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## TECHNICAL NOTE 4297

# FLIGHT INVESTIGATION OF THE ACCEPTABILITY OF A SMALL SIDE-LOCATED CONTROLLER USED WITH AN IRREVERSIBLE HYDRAULIC CONTROL SYSTEM

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## SUMMARY

A flight investigation has been conducted to determine the acceptability of a small side-located controller which is used as the primary airplane controller in an irreversible hydraulic-power control system. The particular controller used in this investigation requires up and down hand motion pivoting at the wrist for longitudinal control and lateral hand or forearm motion for lateral control. Pilot opinion was obtained concerning the acceptability of the controller while performing lateral and longitudinal maneuvers in a jet-trainer airplane at cruising-flight conditions.

The results of this investigation indicate that the location of the controller is consistent with pilot comfort and the airplane is flyable with the side-located controller. Hand motion about the wrist pivot required for longitudinal control is somewhat uncomfortable when large stick motions and high forces are required. Stick breakout force and stick force gradient should be kept at low values consistent with the reduced-force-output requirements of the pilot when operating a small side-located controller of the type used in this investigation.

## INTRODUCTION

Because of the present interest in side-located controllers for use in the primary airplane control system, the Flight Research Division of the Langley Aeronautical Laboratory has conducted a flight evaluation of a specific side-located controller. The side location of a primary controller has been found to be desirable when the controller is used with an electronic control system. In the electronic system the stick-force characteristics can be infinitely varied and such things as linkage friction, elasticity, and valve friction pose no problems. When a side controller is used in conjunction with a hydraulic-power control

system, however, these factors assume primary importance in determining acceptable stick force gradients and stick breakout force. Therefore, the effects of linkage and valve friction on overall-control-system quality should be investigated.

This paper gives results of flight tests made with a side-located controller that requires up and down hand motion pivoting at the wrist for longitudinal control and a lateral hand or forearm motion for lateral control. Two groups of power-control-system characteristics were used for these flight tests so that the airplane controllability was unacceptable in one case and acceptable in the second case. Linkage friction and valve friction are tabulated for these cases, and the levels of stick force gradient and stick sensitivity are indicated. The results of this investigation consist of pilots' opinion and time-history figures of some maneuvers performed with the side-located controller.

## SYMBOLS

| | |
|---|---|
| $\delta_{e,c}$ | side-controller deflection calibrated in terms of elevator angle, deg |
| $\delta_{a,c}$ | side-controller deflection calibrated in terms of total aileron angle, deg |
| $\delta_e$ | elevator deflection, deg |
| $\delta_a$ | total aileron deflection, deg |
| $\theta$ | pitch angle, deg |
| $\phi$ | roll angle, deg |
| $a_n$ | normal acceleration, g units |
| $q$ | pitching velocity, radians/sec |
| $p$ | rolling velocity, radians/sec |

## SIDE-LOCATED-CONTROLLER INSTALLATION

A sketch is presented in figure 1 to show the pertinent dimensions of the side-located controller and its angular orientation with respect

to the airplane axes. The linkage connecting the controller to the servovalve and the simple spring used for control feel and centering is also shown. The controller grip is rotated 20° inward (top of grip toward center of cockpit) and 10° outward from the longitudinal axis. The grip is a standard service type used on conventional center-located sticks. Figure 2 shows the controller and arm rest installed in the cockpit and figure 3 shows the pilot holding the controller as in flight. These figures show the controller pivots for longitudinal and lateral control. The controller dimensions, orientation, and position in the cockpit were adjusted to be consistent with pilot comfort but the basic design principle of using hand motion pivoting at the wrist for longitudinal control does not necessarily reflect pilots' preference. Stick force and motion sensitivity for lateral and longitudinal control are given in table I.

A two-place jet trainer airplane that was modified by the addition of hydraulic-power controls for the human-pilot response studies being conducted by the National Advisory Committee for Aeronautics was used conveniently as a test vehicle for this work. The added hydraulic-power control system was independent of the normal airplane controls which remain functional from the front-cockpit center stick whenever the auxiliary hydraulic system was not engaged. A photograph of the test airplane is shown in figure 4. Elevator sensitivity at the flight conditions used for this study is about 2.5° of elevator per g.

The presence of valve friction can be a very serious detrimental factor in a hydraulic-power control system because it contributes to control overshoot and pilot-induced oscillations as described in detail in references 1 and 2. High-frequency shaker devices were mounted in close proximity to the hydraulic servovalve to reduce the effect of static valve friction on the control quality. The shakers serve to keep the valve spool in constant motion and thereby tend to eliminate the static friction. The amplitude of motion is low and the frequency is high enough so that the system does not respond to this shaking or "dither" motion. A photograph of the shaker device, assembled and with the cover removed to show the internal structure, is shown in figure 5. Shaker frequency is approximately 100 cps and shaking force is about 2 pounds. The opposed rotation of the two eccentric weighted gears produce unidirectional shaking force and the units are mounted so that the shaking direction is in line with the valve motion.

## INSTRUMENTATION

Standard NACA film recording instruments were installed in the test airplane. The quantities recorded for this investigation were rolling and pitching angular velocities, normal accelerations, roll and pitch

attitude, elevator- and aileron-surface deflections, and side-located-controller deflection.

## FLIGHT TESTS

A flight evaluation of the side-located controller when used in conjunction with a hydraulic-power control system has been conducted. The power-control-system characteristics were such as to make the airplane controllability unacceptable in one case (designated as system A) and acceptable in the second case (designated as system B). Data for some of the characteristics of the control systems used are listed in table I. The valve-shaker devices were used in both systems, but the servovalve friction of system A was too high for the shaker to eliminate. A modification to system A resulted in a reduction of the servovalve friction level to a point where the addition of the shaker resulted in essentially zero static servovalve friction. Lost motion in the linkage was also reduced and the linkage flexibility then had no detrimental effects with the reduced servovalve friction. The acceptable system (system B) is the modified control system. All flight tests of the side-located controller were made at cruising-flight conditions.

The initial runs made with system A required the pilot to fly straight and level and then to initiate a 2g pull-up and return to 1g flight. During the level-flight portion of the run, the airplane would maintain trim until a small control disturbance was applied which resulted in a pilot-induced oscillation. Figure 6 shows a time history of controller deflection, elevator deflection, pitch attitude, normal acceleration, and pitching velocity for this run. By observing the lag between the side-controller deflection and elevator deflection, the reason for the pilot's difficulty becomes obvious. (See ref. 1.) Note that the controller must be moved an amount equivalent to about $2^{\circ}$ of elevator before the elevator starts to move and then the elevator moves faster than intended with overshoot resulting. The underlying reason for this poor control characteristic in this case is excessively high static servovalve friction and, to a lesser extent, the lost motion and elasticity in the linkage. The valve restrains the linkage at one end and as the pilot loads the other end of the linkage it stretches until the static-friction level of the servovalve is exceeded. The valve then undergoes a large displacement because of the high spring load and the relatively small restraint of the dynamic servovalve friction. Figure 7 shows a time history of the pilot's attempt to pull up to 2g then push down to 1g flight again. The pilot approached the task very cautiously and pulled up to 1.6g; however, in attempting to return to 1g, he overshot and the airplane went to about 0g because of the same control-system shortcoming described previously.

The poor control-system characteristics of control system A which were used in conjunction with the side-located controller in these initial tests made it difficult for the pilots to evaluate the side-located controller. However, the pilots did object to the wrist pivot motion required for pitch control. The reason for this objection seems to stem from the awkward or unnatural motion and force application required. Actually the pilot must lift up or push down on the stick with the wrist essentially fixed in order to execute longitudinal control. The heavy elevator breakout force (9 inch-pounds about stick pivot) also contributed to the control difficulty, and the elevator-stick force gradient of 26 inch-pounds per degree of elevator was too high for comfortable control.

Figure 8 shows a time history of a roll and recovery. Inspection of the controller deflection and aileron deflection record shows that there is some lag between the time the controller is moved and the ailerons respond. This lag was not as serious as it was for longitudinal control and the pilots reported the lateral system acceptable. Aileron breakout forces were about 3 inch-pounds about the stick pivot. There was no objection to the controller location, motion, or feel. The values of breakout force, sensitivity, and stick force gradient shown in table I for the aileron system were acceptable, though not necessarily optimum values. The tabulated force values for lateral control fall into the acceptable catagory defined in reference 3. Reference 3 presents a compilation of force-output capabilities of a pilot operating a side-located controller and also defines acceptable force levels for this type of airplane controller.

After these initial tests, the hydraulic control system was modified, and as a result of this modification the servovalve friction was reduced and the lost motion in the linkage was eliminated. Additional flight runs were made with the improved system and the same controller used in the previous flights. The characteristics of this modified power control system (system B) are given in table I in which the characteristics of system A are also included. With system B the pilot had no difficulty controlling the airplane laterally or longitudinally. A time-history record of a pull-up to 2g and pushover to 1 g is shown in figure 9 for comparison with figure 7. Note that there is essentially no lag between the controller position and elevator position. Figure 10 is a time-history graph of a rapid turn entry and recovery and is presented to show the accuracy with which a coordinated maneuver can be accomplished with the side-located controller.

Six pilots had an opportunity to fly the airplane with the improved side-controller installation and were asked to complete a rather general questionnaire to aid in evaluating the controller. Table II lists the items included in this questionnaire and a summary of the pilots' ratings.

It seems worthwhile to expand on some of the items in this table. Although the pilots' rating of the wrist pivot motion for longitudinal control is generally acceptable, the motion is somewhat awkward and uncomfortable but does not greatly impair the pilots' ability to fly the airplane. Elevator force gradient was rated acceptable by three pilots and unacceptable by three pilots but the general feeling is that the forces are too high for the amount of deflection available.

It should be pointed out that the elevator deflection per g for the flight condition used in this report is representative of the elevator deflection per g for present-day fighter airplanes at cruising flight. The side-located-controller deflection per g ($6.25^{\circ}/g$) was found to be good for small control motions which were used in this investigation. However, this deflection would have to be reduced to about $2^{\circ}$ per g in order to cover the full elevator-deflection range with the controller-deflection limits set at the maximum values specified in reference 3.

Within the limited range of this investigation it appears that a small side-located controller when used with an irreversible hydraulic-power control system may be acceptable for flying a fighter-type airplane. No attempt was made to optimalize stick sensitivity, force gradient, or stick-motion geometry.

## CONCLUDING REMARKS

Results of flight tests to determine the acceptability of a small side-located controller that requires hand motion pivoted at the wrist for longitudinal control and forearm or lateral hand motion for lateral control indicate the following concluding remarks based on pilots' opinion.

Location of the controller is consistent with pilot comfort and the airplane is flyable with the side-located controller. Wrist pivot motion for longitudinal control is rated acceptable by the pilots but is somewhat strange and uncomfortable, especially when large stick motions and high force levels are required. Lateral hand or forearm motion is comfortable for moving a short stick pivoted below the grip. Stick breakout force and stick force gradient should be kept at low values consistent with the reduced-force-output requirements of the pilot when operating a small side-located controller of the type used.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., April 14, 1958.

## REFERENCES

1. Phillips, William H., Brown, B. Porter, and Matthews, James T., Jr.: Review and Investigation of Unsatisfactory Control Characteristics Involving Instability of Pilot-Airplane Combination and Methods for Predicting These Difficulties From Ground Tests. NACA TN 4064, 1957. (Supersedes NACA RM L53F17a.)

2. Brown, B. Porter: Ground Simulator Studies of the Effects of Valve Friction, Stick Friction, Flexibility, and Backlash on Power Control System Quality. NACA TN 3998, 1957.

3. Brissenden, Roy F.: Some Ground Measurements of the Forces Applied by Pilots to a Side-Located Aircraft Controller. NACA TN 4171, 1957.

TABLE I

HYDRAULIC-POWER CONTROL AND SIDE-LOCATED-CONTROLLER CHARACTERISTICS

| Quantity | Control system A | Control system B |
|---|---|---|
| Stick deflection, deg: | | |
| Elevator | 11 pull; 6 push | 11 pull; 6 push |
| Aileron | ±12.3 | ±12.3 |
| Surface deflection, deg: | | |
| Elevator | 4.2 up; 2.6 down | 4.2 up; 2.6 down |
| Aileron | ±10 total | ±10 total |
| Stick deflection sensitivity (stick deflection per degree of surface deflection), deg/deg: | | |
| Elevator | 2.5 | 2.5 |
| Aileron | 1.23 | 1.23 |
| Stick force gradient (stick force per degree of surface deflection), in-lb/deg: | | |
| Elevator | 26 | 20 |
| Aileron | 3.2 | 3.7 |
| Total breakout force (preload plus static friction), in-lb: | | |
| Elevator | 9 | 6.5 |
| Aileron | 3 | 3 |
| Stick preload, in-lb: | | |
| Elevator | 6 | 5 |
| Aileron | 2 | 2 |
| Total static friction at stick, in-lb: | | |
| Elevator | 3 | 1.5 |
| Aileron | 1 | 1 |
| Static elevator valve friction at stick, in-lb | 1.5 | Negligible |
| Free play in elevator linkage (measured at stick), deg | 0.5 | Negligible |
| Elevator linkage flexibility (stick deflection per pound of stick force), deg/lb | 0.26 | 0.26 |

TABLE II

SUMMARY OF SIX PILOTS' OPINIONS BASED ON THE QUESTIONNAIRE USED TO EVALUATE THE SIDE-LOCATED CONTROLLER IN CONTROL SYSTEM B

| Item on questionnaire | Rating[1] by pilot - | | | | | |
|---|---|---|---|---|---|---|
| | a | b | c | d | e | f |
| Location of controller in airplane cockpit . . . . . | G | G | G | G | A | A |
| Wrist pivot motion for longitudinal control . . . . . | A | A | A | A | A | U |
| Forearm or wrist motion for lateral control . . . . . | A | G | G | G | G | A |
| Breakout force: | | | | | | |
| Elevator . . . . . | A | A | G | A | A | A |
| Aileron . . . . . | A | A | G | G | A | A |
| Force gradient: | | | | | | |
| Elevator . . . . . | A | A | U | U | A | U |
| Aileron . . . . . | A | G | A | G | G | A |
| Deflection sensitivity: | | | | | | |
| Elevator . . . . . | A | G | G | G | A | A |
| Aileron . . . . . | A | G | G | A | G | A |
| Control harmony . . . . . | A | A | A | A | A | A |
| Ability to perform coordinated maneuvers requiring elevator and aileron control . . | A | A | G | A | A | U |

[1]G, good; A, acceptable; U, unacceptable.

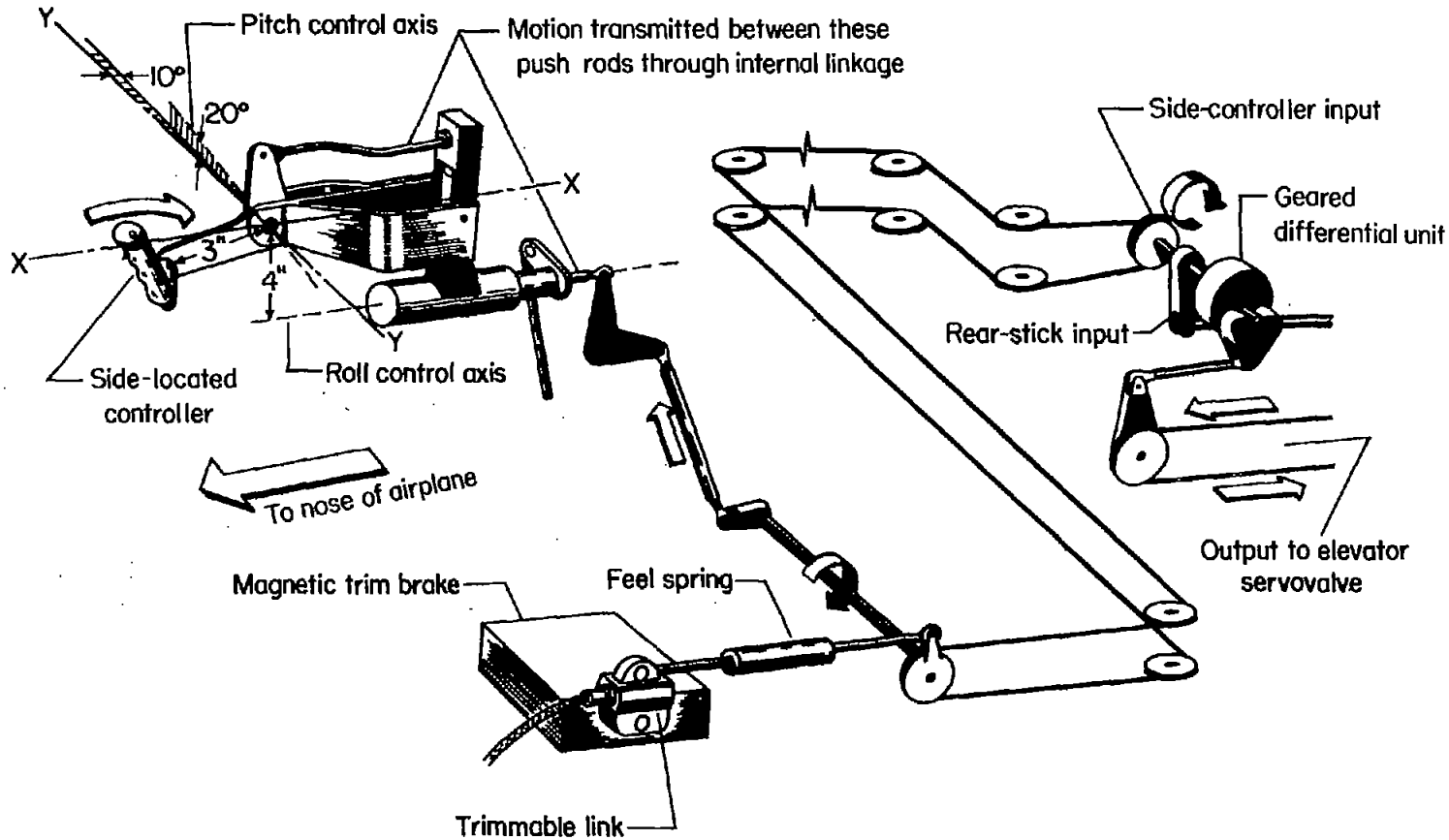



Figure 1.- Schematic drawing of side-located controller with associated linkage. (X-X and Y-Y axes shown parallel to airplane X- and Y-axes.)

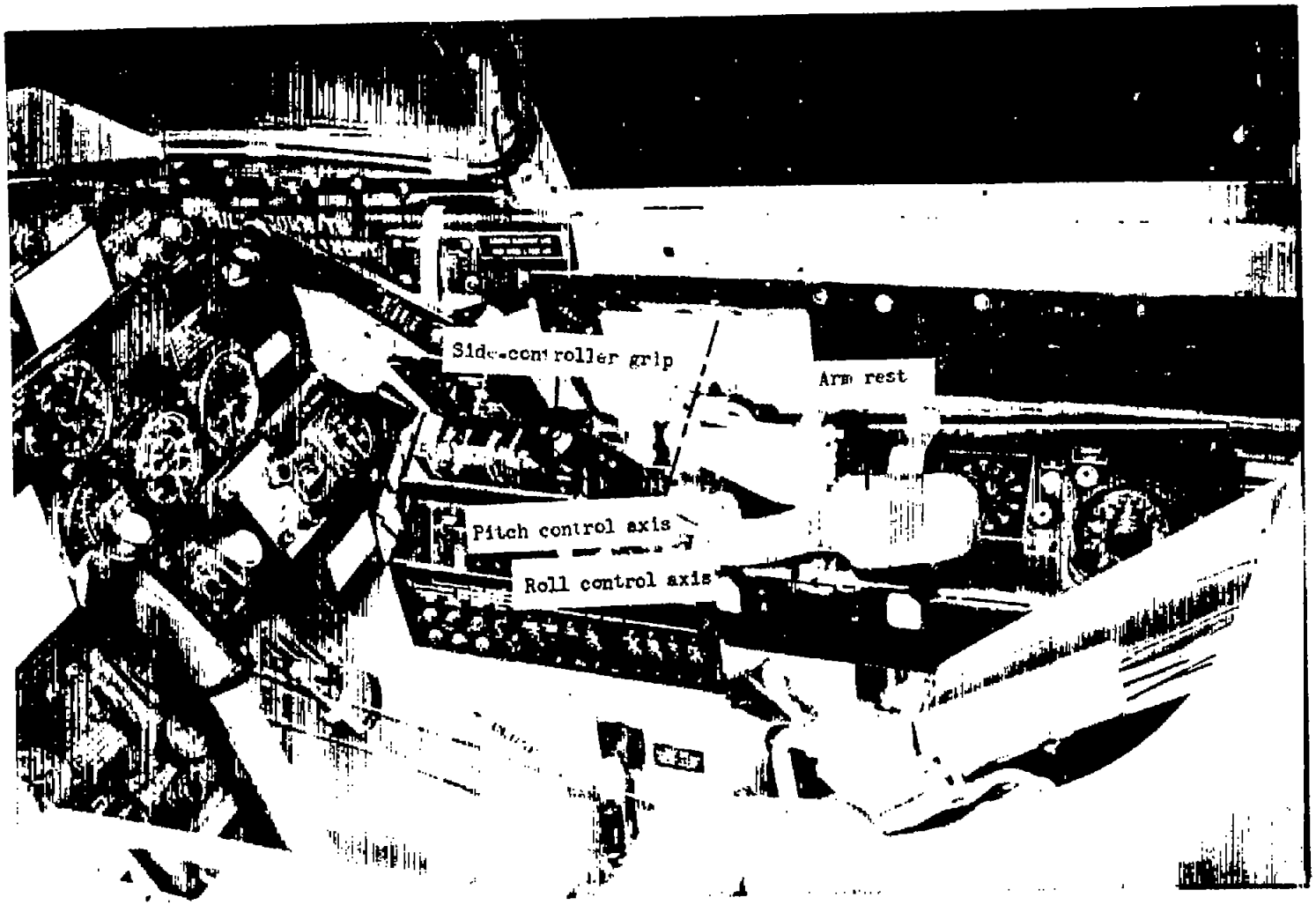



Figure 2.- Photograph of side-located controller installed in test airplane. L-95461.1

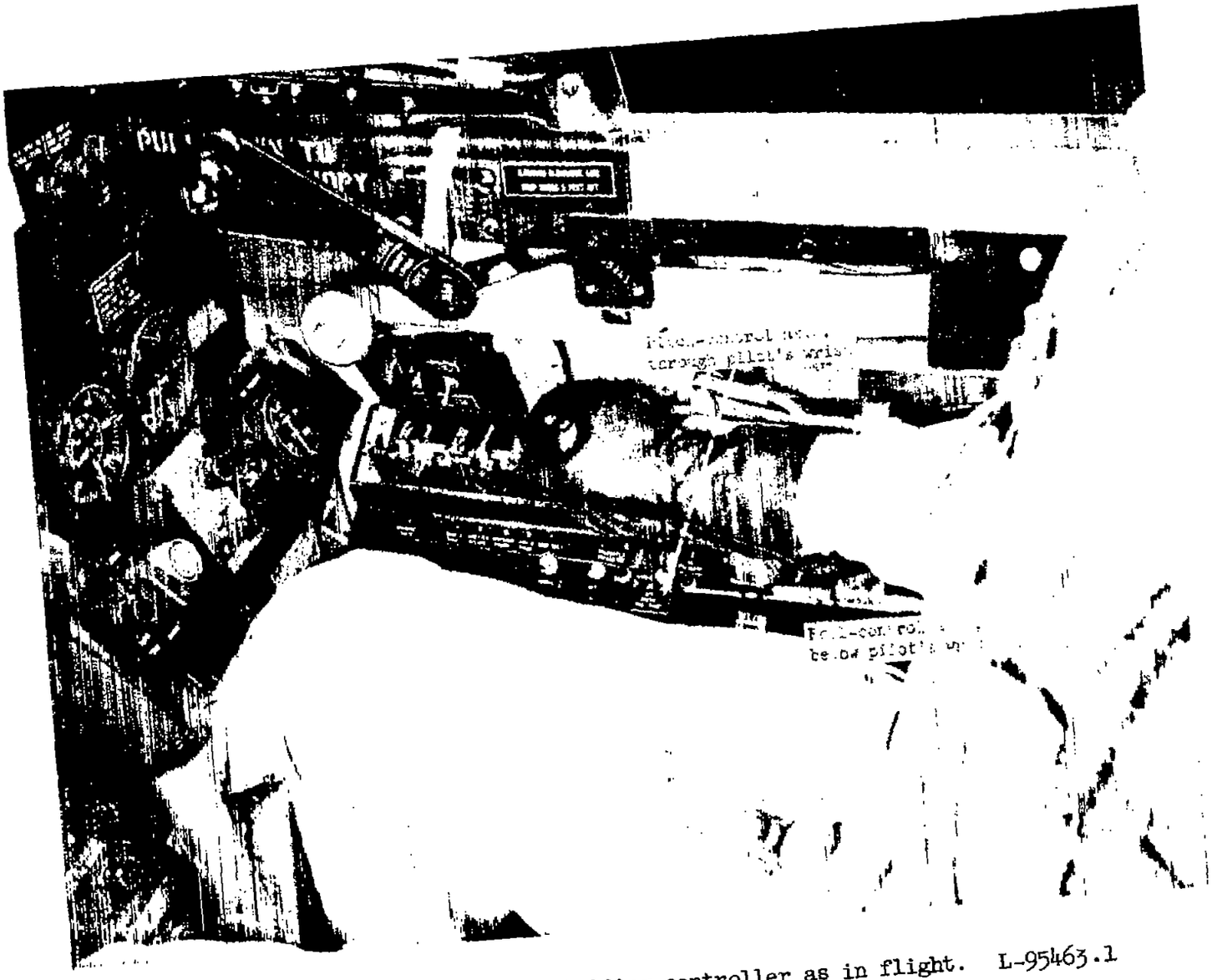


Figure 3.- Photograph of pilot holding controller as in flight. L-95463.1

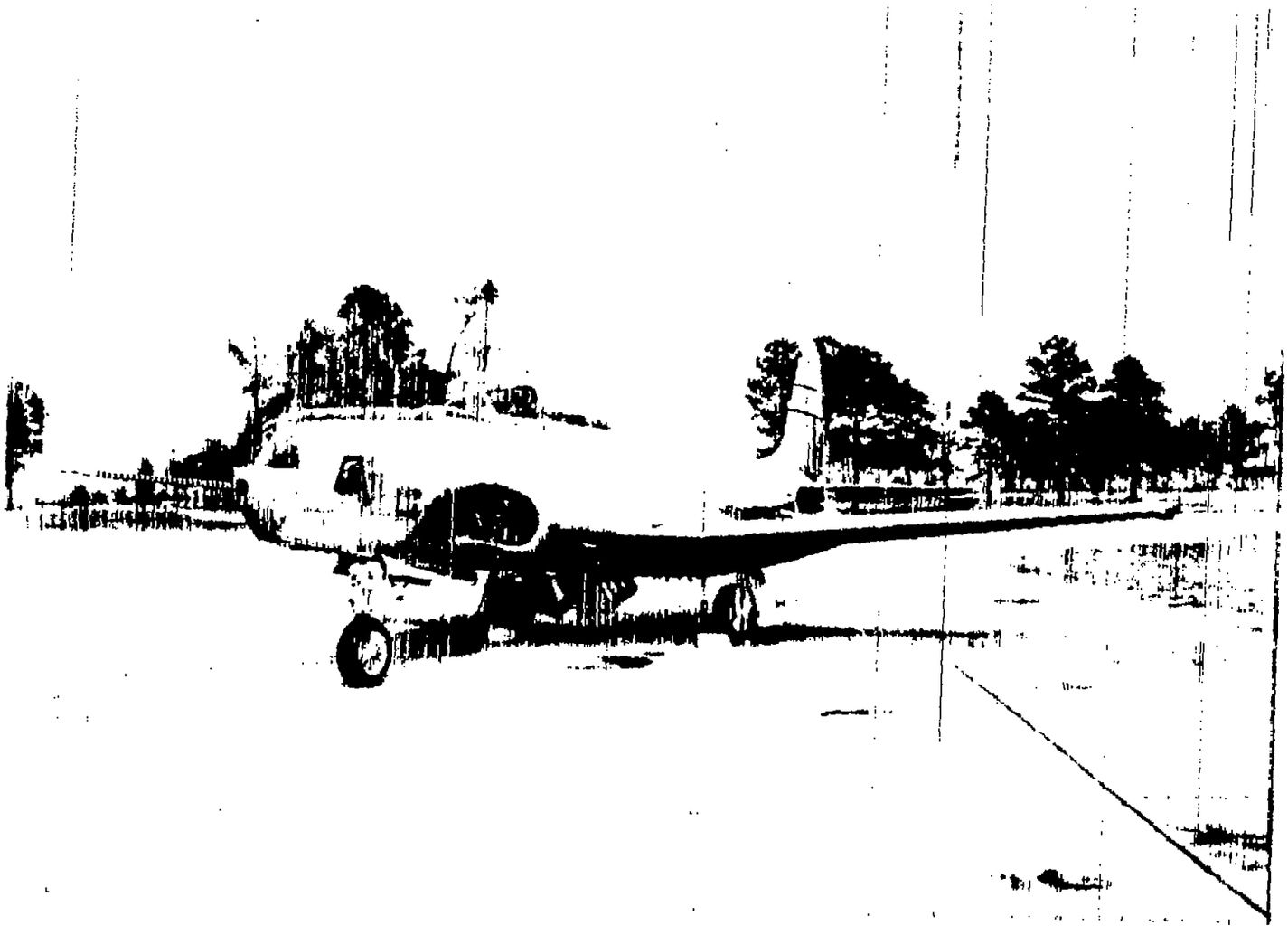
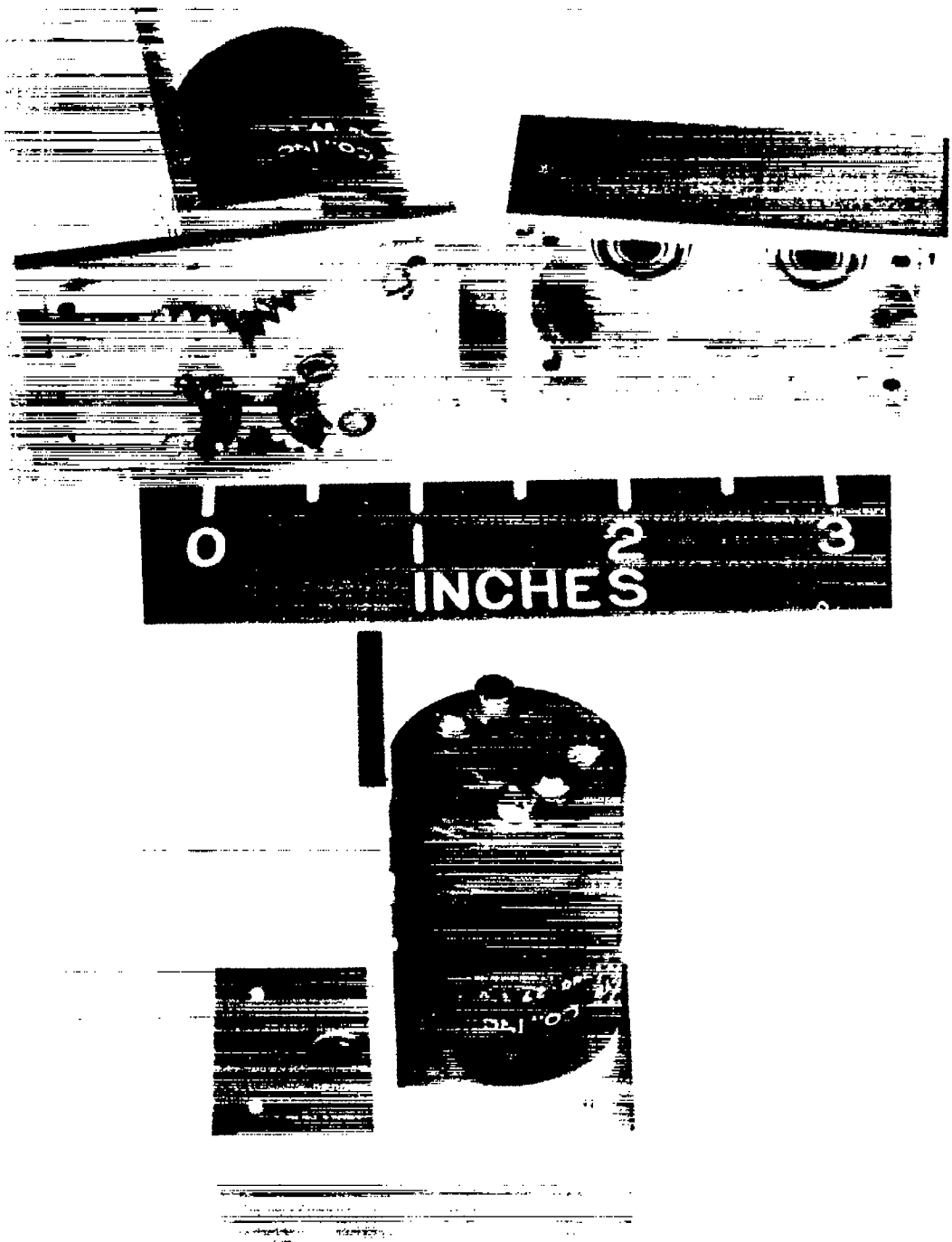


Figure 4.- Photograph of test airplane. L-57-4963




L-58-1614

Figure 5.- Photograph of shaker showing assembly and internal details.

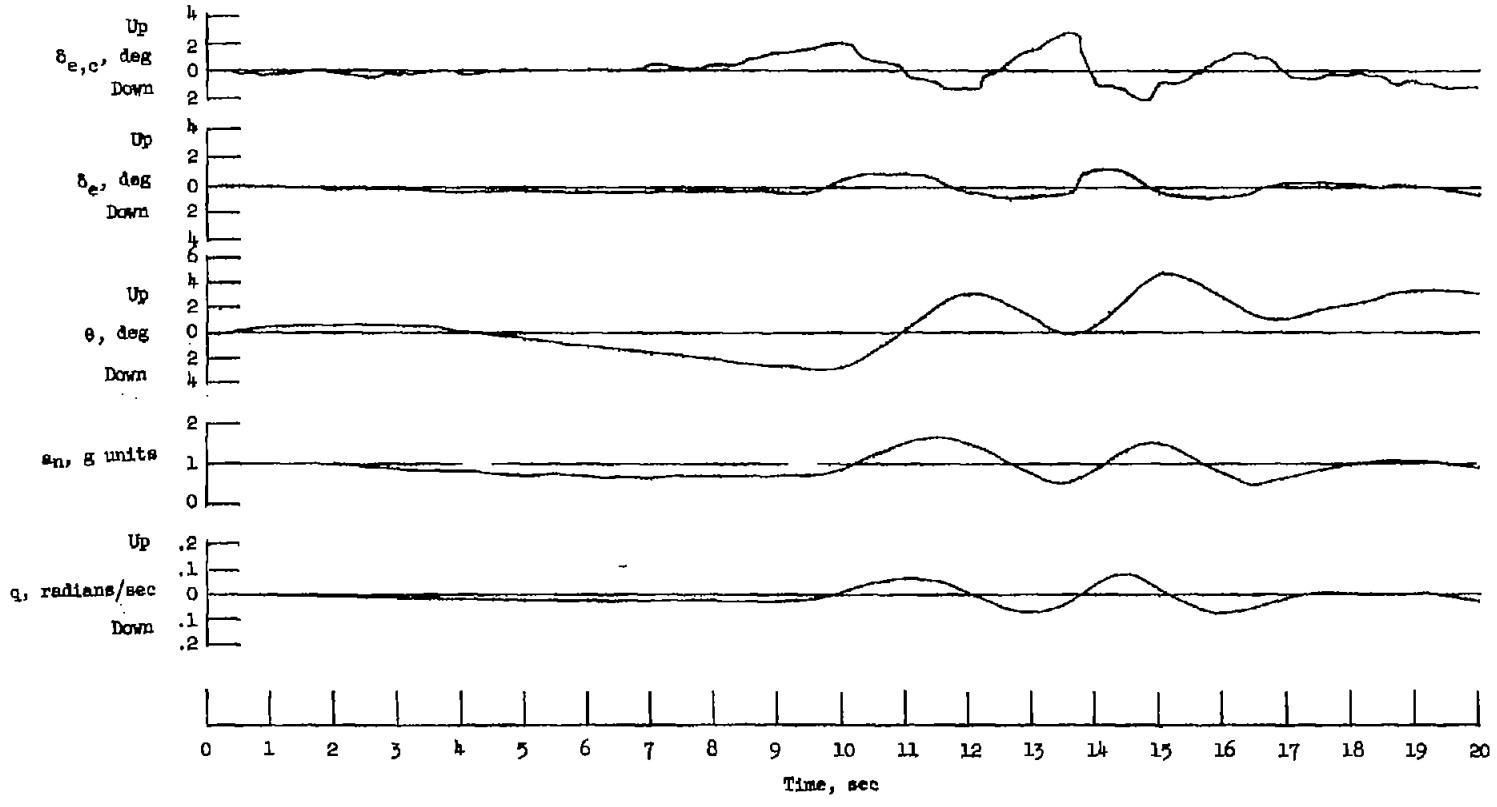



Figure 6.- Time history of pilot attempting to fly airplane at 1 g with side-located controller and control system A.

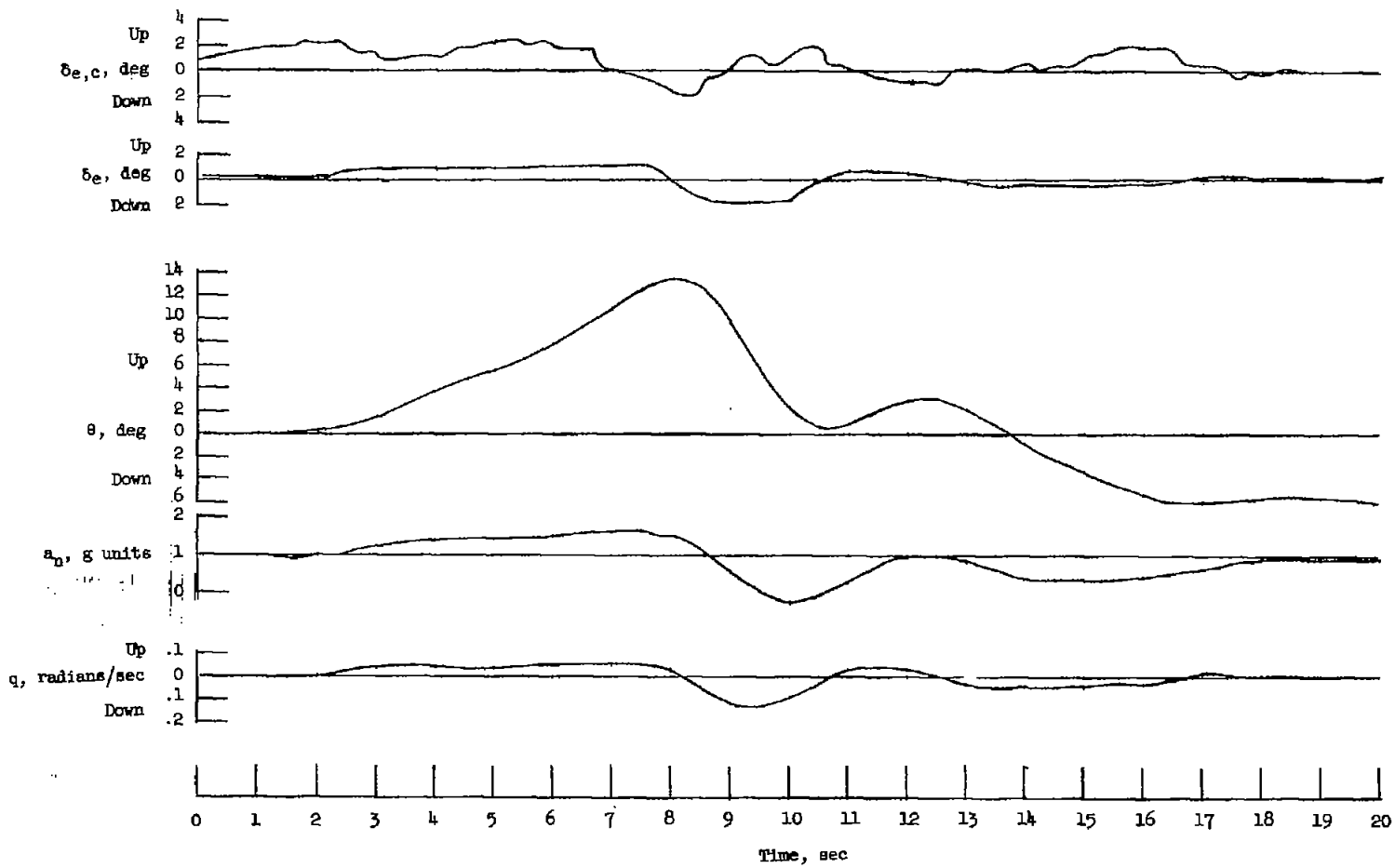



Figure 7.- Time history of pilot attempting to perform a pull-up to 2g and pushover to 1 g with side-located controller and control system A.

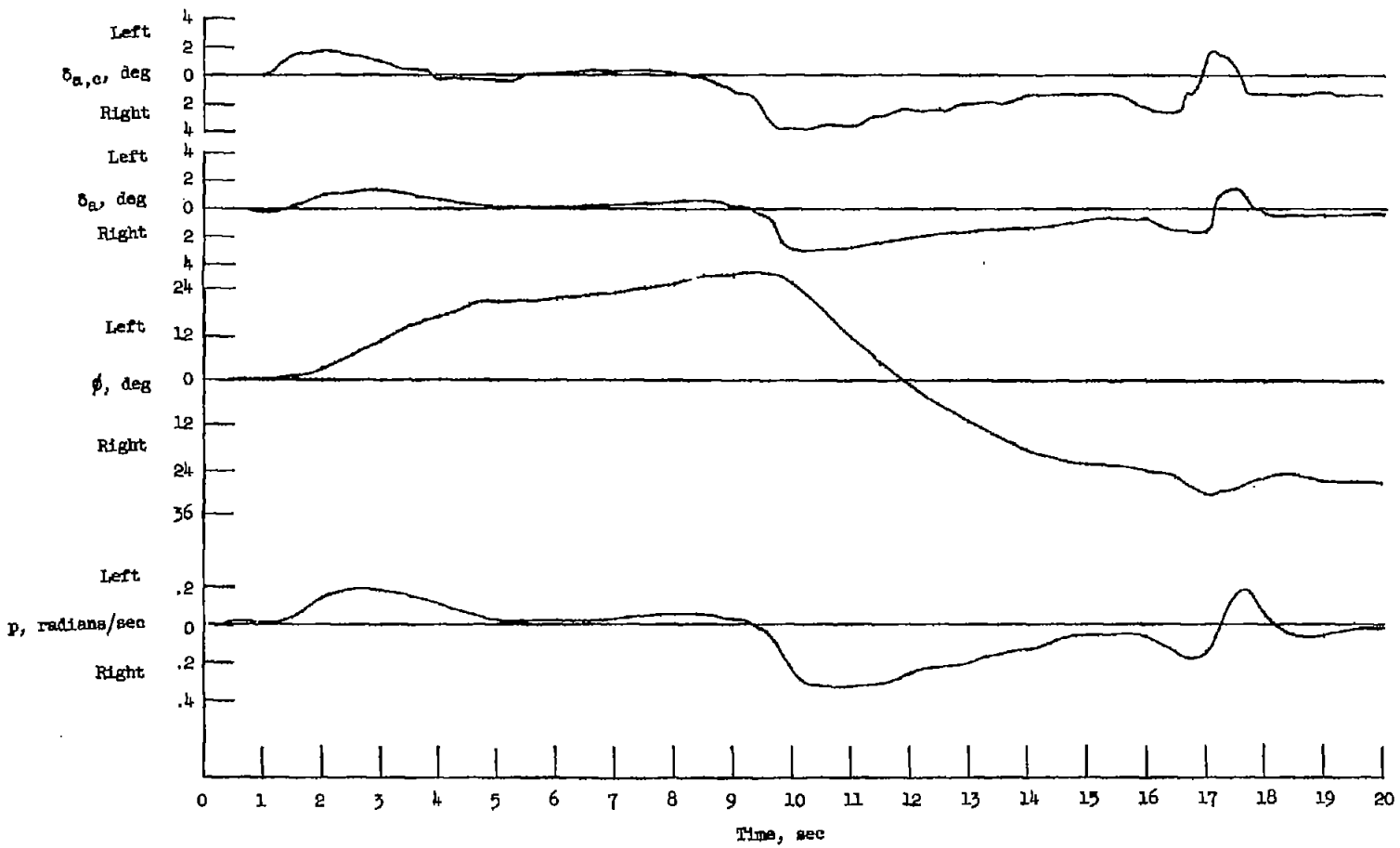



Figure 8.- Time history of pilot performing lateral maneuvers with side-located controller and control system A.

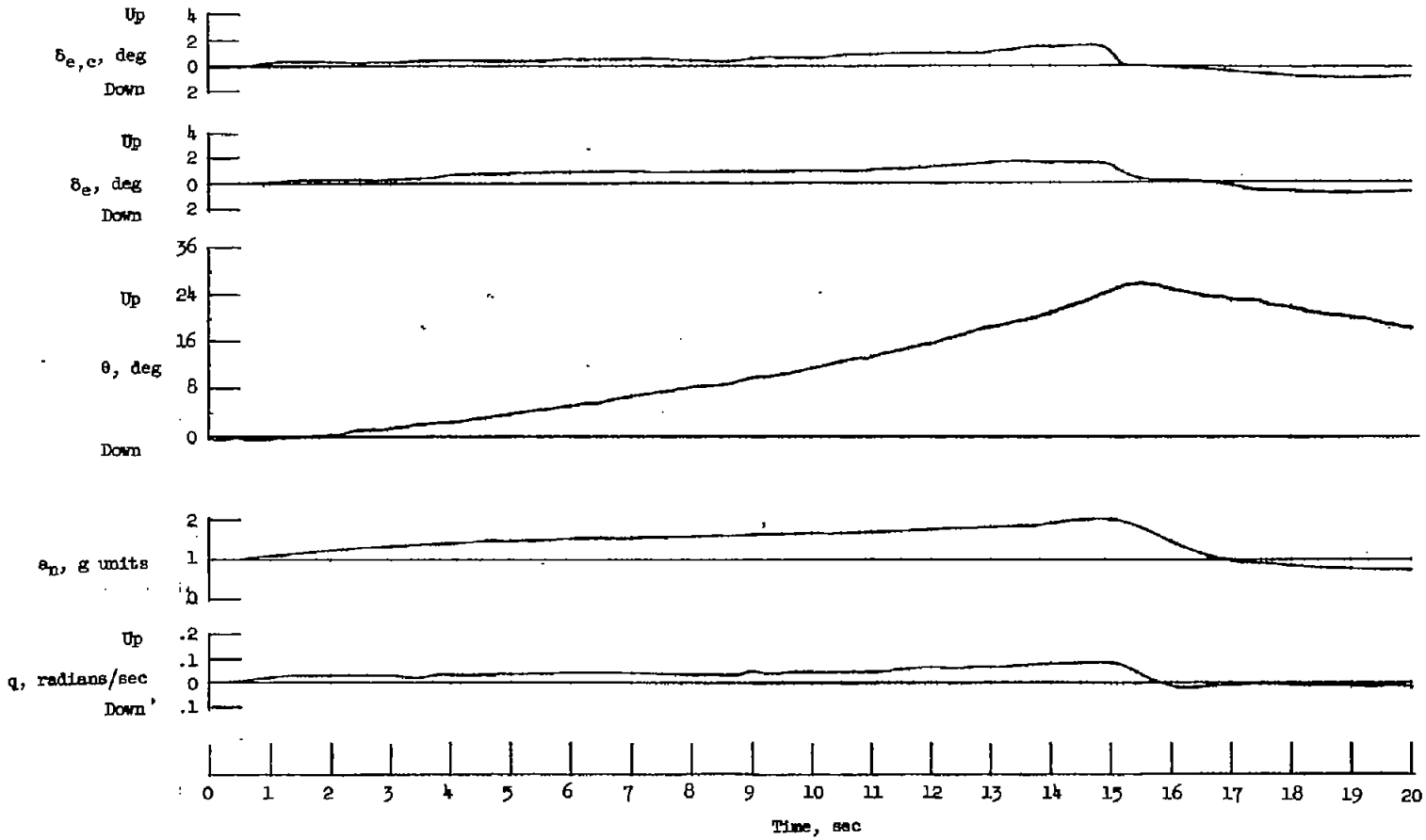



Figure 9.- Time history of a pull-up to 2g and pushover to 1 g with side-located controller and control system B.

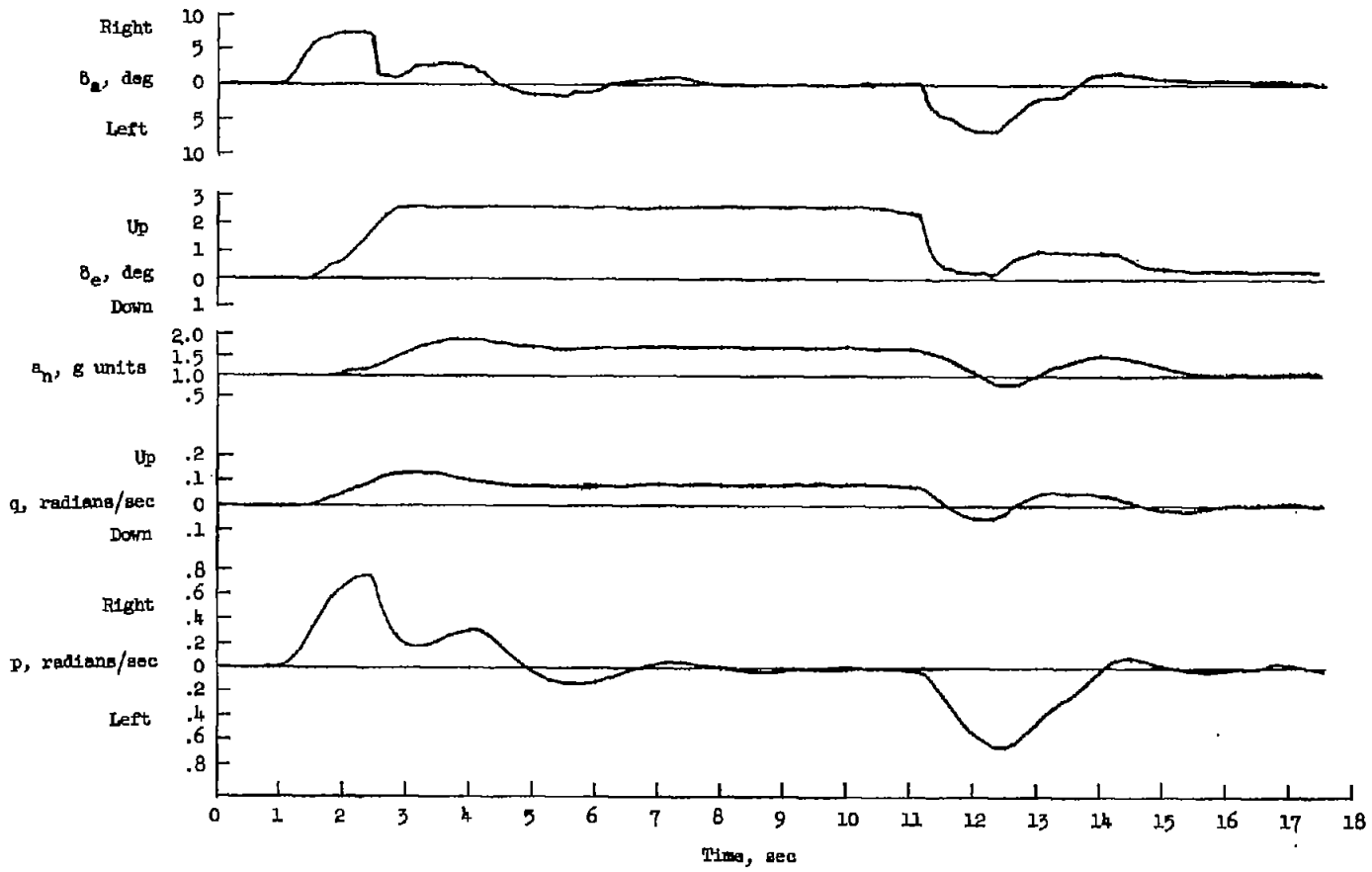



Figure 10.- Time history of pilot performing a rapid turn and recovery with side-located controller and control system B.



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