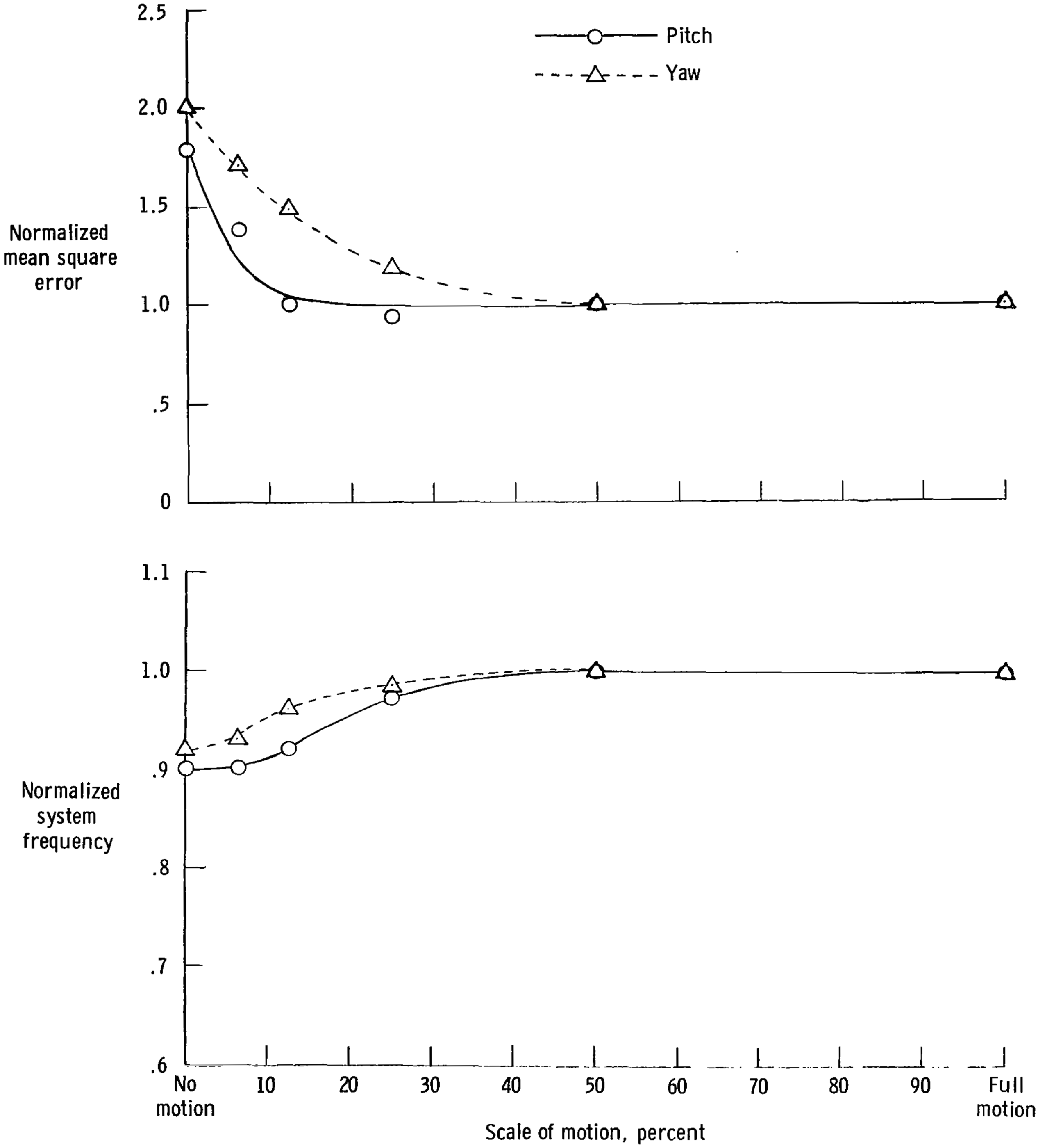


Figure 10.- Scaled-motion data for one subject.

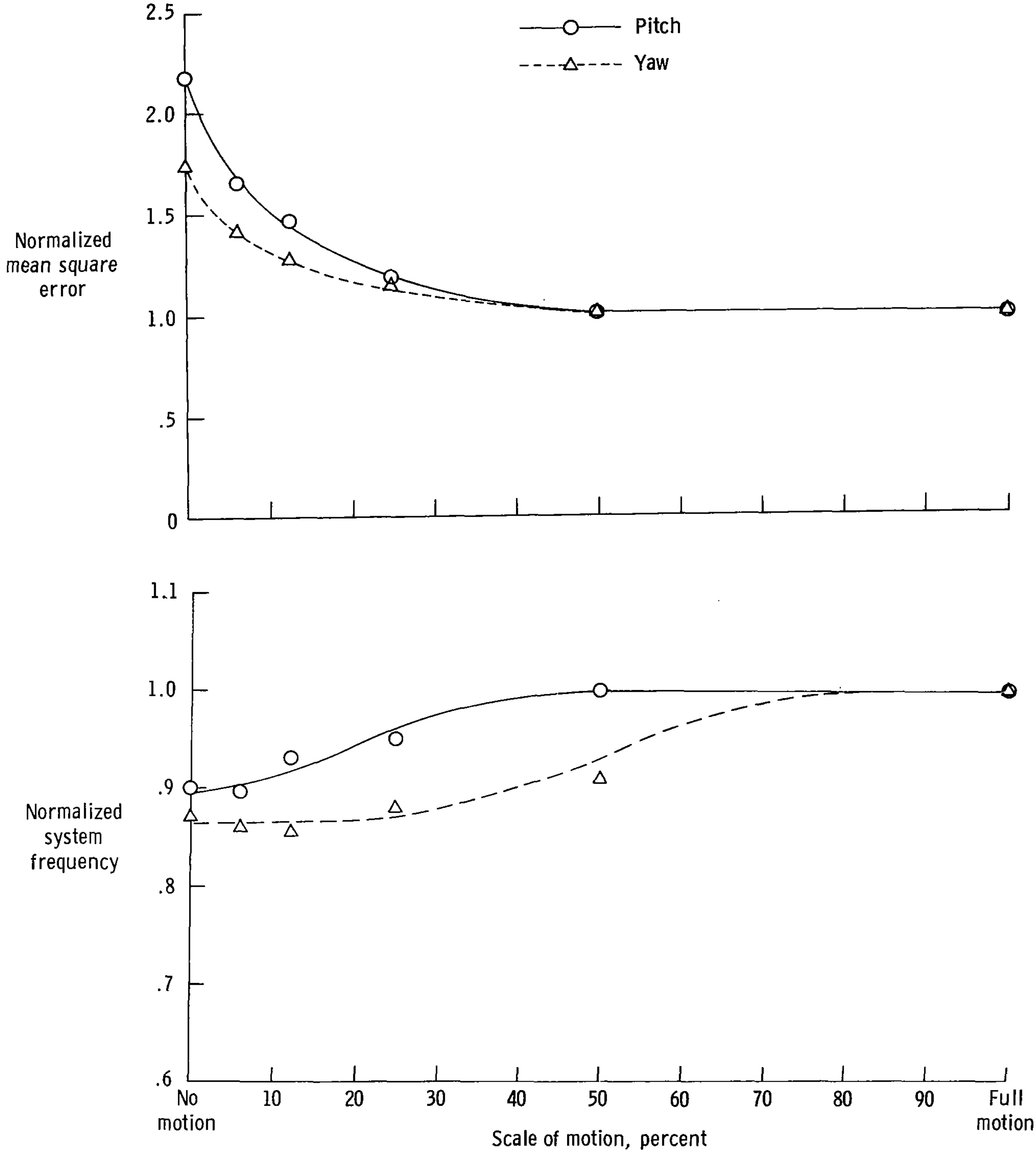
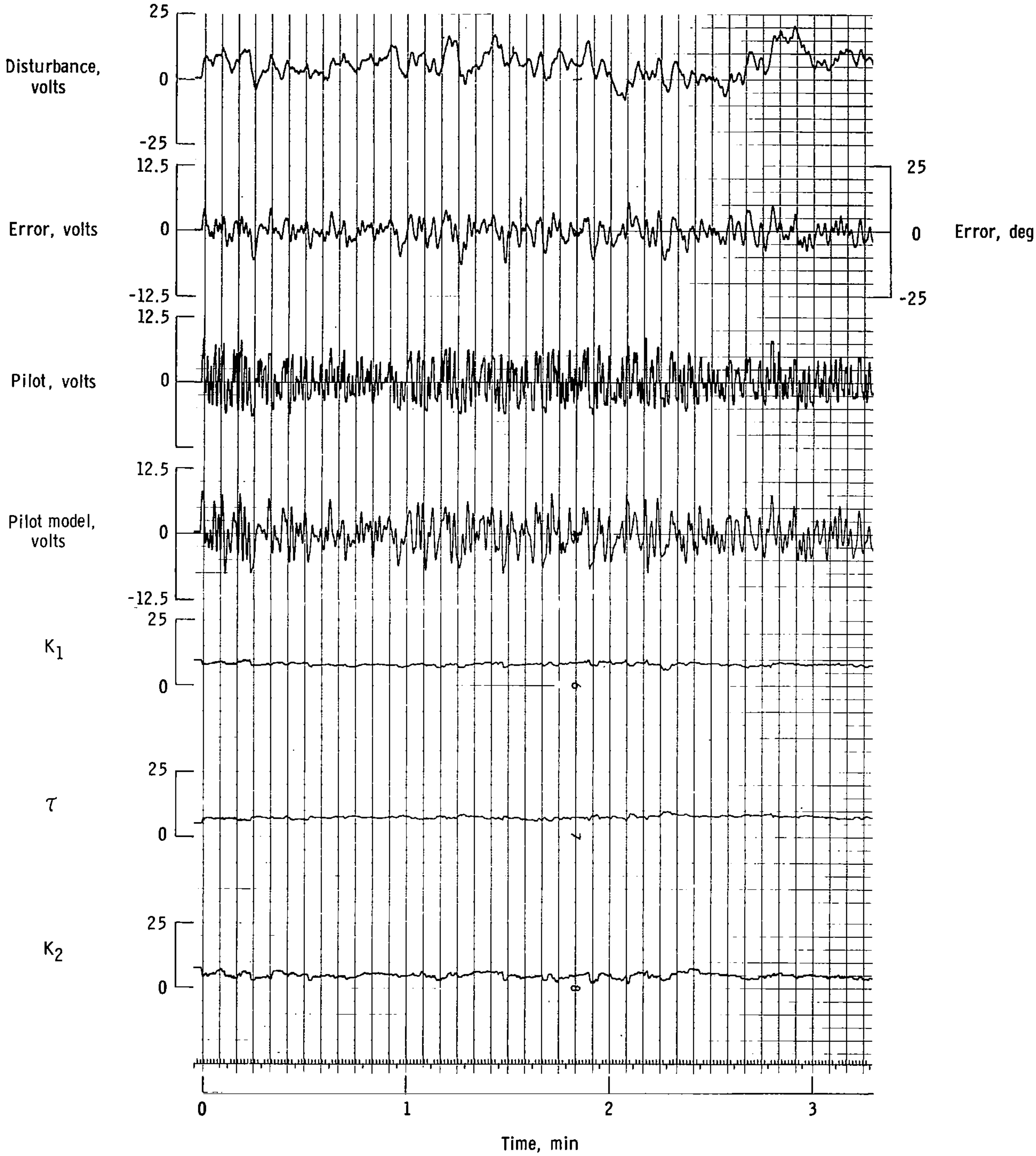
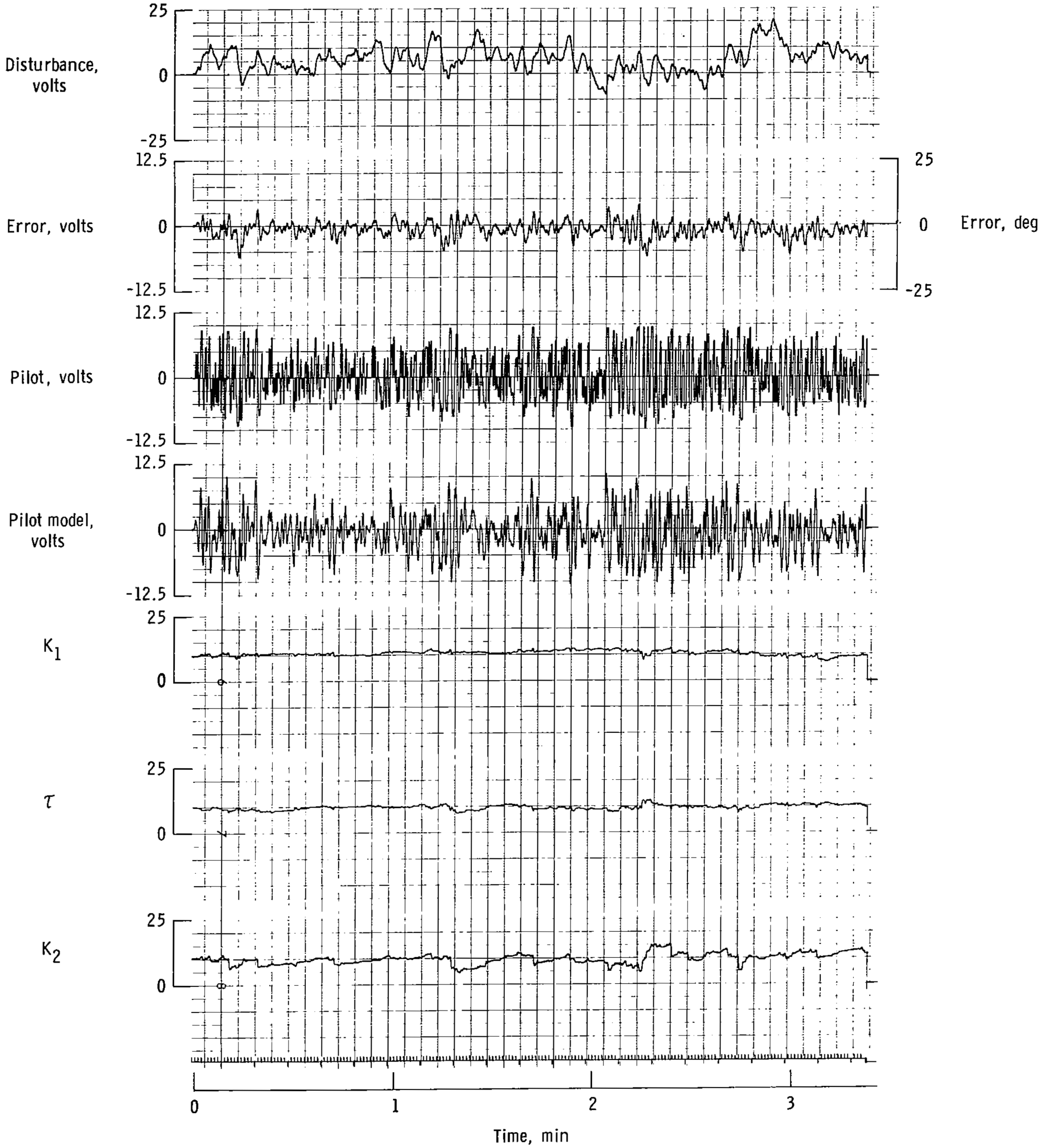


Figure 11.- Scaled-motion data for all subjects.



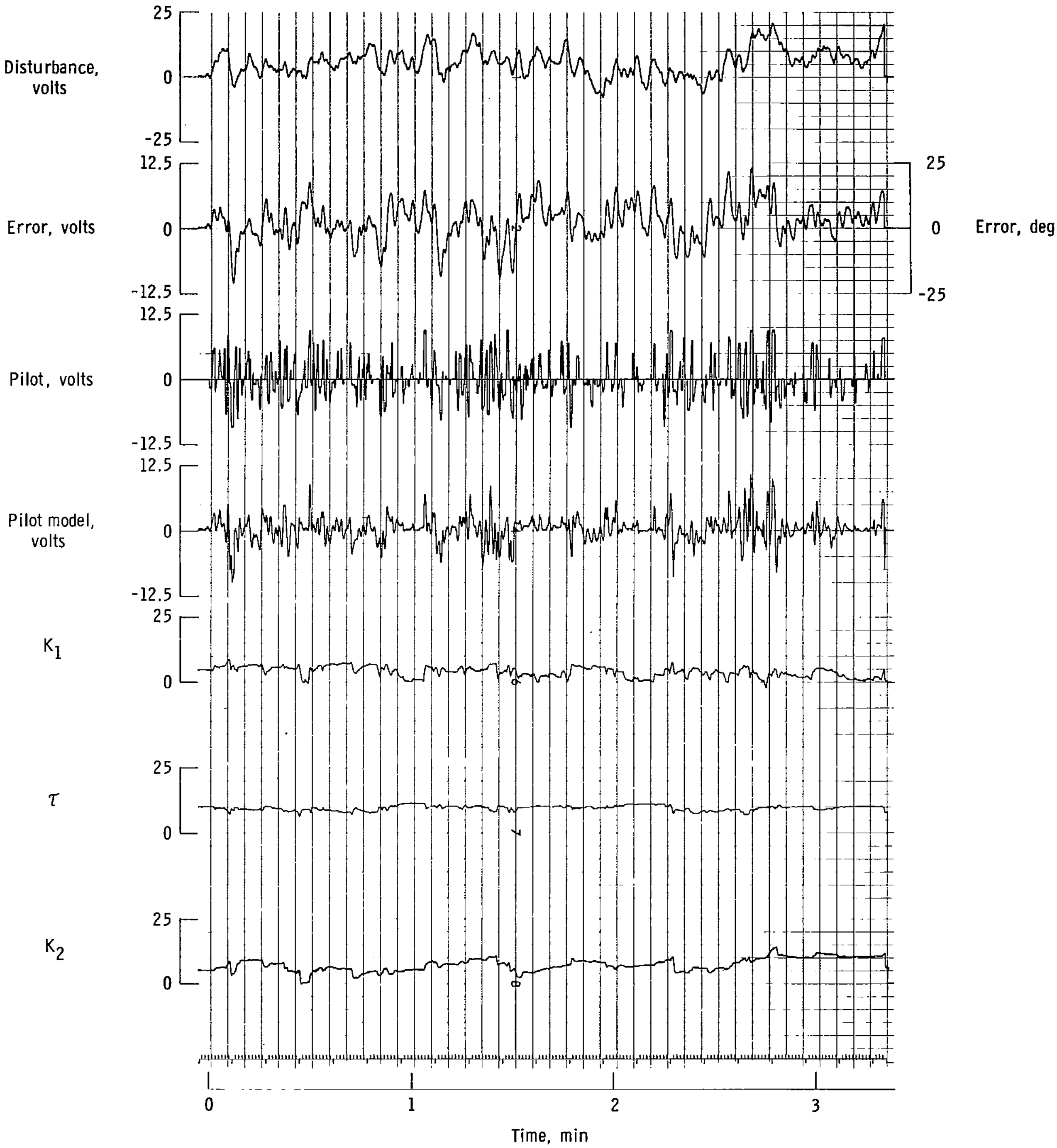
(a) Single-axis task without motion.

Figure 12.- Typical time history for pitch.



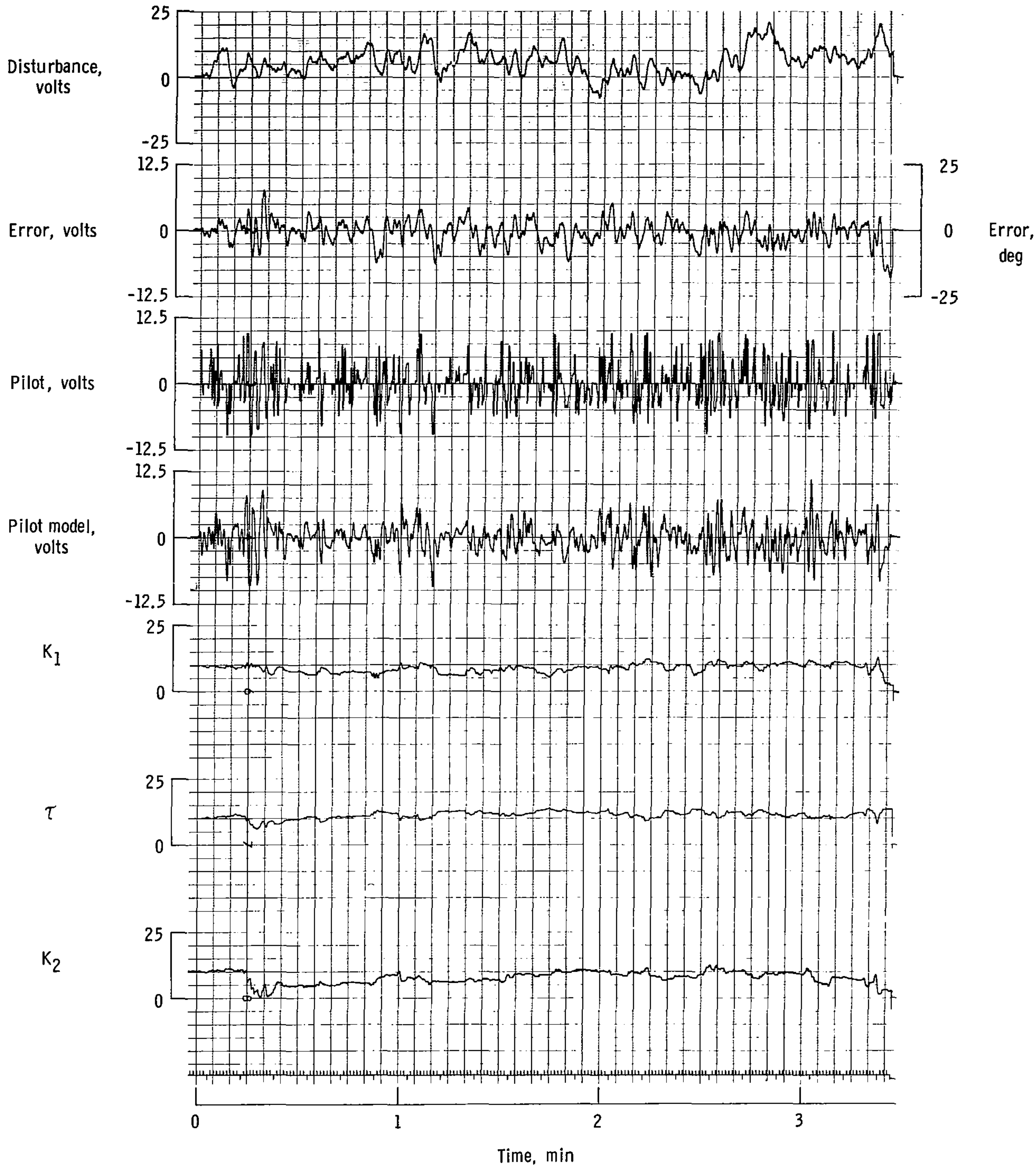
(b) Single-axis task with motion.

Figure 12.- Concluded.



(a) Two-axis pitch and yaw task without motion.

Figure 13.- Typical time history for pitch.



(b) Two-axis pitch and yaw task with motion.

Figure 13.- Concluded.

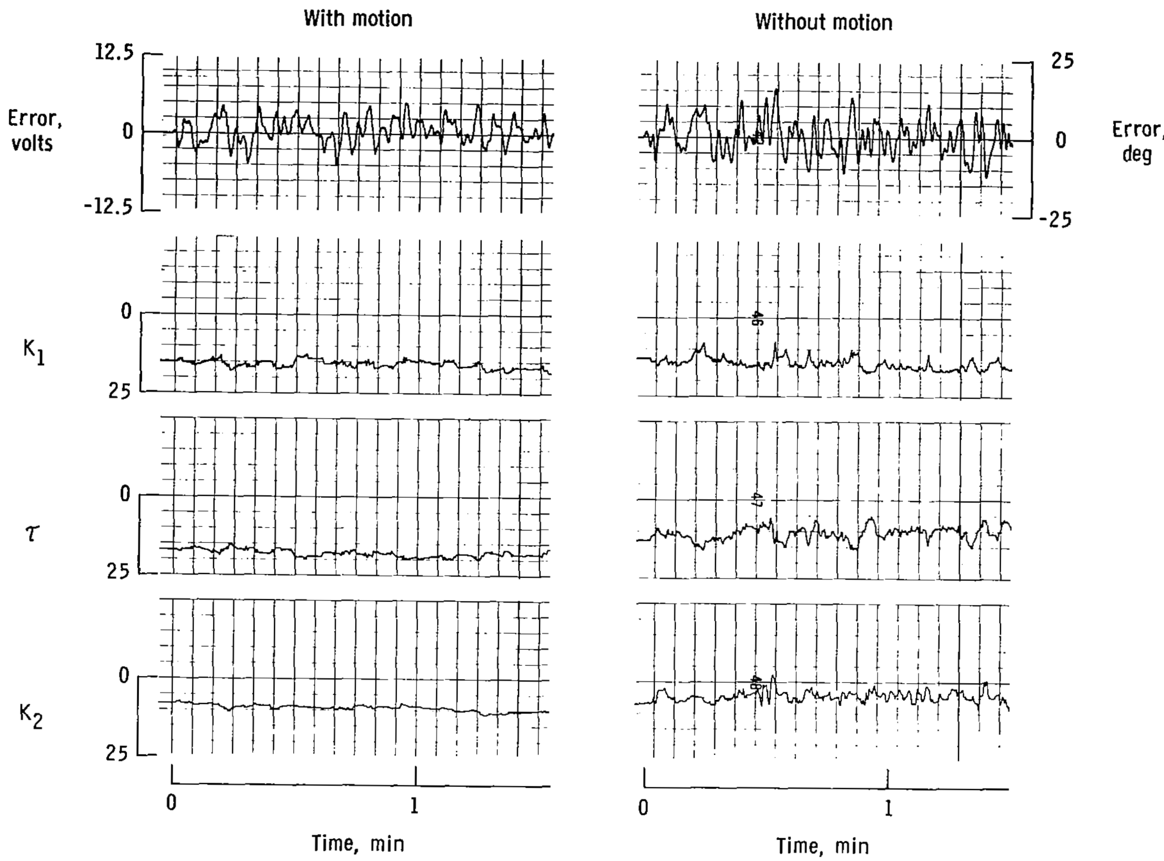


Figure 14.- Illustration of reduction in time variation in measured gains attributed to addition of motion.

The results for all the subjects (fig. 11) are similar to those for the single subject (fig. 10). Therefore, in general, these data demonstrate that it is not always necessary to supply full-scale motion cues to obtain results valid to full-scale motion conditions. Hence, a direct reduction in motion by motion scaling techniques can reduce the size, power, and cost of simulators and therefore make it economically feasible to run valid and realistic simulations.

Comparison of One-Axis and Two-Axis Tests

The nature of the foregoing tests produced results amenable to additional comparison and analysis. The single-axis tasks can be compared with their counterpart in the two-axis tasks. Comparisons of tasks both with and without motion can be made.

The results shown in figures 7, 8, and 9 indicate that the mean square error for a particular axis will increase when a second axis is added. This increase is true for the tests with and without motion; however, it is always less in the motion runs. Also, the system frequency will generally decrease when a second axis is added. However, a few isolated examples did exist where the frequency remained the same or even increased slightly. Similar results are reported in reference 6.

Parameter Variation

It was also noted, both here and in reference 6, that the measured gains of the analog pilot were more time variant in the two-axis tasks. However, the addition of motion reduced this time variation. (See fig. 14.) The time variation in the no-motion two-axis tasks is attributed to the subject's alternating emphasis of control between the two axes. Less emphasis of control on a particular axis also results in an increased mean square error. However, when motion was added to these two-axis tasks, the time variation decreased. The mean square error also decreased. The motion cues supplied the subject with sufficient information for him to detect and correct errors sooner than if he had had only visual cues. This implies that without sufficient cues, motion in this case, the subject tends to be more time varying in his control of multiaxis systems, and this time variation can result in an increased mean square error. Therefore, as was done in this study, any analysis with pilot models should also include a close inspection of the time histories of the analog model parameters. The time variation of these parameters can be an important criterion in evaluating the pilot's control of a system.

CONCLUDING REMARKS

Tests have shown that for certain conditions, angular motion may or may not be useful, depending on the difficulty of the task. Motion cues did not aid in controlling the one-axis pitch, roll, or yaw tests. However, motion did help in the more difficult two-axis tasks. It was also shown that for those conditions where motion is beneficial, it is not always necessary to supply full-scale motion to obtain valid simulated results. The data show that for the conditions of the test as little as 1/4 motion scaling can produce results similar to that when full-scale motion cues are used.

The results are for a particular plant dynamics $\frac{O}{\delta} = \frac{40K}{s^3 + 11s^2 + 40s}$ (where O is the system output, δ is the output of the subject, K is a gain, and s is the Laplace operator) and forcing function (random disturbance with a 1-rad/sec break frequency). A previous work by Richard S. Shirley (Sc. D. Thesis, Massachusetts Institute of Technology, 1968) has shown that the plant dynamics (a form of task difficulty) is a factor when the merits of motion in single-axis control tasks are considered. In general, the relationship of task difficulty (plant dynamics, multiaxis systems, side tasks, etc.) and information cuing (visual, motion, auditory, etc.) is such that information cues are both redundant and additive, depending on the type and degree of task difficulty. For instance, the single-axis tasks did not show the same results as the two-axis tasks when motion was added. This work extends the data field to encompass multiaxis control tasks and suggests that the requirements of full-scale motion in simulations can be significantly reduced.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., December 1, 1970.

APPENDIX A

CONTROLLER CHARACTERISTICS

Control was imparted to the system by a three-axis side-arm controller. Figure 15 shows the controller mounted in the simulator cockpit. Pitch control was obtained by a rotation of the controller handle fore and aft. This rotation was about a pivot point located at the center of the hand grip. Yaw control was obtained by a twisting rotation of the controller handle through the center of the handle. Roll control was obtained by a movement of the handle from one side to the other. This displacement was obtained by pivoting the control handle around a point about 5 cm below the hand grip. Each axis of the controller had a slightly different response to a release from a maximum displacement. Figure 16 shows the time history for a free release from a maximum displacement of the controller for each axis.

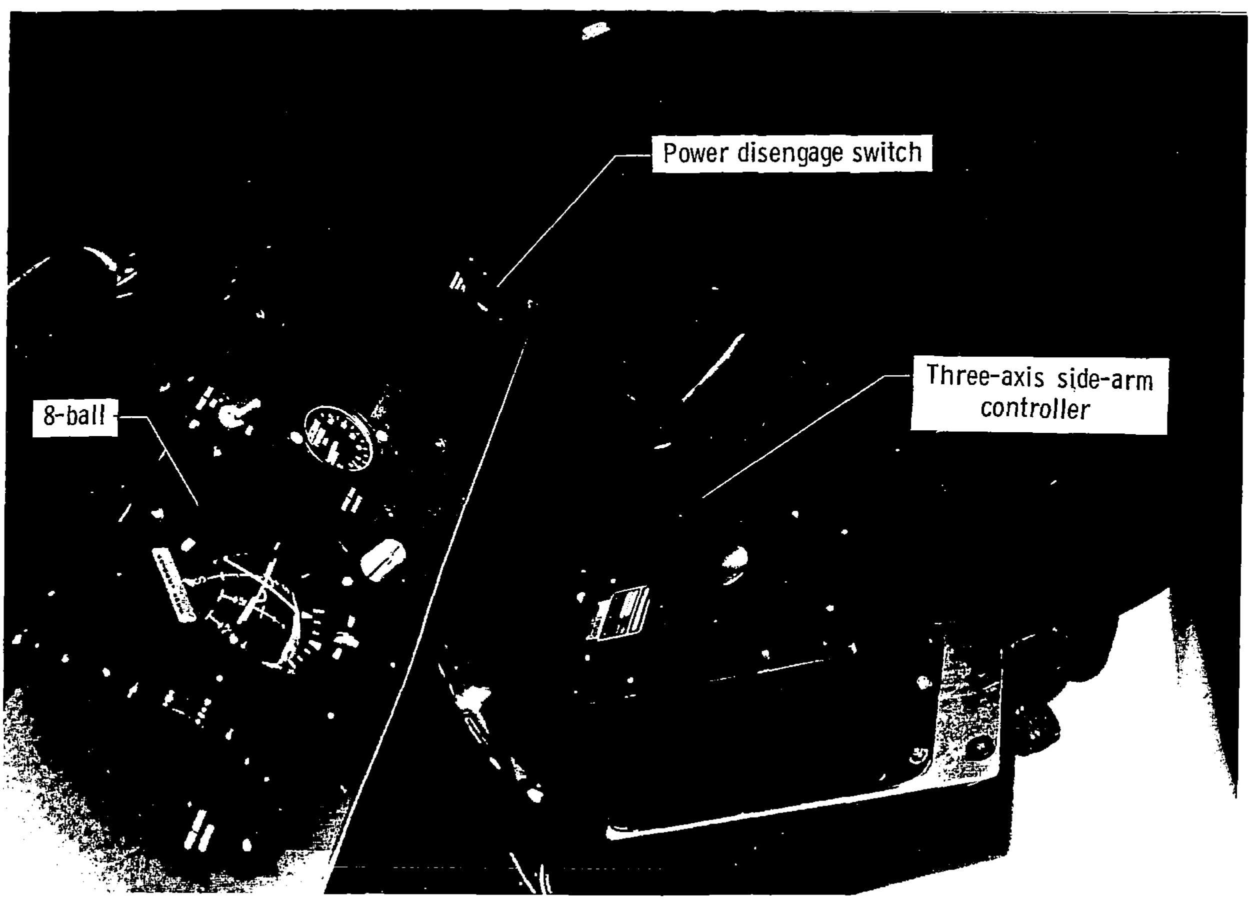


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Figure 15.- Inside view of cockpit.

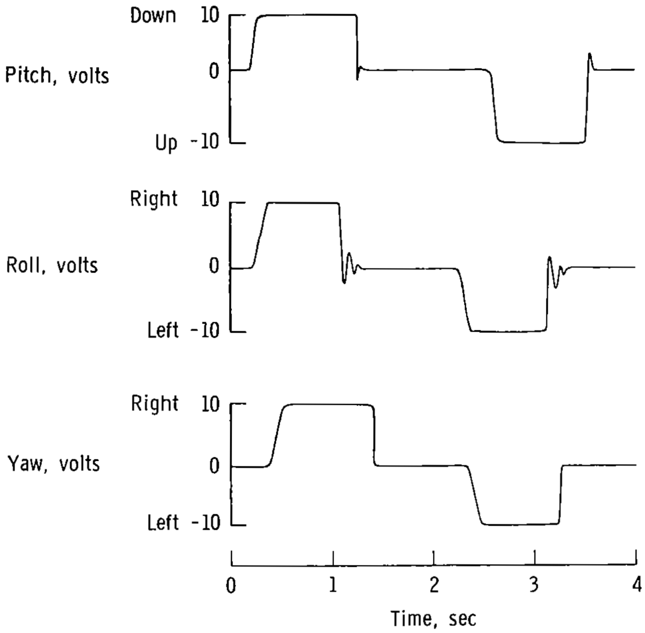

Figure 16.- Free-stick response to a step displacement.

APPENDIX B

PLANT DYNAMICS

The plant dynamics consisted of computer-generated dynamics and the physical dynamics of the simulator. The computer-generated dynamics were K/s. The linear representation of the simulator dynamics for both axes was $\frac{40}{s^2 + 11s + 40}$. However, the simulator dynamics were not completely linear. Both a velocity and an acceleration limit existed. The velocity limit was greater than that encountered in the present tests. However, the acceleration limit (60 deg/sec^2 for both axes) was reached by some of the subjects. One other nonlinearity existed: When the acceleration was one direction and the velocity went through zero, the limit on the acceleration was reduced to 70 percent of its original value. Figure 17 shows the response of the simulator to a step input and illustrates this behavior. The 70-percent value represents the time during which the acceleration is countering friction; the 100-percent value represents the time during which the friction is helping the acceleration, that is, deceleration.

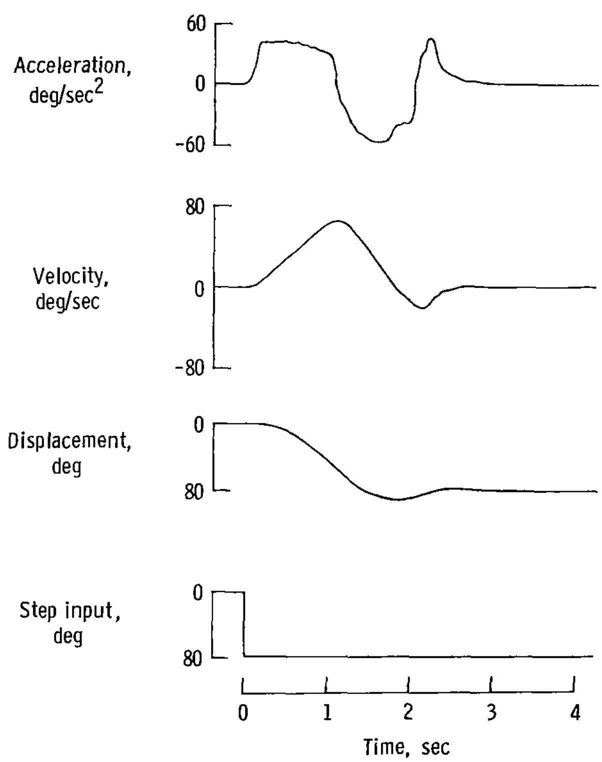

Figure 17.- Response of simulator to step input.

REFERENCES

1. Young, Laurence R.: Some Effects of Motion Cues on Manual Tracking. J. Spacecraft Rockets, vol. 4, no. 10, Oct. 1967, pp. 1300-1303.
2. Shirley, Richard S.: Motion Cues in Man-Vehicle Control. Sc. D. Thesis, Massachusetts Inst. Technol., 1968.
3. Young, Laurence R.; and Meiry, Jacob L.: A Revised Dynamic Otolith Model. Third Symposium on the Role of the Vestibular Organs in Space Exploration, NASA SP-152, 1968, pp. 363-368.
4. Borlace, Frank H.: Flight Simulator Motion, Its Enhancement and Potential for Flight Crew Training. Third International Simulation and Training Conference, Soc. Automot. Eng., Inc., Apr. 1967, pp. 60-65.
5. Adams, James J.; and Bergeron, Hugh P.: Measured Variation in the Transfer Function of a Human Pilot in Single-Axis Tasks. NASA TN D-1952, 1963.
6. Bergeron, Hugh P.; and Adams, James J.: Measured Transfer Functions of Pilots During Two-Axis Tasks With Motion. NASA TN D-2177, 1964.

TABLE I.- TEST CONFIGURATION

Order of presentation	Axis or axes being tested	Subject's body orientation	Percent of motion	
			Pitch	Roll or yaw
Single-axis motion/no motion				
1	Pitch	Supine	0	------
2	Pitch	Supine	100	------
3	Pitch	Seated	0	------
4	Pitch	Seated	100	------
5	Roll	Supine	------	0
6	Roll	Supine	------	100
7	Yaw	Seated	------	0
8	Yaw	Seated	------	100
Two-axis motion/no motion				
1	Pitch and roll	Supine	0	0
2	Pitch and roll	Supine	100	100
3	Pitch and roll	Supine	100	0
4	Pitch and roll	Supine	0	100
5	Pitch and yaw	Seated	0	0
6	Pitch and yaw	Seated	100	100
7	Pitch and yaw	Seated	100	0
8	Pitch and yaw	Seated	0	100
Two-axis motion scale				
1	Pitch and yaw	Seated	0	0
2			6.25	6.25
3			12.5	12.5
4			25.0	25.0
5			50.0	50.0
6			100.0	100.0
7			50.0	50.0
8			25.0	25.0
9			12.5	12.5
10			6.25	6.25
11			0	0

TABLE II.- AVERAGE VALUES FOR ALL SINGLE-AXIS TESTS

Axis	Motion	Frequency	Damping
Pitch[a]	Without	4.61	0.421
	With	5.58	.245
Pitch[b]	Without	4.66	.390
	With	5.40	.312
Yaw	Without	4.59	.397
	With	5.07	.305
Roll	Without	4.22	.469
	With	4.69	.414

[a]Seated position.

[b]Supine position.

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