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TECHNICAL NOTE 4202

QUALITATIVE SIMULATOR STUDY OF LONGITUDINAL STICK FORCES AND DISPLACEMENTS DESIRABLE DURING TRACKING

By Stanley Faber

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Washington
February 1958

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QUALITATIVE SIMULATOR STUDY OF LONGITUDINAL STICK FORCES AND DISPLACEMENTS DESIRABLE DURING TRACKING

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SUMMARY

A qualitative study has been made by use of an airplane simulator with one degree of freedom (pitch) to determine the longitudinal stick forces and displacements desirable during tracking. In the simulator the operator, or subject, was stationary and, therefore, was not subjected to any of the forces and motions associated with airplane accelerations that occur in actual flight. These tests are a continuation of those of NACA Technical Note 3428 and were performed with the same simulation equipment. For the present tests this equipment was modified to give a better representation of the pitch response of an airplane and also to give the subject a tracking task which better simulated air-to-air tracking.

The modified simulator was used to reexamine a phase of the previous study and to expand these tests to two other conditions of airplane dynamics. The conditions investigated were an airplane undamped natural frequency of 1/2 cps with damping ratios of 0.8 and 0.18 and an airplane undamped natural frequency of 1 cps with a damping ratio of 0.11. Additionally, limited tests were made to determine the effects on tracking performance of viscous and static friction on the stick.

For a heavily damped airplane, low longitudinal stick forces and displacements are desirable. This conclusion is in agreement with the results of NACA Technical Note 3428. For the lightly damped airplanes, moderate longitudinal stick forces and displacements are desirable. Viscous damping on the stick, which was tested only for a lightly damped, low-frequency (1/2 cps) airplane configuration, caused a decrease in tracking performance. Static friction on the stick, which was tested only for a heavily damped, low-frequency (1/2 cps) airplane configuration, also caused a slight decrease in tracking performance.

INTRODUCTION

The use of power-actuated control surfaces and mechanical feel systems in present-day airplanes has given the designer a greater flexibility in the selection of the amount of stick force and stick displacement required to produce a given airplane response. Little information has been available, however, on the control-stick characteristics desirable from the standpoint of accuracy and ease of control. In order to provide some pertinent information, a device was constructed which simulated the longitudinal-control problem that exists when a pilot is trying to track a target airplane. Preliminary results with the simulator were reported in reference 1 and indicated that, for the one condition of airplane dynamics simulated (a natural frequency of 1/2 cps with a damping ratio of 0.8), the best tracking performance was obtained with the smallest obtainable values of stick force and stick displacement per unit response. A somewhat similar series of tests were reported on in reference 2 which showed that, for a near-rigid stick, an optimum force gradient existed and, for a free stick, an optimum displacement gradient existed. However, the results are not directly applicable to airplane conditions because no response dynamics were included in the tests of reference 2.

The tracking simulator has been used in the present study to reexamine a phase of the study of reference 1 and also to extend these tests to two other conditions of airplane dynamics, these latter conditions both being characterized by light damping. For the present tests the equipment was modified to give a better representation of the airplane pitch response and also to give the operator a tracking task which better simulated the conditions of air-to-air tracking. In addition, limited tests were made to investigate the effects of viscous and static friction on the stick of a nonflexible control system.

APPARATUS

Simulator

A one-degree-of-freedom (pitch) simulator was used in which only the display moved; that is, the operator was stationary and was not subjected to any forces and motions. A photograph of the simulator is shown in figure 1, and a diagrammatic sketch of it is shown in figure 2. The dynamics of the simulator and of the tracking problem are based on constant airspeed and constant target range with no phugoid mode.

The simulator consisted of a control station, an airplane-dynamics analog, a tracking-problem generator, a gust generator, and a display. The control station consisted of a fixed seat and a control wheel and column. This column was connected with adjustable gearing to an "elevator" bar. (See fig. 2.) This elevator bar was connected to the input of a ball-and-disk integrator and also by a push rod to a "summation" bar which summed this signal with the output of the integrator. Moments to the analog were introduced through a spring by deflection of the summation bar. The analog of the airplane was the mass-spring-dashpot system discussed fully in reference 1. The natural frequency was adjusted by positioning the weights and springs of the analog, and the damping ratio was adjusted by selecting the proper damping fluid. The inertia of the control system for the tests identified subsequently as groups 1, 3, and 4 was 2 slug-feet^2 about the column pivot. For the tests identified subsequently as group 2, the inertia was on the order of 1/4 slug-feet^2. The length of the column from pivot to hand grips was 33 inches.

This arrangement of the control linkages differed from that of reference 1 in the use of the integrated stick signals. The motions of the simulated airplane in response to control applications for the equipment as used in reference 1 did not duplicate those of conventional airplanes. The difference was that, for steady-state and low-frequency stick motions, the simulator in reference 1 would produce a given displacement of the airplane analog or, in effect, a given pitch angle. On most airplanes, these stick motions would produce a given normal acceleration (if constant airspeed is assumed). This normal acceleration shows up visually to the pilot as a continually increasing pitch angle, with the pitch rate being proportional to the normal acceleration. At higher stick-motion frequencies (on the order of, or greater than, one-half the natural frequency of the short-period oscillation of the airplane), the airplane pitch response and that of the simulator of reference 1 become more nearly the same. In order to improve the simulation at low stick-motion frequencies, the simulator linkages were modified for the present tests to include a device which would integrate the stick motions and cause the simulated airplane to respond to both the integrated and direct stick motions. With the addition of the integrated signals, the simulated-airplane response can be made to correspond exactly to the pitch response of an idealized airplane at all frequencies. These integrated signals are identified in the text as the ratio of the rate of change of flight-path angle to angle of attack.

The tracking problem, or task, given the subject also differed from that of reference 1. The task, simulated air-to-air tracking, consisted of tracking a randomly moving target and regulating gusty-air disturbances at the same time. These tasks had been treated separately in reference 1. The motions of the target were produced by a cam as shown in figure 2. The cam was designed to provide a vertical target motion

formed by the summation of the first 24 harmonics of a sine wave in which the harmonics were summed with random phasing. In order to be consistent with motions experienced in flight, the amplitudes of the various harmonics were varied inversely as the frequency of the harmonic. The cam was driven at 1 rpm and produced a frequency content in the target motion of 1/60 to 2/5 cps. A time history of the target motion is shown in figure 3(a).

The gust disturbances were pitching moments produced by a motor-driven cam and were introduced to the analog through a second spring. (See fig. 2.) This cam was also designed by summing the first 24 harmonics of a sine wave at random phasing. In order to make the gust intensity consistent with that experienced in flight, the amplitudes of the various harmonics were varied inversely as the square of the frequency. (See ref. 3.) The cam was driven at 1/5 rpm and produced a frequency content of 1/12 to 2 cps. A time-history representation of the shape of the gust-generating cam is shown in figure 3(b).

Since the motions of the simulated airplane in response to the gust disturbances would be affected by the particular airplane dynamics, especially damping, an arbitrary standard was set for the airplane motion. The standard was that the maximum excursions of the "airplane" due to gust inputs would be the same for any and all conditions of airplane dynamics. Calculations made after completion of the tests indicated that, with the aforementioned standard, the heavily damped airplane would be experiencing somewhat stronger gusts than the lightly damped airplane.

The display was produced by a light-bar projector and mirror arrangement as shown in figure 2. The subject sitting in the "cockpit" saw two horizontal bars of light projected on a blackened wall approximately 12 feet in front of him. Motions of the airplane-dynamics analog were displayed by one bar, and target motion was displayed by the other. In operation the subject attempted to keep the two bars of light together. In order to give the subject an appreciation of the magnitude of the tracking error, a fighter-airplane silhouette was superimposed on the target light bar. With the assumed range of 500 yards, the fuselage silhouette subtended an angle at the eye of the subject of approximately 6 mils, and the tail height subtended an angle of approximately 16 mils. By using the light bars as a reference, the subject could begin to detect a tracking error when the error reached about 1 mil. In terms of this same visual angle, the target motion had a maximum excursion of $\pm 6^{\circ}$ (107 mils), the airplane motion in response to gust disturbances had a maximum excursion of $\pm 4^{\circ}$ (71 mils), and the total range of airplane motion was $\pm 8^{\circ}$ (142 mils).

The average absolute error produced by the target motion with the airplane maintained at a neutral position was equal to about 40 mils of visually subtended angle. The average absolute error produced by the gust disturbances alone (no target motion) at all conditions of airplane dynamics tested was also about 40 mils. With both target motion and gust disturbances, but with no subject effort, the average absolute error was estimated to be about 60 mils.

As in reference 1, the characteristics of the stick-displacement gearing and stick-force gradient are described, respectively, in terms of the static-stability parameters $dX_s/d\alpha$ (stick displacement per degree of angle of attack) and $dF_s/d\alpha$ (stick force per degree of angle of attack). These quantities were selected for the tests of reference 1 because the simulator response closely approximated the angle-of-attack response of an airplane throughout the frequency range. This close agreement was especially true in the very low frequency, stick-motion range. In operation of the simulator of reference 1 and of the present equipment with the integrator off, the deflection of the analog in response to stick displacement was assumed to correspond to the angle of attack of the airplane. For this report, the measurement base of the analog deflection is defined as the angle subtended by the display at the subject's eye. This definition of measurement base is different from that of reference 1 and gives angular values twice those of reference 1.

Recording System

Electronic instrumentation was used to obtain the average absolute tracking error. This instrumentation system used a differential transformer to measure the tracking error. The output of the transformer was amplified, rectified, and put into a low-inertia, direct-current motor in such a way that the speed of the motor was proportional to the error. By counting the total revolutions of the motor over a given length of time, the average absolute error during the test was obtained. A photocell network and an electronic counter were used to obtain the number of revolutions of the motor. With this instrumentation the subject's performance was known immediately upon conclusion of a test.

During two of the groups of tests, identified subsequently as groups 1 and 3, a component of this instrument system acted in a somewhat erratic manner. The effect of the erratic operation was a nonlinear calibration change and an increase in the scatter of the individual test points. This erratic operation did not preclude the determination of desirable gradients and gearings. The only limitation on the

data of groups 1 and 3 is that the data cannot be compared directly with the data of the rest of the report.

TESTS

The investigation covered four groups of tests and, because of differences in setup, each group is discussed separately. A total of nine subjects were used; however, all the subjects did not participate in all the tests. The test subjects included both pilots and nonpilots. After the subjects had completed a learning phase, there was no consistent variation of performance with flight experience. Because of this similarity of performance, no one is identified in the data as to flight experience. The test procedure was for the subject to "fly" the simulator at least three times at each of the conditions under test. During each of these 4-to-5-minute flights, two 1-minute records of average absolute tracking error were obtained. Since no time was required to reduce the data, any number of additional flights could be made and the data be instantly compared so that it could be determined when the subject was operating at a constant level of tracking performance. Generally, one or, at the most, two flights were sufficient to complete the learning phase.

Group 1

The tests of group 1 were made with the integrated stick motions and with the combined target and gust-input tracking task. The characteristics of the airplane were the same as those used in reference 1 with the addition of the integrated signals. These characteristics were an undamped natural frequency of 1/2 cps, a damping ratio of 0.8, and a ratio of rate of change of flight-path angle to angle of attack of 2.8 deg/sec/deg. Also tested with this airplane was a damping ratio of 0.18. The tests were made at two stick-force gradients $dF_s/d\alpha$ of 1/2 and $1\frac{1}{2}$ lb/deg at two stick-displacement gearings $dX_s/d\alpha$ of 0.01 (almost nonmoving) and 0.10 in./deg, respectively. As was described previously, the recording-system operation was erratic for this group.

Group 2

The tests of group 2 were also made with the integrated stick motions and the combined target and gust-input tracking task. The characteristics of the airplane were an undamped natural frequency of 1 cps, a damping ratio of 0.11, and a ratio of rate of change of

flight-path angle to angle of attack of 0.9 deg/sec/deg. This damping ratio corresponds to a damping of 1/2 amplitude in 1 cycle. In these tests the stick gearing was varied from near rigid to the case where $dX_s/d\alpha$ was 1/6 in./deg. The tests were made by using a constant stick-force gradient $dF_s/d\alpha$ of 1/2 lb/deg. Results are presented for both the case in which two hands with arms unsupported were used and the case in which one hand with the wrist or arm supported was used. This latter case was intended to simulate the use of a side-located controller. The tests of group 2 were made with the low-inertia control wheel and column.

Group 3

The tests of group 3 were also made with the integrated stick motions and the combined target and gust-input tracking task. This group of tests was made to determine the effects of a stick force proportional to the rate of stick motion (damped stick) as well as to stick position. The characteristics of the airplane were an undamped natural frequency of 1/2 cps, a damping ratio of 0.18, and a ratio of rate of change of flight-path angle to angle of attack of 2.8 deg/sec/deg. The amount of stick damping tested was 3 lb/in./sec of stick velocity. Two values of stick-force gradient, 1/2 and $1\frac{1}{2}$ lb/deg, were used with a constant value of stick-displacement gearing, 0.10 in./deg. As described previously, the recording-system operation was erratic for this group.

Group 4

The tests of group 4 were made with the simulator as described in reference 1; that is, the integrated stick motions were not used and the task consisted of tracking just target motions (no gust inputs). As in reference 1, the target motions included a large proportion of high-amplitude, high-frequency motions. The characteristics of the airplane were an undamped natural frequency of 1/2 cps and a damping ratio of 0.8. These tests were made to determine the effect of static friction on the control stick. Force gradients $dF_s/d\alpha$ of 0, 5/6, and $3\frac{1}{2}$ lb/deg were tested at a gearing of 1/6 in./deg with static-friction forces of ±1, ±5, and ±10 pounds.

RESULTS AND DISCUSSION

As has been noted previously, the subject of the simulator was not influenced by the motions of the airplane as he would have been in actual flight. As a result the subject did not have the acceleration and rate cues he normally would have, and, also, the effects of acceleration in producing motions of parts of his body (which in turn could produce inadvertent control motions) were not present. These effects, or rather the lack of them, may have an important effect on the tracking errors. Nevertheless, based on the adaptability of the human and on the successful use of similar simulation equipment in ground tests of airplane control systems, the trends obtained from this investigation are expected to apply to flight conditions. This assumption still requires proof by similar tests performed in flight or in more advanced simulators.

A factor that was found to affect the general level of the tracking performance was the motivation or interest of the subject as was demonstrated early in the test program of this report. The tests of reference 1 used a recording system which required complicated data reduction, and the subject often went completely through a test series without knowing his "score." In the present tests the subject knew his score immediately upon completion of a test run, and the general level of performance of the subjects was 30 to 50 percent better than that in the tests of reference 1. As a further demonstration of the effect of the subject's interest, it was noted that, whenever two subjects began competing with one another, their performance level improved by about 50 percent. During the test program an effort was made to eliminate this factor of competition and to maintain the individual interest at a constant level. Also, the trends of a series of tests were always determined from at least two subjects with the average performance being used to evaluate a change in configuration.

The results of the tests are presented in figures 4 to 11 in terms of the average (absolute) tracking error of selected subjects at each condition. The selected subjects were those who had taken test data at all conditions in any given series. Also shown in the figures are trend lines indicating the average performances. Where only one subject had test data at all conditions of a given series, no trend line is shown. The test-point symbols have been kept consistent throughout the report; that is, a given subject is represented by the same symbol in all the figures.

Group 1

The results of the tests of group 1 which repeated a phase of the tests of reference 1 are shown in figure 4. These tests were concerned with the effect of stick gearing on the average tracking error for a heavily damped, low-frequency airplane. The results show that tracking with a very low stick-displacement gearing, 0.01 in./deg., was about 20 percent better than tracking with a gearing 10 times as large, 0.10 in./deg. This trend, this time with the complete simulation of the pitch response, is the same as that noted in reference 1.

The results of the tests with the same low-frequency airplane but with light damping are shown in figures 5 and 6 for the effects of stick-displacement gearing and stick-force gradient, respectively, on the average tracking error. Figure 5 shows that, for the low-force gradient, increasing the gearing from 0.01 to 0.10 in./deg improved the tracking performance by about 25 percent. For the high-force gradient, little or no effect on performance was produced by increasing the gearing. Figure 6 shows that increasing the force gradient from 0.52 to 1.5 lb/deg improved the performance by about 15 percent. This value is for the high-displacement gearing; however, the single subject for the low-displacement gearing shows the same trend. These effects, the improvement in tracking performance with increased stick gearing and gradient, are the reverse of those for the heavily damped airplane (fig. 4 and ref. 1) and illustrate one effect of airplane damping on tracking performance.

A more direct effect of airplane damping ratio on average tracking error is shown in figure 7. The results indicate that, for a stick gearing of 0.01 in./deg, the tracking performance for the heavily damped airplane is 100 percent better than that for the lightly damped airplane. The single subject operating at the high gearing, 0.10 in./deg, shows the same trend.

Group 2

The results of the tests of group 2 are for the lightly damped, high-frequency simulated airplane and are shown in figure 8. The results indicate that, over a range of stick-displacement gearings from 0.033 in./deg to the maximum tested, 0.160 in./deg, the effect of gearing on average tracking performance was small. The best performance was obtained with gearing in the range from 0.10 to 0.160 in./deg. For the "nonmoving" stick (a gearing of 0.01 in./deg) the performance was much poorer, the errors being approximately 30 percent greater than the average. These conclusions may be made for either the case in which two hands with arms unsupported were used or the case in which one hand

with the wrist or arm supported was used, with little difference between the two cases.

Group 3

Group 3 of the tests was concerned with the effect on the average tracking performance of having a viscous damper on the stick, and the results are shown in figure 9 for a lightly damped, low-frequency airplane. The results indicate that the use of a damped stick did not improve the tracking performance; in fact, there was a decrease in accuracy of approximately 15 percent.

Group 4

Group 4 of the tests was concerned with the effect on the average tracking error of having static-friction force on the stick. The results are shown in figures 10 and 11 for a heavily damped, low-frequency airplane. The results shown in figure 10 indicate that, at a given force gradient, as the static friction was increased the tracking performance decreased slightly. For example, increasing the friction from 1 to 10 pounds decreased the accuracy approximately 15 percent. The results of figure 11 indicate that, at a fixed value of static-friction force, increasing the stick-force gradient improved the tracking performance slightly. These results apply only for the case in which the friction is at the control stick and the control system is rigid. Friction in a flexible control system or in the valve of a power-actuated control system has been shown to have effects that are more pronounced. (See ref. 4.)

CONCLUDING REMARKS

A qualitative study to determine the desirable longitudinal stick-force gradients and stick-displacement gearings during tracking has been made by use of an airplane simulator with one degree of freedom (pitch). The simulator was of the moving-display type; that is, the operator, or subject, was stationary and was not subjected to any forces or motions. The simulator was modified from the one used in NACA Technical Note 3428 to include a better representation of the airplane pitch response and to give the subject a tracking task which better simulated air-to-air tracking.

For a heavily damped airplane, low stick displacements (near nonmoving) and low force gradients are desirable. This result is in

agreement with that of NACA Technical Note 3428. For a lightly damped airplane, moderate forces and displacements are desirable. For the lightly damped airplane, the use of a viscous damper on the stick caused slight decreases in tracking performance. The presence of static friction on the stick of the heavily damped airplane also caused slight decreases in tracking performance. The harmful effect of friction could be minimized by increasing the force gradient.

As a result of this investigation it can be generally stated that, for a heavily damped airplane system, the operator desires low longitudinal stick forces and displacements to give a faster acceleration of the response; whereas for a lightly damped airplane system, the operator desires moderate longitudinal stick forces and displacements to discern his input better in order to prevent overshooting. Artificial devices which tend to prevent or restrict overshooting, such as a viscous damper on the stick, do not appear to hold much promise, at least not for control systems similar to that used in this simulator.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., November 20, 1957.

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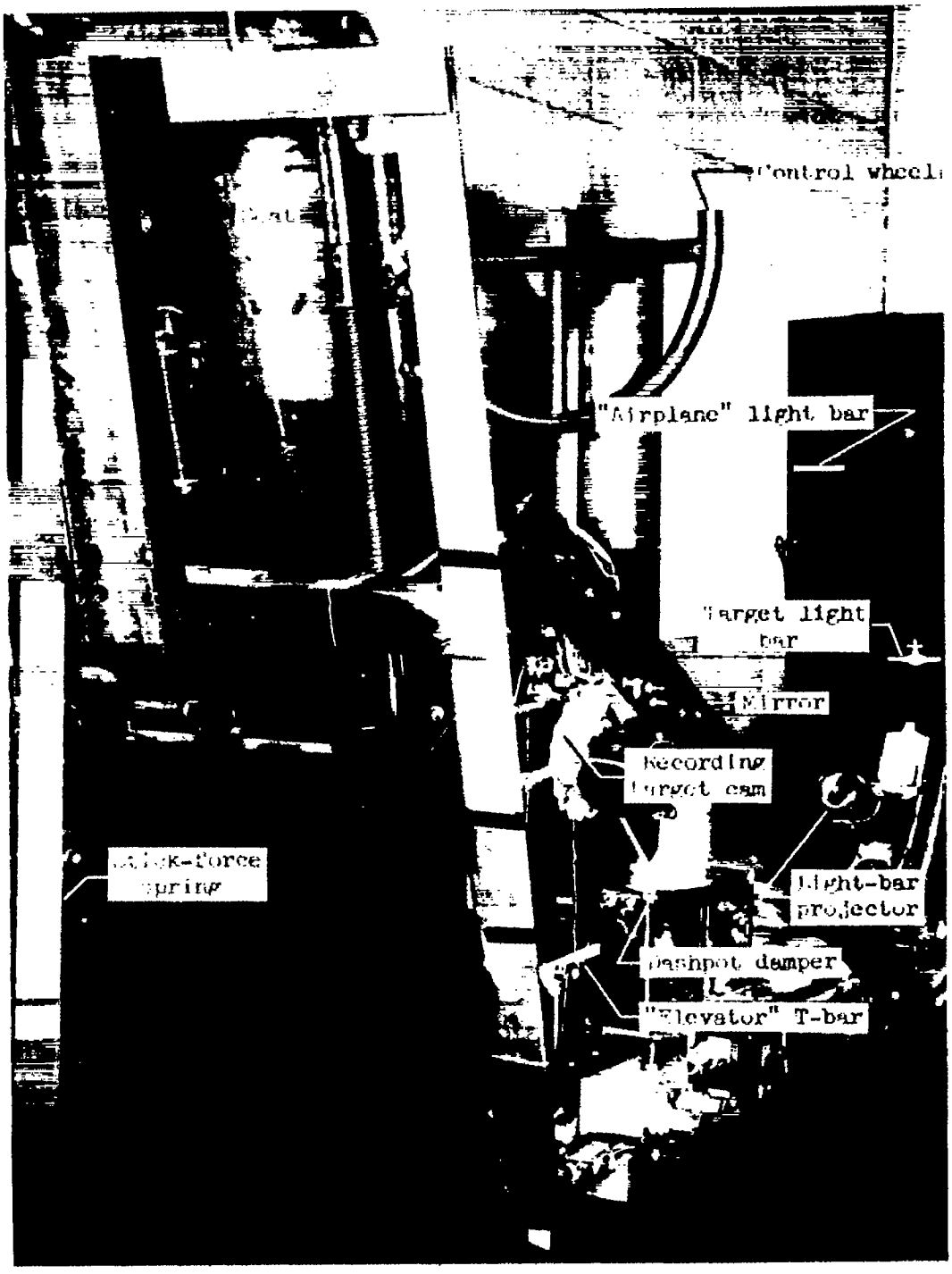


Figure 1.- Photograph of airplane simulator. L-85335.3

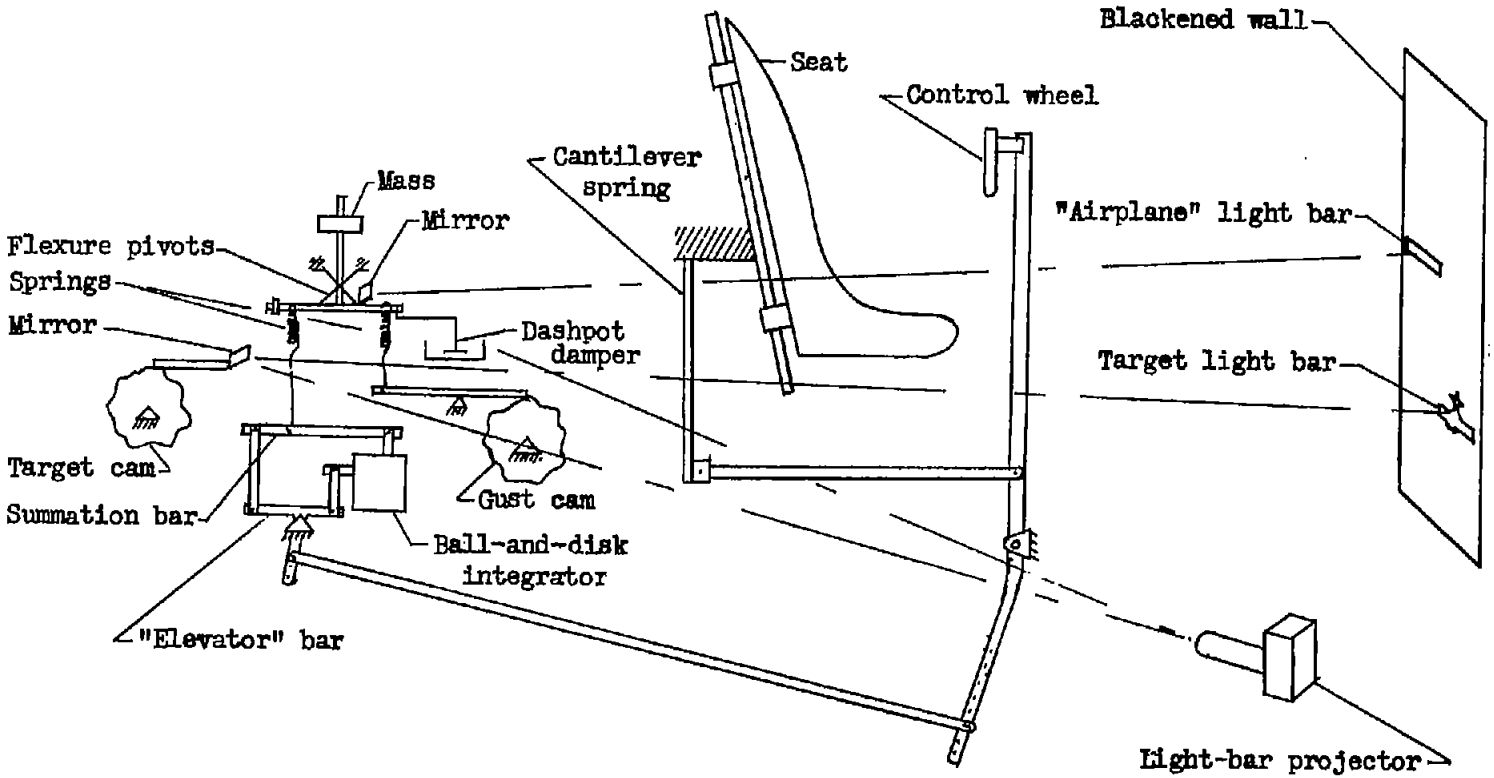
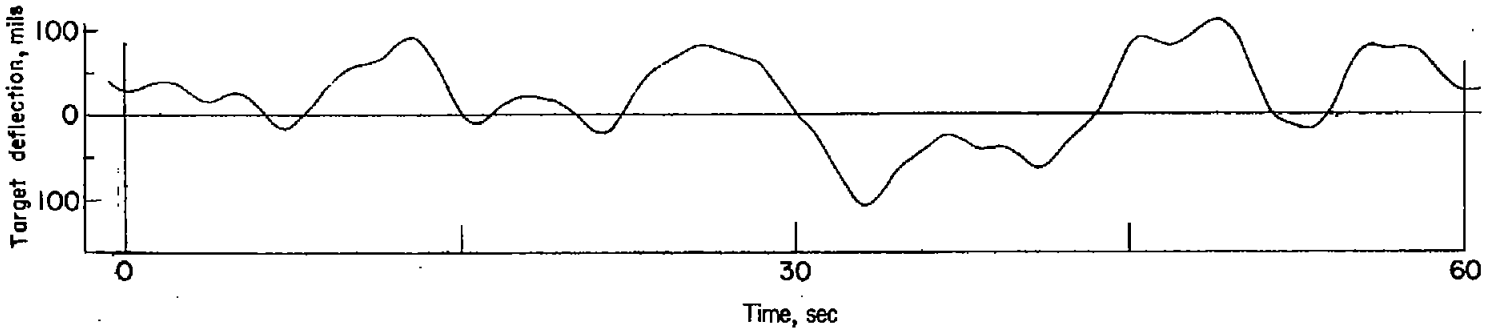
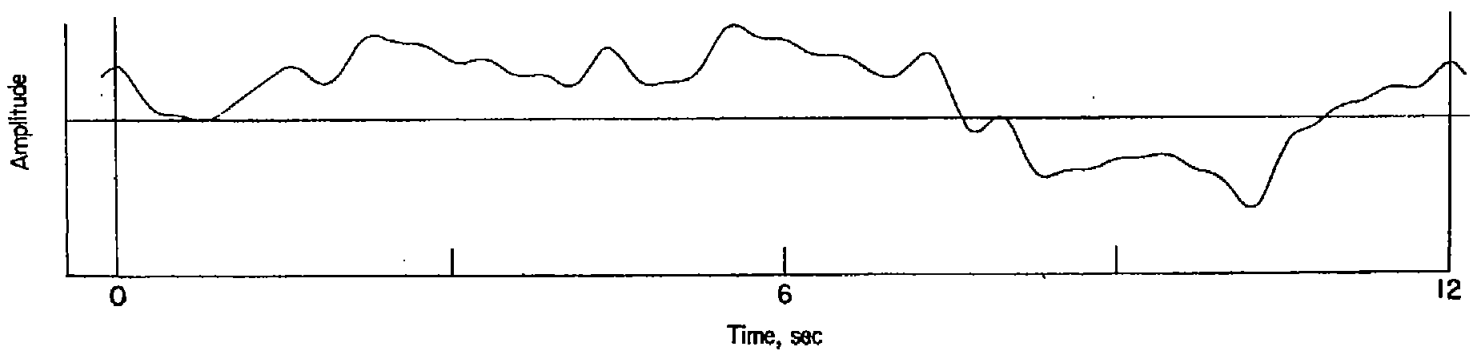


Figure 2.- Diagrammatic representation of airplane simulator.



(a) Target motion; 1 cycle of target cam.



(b) Shape of gust-generating cam; 1 cycle.

Figure 3.- Time histories of tracking inputs.

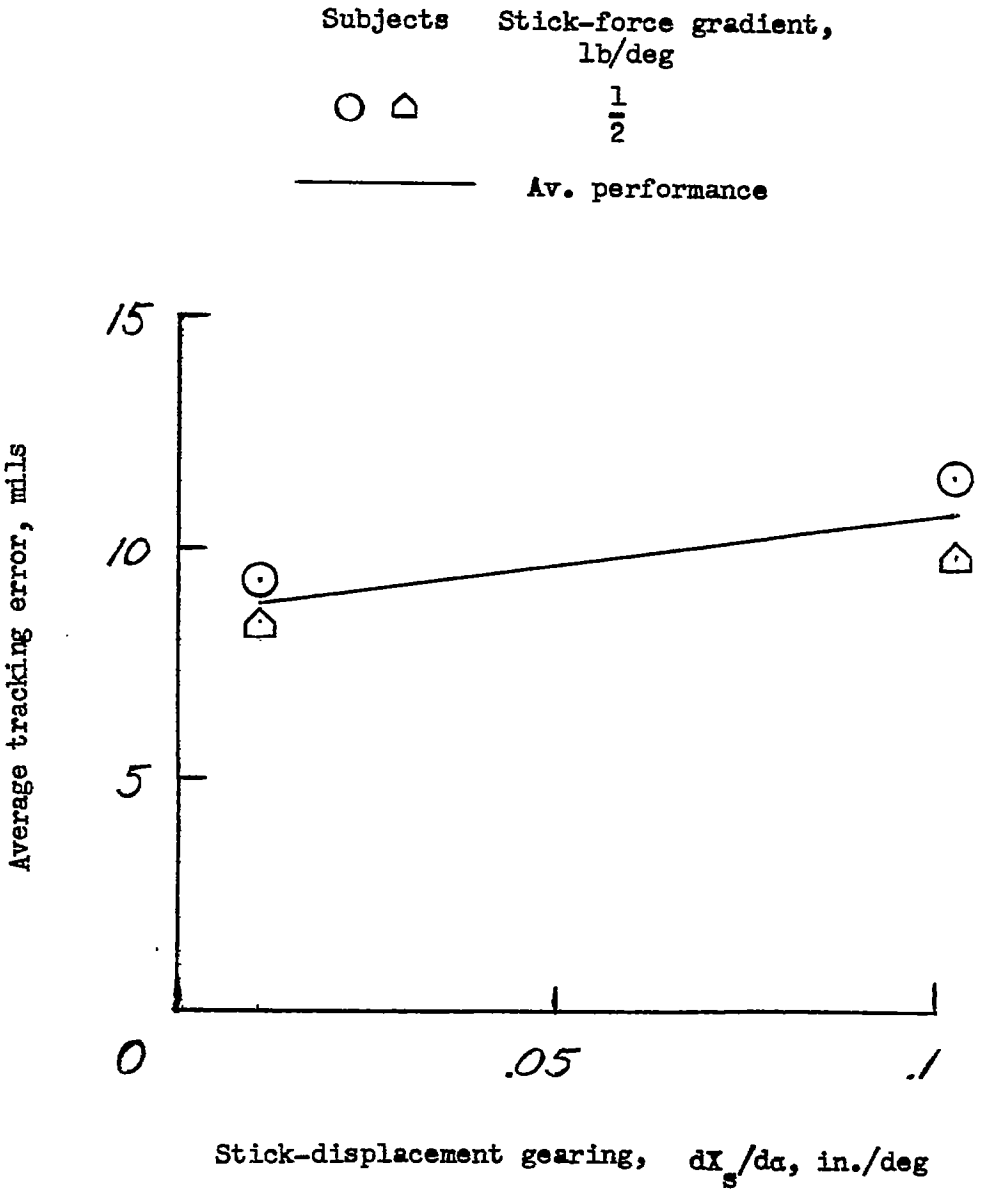


Figure 4.- Effect of stick-displacement gearing on average tracking error for a simulated airplane with a natural frequency of 1/2 cps, a damping ratio of 0.8, and a ratio of rate of change of flight-path angle to angle of attack of 2.8 deg/sec/deg. Group 1.

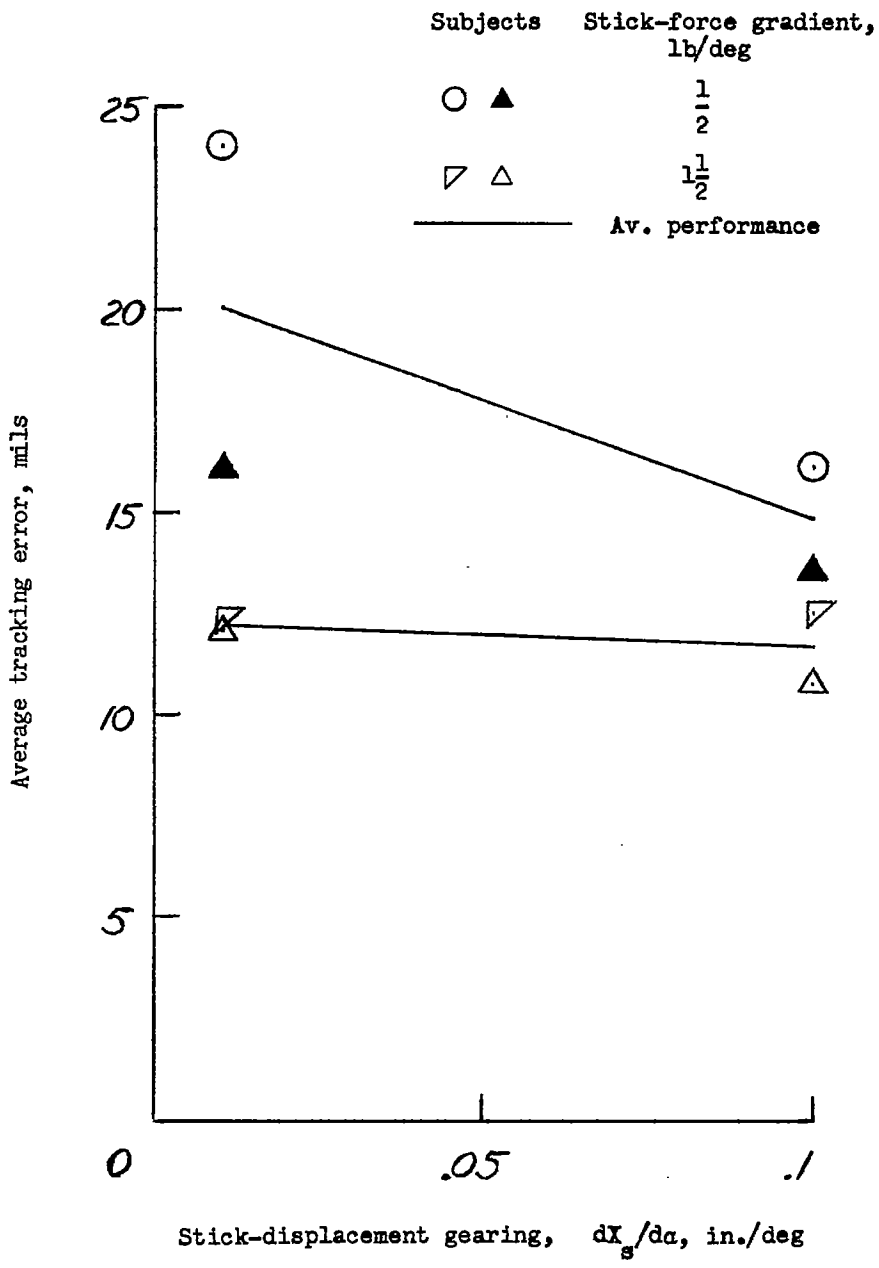


Figure 5.- Effect of stick-displacement gearing on average tracking error for a simulated airplane with a natural frequency of 1/2 cps, a damping ratio of 0.18, and a ratio of rate of change of flight-path angle to angle of attack of 2.8 deg/sec/deg. Group 1.

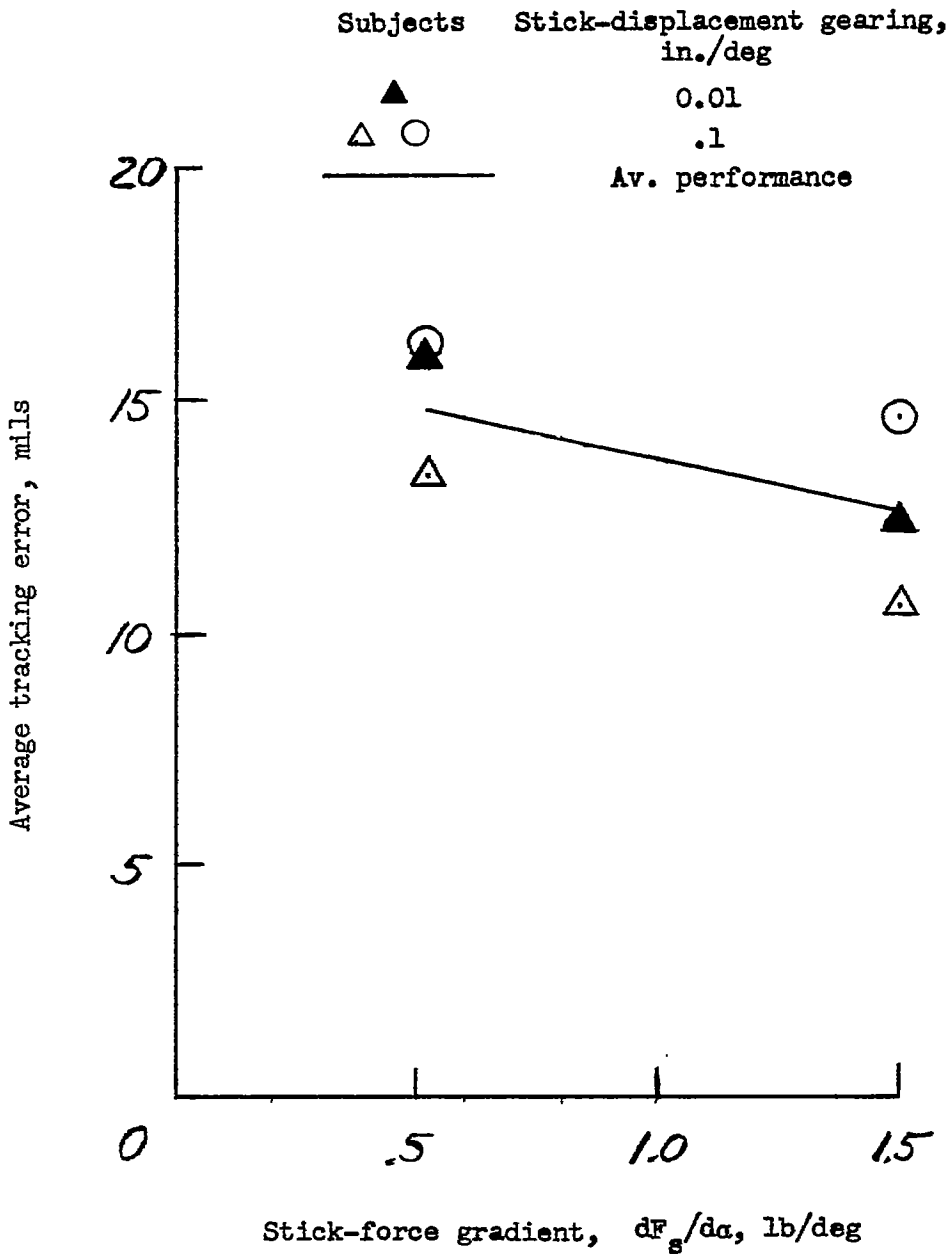


Figure 6.- Effect of stick-force gradient on average tracking error for a simulated airplane with a natural frequency of 1/2 cps, a damping ratio of 0.18, and a ratio of rate of change of flight-path angle to angle of attack of 2.8 deg/sec/deg. Group 1.

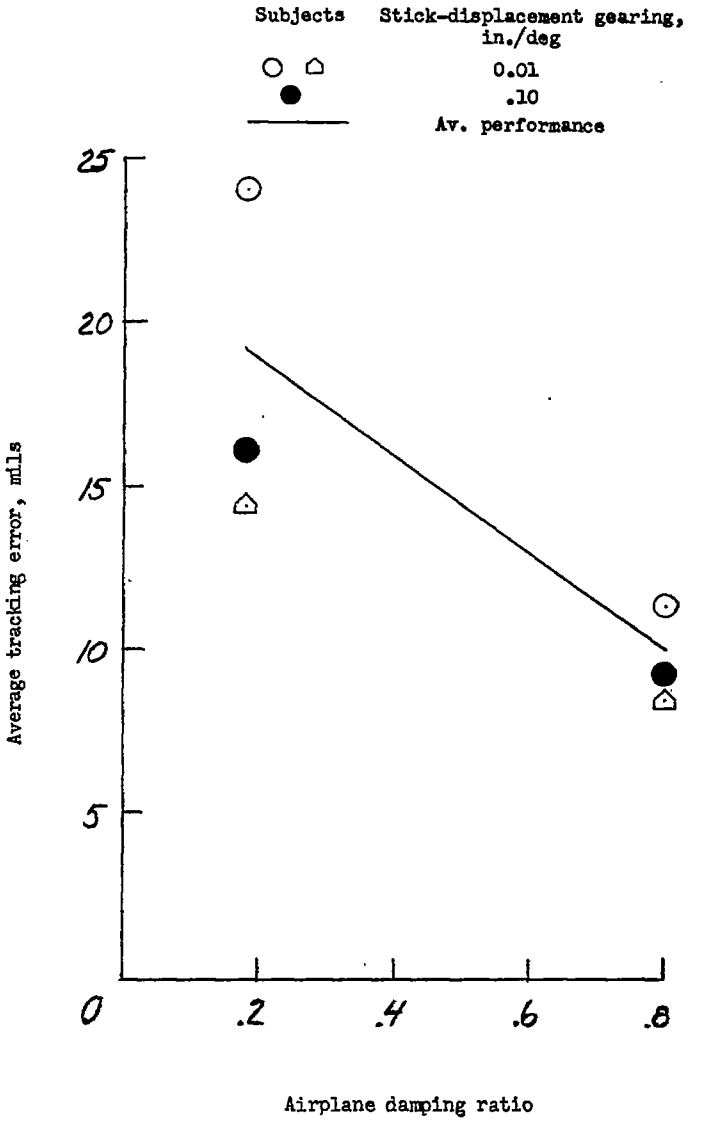
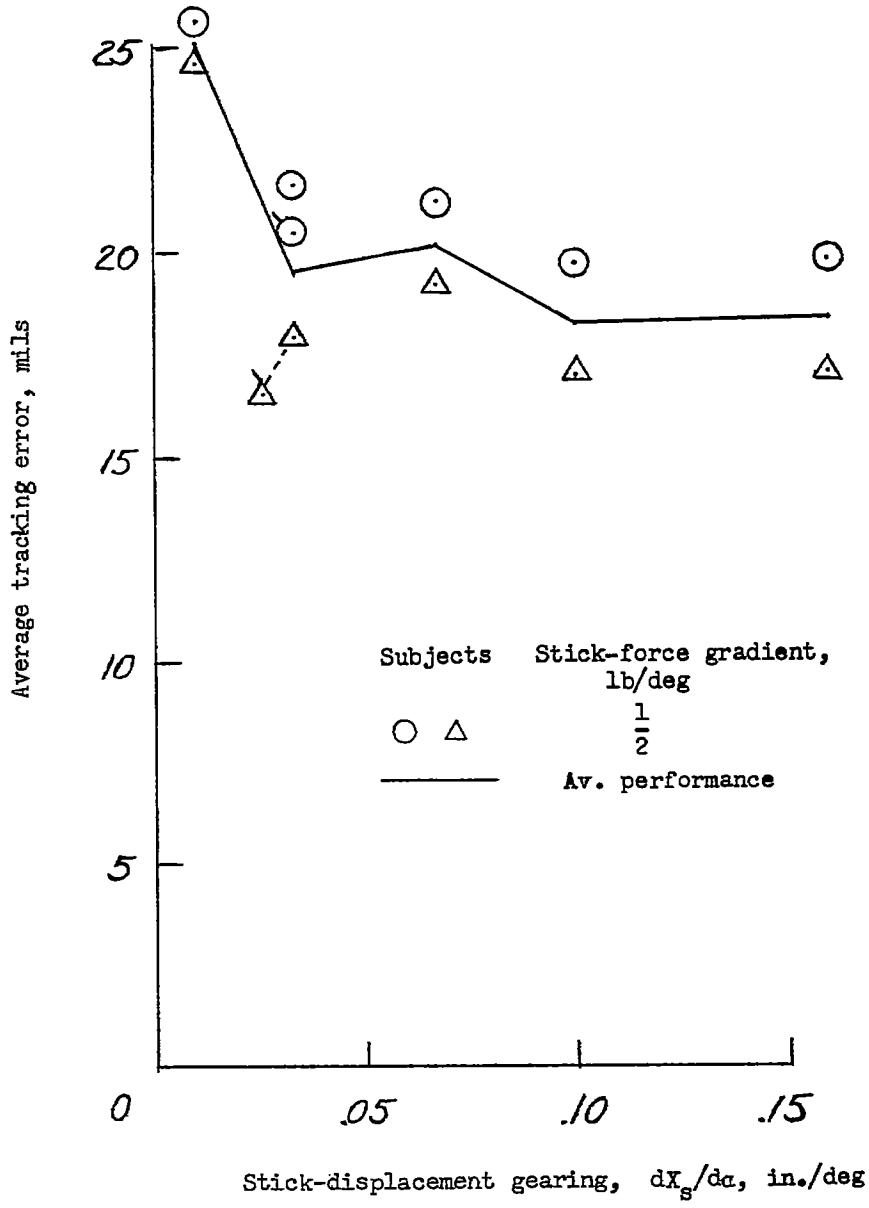
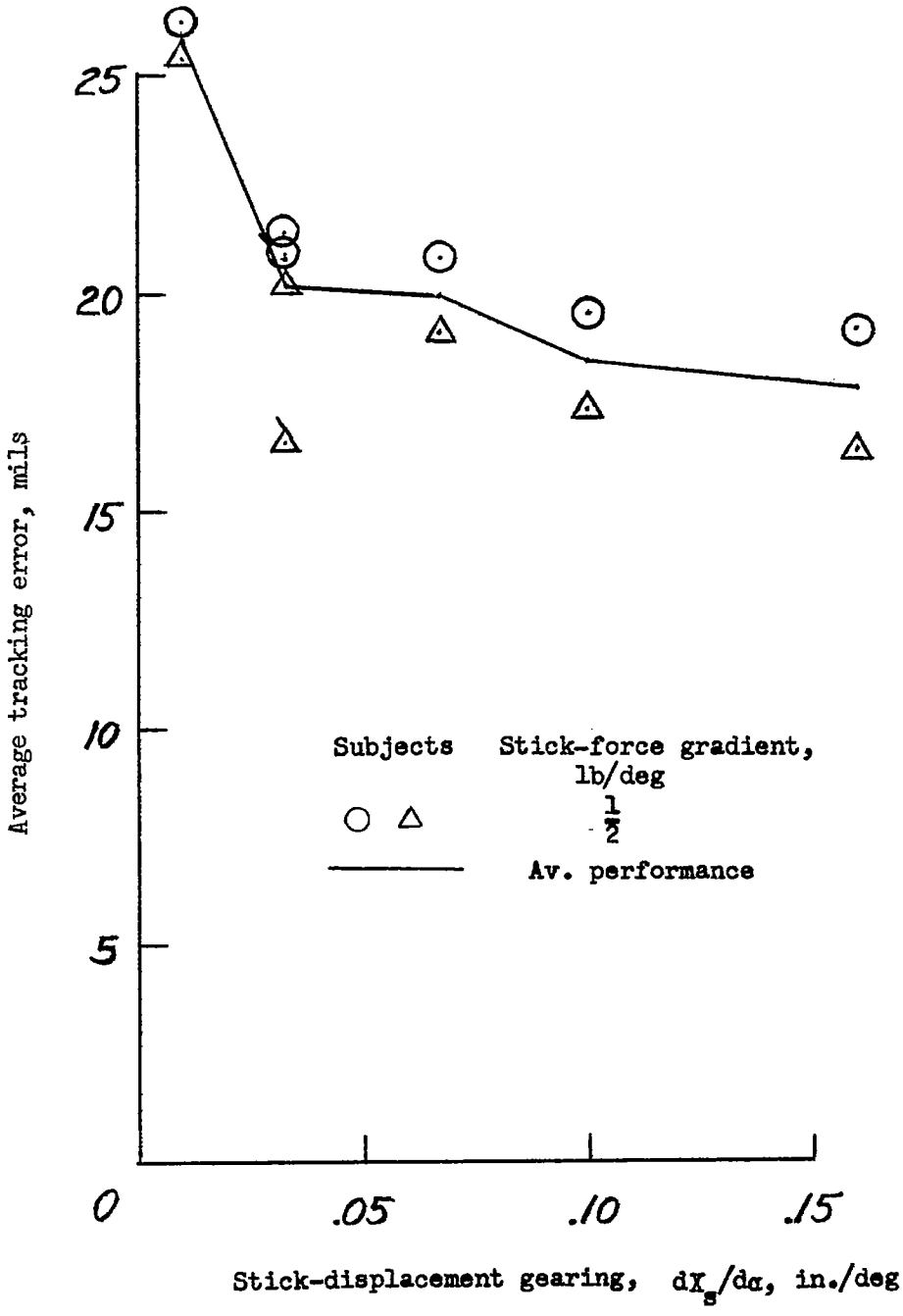


Figure 7.- Effect of damping ratio on average tracking error for a simulated airplane with a natural frequency of 1/2 cps, a stick-force gradient of 1/2 lb/deg, and a ratio of rate of change of flight-path angle to angle of attack of 2.8 deg/sec/deg. Group 1.



(a) Two hands with arms unsupported.

Figure 8.- Effect of stick-displacement gearing on average tracking error for a simulated airplane with a natural frequency of 1 cps, a damping ratio of 0.11, and a ratio of rate of change of flight-path angle to angle of attack of 0.9 deg/sec/deg. Group 2. Flagged symbols indicate reruns.



(b) One hand with wrist or arm supported.

Figure 8.- Concluded.

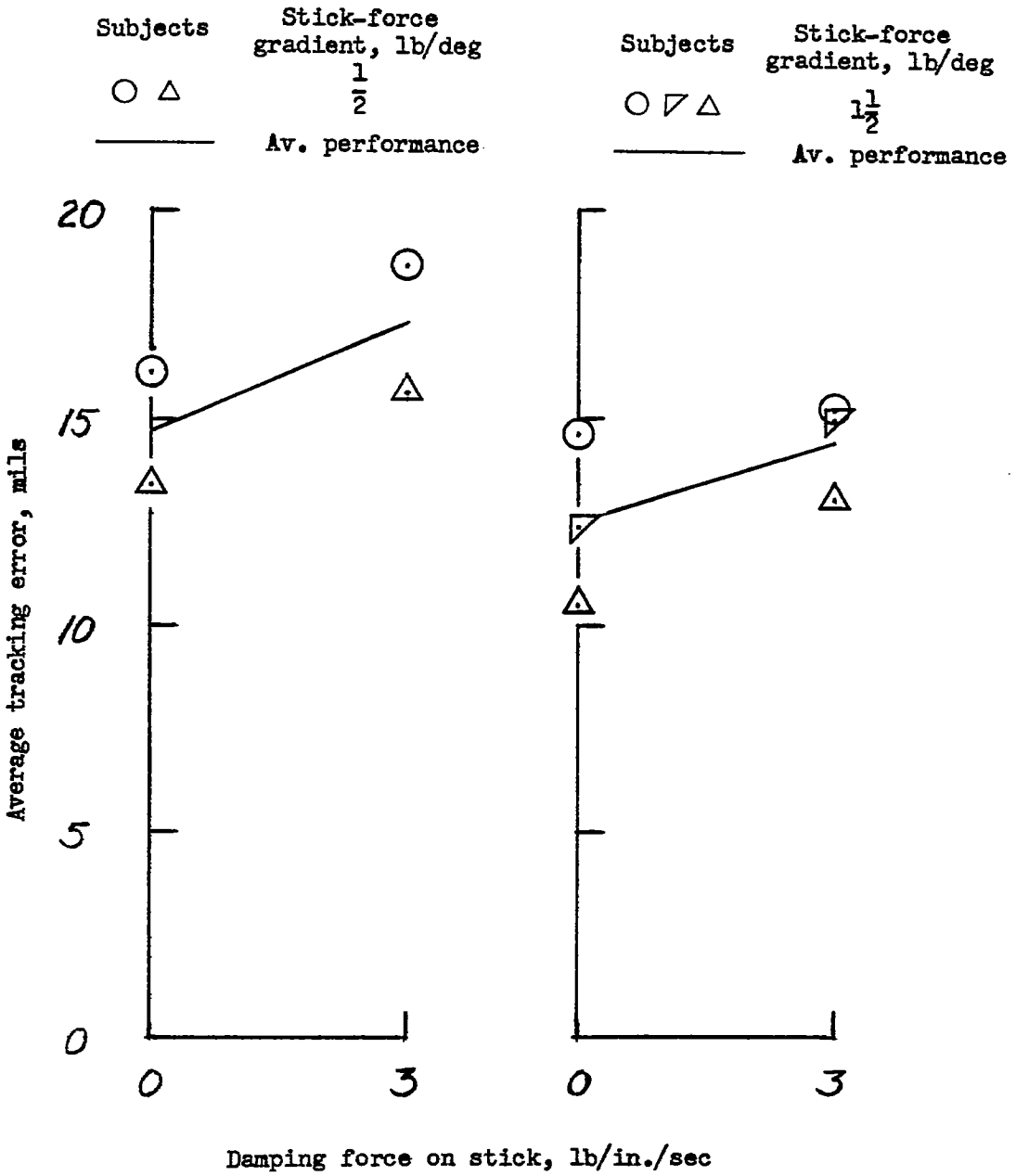


Figure 9.- Effect of viscous damper on stick on average tracking error for a simulated airplane with a natural frequency of 1/2 cps, a damping ratio of 0.18, a stick-displacement gearing of 0.10 in./deg, and a ratio of rate of change of flight-path angle to angle of attack of 2.8 deg/sec/deg. Group 3.

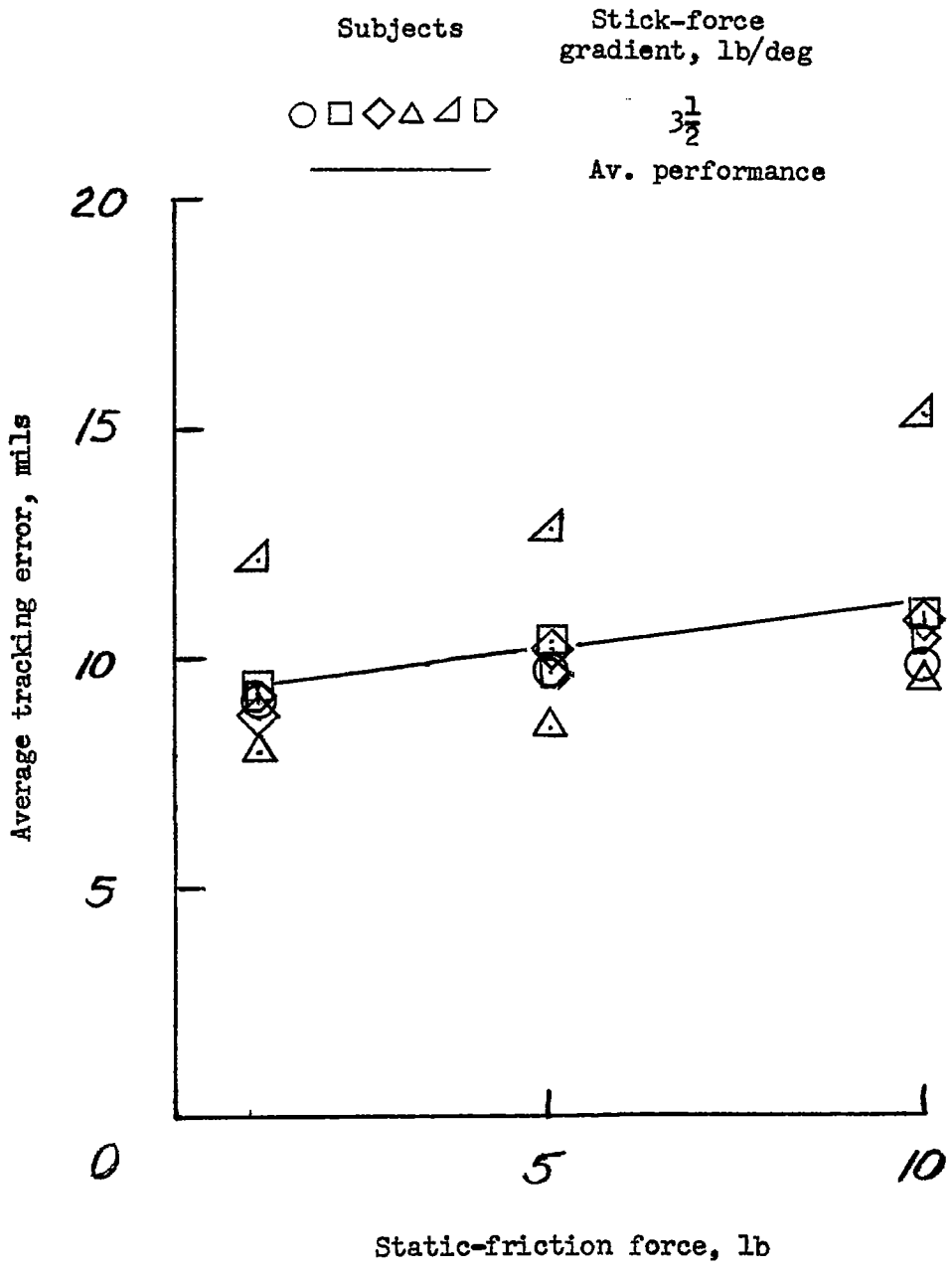
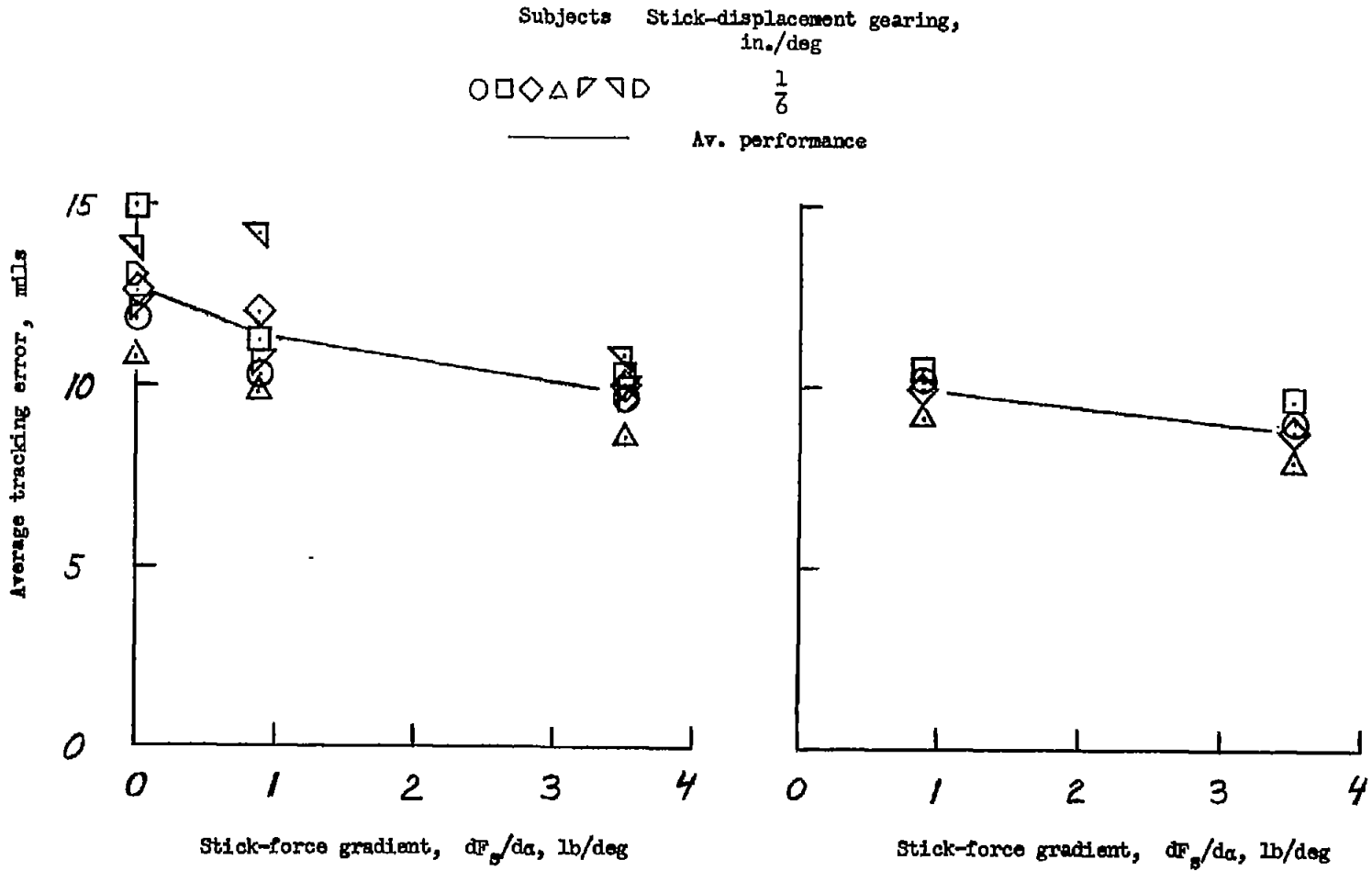


Figure 10.- Effect of static-friction force on average tracking error for a simulated airplane with a natural frequency of 1/2 cps, a damping ratio of 0.8, a stick-displacement gearing of 1/6 in./deg, and a ratio of rate of change of flight-path angle to angle of attack of 0. Group 4.



(a) 5 pounds of static-friction force.

(b) 1 pound of static-friction force.

Figure 11.- Effect of stick-force gradient on average tracking error for a simulated airplane with a natural frequency of 1/2 cps, a damping ratio of 0.8, and a ratio of rate of change of flight-path angle to angle of attack of 0. Group 4.

NACA - Langley Field, Va.