



# RESEARCH MEMORANDUM

GROUND SIMULATOR STUDIES OF A SMALL SIDE-LOCATED  
CONTROLLER IN A POWER CONTROL SYSTEM

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**NATIONAL ADVISORY COMMITTEE  
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## SUMMARY

An investigation was made to determine the operating characteristics of a small side-located control stick with the use of a ground simulator incorporating a power control system. The simulator or pitch chair was designed to produce the pitching motion associated with the short-period mode of an airplane. The short-period dynamic characteristics of the simulator were adjustable so that a large number of airplane flight conditions could be simulated. The quality of the control system using the side-located controller was determined by the ease and precision with which various tracking maneuvers could be accomplished by the pilot.

A general opinion of all the pilots operating the pitch chair was that they were favorably impressed with their ability to track precisely with the small side-located controller provided the control-system characteristics were desirable. The results indicated that an increase in the damping ratio, an increase in the period, or a decrease in the steady-state ratio of pitching velocity to angle of attack tended to improve the tracking performance. Changes in the period were made while the ratio of angle of attack to control deflection was held constant. Tracking ability was also improved by using the lower of two control sensitivities tested and by decreasing static stick friction. Where static stick friction was the limiting factor, about 3 pounds at the grip was found to be the tolerable limit for the side-located controller.

## INTRODUCTION

With the advent of completely powered control systems for airplanes, the possible advantages of a small side-located control stick have been receiving widespread attention. Modern high-speed aircraft are being subjected to larger and more abrupt acceleration loads by rocket-type powerplants as well as loads that are pilot-induced. These loads can

affect the pilot's ability to control the airplane adequately because the acceleration loads on his arm may cause involuntary control inputs. A partial solution of this problem can be made by the use of a side-located controller which can be hand operated and which would permit the pilot's arm to be securely strapped to the arm rest. A recent study reported in reference 1 determined the range of possible hand positions and the forces that could be applied at these various positions with the arm securely fastened. The use of the wrist, hand, and fingers rather than the arm to apply the small control motions necessary permits the pilot to make more precise control deflections. The side-located controller also lends itself to the use of a central radar scope as required by the trend towards radar displays for interception and navigation for fighter airplanes. Ejection-seat design might also be simplified somewhat by avoiding the interference caused by a centrally located control stick.

The feasibility of using a small side-located controller was demonstrated recently in a flight investigation (ref. 2) in which the pilot used the side controller to maneuver the airplane by means of an electronic control system. The side controller that is being considered in this paper, however, was intended to replace a centrally located control stick which operates the powered controls directly. For this case the forces to be overcome by the pilot, aside from those put in for feel, are those existing in the system between the controller and the hydraulic actuator. Because of the smaller mechanical advantage inherent in this type of controller, extraneous forces introduced by such sources as control valve friction and stick friction will have proportionally larger effects on controllability. It is obvious then that the problems peculiar to a side-located controller must be determined and analyzed in order to make proper use of its advantages.

The purpose of this paper, therefore, is to investigate the characteristics of a small side-located controller with the use of a ground simulator incorporating a power control system. The quality of the control system using the side-located controller was determined by the ease and precision with which various tracking maneuvers could be accomplished by the pilot while operating the simulator. The feasibility of using the results obtained in centrally located control-stick investigations for the design of small side-located controllers will also be discussed.

#### SYMBOLS

$\alpha$	angle of attack, deg
$\delta_c$	controller deflection about pivot, deg

$\theta$	pitch (chair) angle, deg
$\dot{\theta}$	pitching velocity, deg/sec
$\dot{\theta}/\alpha$	steady-state ratio of pitching velocity to angle of attack (called pitch-rate gain), deg/sec/deg
$\delta_c/\alpha$	controller sensitivity, steady state
M	Mach number
q	dynamic pressure, lb/sq ft
V	true airspeed, ft/sec
$h_p$	pressure altitude, ft
$a_n$	normal acceleration, ft/sec <sup>2</sup>
$C_L$	lift coefficient
W	weight, lb
S	wing area, sq ft
$C_{L\alpha}$	$= \frac{dC_L}{d\alpha}$ per deg
$\rho$	air density, slugs/cu ft

## DESCRIPTION OF APPARATUS

In order to determine the characteristics of a small side-located controller, a ground simulator described in reference 3 was modified so that it could be operated by such a controller instead of a centrally located control stick. The controller was mounted on the right-hand side, and the mechanical linkages required to incorporate it into the control system were the only major changes made to the original simulator. Figure 1 shows several photographs of the simulator and figure 2 presents a schematic drawing of the simulator and the side controller. Briefly, the simulator was designed to produce the pitching associated with the short-period mode of an airplane. The short-period dynamic characteristics of the simulator were adjustable so that a large number

of airplane flight conditions could be simulated. The controller shown in figure 2 was used for all these tests. The controller could be moved in pitch but not in roll. No studies were made of different controller designs since it was decided that a control with the pivot at the wrist would be an acceptable, even if not the best, arrangement. Provision was made to mass balance the controller and its linkage system and to make the attachment points as friction free as possible. A high and a low value of controller sensitivity was used for these tests. The high-sensitivity case was such that  $1^\circ$  rotation of the controller about its pivot produced  $1^\circ$  rotation in pitch of the chair while for the low-sensitivity case  $4.2^\circ$  rotation of the controller was required to produce  $1^\circ$  rotation of the chair. This rotation of the pitch chair as a result of control deflection was produced by the hydraulic actuator and simulated changes in angle of attack. Simulated rate of change of flight-path angle was superimposed on the changes in angle of attack by means of an integration process and the resulting motion simulated the short-period pitching mode of an airplane. The equations and transfer functions relating these various motions are more fully discussed in reference 3.

In order to indicate visually the pitch attitude of the chair, an arc light mounted on the chair projected a spot of light onto a screen about 30 feet in front of the pilot. An additional cam-controlled spot of light was projected so as to move vertically alongside the chair light. The cam was designed so that the light spot would represent various pullup maneuvers.

All moments and deflections are referred to the controller's pivot shaft. Essentially zero valve friction was obtained by using a high-frequency shaker on the control-valve stem, but no provision was made to test the effects of variations in valve friction except for the shaker-off case. All the stick-friction measurements and results were obtained with the shaker on. Friction measurements about the controller pivot were taken for both controller sensitivities and are presented in the following table:

Controller sensitivity, $\frac{\delta_c}{\alpha}$	Shaker operation	Torque at controller pivot required to start chair in motion, in-lb (a)	Torque at controller pivot required to start motion in links and bellcranks with link to control valve removed, in-lb (a)
1	On	1.8	---
1	Off	17.0	---
1	Removed	----	1.5
4.2	On	1.3	---
4.2	Off	5.25	---
4.2	Removed	----	2.0

(a) Torque values represent an average for up-and-down motion of the controller.

For the low-sensitivity case,  $1.2^\circ$  of lost motion in the controller existed before chair motion could be initiated. This backlash was very noticeable but caused no apparent difficulty in the operation of the chair. This lost motion was difficult to measure and was hardly noticeable for the high-sensitivity case.

Standard NACA recording instruments were used to obtain time histories of controller deflection, chair angle, and target position by the use of slide-wire transmitters. Control forces were not measured during the runs.

#### TESTS AND PROCEDURE

The short-period dynamic characteristics of an assumed fighter airplane in various flight regimes were calculated and incorporated as closely as possible into the simulator. The value of the steady-state ratio of pitching velocity to angle of attack will be referred to in this paper as pitch-rate gain for reasons of brevity. The following table summarizes the pertinent values for the four basic cases tested.

	M	q, lb/sq ft	V, fps	h <sub>p</sub> , ft	Period, sec	Damping ratio	Pitch-rate gain, deg/sec/deg	Controller sensitivity, $\frac{\delta_c}{\alpha}$
Case I	4	2,000	3,876	56,000	1.2	0.3	0.38	1
Case II	4	2,000	3,876	56,000	1.2	.06	.38	1
Case III	1.2	500	1,166	35,000	1.2	.1	.96	1
Case IV	0.9	1,000	985	5,000	2.3	.5	2.22	1

The operating characteristics of each of these basic cases were first determined for various values of booster valve friction and stick friction. Depending on the results obtained for each case, changes were made in the various parameters to determine their effects on the operating characteristics with a view toward improvement or comparison. A complete description of all the simulator conditions tested, including the spring-feel controller force gradients, is given in table I.

The operators of the simulator were asked to track the cam-driven light with the chair light. The ease and precision with which the pilots could follow the cam-driven light spot provided the basis for judging the quality of the control system. When the various configurations were evaluated, the pilot's opinion was carefully weighed along with examination of the recorded data. At least one NACA test pilot and the author obtained data for each of the cases tested.

The pilot's opinion of the tracking quality of the control system in terms of a rating and the figures in which typical results appear are given in table I. One of five numbered ratings was given for each condition. A rating of 1 implies a control system with characteristics that are near perfect. A rating of 2 means a control system with little or no tendency to overshoot and one for which a trimmed position is easy to obtain and hold. A rating of 3 denotes one which leaves room for improvement, but the characteristics are such that a reasonable tracking performance can be expected. A 4 rating means that the simulator was considered controllable only with the greatest concentration and/or the control forces were too high and would have to be improved to be acceptable. A rating of 5 is applied to a set of conditions which easily produced pilot-induced oscillations and made the simulator practically uncontrollable by the pilot.

## RESULTS AND DISCUSSION

Test results were obtained for all the conditions listed in table I and were recorded as time histories of chair position, target position, and controller position with corresponding ratings of the control system by the pilots. Figures 3 to 5 show some typical data obtained for case I which represented an airplane with augmented pitch damping flying at a high Mach number and a high dynamic pressure.

With the shaker on, representing a near-frictionless valve, the pilot was able to track the cam light fairly well even though he seemed to have trouble maintaining a trimmed condition. (See fig. 3(a).) Turning the shaker off (fig. 3(b)) and thereby introducing approximately 17 inch-pounds of torque at the control pivot due to valve friction caused the tracking task to become impossible because of the very high control forces required and because of the large tendency toward uncontrollable oscillations. With the shaker on again, the addition of increasing amounts of stick friction made the tracking task increasingly more difficult until a value of  $11\frac{1}{4}$  inch-pounds of torque made the pilot's rating go to 5 even though the deterioration of tracking was not apparent in the recorded data. (See fig. 3(c).)

It might be well to point out again that the same control valve was used for these tests as was used for those of reference 3. In reference 3, the valve friction measured at the stick was relatively small with the shaker off. In the present case, however, because of the small mechanical advantage of the controller, the valve friction measured at the controller was excessively large. For this reason, the maximum acceptable value of valve friction in terms of controller force could not be determined from these tests. Quantitatively, the valve friction amounted to 6 inch-pounds about the pivot or 0.25 pound at the grip for the center stick in reference 3, whereas for the present tests the valve friction was 17 inch-pounds about the pivot or 5.25 pounds at the grip for the high control sensitivity. This result can be seen to be a factor of about 20:1 at the grip and indicates that the problem of valve friction must be given a great deal of consideration in the design of small side controllers.

A look at the results of figure 3 will show the small control deflections required to track the target light and indicate the high sensitivity of the controller. The effects of decreasing the control sensitivity were investigated and the results are shown in figure 4. A definite improvement in the tracking performance was noted for both the shaker-on case (fig. 4(a)) and the shaker-off case (fig. 4(b)) when compared with the corresponding cases in figure 3. However, because of the higher mechanical advantage provided by the lower control

sensitivity, the valve friction measured about the controller pivot with the shaker off was only about 1.6 pounds at the grip. This value should be compared with the 5.25 pounds at the grip for the higher control sensitivity, a factor of about 3.3:1, which must be considered to contribute to the reasons for a better rating. Another point is that, if given enough control movement for small valve motion, the pilots were able to counteract the effects of valve friction to a large extent.

Where stick friction was the variable with the low control sensitivity, the pilot's rating did not go to 4 until the friction force became 15 inch-pounds, which was a higher value of friction than was reached previously. Increasing stick friction caused increasingly poorer ratings, primarily as a result of the undesirable breakout forces rather than as a result of any oscillatory condition. Backlash, or lag between stick deflection and chair response, was present for both cases of control sensitivity but was much more noticeable to the pilot for the lower sensitivity tests. The backlash was considered undesirable but the pilots did not believe that it affected their tracking ability to any great extent.

The effects caused by increasing the pitch-rate gain were investigated for the high and low control sensitivities and the results are presented in figure 5. For both cases, a decided deterioration in tracking performance was noted, as can be seen by comparing figures 3(a) and 4(a) with figures 5(a) and 5(c). It was very difficult to obtain and hold a trimmed position and there was a decided tendency to oscillate, especially for the higher control sensitivity and the higher valve friction. This change in gain represents an airplane with increased pitch response per unit of normal acceleration as determined by the

$$\text{equation } \frac{\dot{\theta}}{a_n} = \frac{32.2}{V}. \quad \text{This equation may be written as } \frac{\dot{\theta}}{\alpha} = \frac{32.2 C_{L\alpha} \frac{\rho}{2} V}{\frac{W}{S}}$$

where  $a_n = \frac{\alpha C_{L\alpha} q S}{W}$ ; therefore, the pitch-rate gain is proportional to the product  $\rho V$  for a given airplane. One should note that changes in  $\rho V$  would usually change the period and damping of the airplane somewhat, but that these changes were not incorporated in the pitch chair. Hence, changes in pitch-rate gain should not be considered so much as applying to a given case as to illustrating qualitatively the effects of such changes.

A set of runs (case II) were made to determine the effects of a decrease in the damping ratio from 0.3 to 0.06 of the critical value representing a change from a stability-augmented airplane to that of

one where the damper failed. The ratings for the high-control sensitivity cases (fig. 6) were all 4 or 5, mainly because the control forces were considered to be too high. The ratings for the low-sensitivity cases (fig. 7) were about the same as those for the higher damping tests of case I; therefore, there was little effect due to a change in damping. Here again low control sensitivity permitted the pilot to overcome the normally destabilizing effects to be expected from a decrease in damping. In either case, the lack of oscillatory motions in the records due to the low damping may be explained somewhat by noting that the controls were moved very smoothly and that the pitch-rate gain was very small. A change in the pitch-rate gain gave results similar to the higher damping case for the low-control-sensitivity tests (compare figs. 4(a) and 5(c) with figs. 7(a) and 8(a)). The higher pitching velocity effects were not tested on the high-sensitivity cases because it was believed that this condition would undoubtedly result in unsatisfactory ratings and would cause possible damage to the simulator.

Case III, with values of damping and pitching velocity approximately between those of cases I and II, represented an airplane flying at  $M = 1.2$  and a dynamic pressure of 500 pounds per square foot at an altitude of 35,000 feet. The results of tests for this case are shown in figures 9 and 10 and in general are similar to those obtained in case I (figs. 3 and 4). The main difference was for the high-control-sensitivity case where a larger value of stick friction could be tolerated for case III than for case I.

A subsonic, low-altitude flight condition was simulated and tested in case IV. A high value of damping, a long period, and a high pitch-rate gain characterized this condition. As shown by the data in figures 11(a) and (b), representing the high and the low control sensitivities with the shaker on, the pilot found it impossible to hold a trimmed position and therefore gave these two conditions a rating of 5. However, by decreasing the pitch-rate gain from  $2.22^\circ/\text{sec}/\text{deg}$  to  $0.96^\circ/\text{sec}/\text{deg}$ , the tracking task became much easier for the low-control-sensitivity case (fig. 11(c)) and was given a rating of 2. In order to see whether an increase in damping would also improve tracking performance, figure 12(a) shows the data obtained for the pitch chair approximately 0.7 critically damped. The rating for this case was also 2, but comparison with figure 11(c) shows that somewhat more control motions are required to track. With the 0.7 damping, the effects of an increase in control sensitivity were investigated and the results presented in figure 12(b). As expected, the tracking performance was poorer but was still considered good enough for a rating of 3. Although the higher sensitivity was maintained, the damping ratio was decreased to 0.1 critical. This change made it difficult to obtain and to hold a trimmed position and resulted in pilot-induced oscillations which approached an unstable condition. (See fig. 12(c).) Decreasing the

pitch-rate gain from  $2.22^{\circ}/\text{sec}/\text{deg}$  to  $0.96^{\circ}/\text{sec}/\text{deg}$  improved the tracking so that this condition again was given a rating of 3. (See fig. 13(a).) Decreasing the control sensitivity gave the expected result of improving the ability to track enough to change the rating to 2. (See fig. 13(b).) An increase in the pitch-rate gain back to  $2.22^{\circ}/\text{sec}/\text{deg}$  required somewhat slower control rates to prevent overshoot and thereby was given a 3 rating.

The feasibility of correlating the present results with those of reference 3 was considered and it was decided that there was not enough comparable data with which to draw any specific conclusions. However, it appears that, where static stick friction was the limiting factor, about 3 pounds at the grip was the tolerable limit for either the side-located or the centrally located control stick.

The pilots associated with this project were all impressed with the ease and naturalness of the control that was possible with the side-located controller. It was noted that the forearm remained relatively fixed and completely supported; thus the pilot was provided with a fixed reference not possible with centrally located control sticks. Even though the controller was designed to pivot at the wrist by using an up-and-down movement of the hand, it was possible to intersperse force couples within the hand superimposed on the normally rotational and translational forces in order to obtain a more precise control. Prior to the present tests, a side controller with its pivot line through the center of the hand was temporarily installed in the simulator. The operators of the simulator who tried this controller as well as that used for the test program on the whole preferred the controller with the pivot through the hand. However, it was pointed out that the merits of several pivot locations should be investigated before any decision as to an optimum location could be made.

#### CONCLUDING REMARKS

The operating characteristics of a small side-located controller were determined from tests of a ground simulator incorporating a power control system. The effects of period and damping and ratio of pitching velocity to angle of attack were determined, various Mach number and altitude conditions being simulated. A limited investigation of control-system variables, such as control sensitivity, control friction, and booster valve friction, and their effects on control-system quality was also made. The quality of the control system using the controller was determined by the ease and precision with which various tracking maneuvers could be accomplished by the pilot.

Without exception, the operators of the simulator commented favorably on their ability to track precisely with the small side-located controller provided the control-system characteristics were desirable. Generally speaking, increasing the damping ratio, increasing the period, and decreasing the pitch-rate gain tended to improve the tracking performance. The maximum acceptable value of valve friction in terms of controller force could not be determined from these tests because the force obtained with the valve alone was excessive. However, the valve friction was effectively reduced to zero by means of a vibrator on the valve stem which permitted the study of the effects of stick friction and other control system and airplane parameters. Where static stick friction was the limiting factor, about 3 pounds at the grip was found to be the tolerable limit for either the side-located controller or the centrally located control stick of NACA Technical Note 3998.

Langley Aeronautical Laboratory,  
National Advisory Committee for Aeronautics,  
Langley Field, Va., January 31, 1958.

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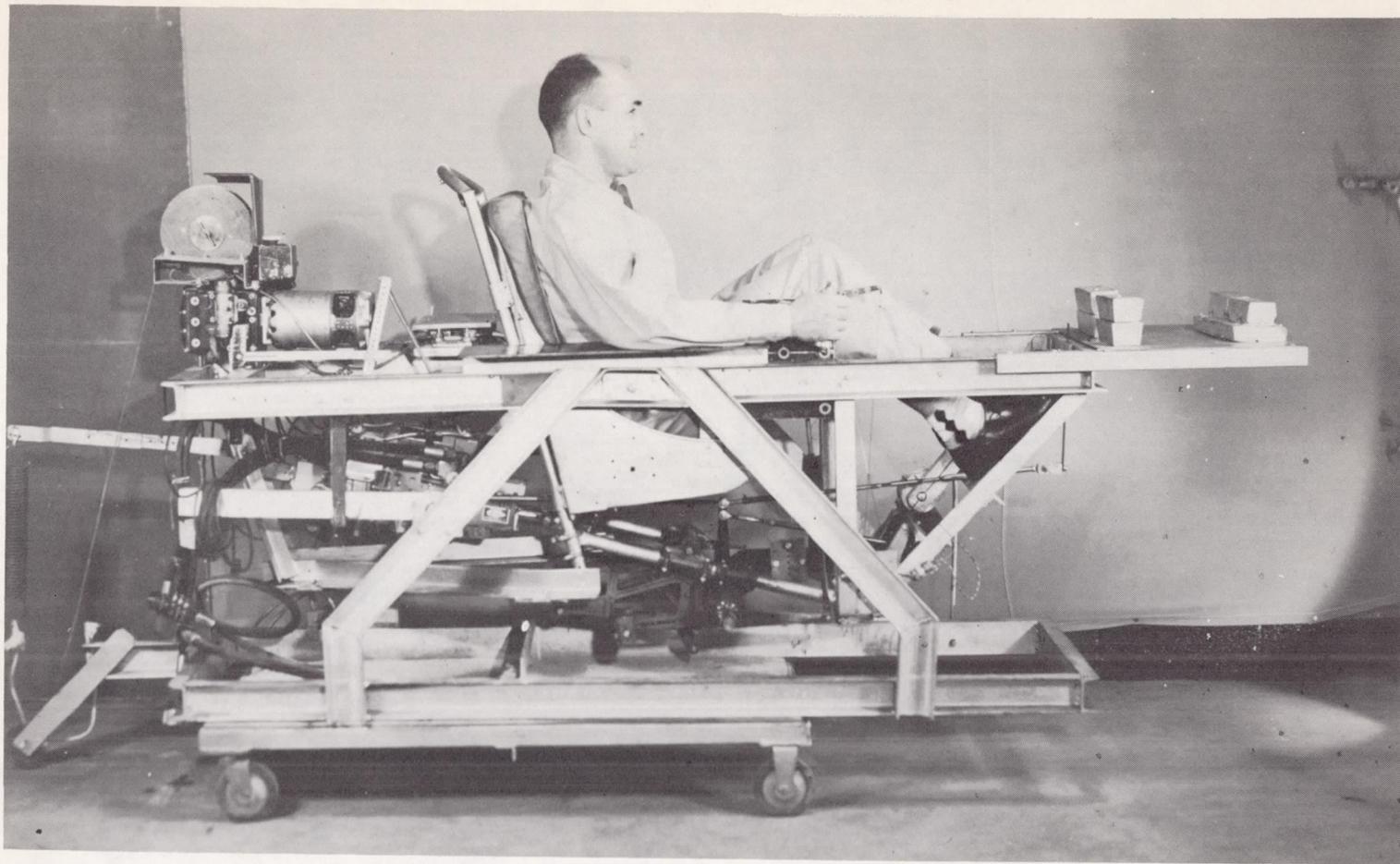
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TABLE I.- SIMULATED CONDITIONS, CONTROL SYSTEM CHARACTERISTICS, AND PILOTS' RATING FOR ALL TESTS

Figure	Case	Period, sec.	Damping ratio	Pitch-rate gain deg/sec/deg	Valve friction, in-lb at pivot	Stick friction, in-lb at pivot	Side controller sensitivity, $\delta_c/\alpha$	Spring feel force gradient, in-lb/ $\delta_c$	Pilots' rating (1)
3(a)	I	1.2	0.3	0.38	Shaker on	1.8	1	5.55	2
3(b)	I	1.2	.3	.38	17.0		1	5.55	5
	I	1.2	.3	.38	Shaker on	1.9	1	5.55	2
	I	1.2	.3	.38	Shaker on	3.8	1	5.55	2
	I	1.2	.3	.38	Shaker on	7.5	1	5.55	3
	I	1.2	.3	.38	Shaker on	11.25	1	5.55	5
4(a)	I (mod.)	1.2	.3	.38	Shaker on	1.3	4.2	.32	1
4(b)	I (mod.)	1.2	.3	.38	5.25		4.2	.32	3
	I (mod.)	1.2	.3	.38	Shaker on	7.5	4.2	.32	3
	I (mod.)	1.2	.3	.38	Shaker on	11.25	4.2	.32	3
	I (mod.)	1.2	.3	.38	Shaker on	15	4.2	.32	4
5(a)	I (mod.)	1.2	.3	1.67	Shaker on	1.8	1	5.55	4
5(b)	I (mod.)	1.2	.3	1.67	17.0		1	5.55	5
5(c)	I (mod.)	1.2	.3	1.67	Shaker on	1.3	4.2	.32	4
	I (mod.)	1.2	.3	1.67	5.25		4.2	.32	5
6(a)	II	1.2	.06	.38	Shaker on	1.8	1	5.55	4
6(b)	II	1.2	.06	.38	17.0		1	5.55	5
6(c)	II	1.2	.06	.38	Shaker on	10	1	5.55	4
7(a)	II (mod.)	1.2	.06	.38	Shaker on	1.3	4.2	.32	3
7(b)	II (mod.)	1.2	.06	.38	5.25		4.2	.32	3
	II (mod.)	1.2	.06	.38	Shaker on	7.5	4.2	.32	2
	II (mod.)	1.2	.06	.38	Shaker on	10	4.2	.32	3
	II (mod.)	1.2	.06	.38	Shaker on	15	4.2	.32	3
7(c)	II (mod.)	1.2	.06	.38	Shaker on	20	4.2	.32	4
8(a)	II (mod.)	1.2	.06	1.67	Shaker on	1.3	4.2	.32	4
8(b)	II (mod.)	1.2	.06	1.67	5.25		4.2	.32	5
9(a)	III	1.2	.10	.96	Shaker on	1.8	1	5.55	3
9(b)	III	1.2	.10	.96	17.0		1	5.55	5
	III	1.2	.10	.96	Shaker on	10	1	5.55	3
9(c)	III	1.2	.10	.96	Shaker on	15	1	5.55	4
10(a)	III (mod.)	1.2	.10	.96	Shaker on	1.3	4.2	.32	2
10(b)	III (mod.)	1.2	.10	.96	5.25		4.2	.32	3
	III (mod.)	1.2	.10	.96	Shaker on	10	4.2	.32	3
10(c)	III (mod.)	1.2	.10	.96	Shaker on	15	4.2	.32	4
11(a)	IV	2.3	.50	2.22	Shaker on	1.8	1	5.55	5
11(b)	IV	2.3	.50	2.22	Shaker on	1.3	4.2	.32	5
	IV	2.3	.50	2.22	5.25		4.2	.32	5
11(c)	IV	2.3	.50	.96	Shaker on	1.3	4.2	.32	2
	IV	2.3	.50	.96	5.25		4.2	.32	3
12(a)	IV (mod.)	2.3	.70	2.22	Shaker on	1.3	4.2	.32	2
	IV (mod.)	2.3	.70	2.22	5.25		4.2	.32	4
12(b)	IV (mod.)	2.3	.70	2.22	Shaker on	1.8	1	5.55	3
12(c)	IV (mod.)	2.3	.10	2.22	Shaker on	1.8	1	5.55	4
13(a)	IV (mod.)	2.3	.10	.96	Shaker on	1.8	1	5.55	3
	IV (mod.)	2.3	.10	.96	17.0		1	5.55	4
13(b)	IV (mod.)	2.3	.10	.96	Shaker on	1.3	4.2	.32	2
	IV (mod.)	2.3	.10	.96	5.25		4.2	.32	3
13(c)	IV (mod.)	2.3	.10	2.22	Shaker on	1.3	4.2	.32	3
	IV (mod.)	2.3	.10	2.22	5.25		4.2	.32	4

<sup>1</sup>Pilots' ratings were based on the following:

1. A control system with characteristics that are near perfect.
2. A control system with little or no tendency to overshoot and one for which a trimmed position is easy to obtain and hold.
3. A control system which leaves room for improvement but with characteristics such that a reasonable tracking performance can be expected.
4. The simulator is controllable only with the greatest concentration and/or the control forces were too high and would have to be improved to be acceptable.
5. Applied to a set of conditions which easily produced pilot-induced oscillations and made simulator practically uncontrollable.



(a) Pilot holding controller as in normal operation.

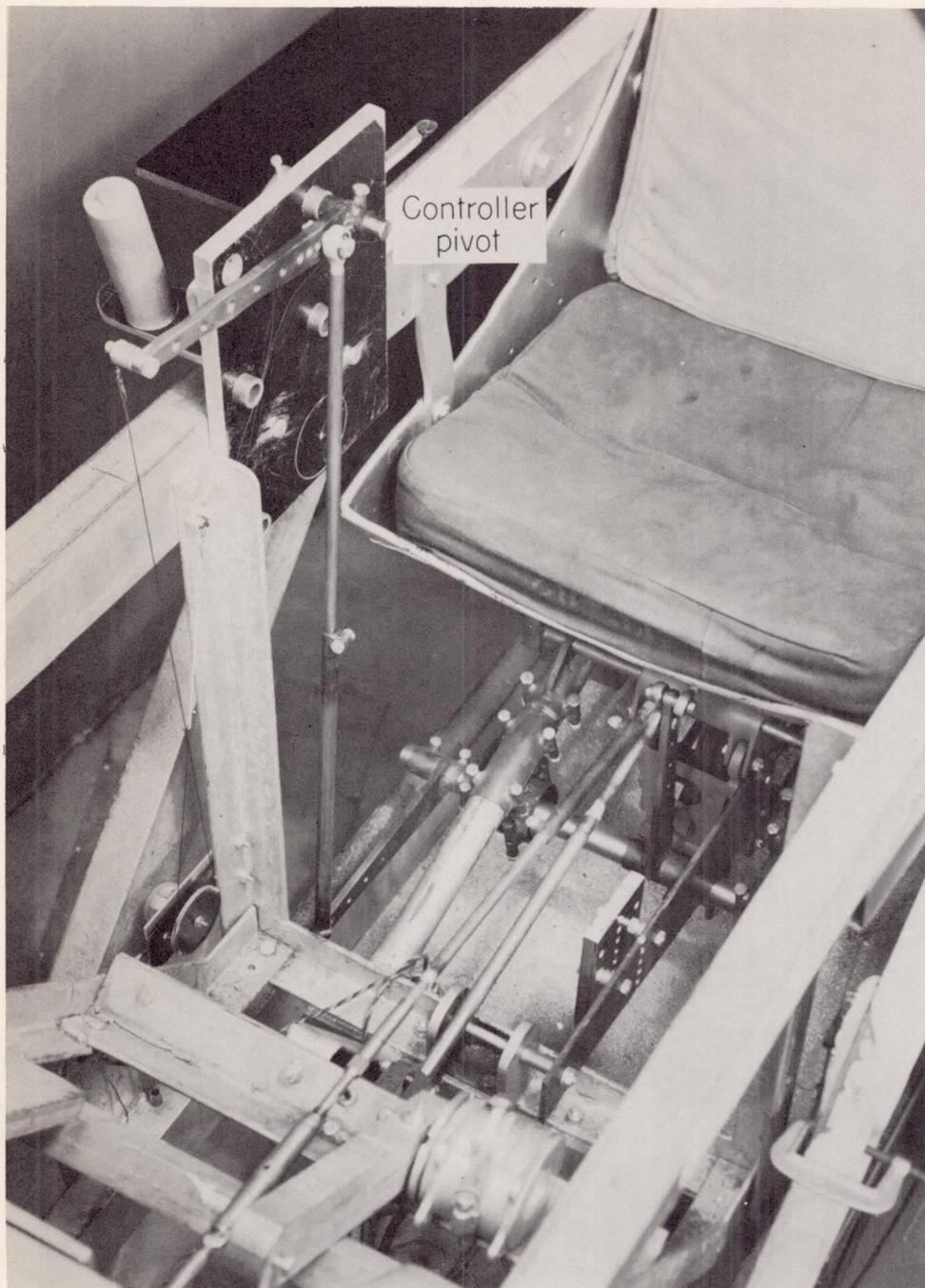
L-96074

Figure 1.- Photographs of the longitudinal power control simulator (Pitch chair) equipped with a small side-located controller.



(b) Closeup showing controller grip and pivot location. L-96079.1

Figure 1.- Continued.



(c) Closeup showing controller grip and associated linkages. L-96077.1

Figure 1.- Concluded.

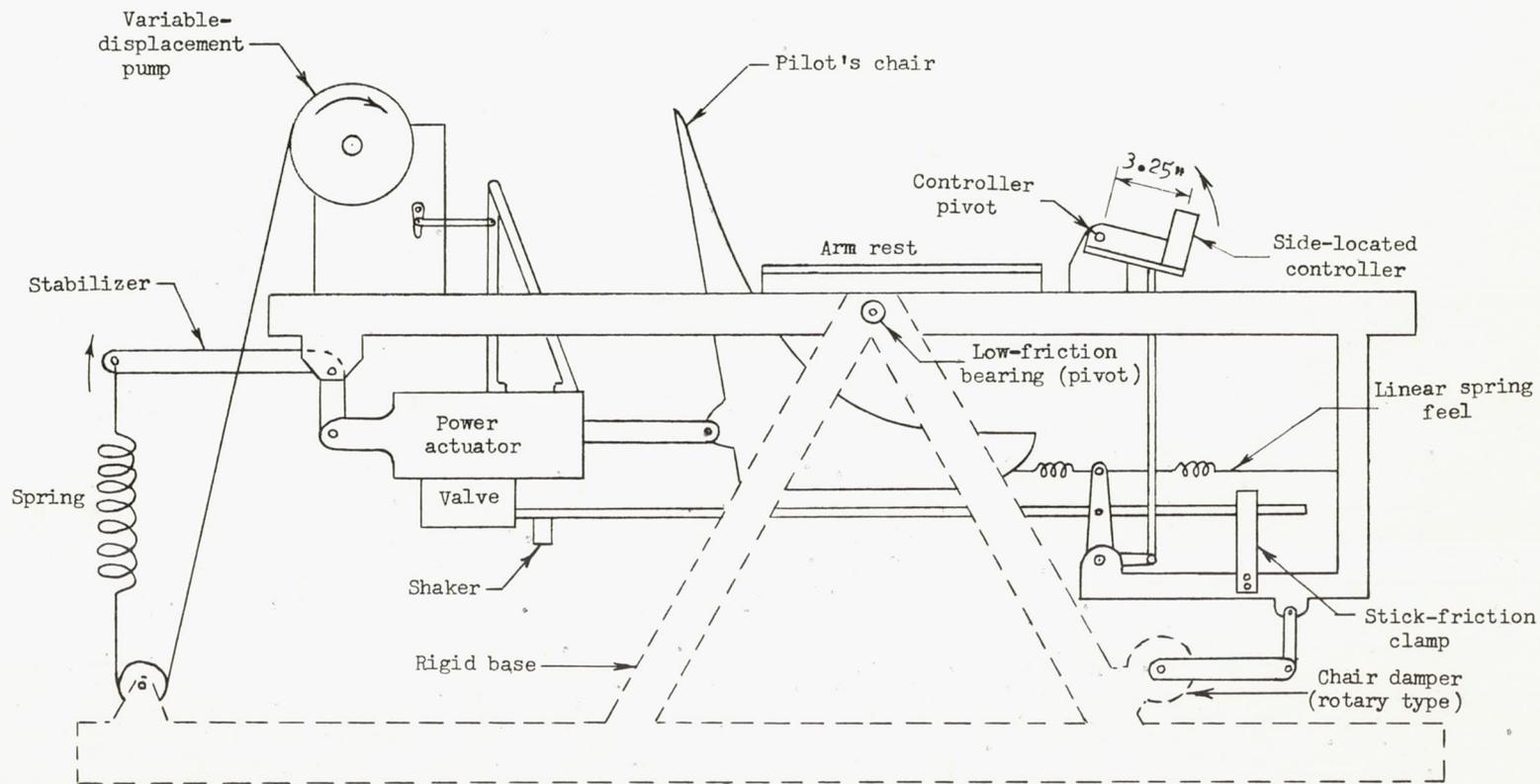
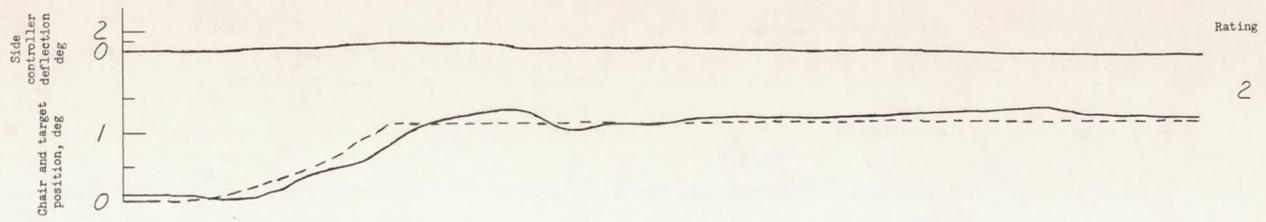
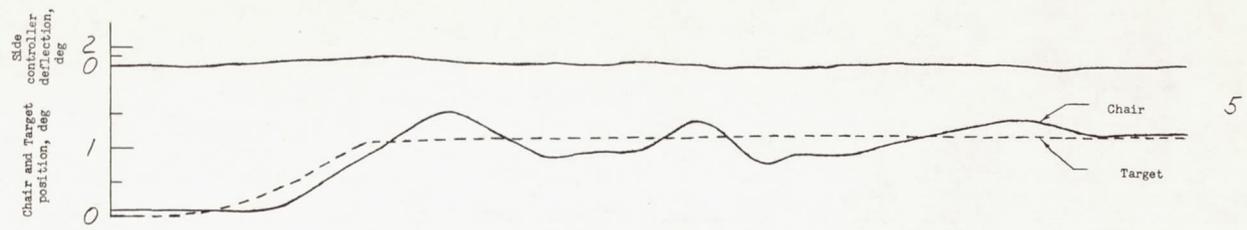


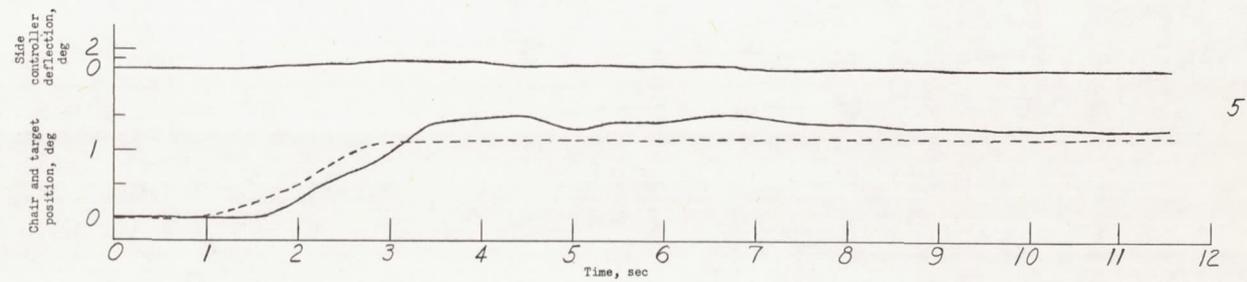
Figure 2.- A schematic drawing of the simulator with solid lines indicating movable parts. Arrows indicate direction of controller, stabilizer, and pump drum associated with a pullup.



(a) Negligible valve friction. Shaker on.

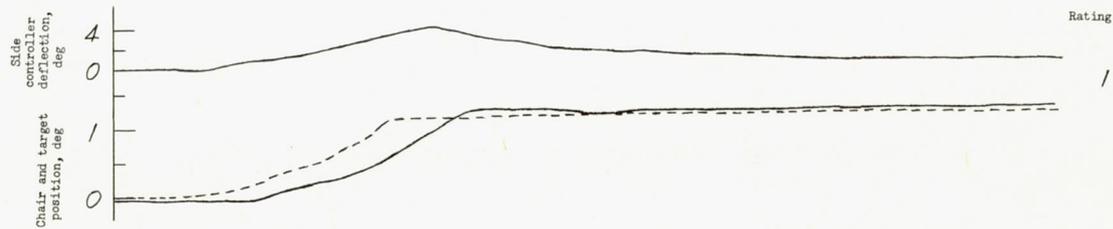


(b) 17 in-lb valve friction. Shaker off.

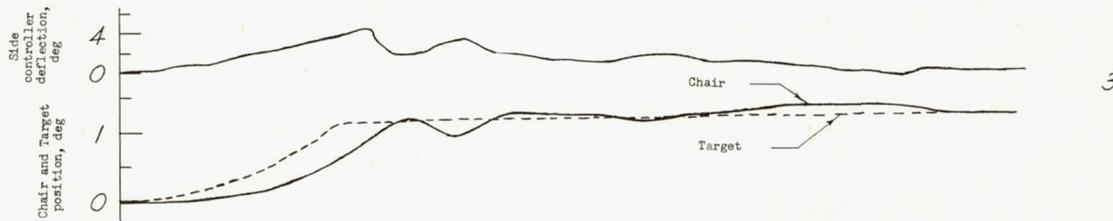
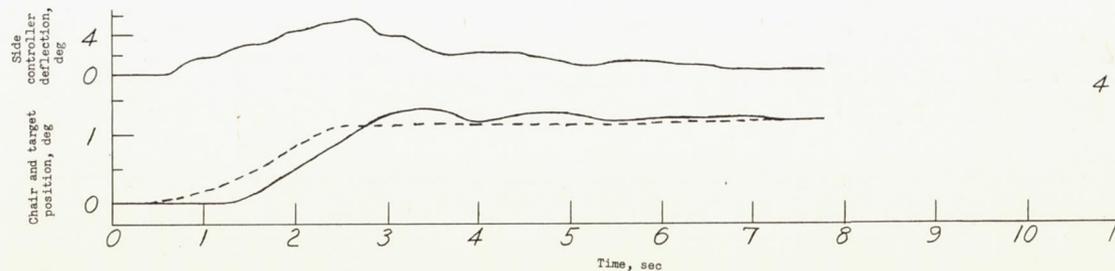


(c)  $11\frac{1}{4}$  in-lb stick friction. Shaker on.

Figure 3.- Typical time histories obtained for case I showing the effects of valve friction and stick friction. Period, 1.2 sec; damping, 0.30; pitch-rate gain,  $0.38^\circ/\text{sec}/\text{deg}$ ; controller sensitivity, 1:1; spring feel, 5.55 in-lb/deg.

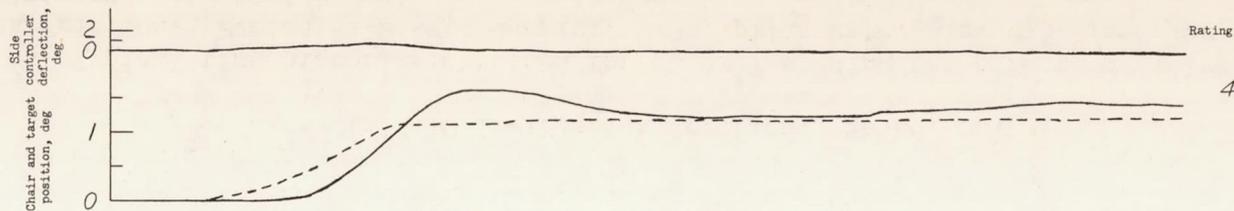


(a) Negligible valve friction. Shaker on.

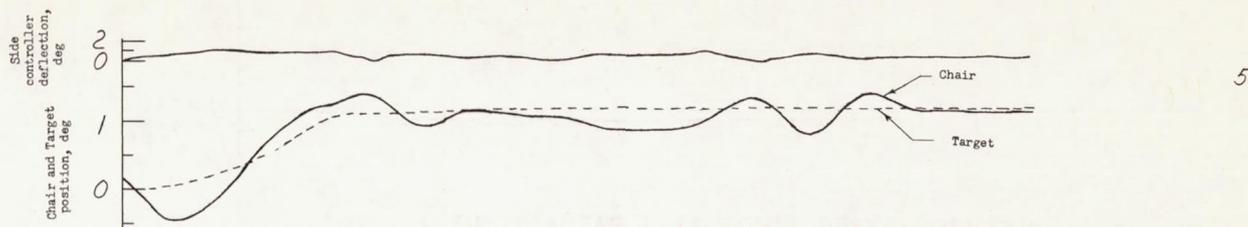
(b)  $5\frac{1}{4}$  in-lb valve friction. Shaker on.

(c) 15 in-lb stick friction. Shaker on.

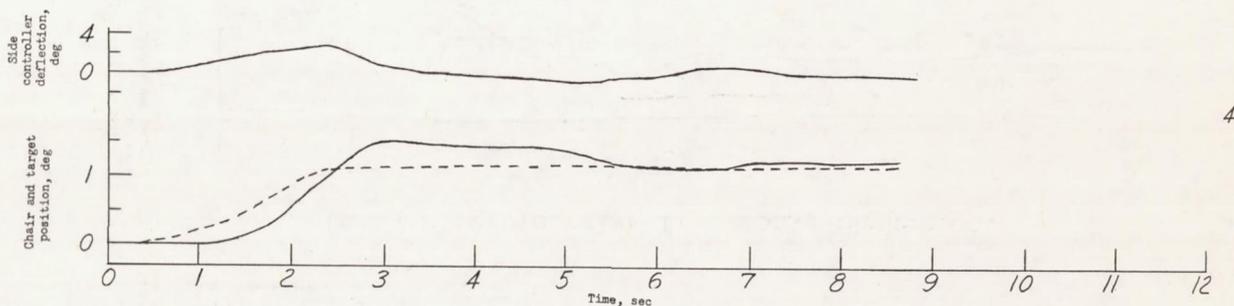
Figure 4.- Typical time histories obtained for case I showing the effects of valve friction and stick friction. Period, 1.2 sec; damping, 0.30; pitch-rate gain,  $0.38^\circ/\text{sec}/\text{deg}$ ; controller sensitivity, 4.2:1; spring feel, 0.32 in-lb/deg.



(a) Negligible valve friction; shaker on; controller sensitivity, 1:1.

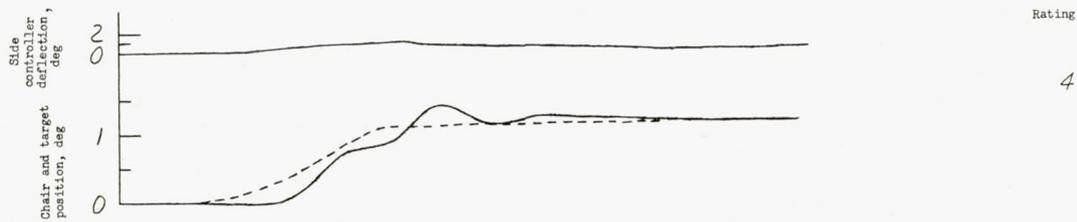


(b) 17 in-lb valve friction; shaker off; controller sensitivity, 1:1.

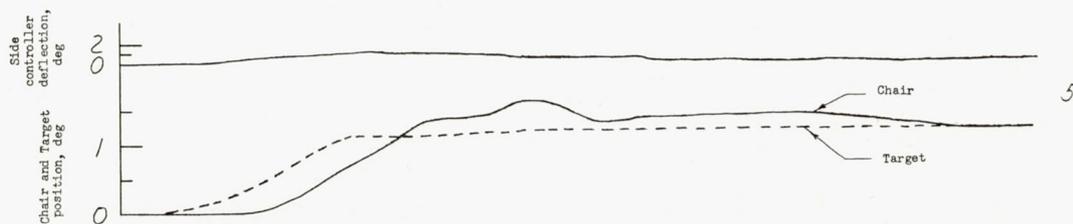


(c) Negligible valve friction; shaker on; controller sensitivity, 4.2:1.

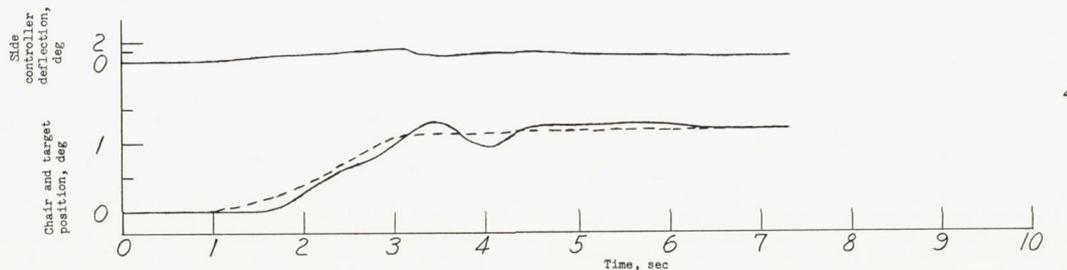
Figure 5.- Typical time histories obtained for case I showing the effects of valve friction and controller sensitivity. Period, 1.2 sec; damping, 0.30; pitch-rate gain,  $1.67^{\circ}/\text{sec}/\text{deg}$ .



(a) Negligible valve friction. Shaker on.

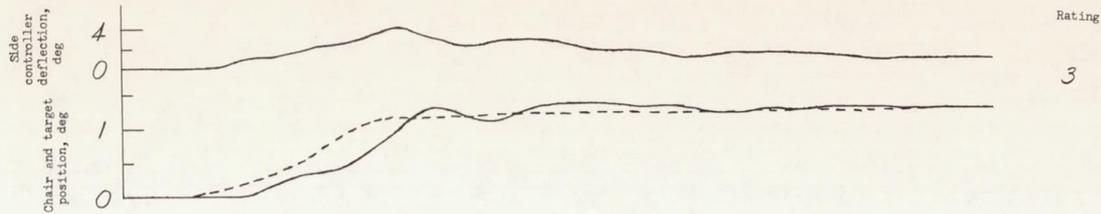


(b) 17 in-lb valve friction. Shaker off.

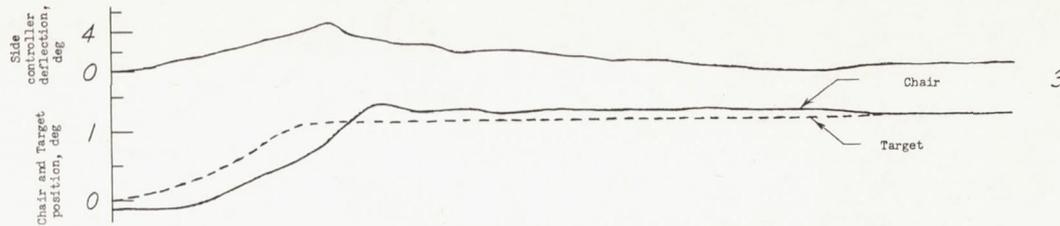


(c) 10 in-lb stick friction. Shaker on.

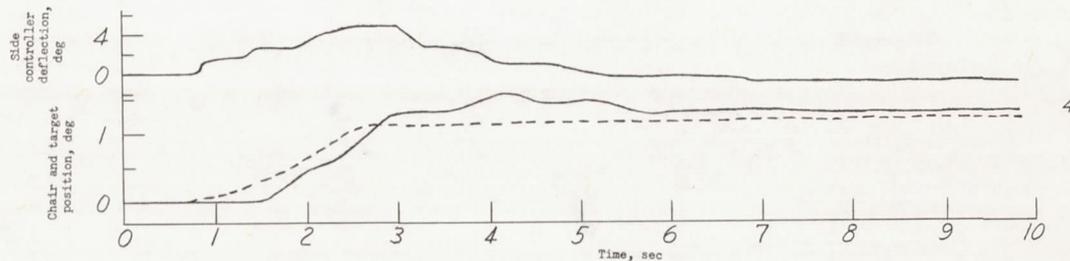
Figure 6.- Typical time histories obtained for case II showing the effects of valve friction and stick friction. Period, 1.2 sec; damping, 0.06; pitch-rate gain,  $0.38^{\circ}/\text{sec}/\text{deg}$ ; controller sensitivity, 1:1, spring feel, 5.55 in-lb/deg.



(a) Negligible valve friction. Shaker on.

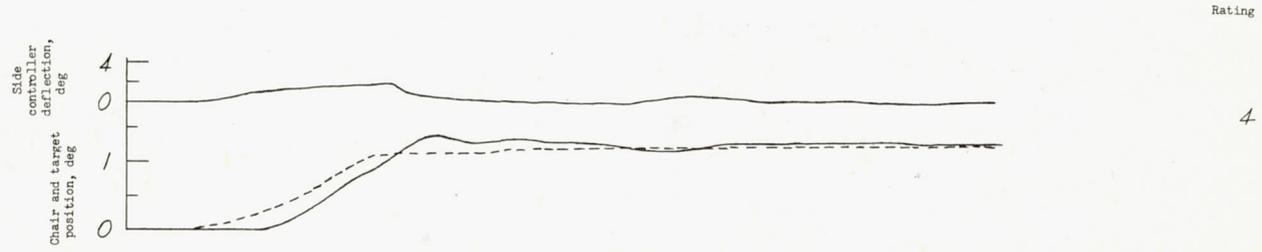


(b)  $5\frac{1}{4}$  in-lb valve friction. Shaker on.

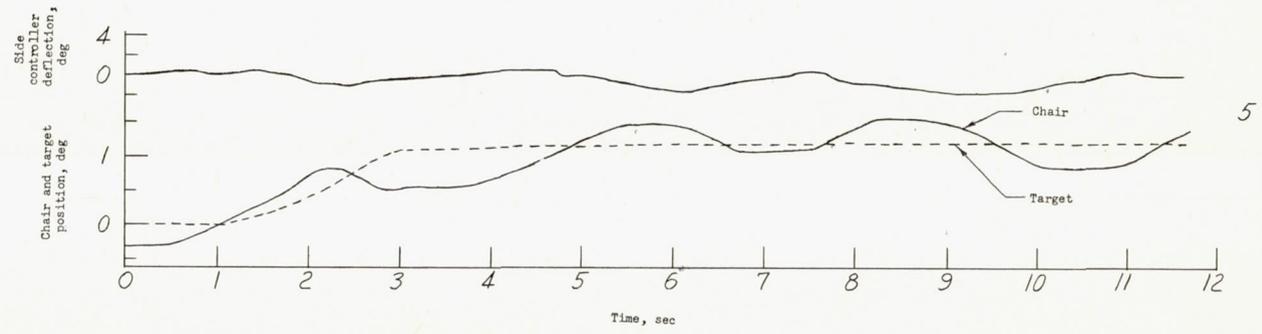


(c) 20 in-lb stick friction. Shaker on.

Figure 7.- Typical time histories obtained for case II showing the effects of valve friction and stick friction. Period, 1.2 sec; damping, 0.06; pitch-rate gain,  $0.38^{\circ}/\text{sec}/\text{deg}$ ; controller sensitivity, 4.2:1; spring feel, 0.32 in-lb/deg.

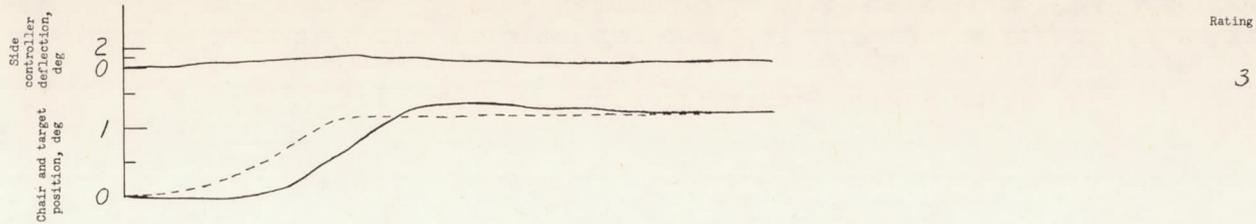


(a) Negligible valve friction. Shaker on.

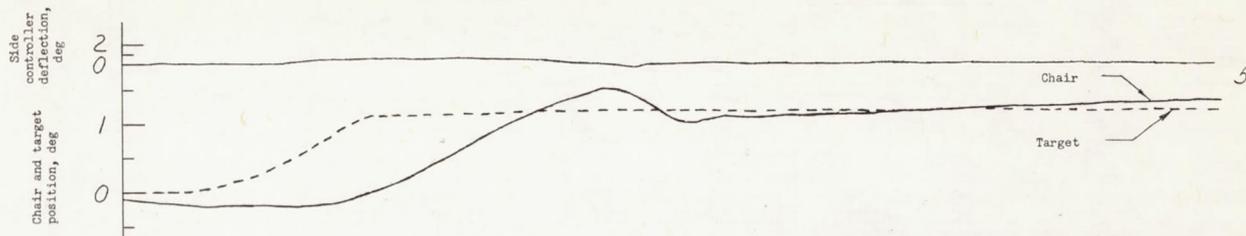


(b)  $5\frac{1}{4}$  in-lb valve friction. Shaker off.

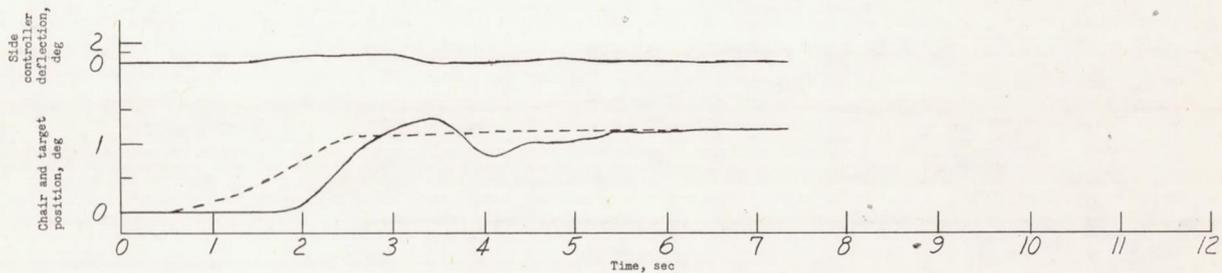
Figure 8.- Typical time histories obtained for case II showing the effects of valve friction. Period, 1.2 sec; damping, 0.06; pitch-rate gain,  $1.67^{\circ}/\text{sec}/\text{deg}$ ; controller sensitivity, 4.2:1; spring feel, 0.32 in-lb/deg.



(a) Negligible valve friction. Shaker on.



(b) 17 in-lb valve friction. Shaker off.

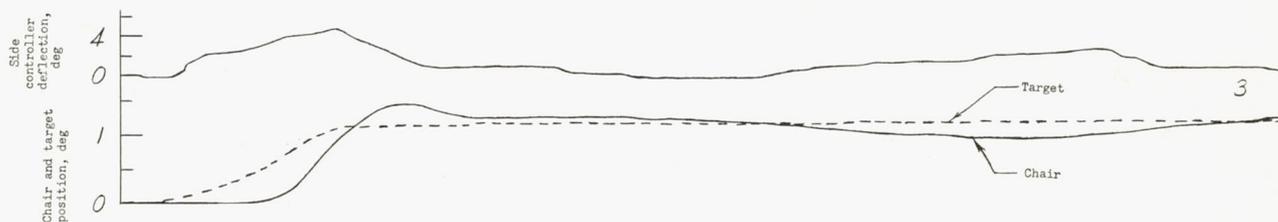


(c) 15 in-lb stick friction. Shaker off.

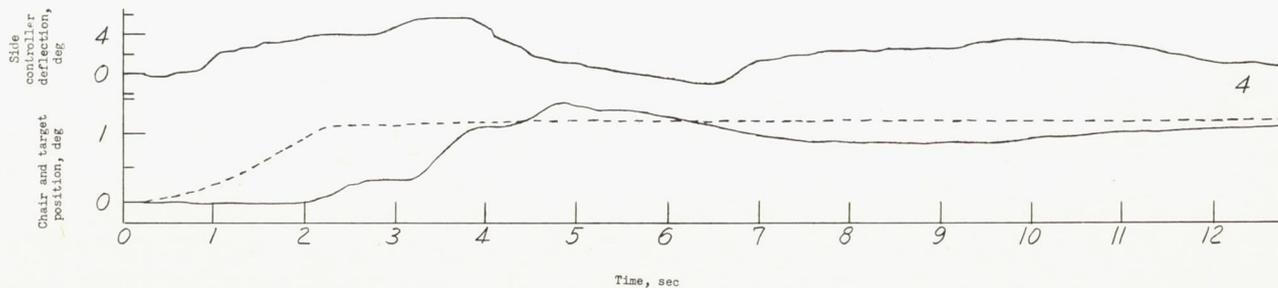
Figure 9.- Typical time histories obtained for case III showing the effects of valve friction and stick friction. Period, 1.2 sec; damping, 0.1; pitch-rate gain,  $0.96^{\circ}/\text{sec}/\text{deg}$ ; controller sensitivity, 1:1; spring feel, 5.55 in-lb/deg.



(a) Negligible valve friction. Shaker on.

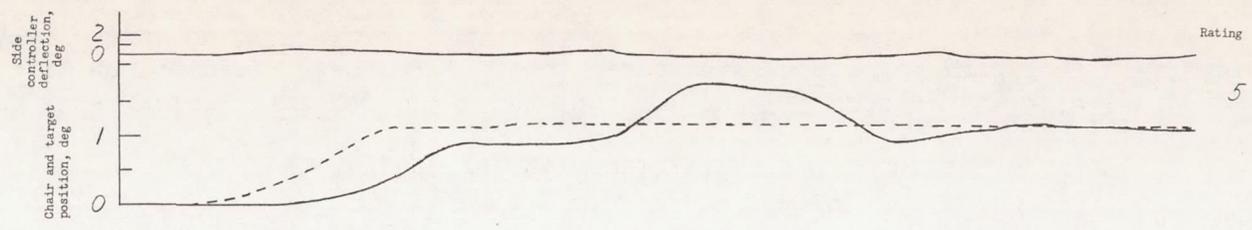


(b)  $5\frac{1}{4}$  in-lb valve friction. Shaker off.

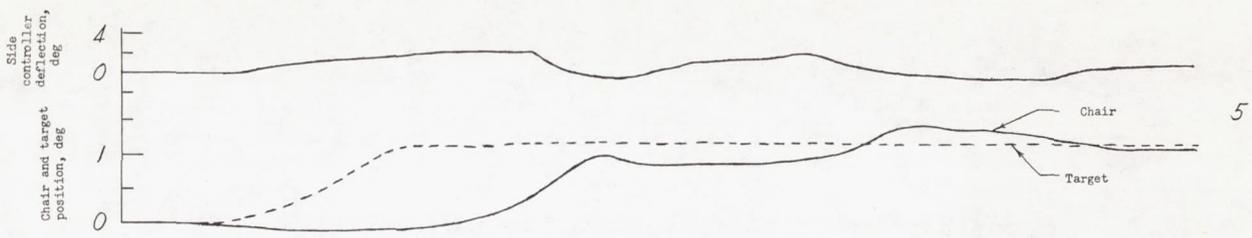


(c) 15 in-lb stick friction. Shaker on.

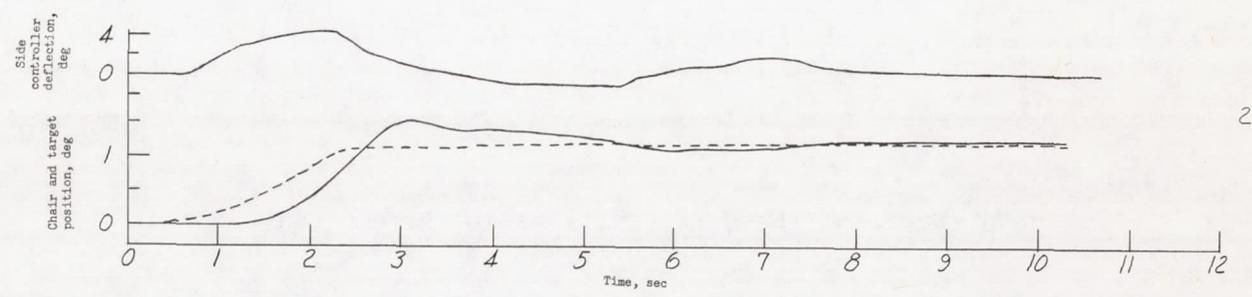
Figure 10.- Typical time histories obtained for case III showing the effects of valve friction and stick friction. Period, 1.2 sec; damping, 0.1; pitch-rate gain,  $0.96^{\circ}/\text{sec}/\text{deg}$ ; controller sensitivity, 4.2:1; spring feel, 0.32 in-lb/deg.



(a) Controller sensitivity, 1:1; pitch-rate gain,  $2.22^\circ/\text{sec}/\text{deg}$ .

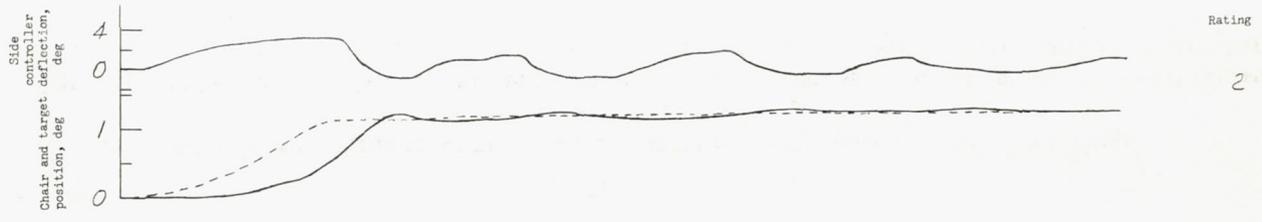


(b) Controller sensitivity, 4.2:1; pitch-rate gain,  $2.22^\circ/\text{sec}/\text{deg}$ .

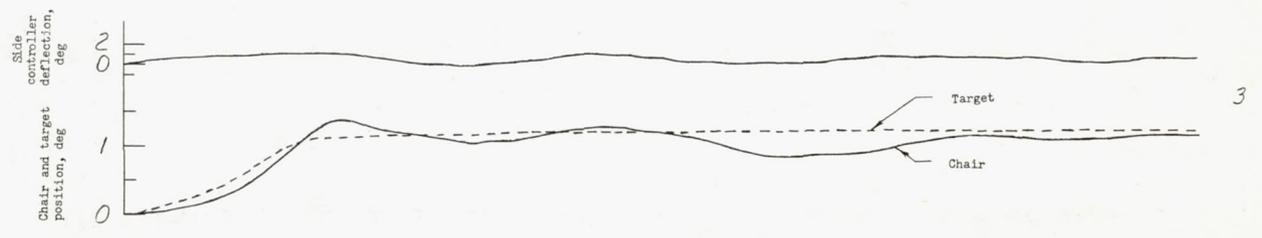


(c) Controller sensitivity, 4.2:1; pitch-rate gain,  $0.96^\circ/\text{sec}/\text{deg}$ .

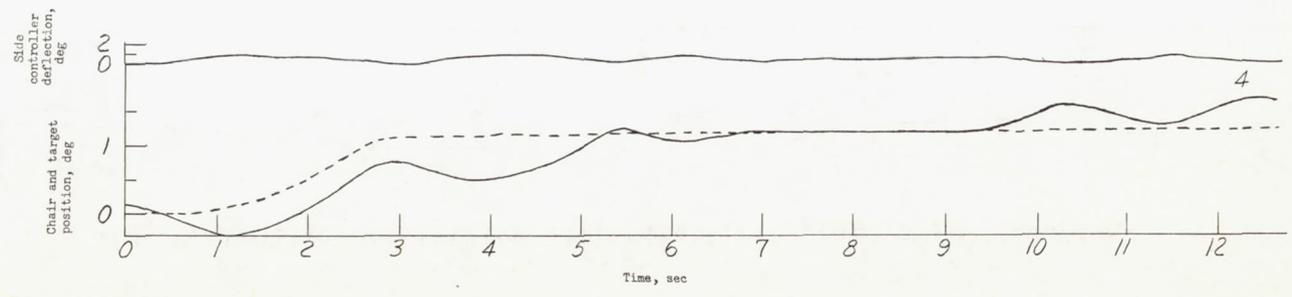
Figure 11.- Typical time histories obtained for case IV showing the effects of controller sensitivity and pitch-rate gain. Period, 2.3 sec; damping, 0.5; negligible valve friction; shaker on.



(a) Controller sensitivity, 4.2:1; damping, 0.7.

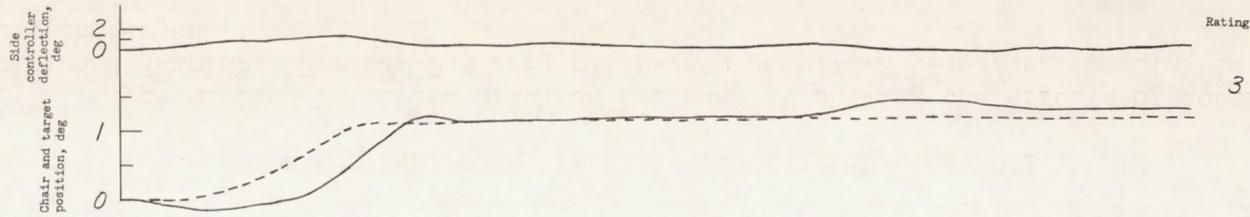


(b) Controller sensitivity, 1:1; damping, 0.7.

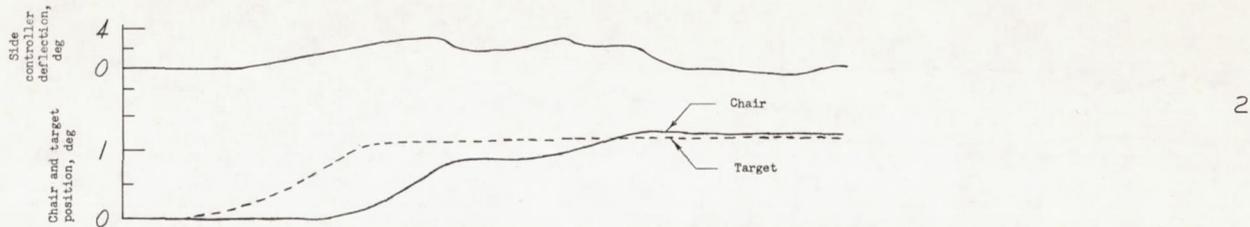


(c) Controller sensitivity, 1:1; damping, 0.1.

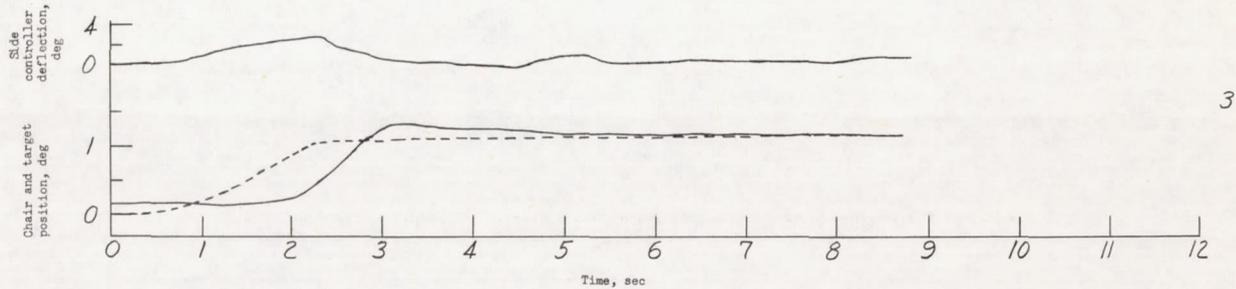
Figure 12.- Typical time histories obtained for case IV showing the effects of controller sensitivity and damping. Period, 2.3 sec; pitch-rate gain, 2.22°/sec/deg; negligible valve friction; shaker on.



(a) Controller sensitivity, 1:1; pitch-rate gain,  $0.96^\circ/\text{sec}/\text{deg}$ .



(b) Controller sensitivity, 4.2:1; pitch-rate gain,  $0.96^\circ/\text{sec}/\text{deg}$ .



(c) Controller sensitivity, 4.2:1; pitch-rate gain,  $2.22^\circ/\text{sec}/\text{deg}$ .

Figure 13.- Typical time histories obtained for case IV showing the effects of controller sensitivity and pitch-rate gain. Period, 2.3 sec; damping, 0.1; negligible valve friction; shaker on.