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TECHNICAL NOTES
NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 550

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TO AIRPLANE CONTROLS

By M. N. Gough and A. P. Beard
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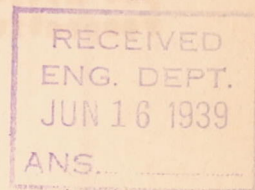
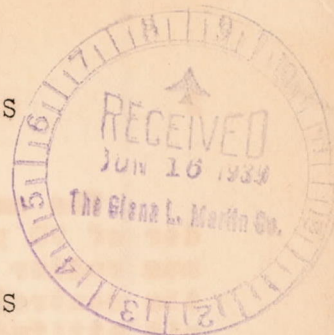
LIMITATIONS OF THE PILOT IN APPLYING FORCES
TO AIRPLANE CONTROLS

By M. N. Gough and A. P. Beard

SUMMARY

Measurements were made to determine the relative maximum forces a pilot can exert on the controls of an airplane with a view to obtaining systematic data upon which to base the location of controls within the cockpit and the design of the control surfaces. A cockpit model of generous proportions, capable of being rotated to any attitude, was built with the location of the control stick and rudder pedals adjustable over a wide range of positions with respect to the seat. Besides measurements of maximum forces obtainable with various control locations and with the pilot in several attitudes, estimates of forces within the range normally encountered in flight were made to gain an indication of the accuracy of estimating control forces. No accelerations were imposed upon the pilot while the data were being obtained.

The measurements indicated that: the lateral push possible on the stick is greater than the pull and both decrease fairly uniformly with increasing distance of the stick from the seat; the longitudinal pull on the stick increases with increasing distance of the stick from the seat and is greater than the push except in rearmost positions; for the range of positions tested there is a slight increase in the force that can be applied as the height of the stick above the seat is increased; there is a pronounced peak in the variation of rudder force with distance of the rudder pedals from the seat; when the pilot is securely fastened to the seat, the attitude has little effect on the forces that he can apply to the controls; positions of comfort for the pilot are not necessarily ones in which he can apply the most force to the controls; estimation of control forces is most accurate for intermediate forces.



The maximum aileron forces measured were of the order of 90 pounds, maximum elevator 200 pounds, and maximum rudder 450 pounds. The average forces applied with the controls in the neutral position for the various cockpit attitudes were of the order of 35, 95, and 400 pounds, respectively, for the ailerons, elevators, and rudder.

INTRODUCTION

The forces that a pilot might exert on the controls of an airplane are of interest in connection with the design of control surfaces and of operating mechanisms, and also in connection with studies of controllability and maneuverability. The approximate physical limitations of the pilot and the magnitude of the forces he can exert as affected by the positions of the controls relative to his seat with the airplane in various attitudes should be known. Pilots are usually able to describe the forces required to operate the controls only in such general terms as "heavy" or "light." The meaning of such terms is dependent on various factors, for example, whether the force is a pull or a push, is lateral or longitudinal, and is applied with the hands or the feet.

Very little qualitative information exists regarding the relative magnitude of the forces which pilots actually apply or which they regard as satisfactory. The tests reported in reference 1 were concerned with a study of the time required to apply stick forces of various magnitudes.

In the present investigation measurements were made of the maximum forces that could be applied and maintained for several seconds on the stick and rudder pedals as normally used for operating the ailerons, the elevators, and the rudder. The influence of the location of control-stick levers, or pedals, relative to the pilot's seat and of the attitude of the airplane in space was studied. Measurements were also made to determine the accuracy with which applied forces could be estimated. A cockpit model that could be rotated to any desired attitude to simulate various flight conditions was used and the measurements were made with the Committee's two test pilots as subjects. Both pilots are right-handed and the forces were applied only with the right hand and the right foot. Five flight attitudes other than airplane level attitude were

simulated, namely, airplane banked to the right 90° , airplane banked to the left 90° , airplane nosed up 90° , airplane nosed down 90° , and airplane inverted. The conditions under which the tests simulating an airplane banked were made are not directly comparable with flight conditions, excepting aerobatics, because the accelerating forces normally imposed upon the pilot in these flight attitudes did not exist.

The ability to apply control forces undoubtedly varies considerably with different pilots so that results obtained with only two pilots cannot be regarded as representing the ultimate in forces that a pilot might exert. The results obtained, however, are considered fairly representative as regards the relative magnitude of the maximum forces and reasonably satisfactory as regards the relative variation with position and attitude.

APPARATUS

The cockpit model (figs. 1 and 2) is a box-like framework of angle iron within which is mounted a bucket-type pilot's seat, a control stick, and a rudder bar. The framework can be rotated to any desired attitude. The location of the control-stick grip and rudder with respect to the seat can be varied through the limits shown in table I.

The control stick is simulated by a tube, as shown in the photographs, on which is a hand grip incorporating a mechanism used to indicate the applied force. This control stick may be attached to a beam at any one of various points spaced 4 inches apart in a lateral direction. The height of the hand grip can be varied as desired by sliding the tube up or down and the beam can be placed at any desired fore-and-aft location. Thus the hand grip can be placed in any desired position within the cockpit but is immovable under the influence of an applied control force. In addition, the major axis of the hand grip is at all times maintained parallel to the Z axis of the cockpit model.

The control-force indicator consists of a flexible beam and an Ames strain gage mounted directly on the stick; it provides an auxiliary hand grip. The deflection of the beam caused by the application of force is

transmitted to the strain gage, which has been calibrated for both positive and negative deflection. Two beams, one of 100 and the other of 300 pounds capacity, are used. The 100-pound beam was used to obtain higher accuracy in measuring small forces. Aileron forces are measured by rotating the control-force indicator through 90° from its position for measuring elevator forces.

The rudder bar is a piece of oak reinforced with steel covering; it has a straight frontside and fixed pedals mounted 20 inches apart. Rudder forces are measured by a spring balance of 500 pounds capacity, graduated in 5-pound intervals, and fitted with a maximum-force indicator. One end of the balance is secured to the fixed structure and the other to the right tip of the rudder bar 4 inches outboard of the point of application of the force. Measurements made at this point are corrected for this offset and represent actual effective force applied to the pedals. No variation in the distance between right and left rudder pedals is provided because it is believed that, except for comfort, there would be little effect on the rudder force which could be applied. Holes are provided along the rudder-bar mount to allow fore-and-aft variation of location. A large turnbuckle connected to the spring balance keeps the rudder bar normal to the longitudinal axis when the rudder position is varied.

Three safety belts comparable with the most bulky acrobatic harness likely to be used secured the pilot in the seat. These belts consisted of the usual thigh belt; a chest belt just beneath the armpits; and an acrobatic shoulder harness of four straps, two anchored to the back of the seat and passing over the pilot's shoulders, and two anchored to the sides of the seat near the front, all four meeting at a point near the lower part of the pilot's chest where they were secured by a quick-release pin. These belts, particularly the chest strap, restricted the reach of the pilot but tended to standardize the results.

The subjects used in these tests were the Committee's two test pilots. Their principal physical dimensions are given in table II.

METHODS

The investigation was divided into four parts. The first part concerned the measurement of maximum aileron and elevator forces that the pilots could apply with a normal-length stick in various locations covering practically the entire horizontal plane with the cockpit in a level attitude. Similar measurements were made to determine the variation of maximum stick force with height of stick relative to the seat. A stick height such that the center of the hand grip was 8 inches above the seat was chosen from experience by the pilots as a normal-length stick; 6 inches more and 6 inches less than normal length were used as the variations. For these measurements, as well as for those of parts 2 and 4, the rudder bar was located at a station chosen by the pilot as being the most comfortable for a footrest; however, every precaution was taken to insure that no assistance was received from it, and it was believed not to have influenced the results because of the firm anchorage of the pilot's body to the seat.

In the second part, measurements were made in a similar manner with the stick at the chosen normal height and with the cockpit model in the following attitudes: level, nosed downward 90° , nosed upward 90° , rolled 90° to the right, rolled 90° to the left, and inverted. The first part of the measurements indicated that investigation for more than one stick height was not warranted; also that the lateral range of stick location could be reduced to 13 inches without sacrificing completeness. For measurements made in attitudes other than normal the pilot was not required to remain in strained positions for periods longer than 2 or 3 minutes.

The third part of the measurements was made to determine the effect of seat height, horizontal distance of the rudder bar from the seat, and attitude of the cockpit on the maximum horizontal or effective force that could be applied to the rudder. Measurements of rudder force with the rudder pedal located at various points along the longitudinal axis and with the seat at the lower extreme of its travel were made in each of the six attitudes tested in the second part. Similar measurements were made in the normal attitude with the seat full up. For each individual measurement the linkage containing the

spring scale was adjusted so that when the spring was extended the rudder pedal was approximately normal to the longitudinal axis of the cockpit.

Experience gained in previous flight tests suggested the desirability of determining the accuracy with which pilots can estimate stick forces normally encountered. Although interest in such information is limited chiefly to test pilots, such measurements of limited scope were made and they constitute the fourth part of the measurements. The location of the normal-length stick was varied along the plane of symmetry and attempts were made to apply forces of predetermined magnitude. An observer noted the forces actually applied. The subject under test was not allowed to know the agreement of estimates until the completion of the measurements. Two attitudes only, normal and facing downward, were considered; the face-downward attitude is of interest chiefly in connection with vertical dives.

ACCURACY

Measurements of elevator forces are believed to be accurate to ± 3 pounds; aileron measurements, in that a spring beam of one third the capacity of the one used for elevator measurements was used with the same strain dial, are accurate to ± 1 pound.

Rudder forces are estimated to be accurate to ± 20 pounds even though the scale of the spring balance used was graduated in 5-pound intervals. The accuracy is probably no greater because the point of application of the force may easily have varied as much as $1/4$ inch due to the necessity of rigidly securing the rudder pedal to the rudder bar.

Perhaps the factor warranting most consideration in connection with accuracy is that of obtaining the same degree of exertion from a subject under the several conditions of test. This factor is, of course, dependent on the subject's ability to duplicate the effort expended. The agreement of the trends shown by each of the two pilots indicates that such a consideration had not caused erroneous conclusions to be reached in these tests.

RESULTS AND DISCUSSION

The results of measurements to determine the maximum stick forces that a pilot can apply under various conditions of stick length, lateral and longitudinal position of the stick within the cockpit, and attitude relative to the gravitational force, are presented in figures 3 to 13, inclusive. Figures 3 to 9 are constructed in isometric form because it is believed that this method allows a rigid interpretation of the variation of the relative magnitude of the stick forces for variations in positions of the grip. The interpretation of each of the isometric figures is as follows: fore-and-aft location of the stick relative to the pilot's seat is measured along lines inclined upward to the right; lateral location is measured along lines upward to the left; elevator forces are plotted on vertical lines; aileron forces originating at the same point are plotted along lines representing lateral displacement; solid envelope lines connect extremities of pull forces for both elevator and aileron; dashed lines join push forces; vectors of all aileron forces are shown; vectors of both the elevator push and pull forces at the same point are shown. With one exception, the longitudinal range of stick location covers 18 inches and the lateral range covers 16 inches (8 inches on either side of the plane of symmetry). The one exception (fig. 4) covers a lateral range of 24 inches in 4-inch steps. As previously stated, it was decided that such detail was not warranted in subsequent measurements.

Figure 3 shows the effect of the height of the grip above the seat on the magnitude of the force that can be applied to the control stick. It will be noticed that the forces applied with the center of the hand grip 14 inches above the seat throughout the range of stick location investigated are generally greater than those applied with the normal 8-inch grip position, which are in turn greater than those with the grip 2 inches above the seat. Figures 3 and 4 both show the effect of lateral and longitudinal positions of the stick (corresponding to positions when deflected) on the force that can be applied to it with the cockpit model in a level attitude. It will be seen that elevator pull forces are greater than push forces except in the rearmost positions, that pull forces increase with distance as long as the stick can be reached, and that push increases with distance to the point where

the arm is straight, after which it decreases. Unfortunately, pull on the stick is a minimum at the rearmost position, the position used to get the tail of an airplane down in a landing. During the tests it was noted that comfortable positions of the pilot's arm and hand were not associated with the positions in which maximum force could be applied.

Lateral forces that can be applied to the stick (corresponding to aileron movements) are a maximum for the rearmost positions and decrease with distance and with lateral deflection of the stick. Push forces (corresponding to up left aileron for a right-handed pilot) are greater than pull forces at corresponding positions of the stick.

The remainder of the measurements of maximum stick forces were made to determine the effect of cockpit model attitude. Results of measurements made with the cockpit model rolled 90° to the right are shown in figure 5. It will be seen that the variation of forces is generally the same as with the cockpit model in a level attitude, except that forces which can be exerted to the left of neutral are less and those to the right greater. These differences are explained by the fact that, in effect, the pilot shifts to the right in the seat despite restraining belts and his weight is borne by his right side.

With the cockpit model rolled 90° to the left, elevator forces with the stick in the plane of symmetry and displaced to the left are greater than with the pilot in a level attitude (fig. 6). This result is explained, as in the foregoing case, by the fact that the pilot shifts to the left, placing his right arm more nearly in line with the stick. Aileron pull forces with the stick in the plane of symmetry are less, particularly for the rear position.

With the pilot facing upward, elevator pull forces are greater, particularly for the stick-forward position (fig. 7). Push forces are generally the same as for the level case except as impaired at a distance by the pilot's being forced back into the seat by his own weight, thus limiting his reach. Aileron forces are noticeably smaller.

Figure 8 shows that facing downward is favorable for

both elevator push and pull forces. Aileron forces are slightly less than corresponding forces in the level attitude, probably due to the tendency of the pilot to hang in his belt rather than to be firmly seated.

The outstanding features of the results obtained with pilot inverted, are the high elevator push forces obtained in the vicinity of mid position of the stick and the rapidity with which these forces decrease as the limit of reach is approached (fig. 9). Again, aileron forces are slightly less than those obtained in the level attitude. It is more difficult to reach the stick in the left front corner.

Figures 10 to 13 show the data from figure 4 plotted in coordinate form. As there is little effect of variation in stick force with cockpit-model attitude, figure 4 is chosen as most representative of all conditions. If the actual magnitude of the stick forces should be of interest, bearing in mind the limitations under which the values were obtained, they may be more readily determined from the curves of figures 10 to 13.

Figure 14 presents the results of measurements made to determine the maximum force that can be applied to a rudder pedal. The upper half of the figure shows the effect of seat height on maximum force for the two pilots. Each pilot exerted a horizontal force of 430 pounds with the seat down. For pilot A the maximum occurred at a distance of 36 inches from the back of the seat; for pilot B at 35 inches. With the seat raised 6 inches vertically, pilot A pushed a maximum of 290 pounds at 32 inches and pilot B pushed a maximum of 330 pounds at 33 inches. It is thus seen that a vertical seat adjustment of 6 inches was responsible for a difference in maximum effective force of 100 to 140 pounds and caused the maximum to occur from 2 to 4 inches nearer the seat with the seat up. The lower half of figure 14 shows the effect of cockpit-model attitude on the maximum force that can be applied. A comparison of the results obtained with the two pilots indicates that attitude has little effect on either the fore-and-aft location or the magnitude of the maximum force. It is interesting to note that the maximum force for all attitudes and for both pilots occurred with the rudder pedals between 34 and 37 inches from the back of the seat and that the greatest force registered by pilot A was 490 pounds when on the right side and with

the rudder bar 35 inches from the seat; the greatest force exerted by pilot B was 470 pounds while facing upward and with the rudder bar located 35 inches from the seat. From these results it appears that if the fore-and-aft location of the neutral position of the rudder pedals (dimension A, table I) is given ample limits to cover the range required by the physical dimensions of the pilot, then a fore-and-aft displacement of the pedals of 6 inches for full rudder travel would enable the pilot to apply the maximum force of which he is capable to the rudder, regardless of its position or the attitude of the airplane.

A study of the maximum forces obtained might lead to some conclusions regarding so-called "control coordination," although it is realized that the actual control effectiveness in displacing the airplane is equally important. From these tests it appears that the average of the lesser of the push and pull forces that could be exerted in all attitudes with the controls in the neutral positions is 35, 95, and 400 pounds, respectively, or a ratio of approximately 1:3:10, which it is believed might be a good figure for the ratio of the forces required to actuate the ailerons, elevators, and rudder for a desired angular displacement of the airplane and apparently for an equal expenditure of effort to each control by the pilot.

The results shown in figures 15 and 16 were determined as a result of questions arising from dive testing and research on lateral-control devices. Pilot B was more consistent than pilot A in estimating elevator forces but overestimated the higher forces quite badly, applying 30 pounds when estimating 50. He was inclined to overestimate the forces slightly more when facing downward than when in a level attitude. Pilot A estimated elevator forces more accurately and underestimated them a great deal more when in a level attitude than when facing downward, as in a vertical dive. Both pilots were fairly accurate in estimating an aileron force of 10 pounds with a tendency by both to underestimate a push force and overestimate a pull force. These estimates of aileron forces are probably not so representative as the estimates of elevator forces because the Committee's pilots have had considerable experience in lateral-control testing, in which the applied forces are actually measured.

CONCLUSIONS

With due regard for the conditions under which these tests were made, it may be concluded from them that:

1. The ability to pull on the elevators was greater than the ability to push, except with the stick well back; both increased with distance from the seat (push gradually, pull rapidly) up to a point beyond which push decreased.

2. The ability to push on the ailerons was greater than the ability to pull; both decreased with lateral deflection of the stick and with increasing fore-and-aft distance from the seat.

3. For the range of positions used in these tests the force that could be applied to the control stick increased slightly with increased stick height above the seat.

4. Pronounced peaks in the graphs of the rudder forces indicate that the fore-and-aft range of rudder positions in which a pilot can exert a maximum force is small. A low seat position with respect to the rudder is desirable for maximum force application.

5. When the pilot's body is firmly anchored to the seat, the attitude of the airplane has little effect on the forces that he can apply to the controls.

6. Locations of the controls for positions of comfort on the part of the pilot are not necessarily ones in which the maximum force may be applied.

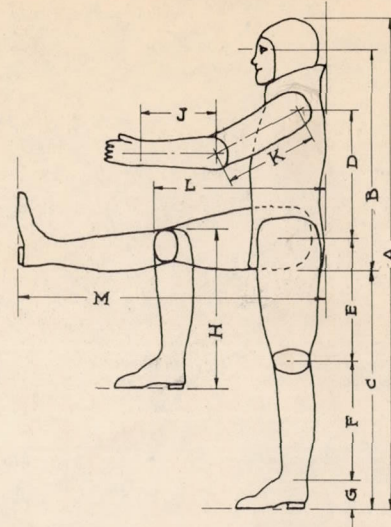
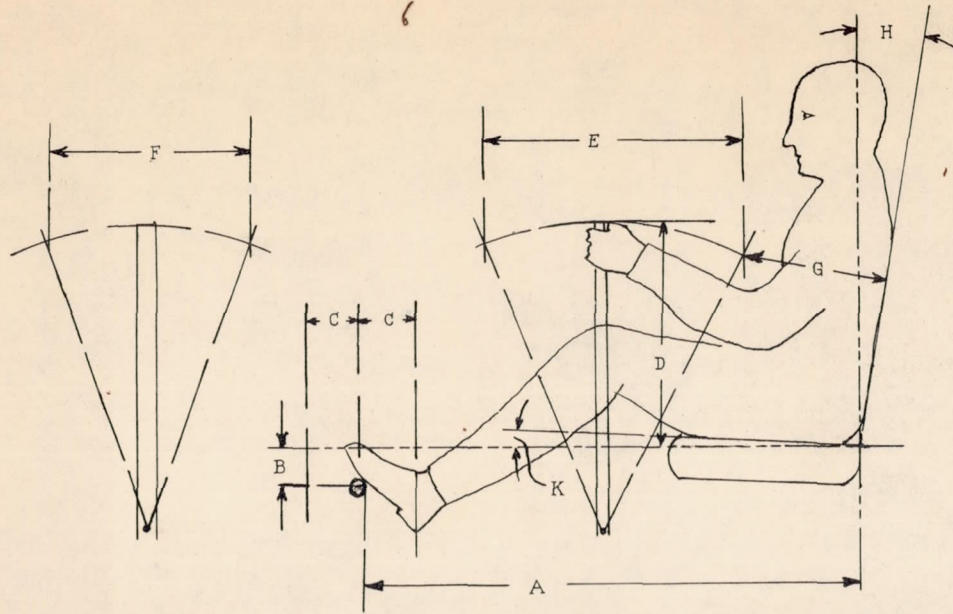
7. It appears that the forces required on aileron, elevator, and rudder should be in the ratio of approximately 1:3:10 for the application of equal efforts by the pilot.

8. The estimates by a pilot of stick forces of reasonable magnitude are likely to be in error by as much as 50 percent; low for small forces and high for large forces.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., November 6, 1935.

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1. Hortel, Heinrich: Determination of the Maximum Control Forces and Attainable Quickness in the Operation of Airplane Controls. T.M. No. 583, N.A.C.A., 1930.
2. Materiel Division, U. S. Army Air Corps: Dimensions of Average Pilot. Handbook of Instructions for Airplane Designers, vol. I, seventh edition, 1932, fig. 163, p. 325.



Dimension	U.S. Navy specification	U.S. Army Air Corps specification	Average of 7 N.A.C.A. airplanes (military and commercial)	Cockpit model used in tests
	Inches	Inches	Inches	Inches
A	35 to 41	35-3/8 to 39-3/8	35 to 39	27 to 41
B	6 to 10	2-1/4 to 10-3/4	3 to 5	6 and 12
C	3 to 5	3-1/4	3 to 4	--
D	15 to 17	12 to 19-1/2	14 to 22	4-1/2 to 16-1/2
E	18 to 22	18	14 to 19	18
F	16 to 18	18	11 to 20	24
G	12 in. (minimum)	16-5/8	9 to 13	12
H	8° to 10°	13-1/2°	6° to 10°	14°
K	3°	--	5° to 12°	10°
Lateral distance, center to center, of rudder pedals		16-1/4	12 to 21	20

Table I.- Arrangement of cockpit controls.

Dimension	Average pilot (reference 2)	Pilot A	Pilot B
	Inches	Inches	Inches
A	68.20	66.5	66.0
B	30.70	30.5	31.3
C	33.28	33.4	33.0
D	17.84	17.5	19.0
E	17.12	16.5	14.8
F	16.40	16.2	16.0
G	4.12	4.4	4.5
H	22.00	21.5	21.5
J	10.48	10.1	9.0
K	13.12	9.8	10.0
L	23.85	23.3	22.5
M	42.80	41.3	41.0
Distance between finger tips with arms spread, in.		67.0	68.0
Weight without flying gear, lb.		145.0	165.0

Table II.- The physical dimensions of the two pilots.

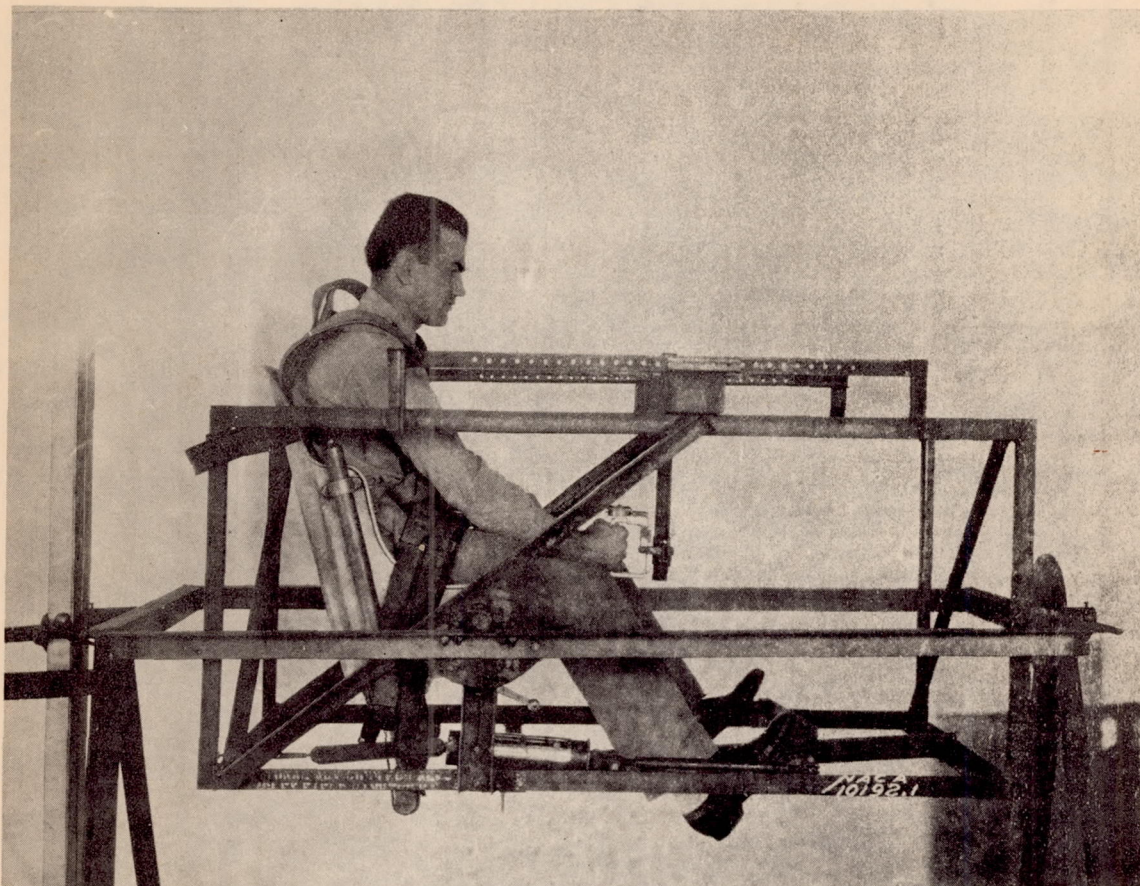


Figure 1.- The cockpit model used in measuring the forces that a pilot can exert on the controls. The position corresponds to an airplane in the level attitude.

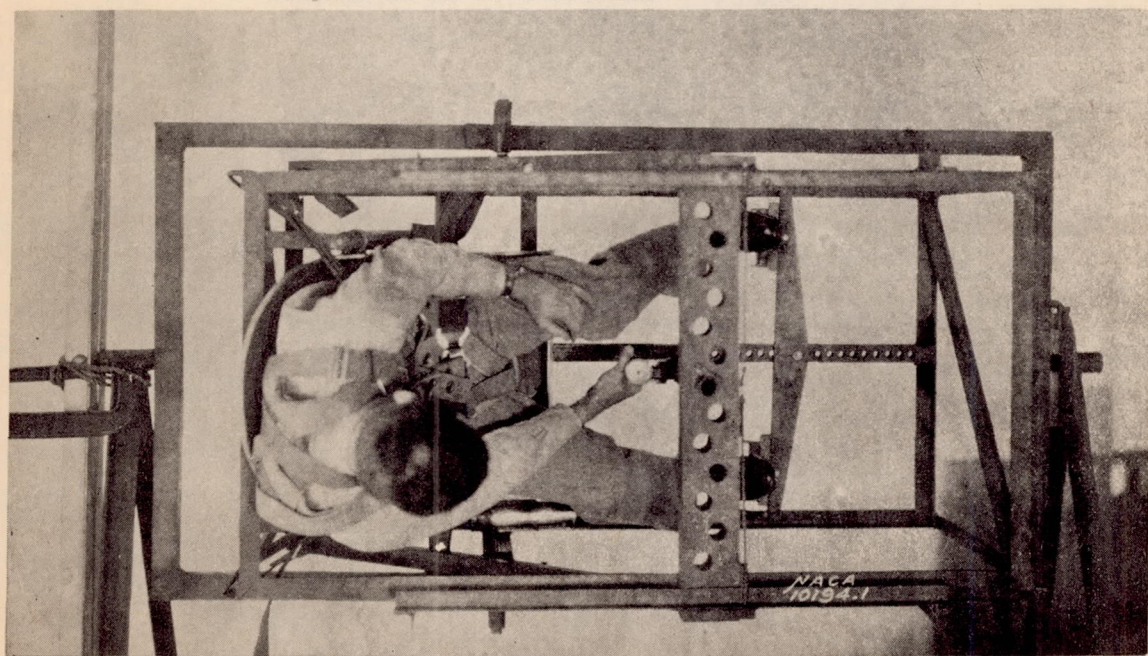


Figure 2.- The cockpit model rolled to the right 90°.

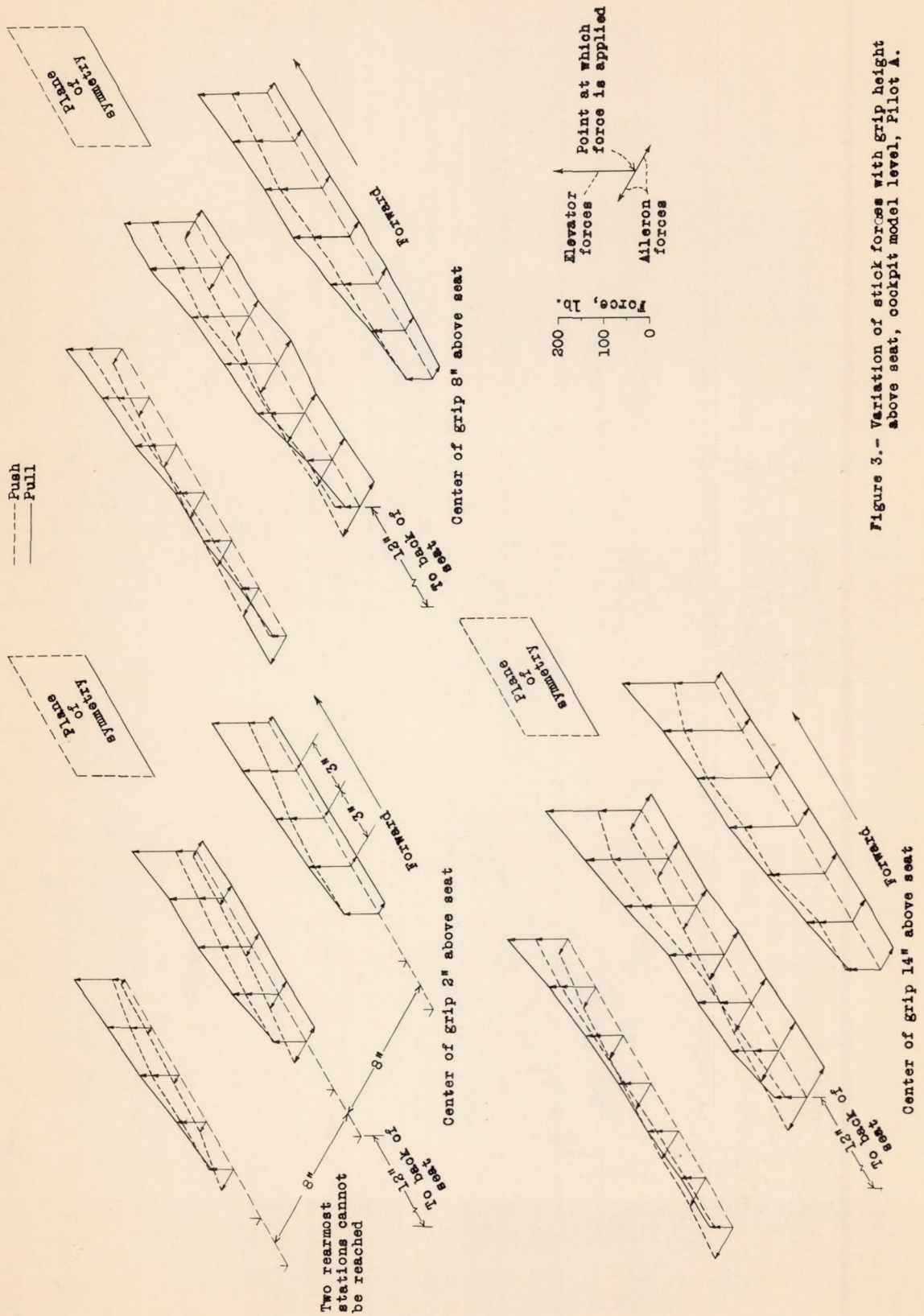


Figure 3.- Variation of stick forces with grip height above seat, cockpit model level, Pilot A.

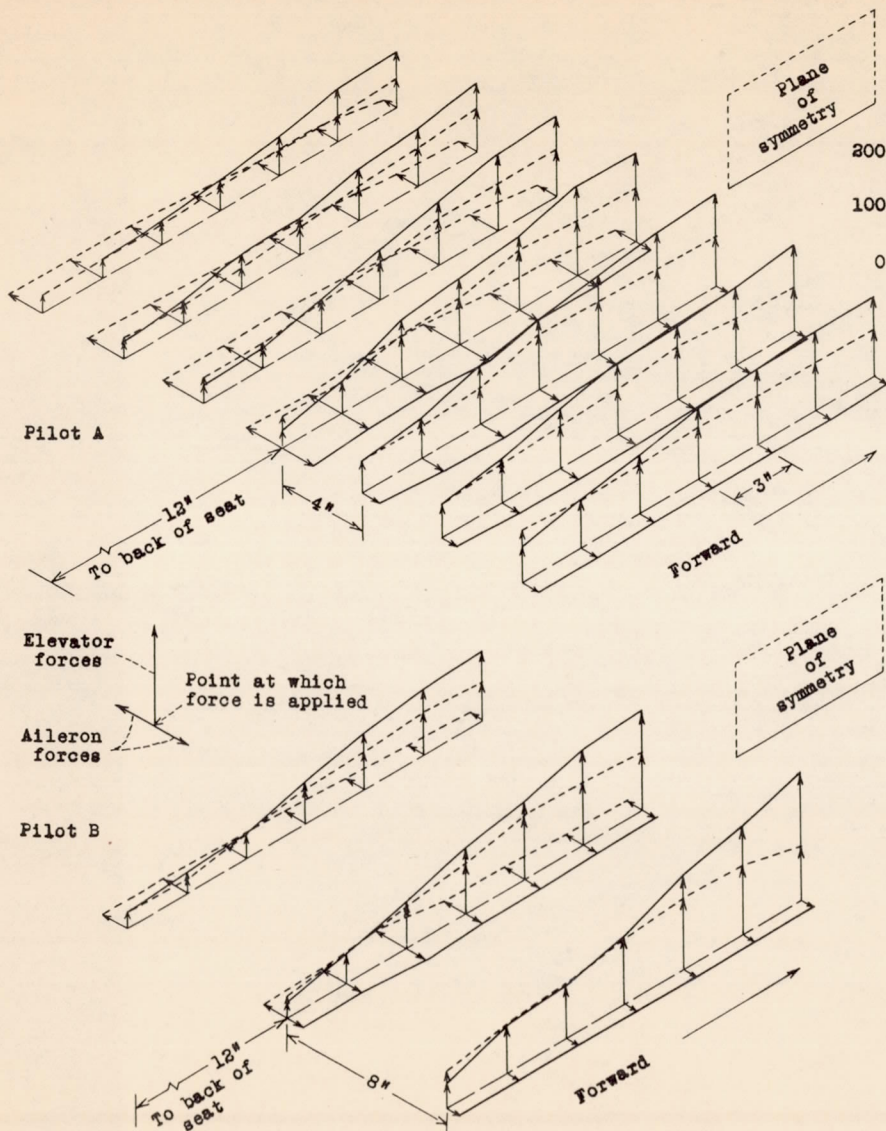


Figure 4.- Variation of stick forces with grip 8 inches above seat, cockpit model level.

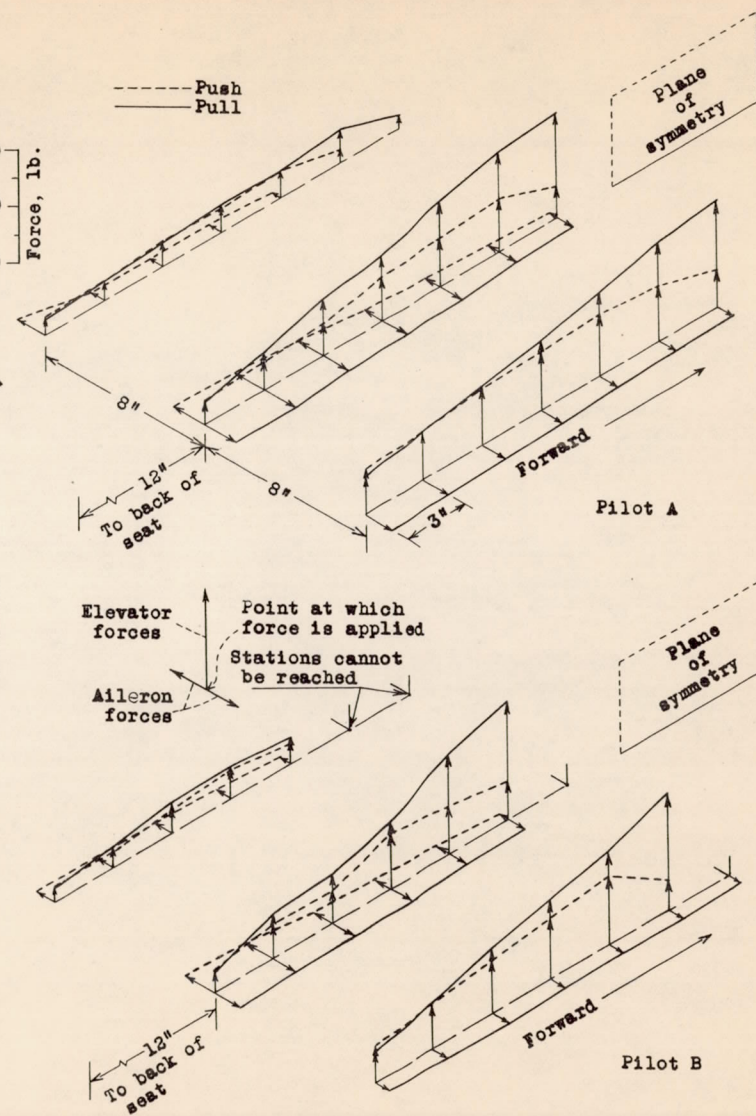


Figure 5.- Variation of stick forces with grip 8 inches above seat, cockpit model rolled to right 90°.

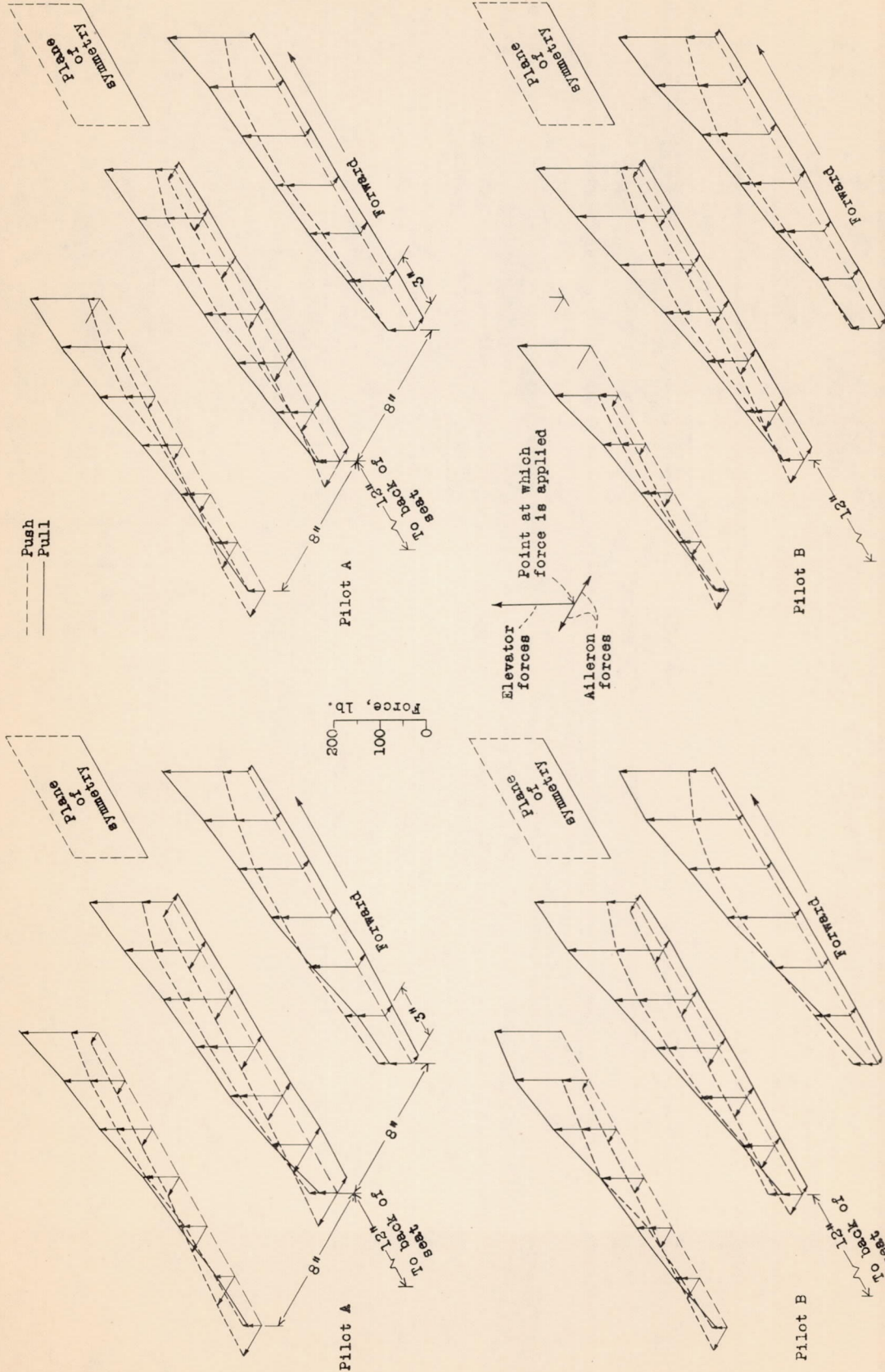


Figure 7.- Variation of stick forces with grip 8 inches above seat, cockpit model nosed up 90°.

Figure 6.- Variation of stick forces with grip 8 inches above seat, cockpit model rolled to left 90°.

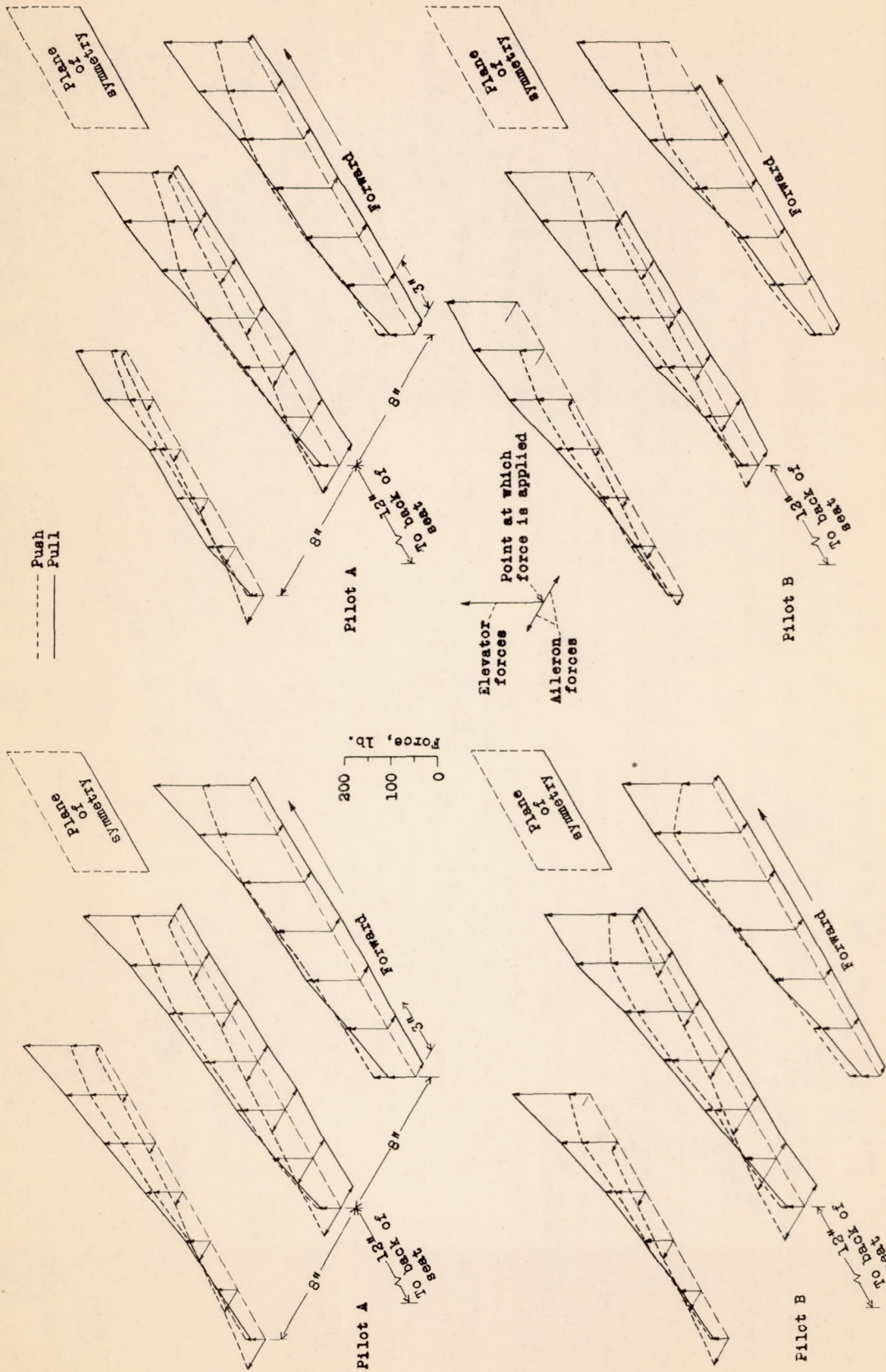


Figure 9.- Variation of stick forces with Grip 8 inches above seat, cockpit model inverted.

Figure 8.- Variation of stick forces with grip 8 inches above seat, cockpit model nosed down 90°.

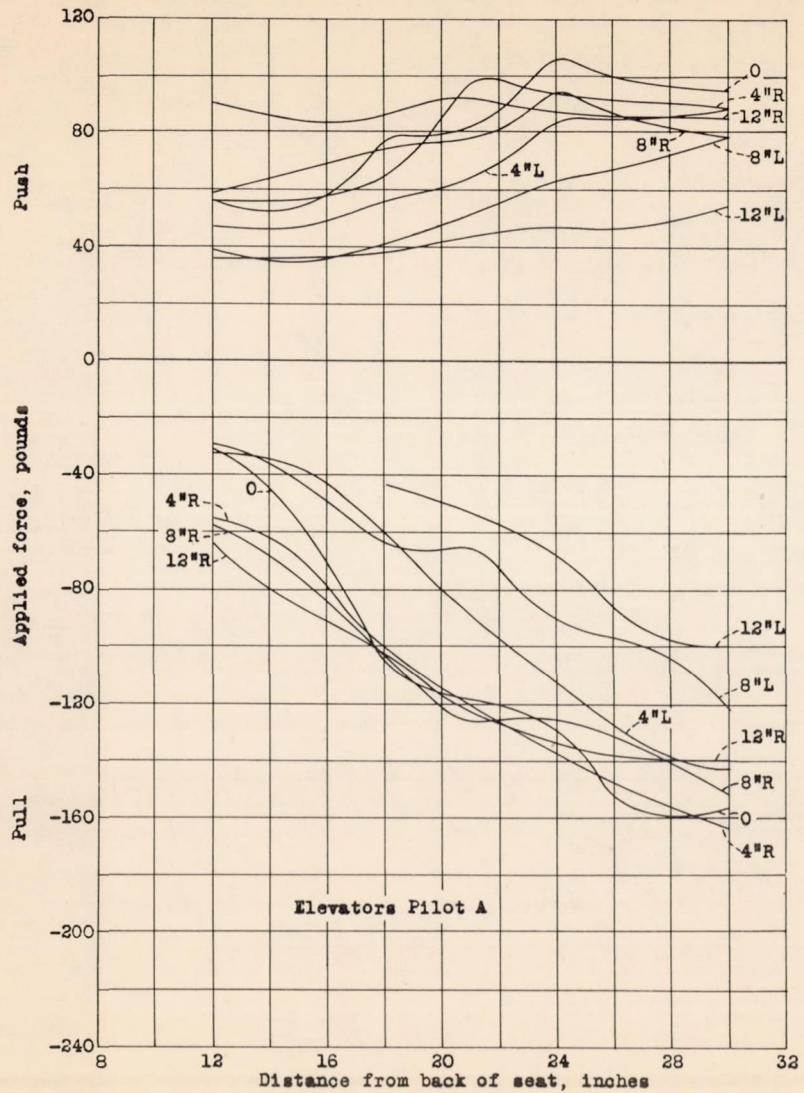


Figure 10.- Variation of stick forces with grip 8 inches above seat, cockpit model level.

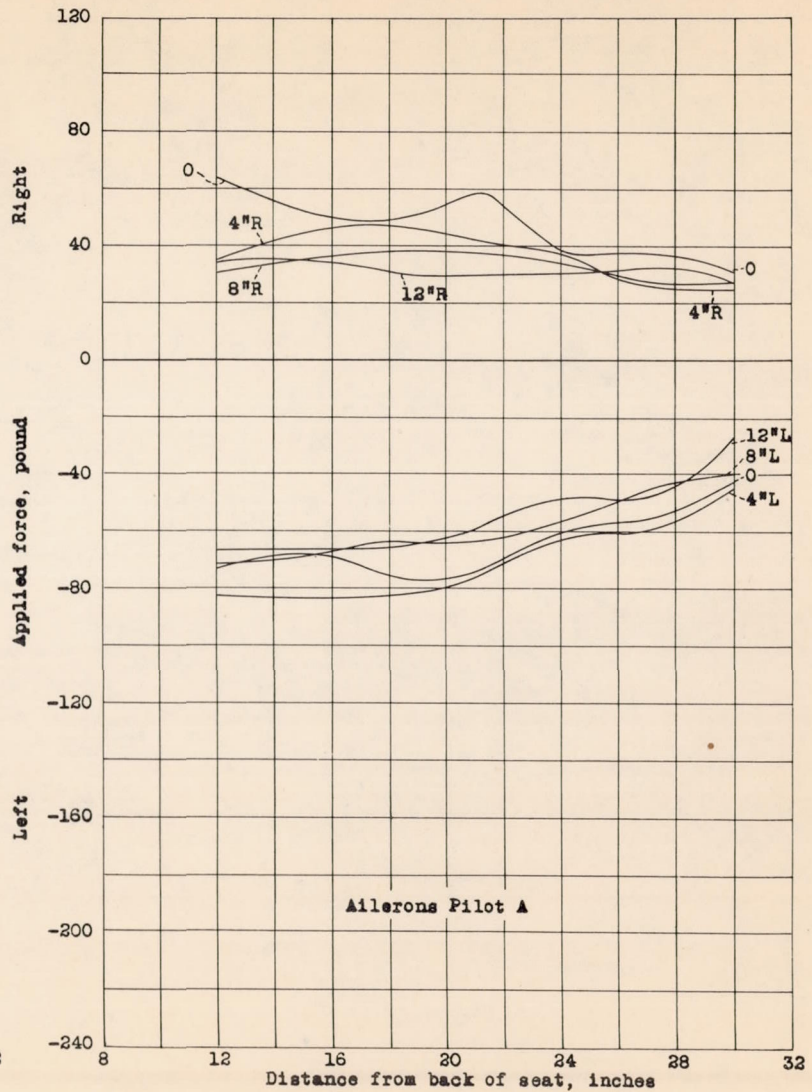
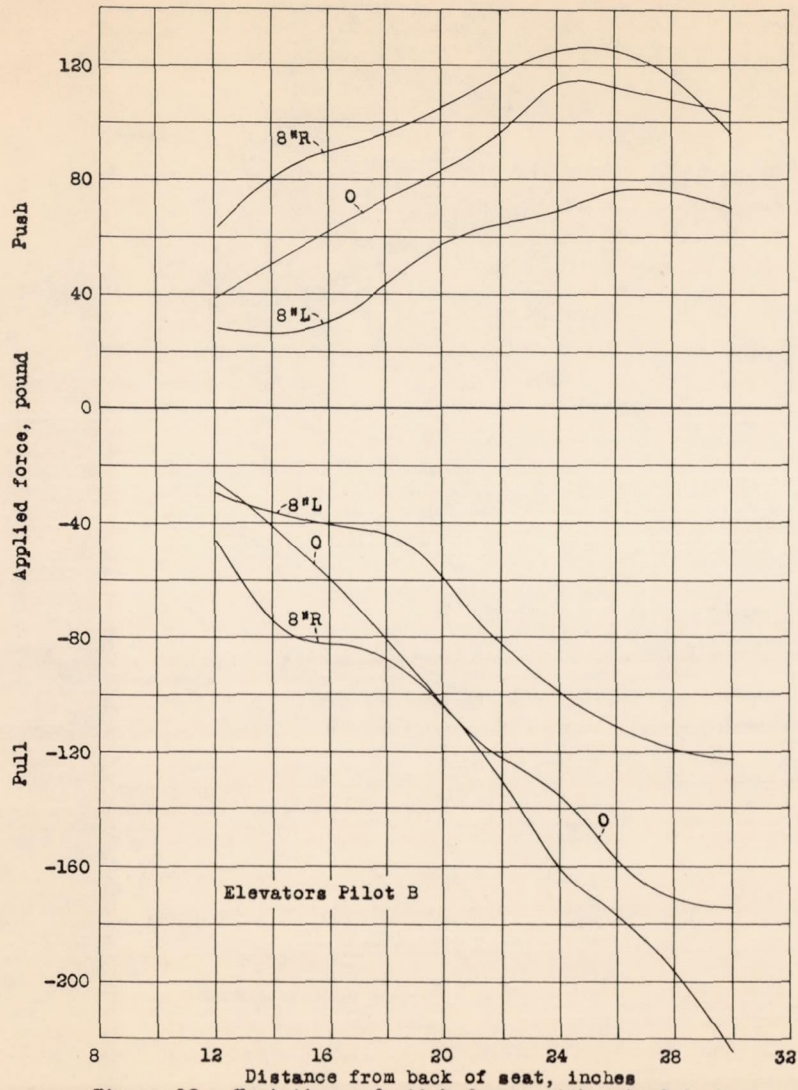
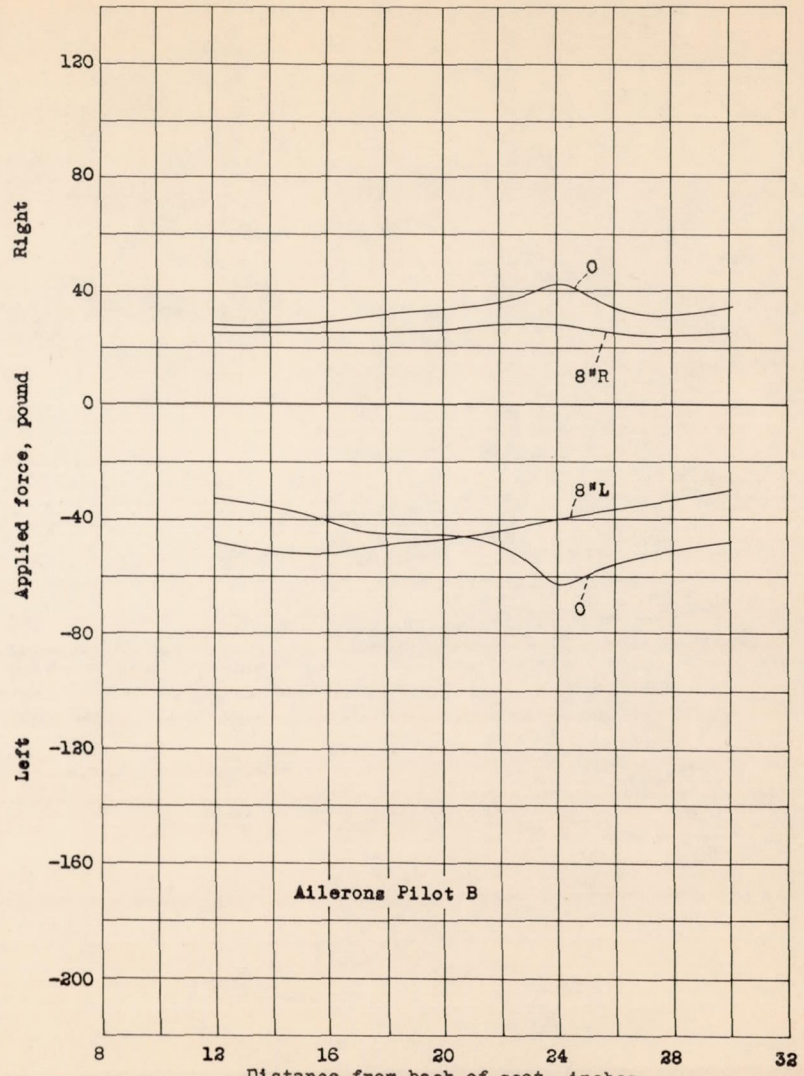


Figure 11.- Variation of stick forces with grip 8 inches above seat, cockpit model level.



Distance from back of seat, inches
 Figure 12.- Variation of stick forces with grip 8 inches above seat, cockpit model level.



Distance from back of seat, inches
 Figure 13.- Variation of stick forces with grip 8 inches above seat, cockpit model level.

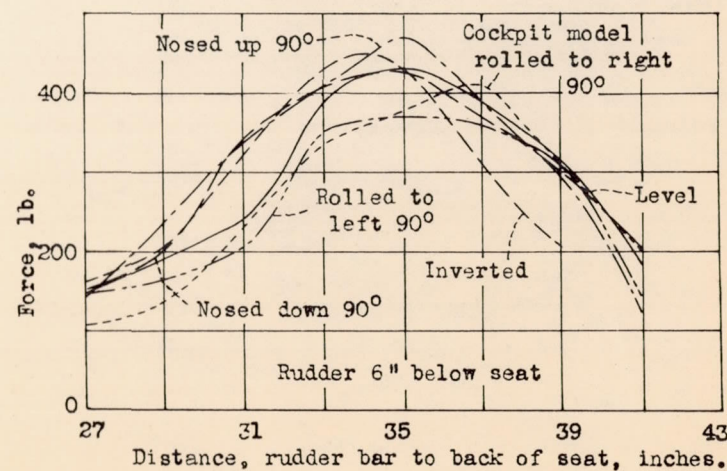
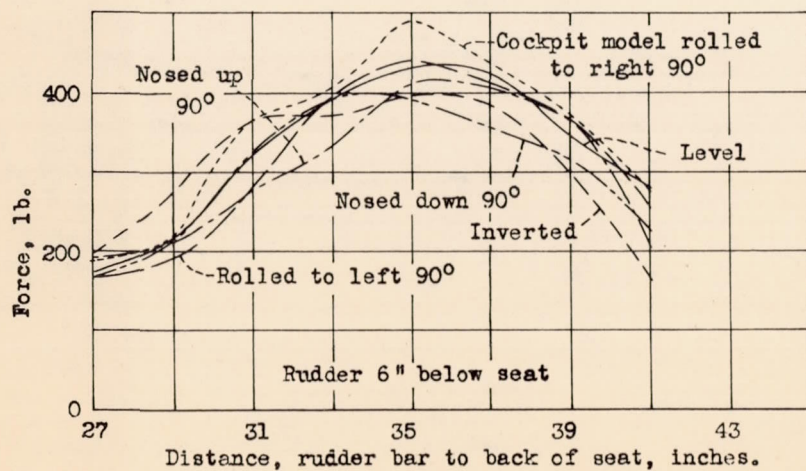
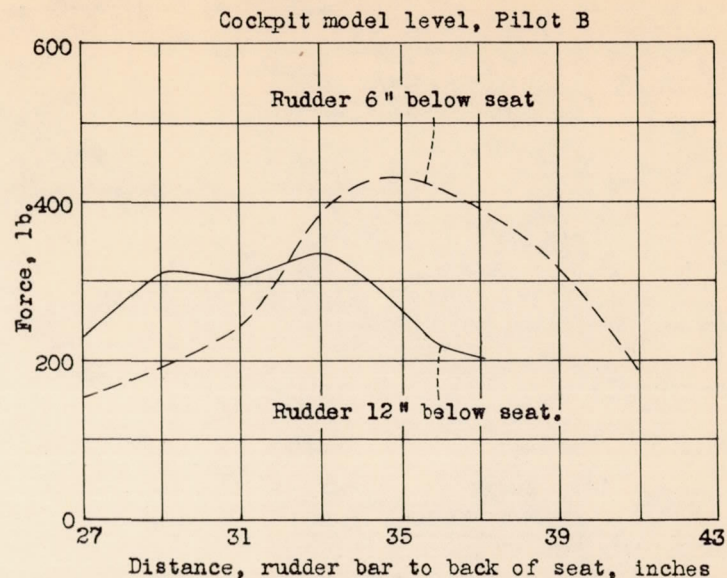
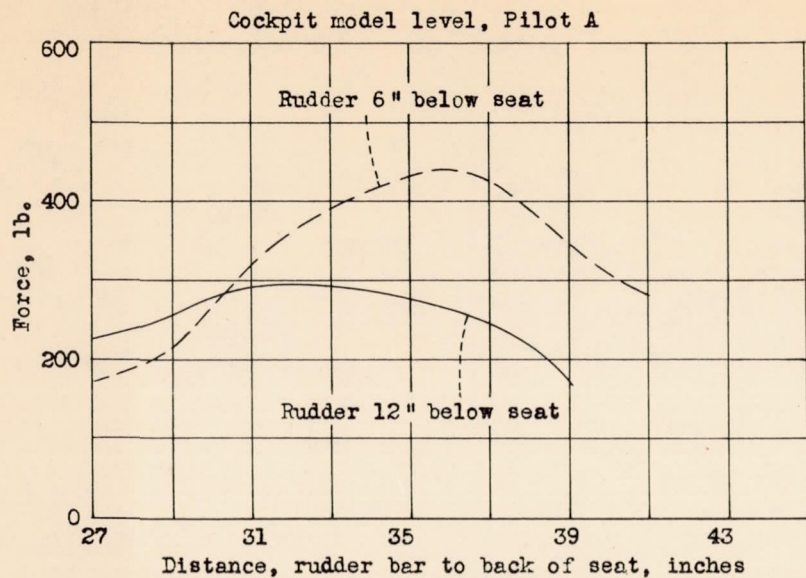


Figure 14.- Variation of rudder forces.

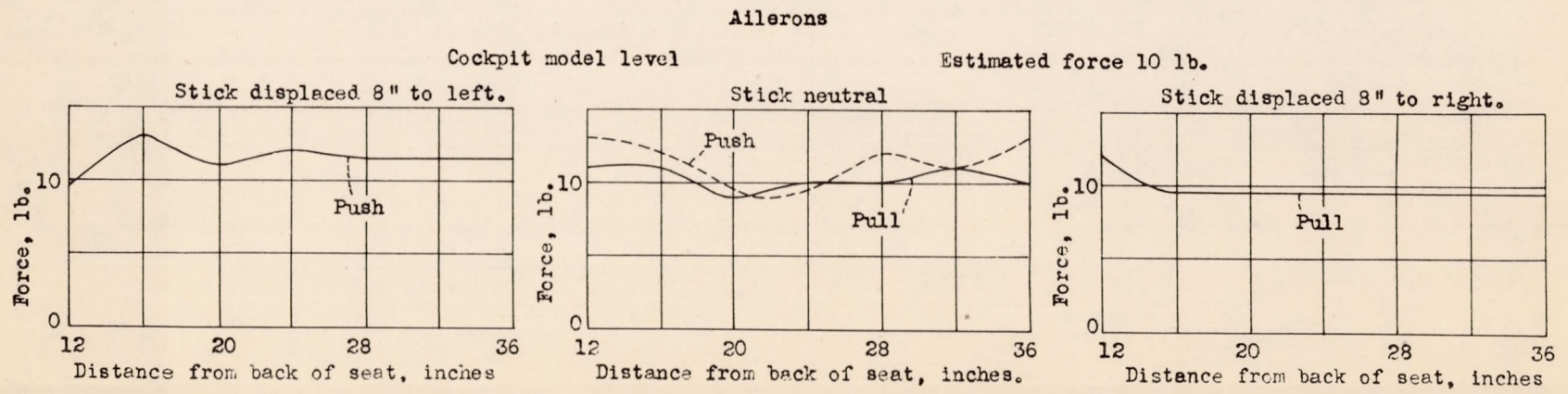
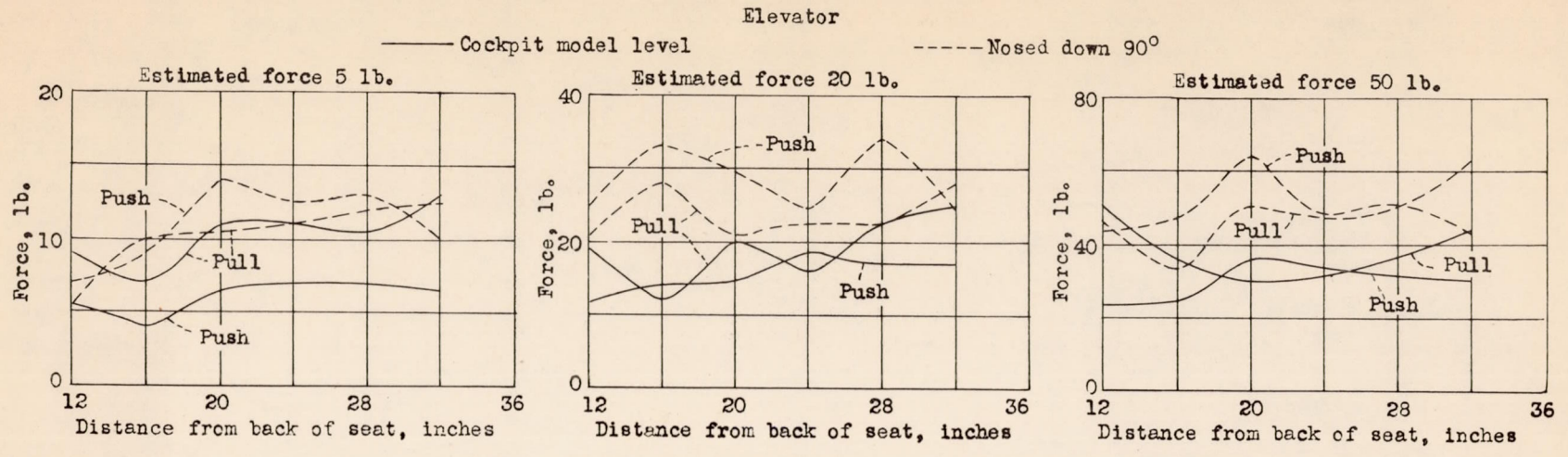


Figure 15.- Comparison of measured and estimated stick forces. Pilot A.

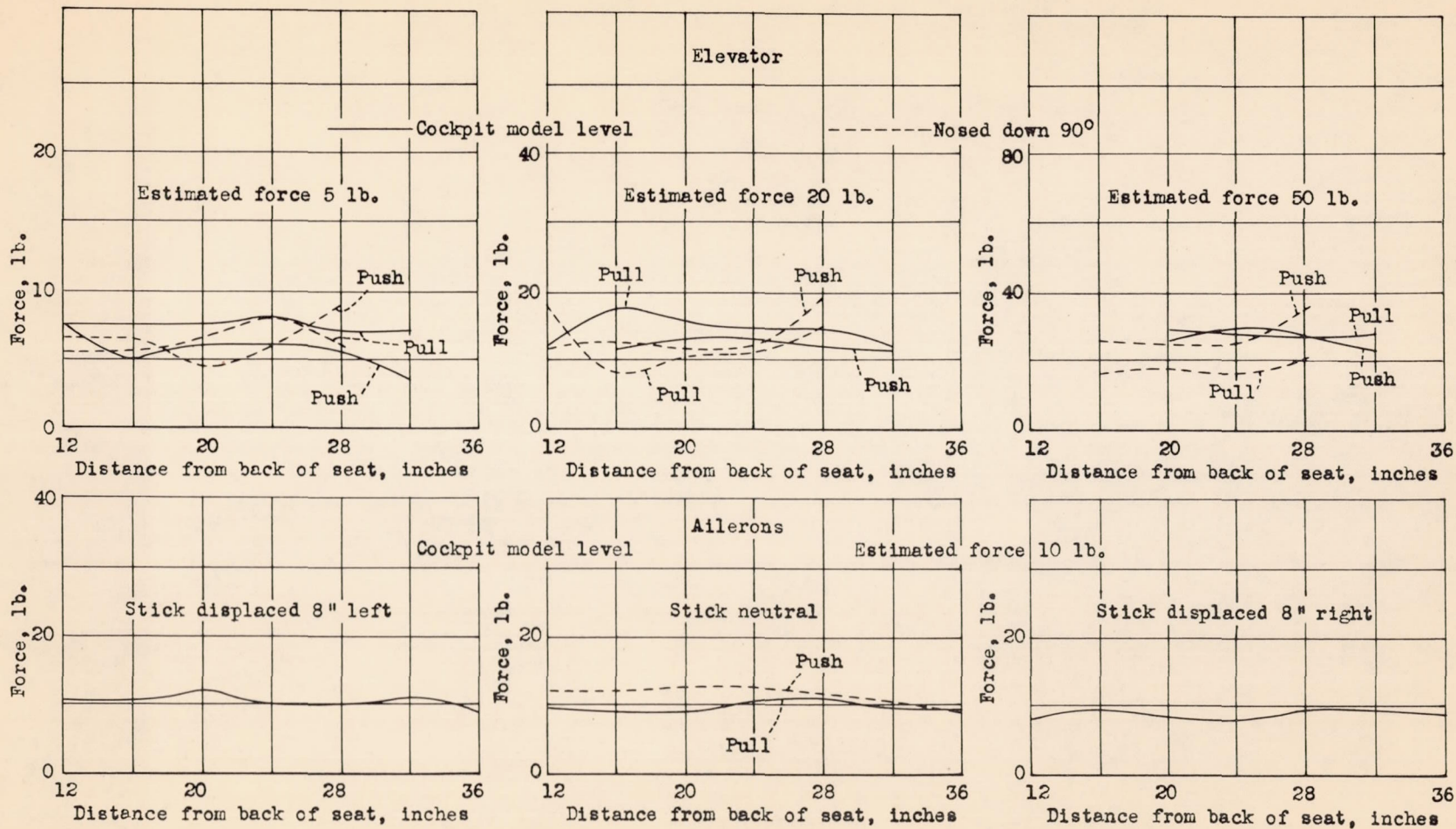


Figure 16.- Comparison of measured and estimated stick forces, Pilot B.