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A FLIGHT INVESTIGATION OF NACA AILERON MODIFICATIONS FOR THE IMPROVEMENT OF THE LATERAL CONTROL CHARACTERISTICS OF A HIGH-SPEED FIGHTER AIRPLANE

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ADVANCE [redacted] REPORT

A FLIGHT INVESTIGATION OF NACA AILERON MODIFICATIONS FOR THE IMPROVEMENT OF THE LATERAL CONTROL CHARACTERISTICS OF A HIGH-SPEED FIGHTER AIRPLANE

By Walter C. Williams

SUMMARY

A flight investigation was made to improve the lateral control of a high-speed fighter airplane. Tests were made of the airplane with the original aileron installation and with a set of modified ailerons developed by the NACA. This modification consisted of an increased balance chord and increased nose radius. In order to determine the best aileron performance with the NACA modified aileron, tests were made with various aileron-deflection ranges and riggings with the original control assembly and with an experimental differential control unit developed by the manufacturer. The test program included the speed range from 150 to 400 miles per hour.

The NACA modified ailerons with either of two mechanical advantages were found to improve the aileron performance over that obtained with the original ailerons. The modified ailerons with a deflection range of ±15° and the differential control unit appreciably increased the aileron effectiveness obtainable at level-flight speeds with a 50-pound stick force, but showed a slight decrease in the effectiveness obtainable at a speed of 400 miles per hour with a 50-pound stick force. On the other hand, the modified ailerons with a deflection range of ±13.4° and the modiffed differential control unit gave only a slight increase in the effectiveness obtainable at level-flight speeds, but gave an appreciable increase in the aileron effectiveness obtained at a speed of 400 miles per hour with a 50-pound stick force. Indications were that the aileron structure would need to be strengthened, however, before the latter arrangement could be safely used.

INTRODUCTION

The original ailerons of a high-speed fighter airplane gave very light stick forces at small aileron deflections, but because of separation about the very sharp aileron lead-ing edge, the forces near full deflection were very heavy. The sharp-nose balance on this aileron was also considered to be the cause of aileron overbalance and oscillation in extreme high-speed dives. It appeared that a balance of increased nose radius would eliminate the separation about the balance nose at high aileron deflections and would also decrease the tendency of the aileron to overbalance at extremely high speeds. The NACA, therefore, undertook a flight investigation to determine the control characteristics of modified ailerons on the airplane. Tests were also made to determine the characteristics of the original ailerons in order to have comparable data.

SYMBOLS

p rolling velocity, radians per second

b wing span, feet

V_i indicated airspeed, miles per hour $\left(K\sqrt{\frac{2q}{\rho_o}}\right)$ (reference 1)

V true airspeed, feet; per second $\left(\sqrt{\frac{2q}{\rho}}\right)$ (reference 1)

q dynamic pressure, pounds per square foot $\left(\frac{1}{2}\rho V^2 = K\frac{1}{2}\rho_o V_i^2\right)$ (reference 1)

$\bar{c}_w$ average wing chord of portion of wing ahead of aileron

$\bar{c}_a$ average aileron chord

$\bar{c}_b$ average aileron balance chord

AIRPLANE AND APPARATUS

The plan form of the airplane and the location of the ailerons are shown in figure 1. Sections of the original aileron and the NACA modified aileron are compared in figure 2. Figure 3 is a schematic sketch showing the original aileron control assembly and the experimental differential control unit that was used in the latter part of the tests. The dimensions pertinent to the aileron installation are as follows:

Wing span, feet	40.776
Wing area, square feet	300
Wing plan form	Elliptical
aileron area, square feet	9.54
Aileron chord, fraction $\bar{c}_w$	0.18
Original aileron balance chord, fraction $\bar{c}_a$	0.375
NACA modified aileron balance chord, fraction $\bar{c}_a$	0.402

Airspeed, rolling velocity, and aileron position and stick force were measured by standard NACA flight instruments, The control deflections were measure8 at the ailerons in all of the tests except those of the production ailerons, and in this case they were measured at the control stick.

TESTS, RESULTS, AND DISCUSSION

The aileron characteristics were measured in abrupt aileron rolls from laterally level flight with the rudder held fixed. Records were taken of airspeed, rolling velocity, control position, and stick force. From these data, the variation of aileron effectiveness $pb/2V$ and aileron operating force with aileron deflection was determined. Aileron rolls were made at increments of approximately 50 miles per hour indicated airspeed from 150 to 400 miles per hour for most of the aileron arrangements tested.

The aileron test program can be divided as follows:

(1) Tests of the original aileron installation

(2) Tests of the NACA modified ailerons, having wooden leading edges with the following riggings:

(a) Deflection range from -16° to 12° (original aileron differehtial and mechanical advantage)

(b) Deflection range of ±11°

(c) Deflection range of ±15°

(d) Deflection range of ±15° with original differential control unit

(3) Tests of all-metal ailerons built by the manufacturer to conform to' measurements, made by their personnel, of the NACA modified ailerons and a modified differential control unit giving a deflection range of ±13.4°; tests were made with the following riggings:

(a) Normal rigging

(b) Rigging with $\frac{1}{16}$-inch shim between the aileron and hinge bracket, whfch in effect moved the hinge line forward, and thus reduced the aileron balance

(c) Rigging for 0.6° droop

(d) Rigging for 0.95° droop

For each aileron installation tested, results are presented to show:

(1) The variation of right and left aileron angle with stick position

(2) The variation of the helix angle pb/2V with change in total aileron angle

(3) The change in aileron stick force with change in total aileron angle

Tests were made with the original aileron installation, so that any tests made with the modified ailerons

on the airplane would be directly comparable. The characteristics of this aileron installation are given in figures 4, 5, and 6. Figure 4 gives the ,variation of right and left aileron angle with stick position. The variation of helix angle pb/2V with change in total aileron angle for various indicated airspeeds is given in figure' 5, and figure 6 shows the change in aileron stick force with change in total aileron angle for various airspeeds. These data indicate that the aileron stick forces were quite light for small' aileron deflections, but that they became very heavy before full deflection was reached, as shown by the sharp rise in the force curves beyond half the total aileron deflection. An aileron shake was also present.

The stick-force characteristics presented in 'figure 6 indicated that separation was occurring .around the sharp nose of the aileron balance, It was felt that an incre'ase in nose radius would eliminate separation within the aileron-deflection range used. With an increase in nose radius, however, a decrease of aerodynamic balance would be expected in the range of small aileron deflections. In order to obtain the same amount of aerodynamic balance with a well-rounded nose as was obtained with the sharp nose, an increase in the chord of the balance was considered desirable. An aileron balance of increased nose radius and increased chord was then designed, and a pair of ailerons was modified to incorporate this balance. The leading edges of these ailerons were made of wood. The nature of this change can be seen in figure 2, which compares the original aileron and the NACA modified aileron.

In the first installation of the modified ailerons, the aileron differential and mechanical advantage of the original installation were used. Figure 7 gives the variation of right and left aileron angle with stick position. The flight-test data are presented in figure 8 as the variation of pb/2V and change In aileron stick force with change in total aileron angle. It can be seen by comparing figure 8 with figure 5 that the' effectiveness per degree aileron deflection is increased with the modified ailerons, which indicates that separation does not occur over the nose of the modified ailerons. The aileron-stick-fbrce data as given in figure 8 show' that, beyond half of the total aileron deflection, the variation of aileron stick'force with aileron deflection reversed slope. This lightening in the stick force

indicated possible aileron overbalance. It is interesting to note that, in the range of total aileron angle where the force variation is linear, up and down aileron deflections are about equal (fig. 7); beydnd the total aileron deflection. at which the slope reversal occurs there is more up aileron than down. This result indicates that the up aileron was providing more balance than was needed to obtain a uniform variation of stick force with aileron deflection. On the basis of these data tests were planned of the NACA modified ailerons rigged to give equal up and down aileron deflection throughout the deflection range.

Aileron bell cranks that would give an aileron-deflection range of' approximately ±11° were available. Although the use of these bell cranks would cause a reduction in the available pb/2V because of the restricted aileron travel, it was felt that the data obtained from tests with this deflection range would indicate whether or not equal up and down aileron travel would eliminate the reversal in slope of the variation of stick force with aileron deflection. The relation of the motion of the right and left aileron with stick deflection is given in figure 9. The data obtained in flight are given in figures 10 and 11 in the sane form as that for the preceding data. Inspection of the aileron-stick-force curves given in figure 11 shows that the slope reversal was eliminated.

Upon completion of the tests of' the NACA modified ailerons with the deflection range of ±11°, 'it was decided to increase the total aileron-deflection range' and' thus to Increase the available pb/2V. Aileron bell cranks that would give a deflection range of ±15° were designed and manufactured. The motion of the right and left aileron with stick deflection obtained with these bell cranks is given in figure 12. The stick travel to the right was limited by the balance of the downgoing left aileron striking the face of the slot. The flight-test data for this modification are presented in figures 13 and 14. Figure 13 shows that a value of pb/2V of 0.097 was obtained. It should also be noted that the slope of the stick-force curves in figure 14 is greater than that of the curves in figure 11, because of the decreased mechanical advantage with the aileron deflection range' of ±15°.

From the data obtained in the tests described thus far, figure 15 was constructed. This figure gives the

values of pb/2V obtained throughout the speed range with a 50-pound stick-force limitation for the original ailerons, the NACA modified ailerons with a deflection range of ±11°, and the NACA modified ailerons having a deflection range of ±15°. It can be seen from this figure that the NACA modified ailerons with a deflection range of ±15° caused an appreciable increase over the original ailerons in the pb/2V obtained at level-flight speeds, but the rolling obtained at diving speeds was reduced.

When the tests that have been described were completed, the manufacturer became interested in the NACA modified ailerons. A lateral control problem peculiar to extremely high speeds had arisen; the original ailerons were overbalancing and oscillating in high-speed dives. The NACA modified aileron, which gave lower pressure peaks with the round-nose balance than did the original aileron with the sharp-nose balance, was considered to be less susceptible to this overbalancing condition. In addition to giving lower pressure peaks, the NACA modified balance does not unport as early as the original balance, which should delay any "snatch" in the ailerons. It was felt, however, that the pb/2V available with a 50-pound stick force at high speeds with the NACA modified ailerons should be increased. In order to accomplish this improvement in control at high speeds, the manufacturer suggested a differential control unit; this differential control unit is a device that gives increased mechanical advantage at the smaller aileron deflections and a resultant decrease in mechanical advantage near full deflection. The control unit was incorporated in the stick cradle, (See fig. 3(b).)

Figure 16 gives the variation of right and left aileron angle with stick position obtained with the differential control unit. The results presented in this figure show that, in addition to the changes in mechanical advantage described previously, an increase in the overall mechanical advantage of approximately 9 percent over the NACA installation was obtained. This increase was caused by the increased stick travel, The differential control unit used 9.8 inches' of stick travel to obtain aileron deflections of ±15°, whereas the NACA installation used 9 inches, which is the Army standard (reference 2), to obtain the same deflection range. The data obtained from the flight tests are shown in figures 17 and 18. A comparison of figures 18 and 14 shows that the

differential control unit changed the variation of stick force with aileron deflection from linear to a curve with lower forces at the small deflections and higher forces at full deflections. For direct comparison, a curve showing the values of $pb/2V$ obtained throughout the speed range with the NACA modified ailerons and the differential control unit was plotted on figure 15. Inspection of this curve shows that, although the values of $pb/2V$ obtainable at level-flight speeds were somewhat reduced with the differential control unit, an increase of approximately 20 percent was obtained in the effectiveness for a 50-pound stick force at a speed of 400 miles per hour.

Upon completion of the tests described in the preceding paragraph, the differential control unit was modified by the manufacturer to obtain a greater increase in mechanical advantage at the sacrifice of some aileron deflection, The manufacturer also constructed a set of all-metal ailerons made to the same contour as that of the NACA modified aileron. The modified differential control unit gave an aileron-deflection range of approximately ±13.4°, with the sane stick travel as that of the original differential control unit. The variation of left and right aileron deflection with stick position is shown in figure 19. The flight-test data are presented in figures 20 and 21. A comparison of the force data given in ffgure 21 with that given in figure 18 shows that, except for approximately the first $7\frac{1}{2}°$ of aileron deflection, the metal ailerons and modified differential control unit had lighter stick forces than did the NACA aileron and original differential control unit. Comparison of the aileron deflections obtainable at high speeds with unpublished data on the loads on the ailerons, however, showed that it was possible for the pilot to obtain aileron deflections at which critical aileron loads are incurred. Steps were then taken to increase the aileron forces.

The first modification tested consisted of a $\frac{1}{16}$-inch shim placed between the aileron and the hinge bracket, which in effect moved the hinge line forward and thus reduced the aileron balance. Figure 22 gives the variation of right and left aileron angle with stick position with the $\frac{1}{16}$-inch shim in place. Figures 23 and 24 give

the data obtained in flight for the ailerons with $\frac{1}{16}$-inch shims in place. Comparison of the aileron-stick-force data presented in figure 24 with that of figure 21 shows that the shims increased the stick forces somewhat. It was felt, however, that drooping the ailerons would accomplish more in reducing the danger of exceeding the aileron deflections for critical loads than would the shims. The critical aileron deflections were up-aileron angles. Drooping the ailerons would not only increase the stick forces but would also, for the same change in total aileron angle, result in lower up-aileron angles. Tests were made with the ailerons drooped 0.6° and 0.95°. The data obtained with ailerons drooped 0.6° are given in figures 25, 26, and 27. These figures give, respectively, the variation of right and left aileron angle with stick position, the variation of helix angle $pb/2V$ with change in total aileron angle, and the change in aileron stick force with change in total aileron angle. In like manner, figures 28, 29, and 30 present the data obtained with the ailerons drooped 0.95°. Comparison of the force data given in figures 27 and 30 for the drooped ailerons with the force data of figure 21 for the ailerons rigged normally shows that drooping the ailerons not only increased the stick forces but also made their variation with aileron deflection more nearly linear. Comparison of these stick-force data with the unpublished data on aileron loads showed that the ailerons with 0.95° droop would make it impossible for the pilot to exceed the critical aileron deflections. It should also be noted that if the modified ailerons tended to overbalance at extremely high speeds in a manner similar to the original ailerons, the overbalance could be lessened by drooping the ailerons.

In order to show more clearly the effects of the small modifications tested, the results are summarized in figure 31, which gives the values of $pb/2V$ obtained with a 50-pound stick force throughout the speed range with the modified differential control unit and the all-metal modified ailerons with normal rigging, $\frac{1}{16}$-inch shim, 0.6° droop, and 0.95° droop. This figure shows that highly balanced surfaces such as the ailerons tested are very sensitive to small changes in rigging.

Ffgure 32 was prepared so that a selection could be made of the mechanical advantage to be used with the

modified ailerons to produce the best all-round aileron performance. The NACA modified ailerons with a deflection range of ±15° and the original differential control unit gave the best performance of the modified-aileron configurations presented in figure 15. The best performance of the configurations presented in figure 31 is given by the metal modified ailerons with the normal rigging and the modified differential control unit. It must be remembered, however, that the latter arrangement can be used only if the ailerons are strengthened. Figure 32 gives the pb/2V values obtained with a 50-pound stick force throughout the speed range with the two aileron installations just described. Data for the original ailerons are included on this figure as a reference. Inspection of this figure shows that the modified ailerons with either mechanical advantage show an appreciable increase in effectiveness over that obtained with the original ailerons with a 50-pound stick force. The modified ailerons with a deflection range of ±15° and the original differential control unit offer an appreciable increase in pb/2V obtainable with a 50-pound stick force at level-flight speeds but give a slight decrease at a speed of 400 miles per hour. The modified ailerons with a deflection range of ±13.4° and the modified differential control unit show an increase in pb/2V obtainable with a 50-pound stick force throughout the speed range. This increase is small at level-flight speeds but is appreciable at a speed of 400 miles per hour.

No quantitative data are available on the modified ailerons at extremely high speeds, but high-speed dives are reported to have been made with these ailerons without overbalance or aileron oscillations being encountered. It is believed that the ailerons in this case had a deflection range of ±15° with the differential control unit and were drooped about 1°. With this arrangement the values of pb/2V obtained with a 50-pound stick force would be somewhat less than those obtained with the similar arrangement without droop shown in figure 32. The effects of droop are shown in figure 31.

CONCLUSIONS

From the results of flight tests made to improve the lateral control of a high-speed fighter airplane, the following conclusions were drawn:

1. The data demonstrate that the problem of aerodynamically balancing control surfaces on high-speed airplanes is complex, since the aerodynamic balance necessary for satisfactory control-operating forces is very sensitive to small changes in rigging and balance contour.

2. NACA modified ailerons were developed with an increased balance chord and increased nose radius and were found, with either of two mechanical advantages, to improve the aileron performance over that obtained with the original ailerons. The modified ailerons with a deflection range of ±15° and a differential control unit developed by the manufacturer appreciably increased the aileron effectiveness obtainable at level-flight speeds with a 50-pound stick force but showed a slight decrease in the effectiveness obtainable at a speed of 400 miles per hour with a 50-pound stick force. On the other hand, the modified ailerons with a deflection range of ±13.4° and a modified differential control unit gave only a slight increase in the effectiveness obtainable at level-flight speeds but gave an appreciable increase in the aileron effectiveness obtained at a speed of 400 miles per hour with a 50-pound stick force. Indications were that the aileron structure would need to be strengthened, however, before the latter arrangement could be safely used.

3. The NACA modified ailerons appear to offer a solution to the problem of aileron overbalance and oscillation in high-speed dives with the airplane tested.

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2. Anon.: Handbook of Instructions for Airplane Designers. Vol. I, Materiel Div., Amy Air Corps, 8th ed., Revision 6, Oct. 1, 1942.

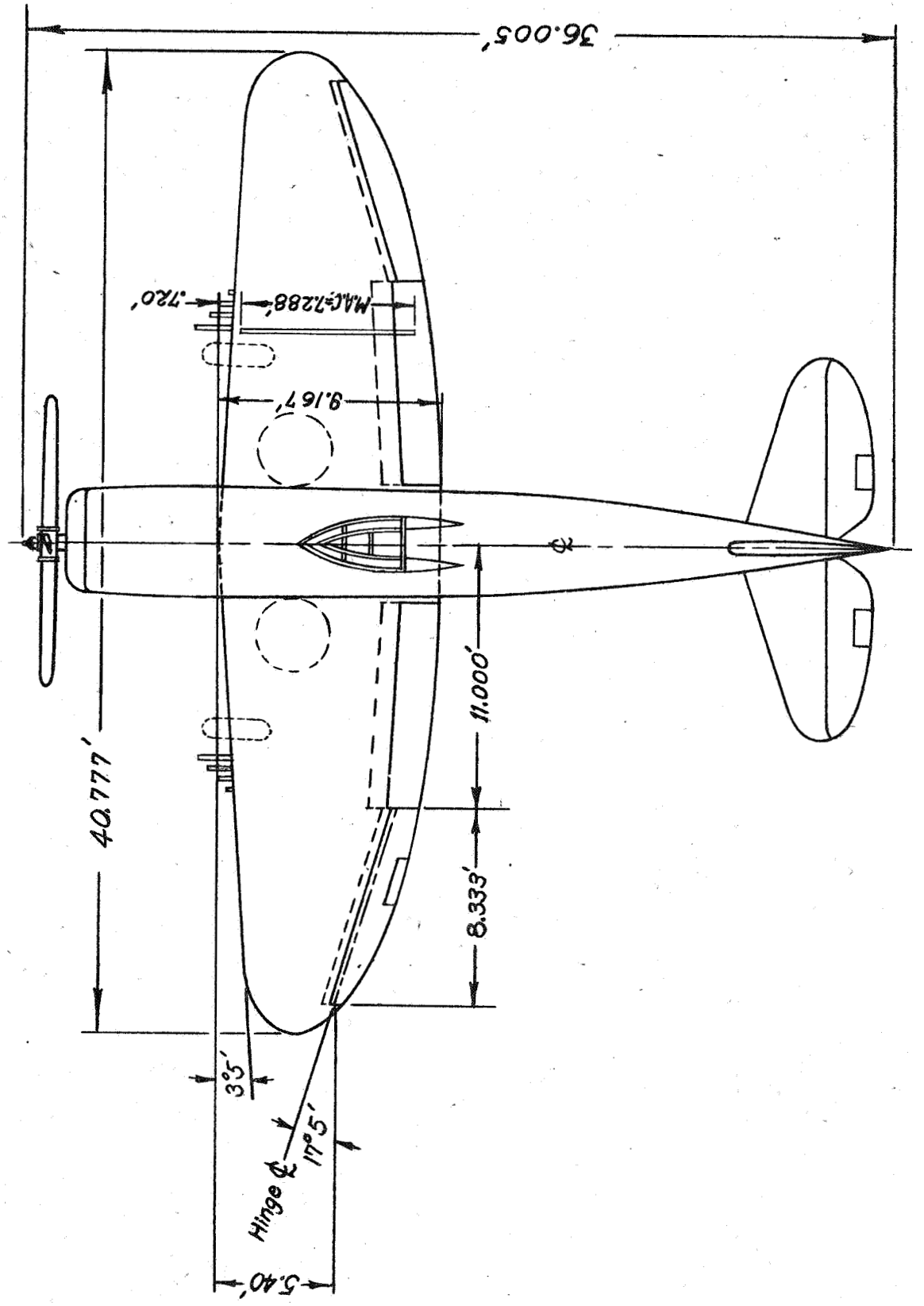

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Figure 1. - Plan form of airplane tested.

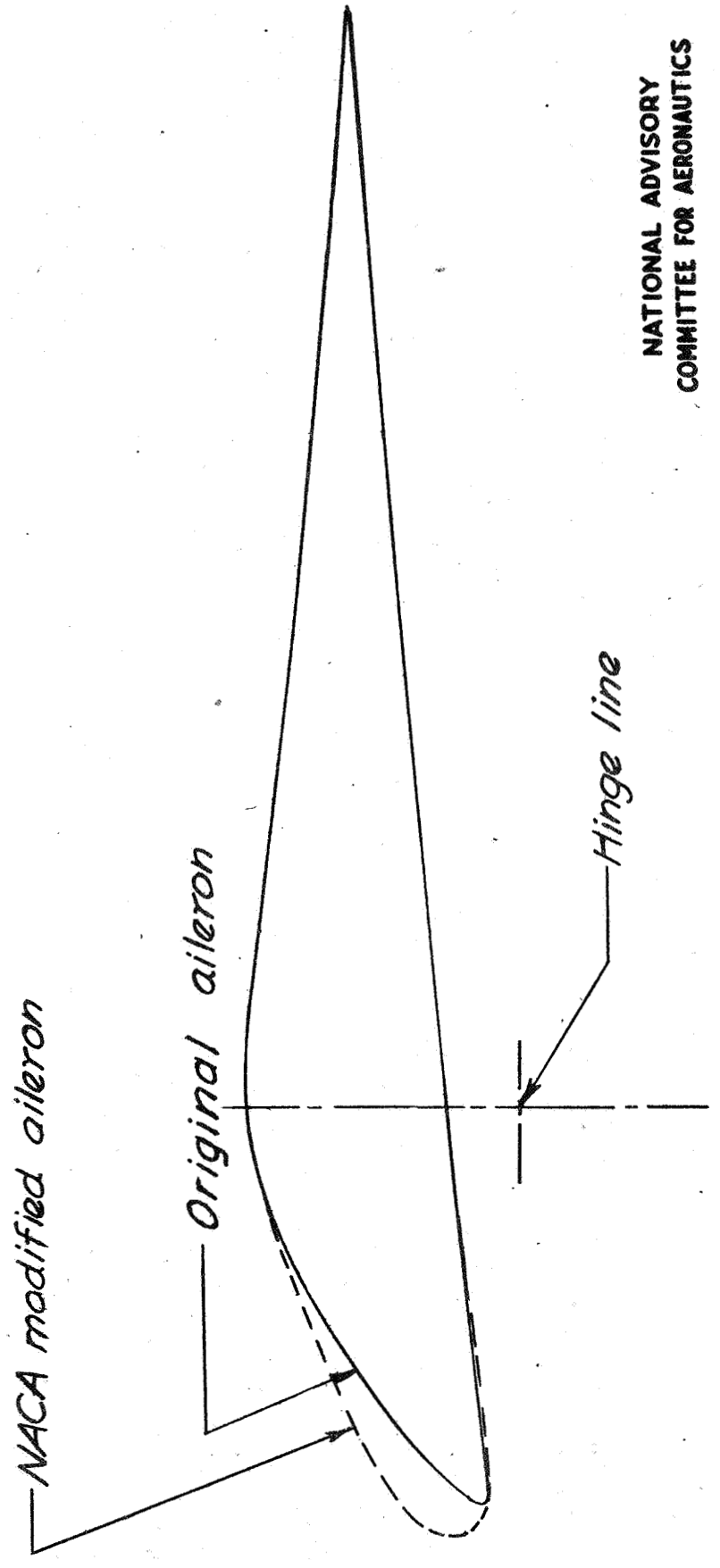

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Figure 2. - Typical cross section of original aileron showing NACA modification.

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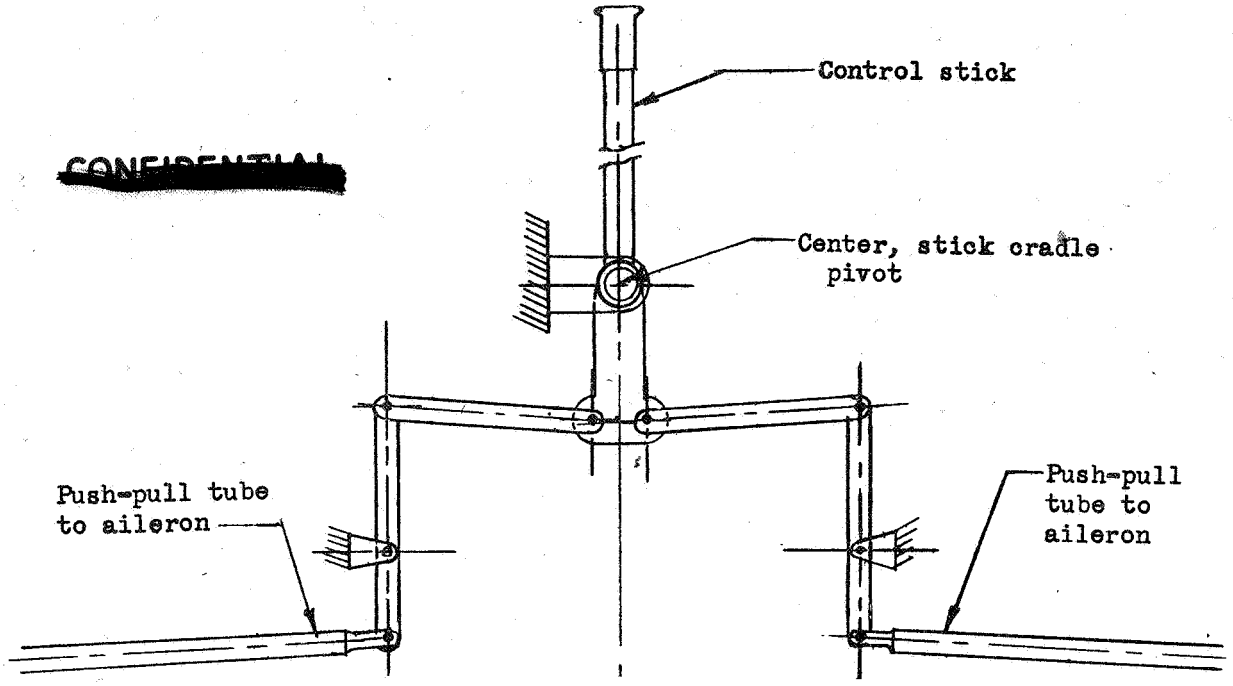
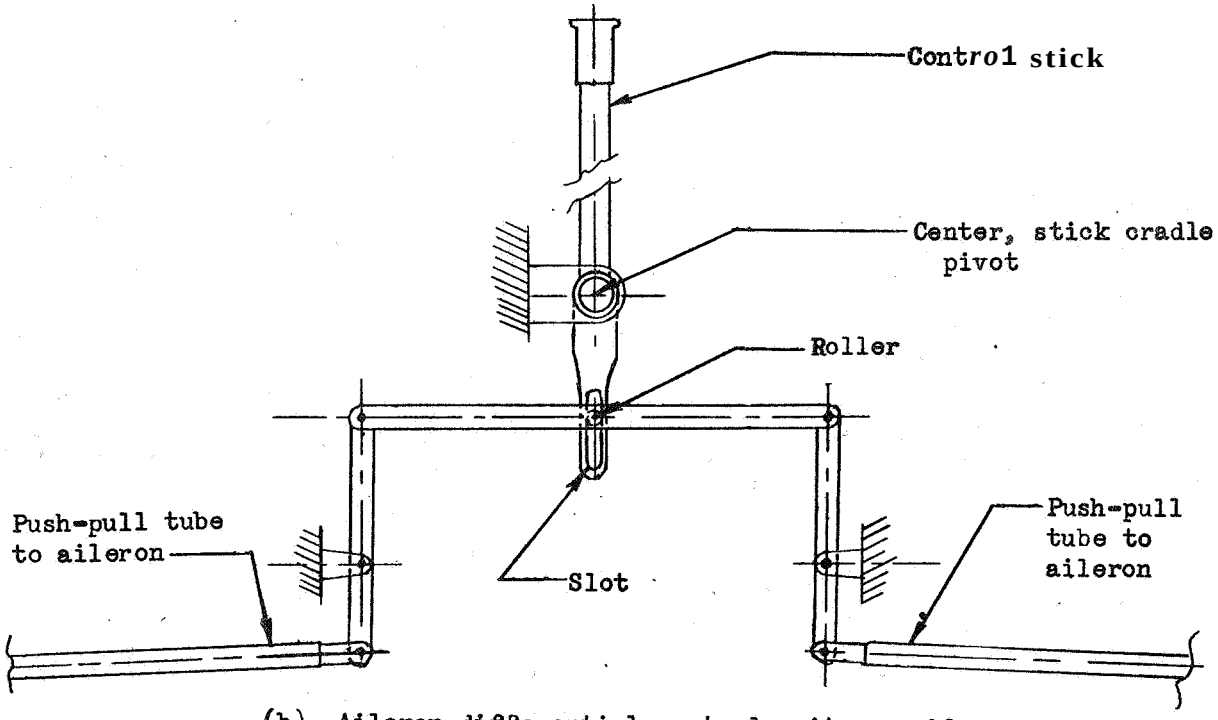


(a) Original aileron control assembly.



(b) Aileron differential-control-unit assembly.

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Figure 3. - Aileron control assemblies.

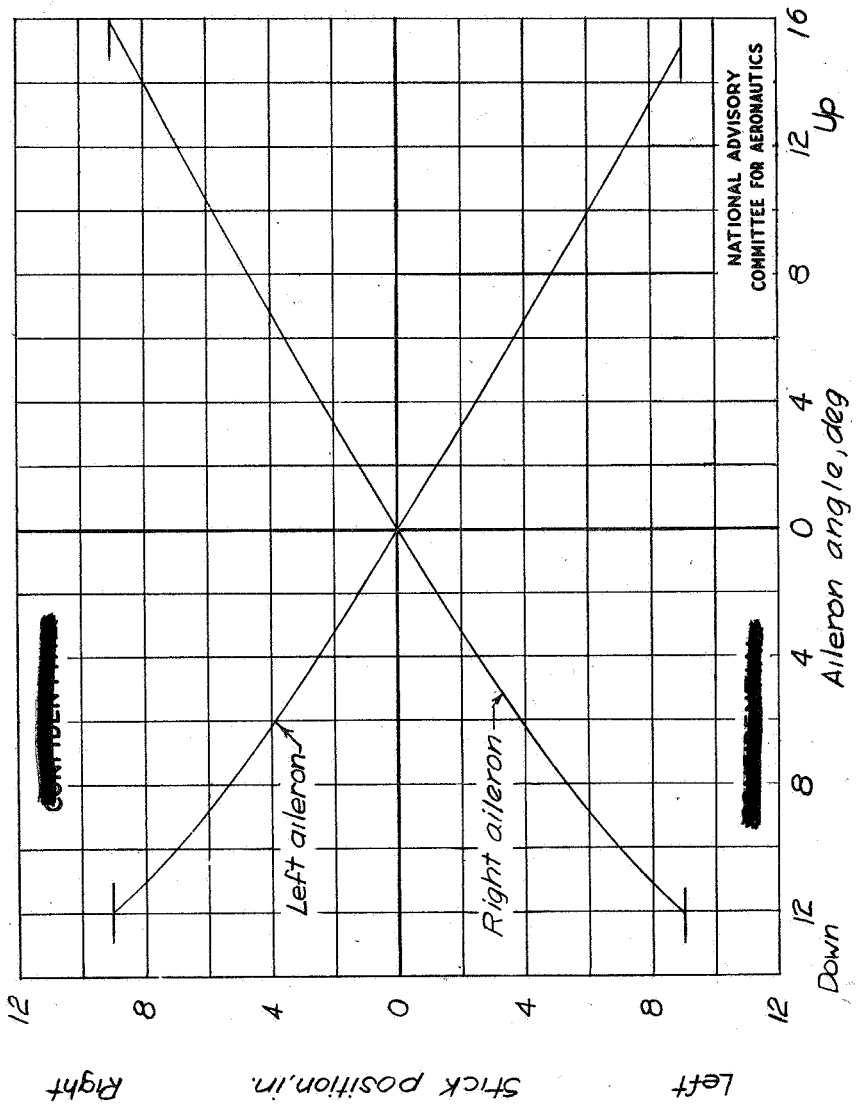

Figure 4. - Variation of left and right aileron angle with stick position. Original aileron installation.

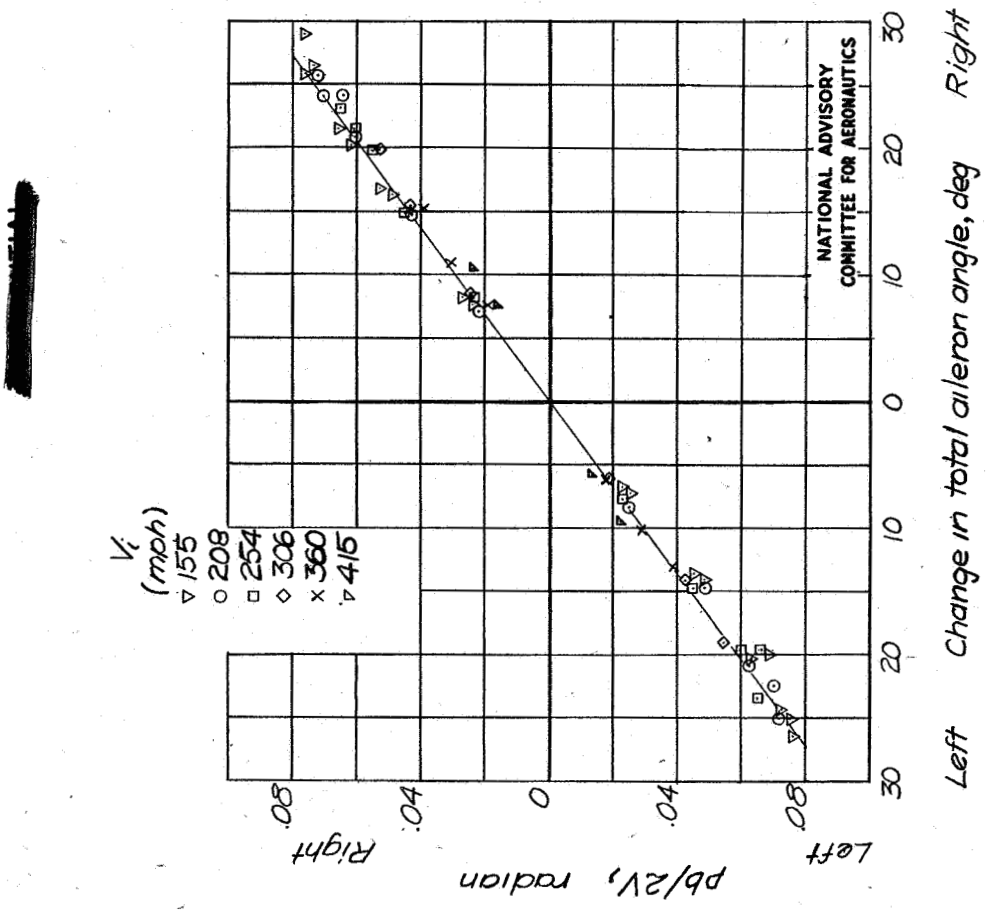

Figure 5. - Variation of helix angle pb/2V with change in total aileron angle. Original aileron installation.

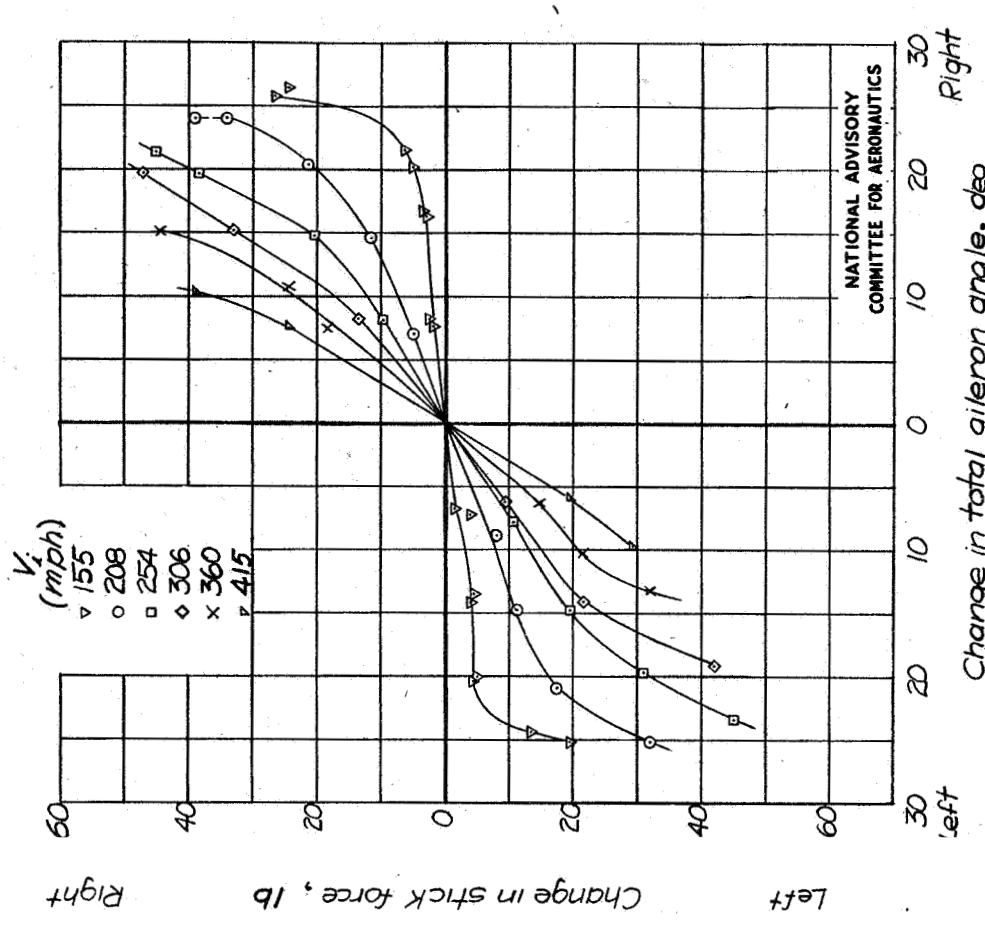

Figure 6. - Variation of change in aileron stick force with change in total aileron angle. Original aileron installation.

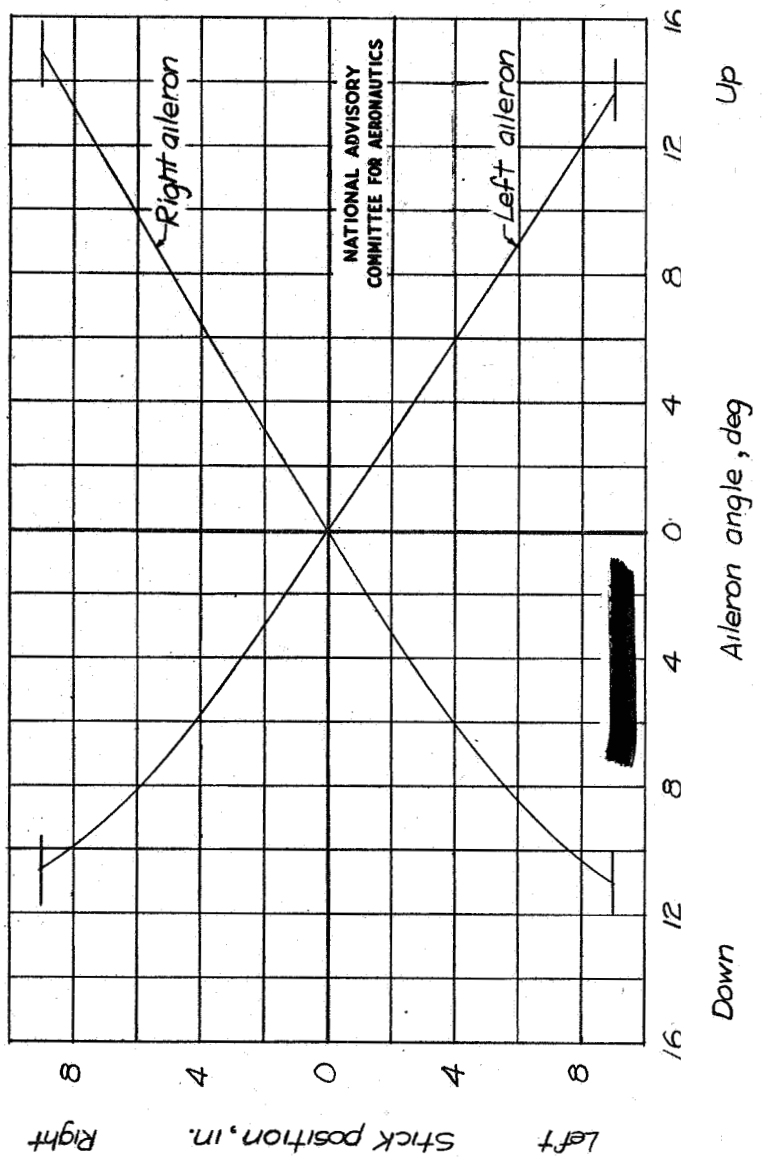

Figure 7. - Variation of left and right aileron angle with stick position. NACA modified ailerons; original aileron differential and mechanical advantage; aileron-deflection range, -16° to 12°.

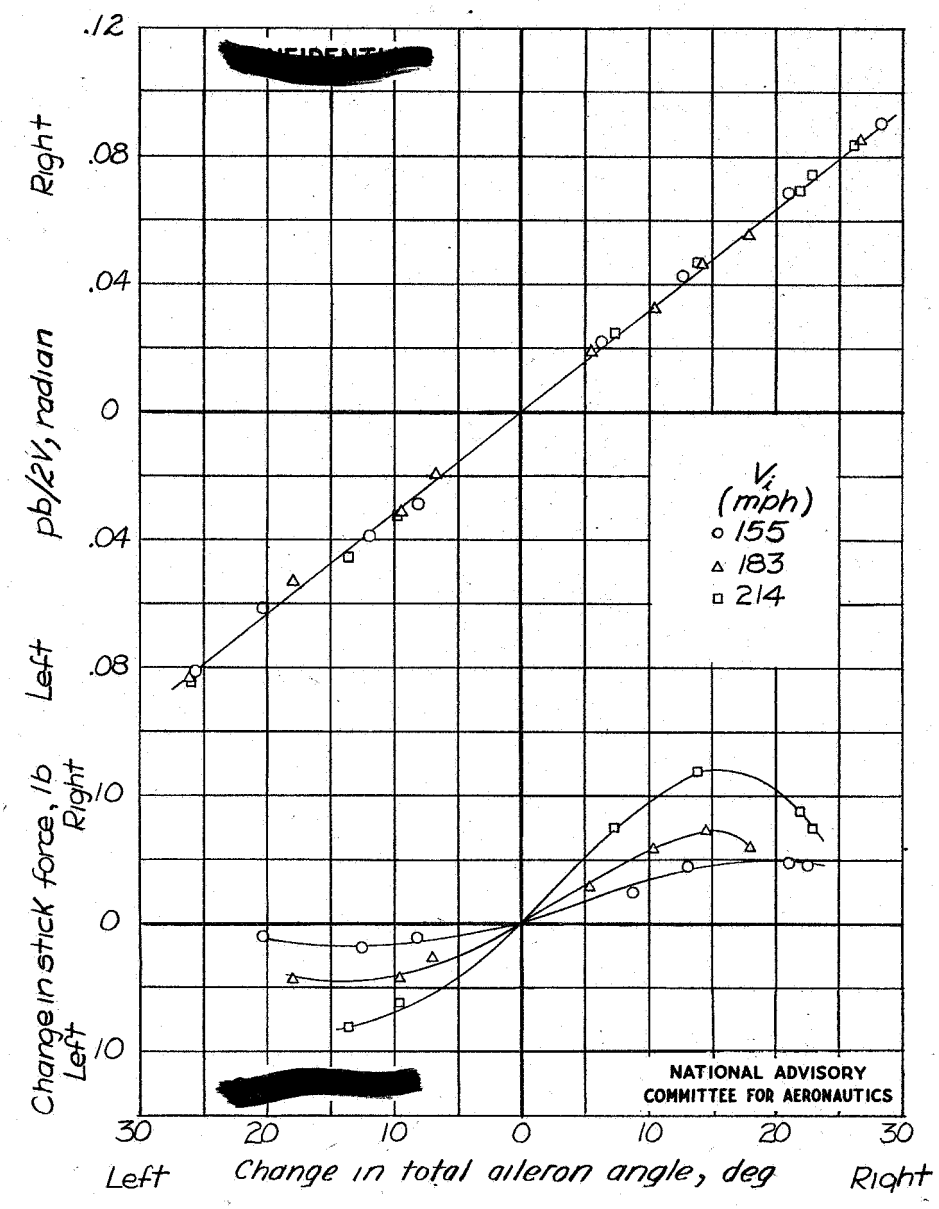

Figure 8. - Variation of helix angle $pb/2V$ and change in aileron stick force with change in total aileron angle. NACA modified ailerons; original aileron differential and mechanical advantages aileron-deflection range, -16° to 12°.

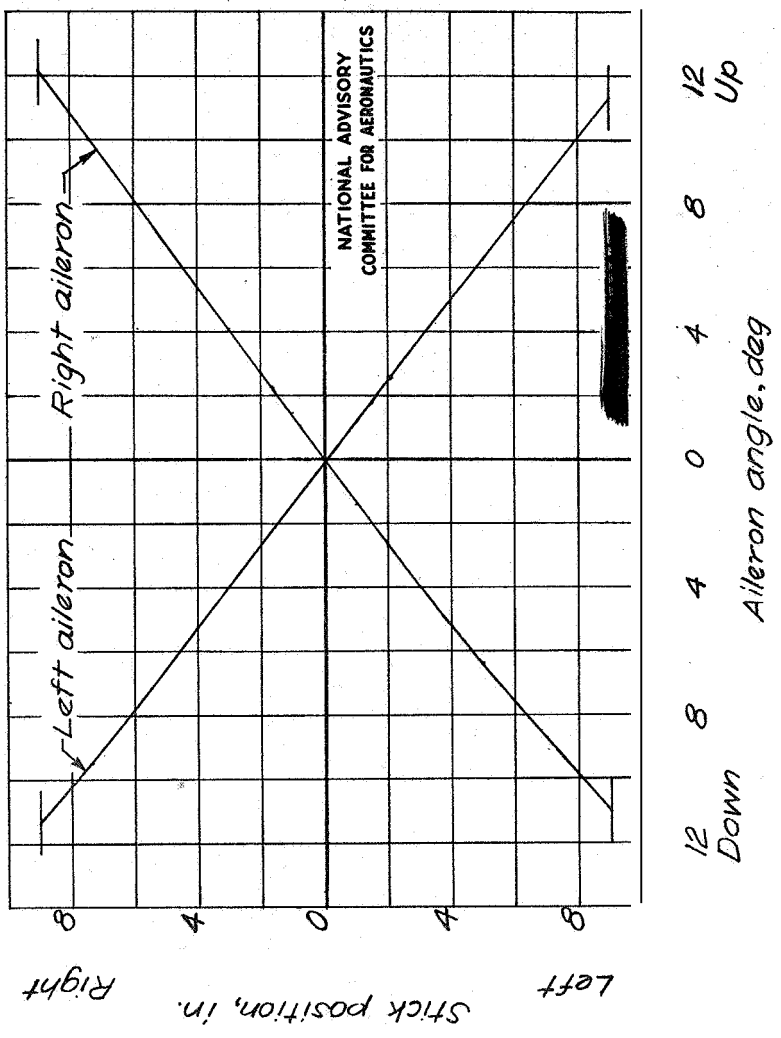

Figure 9. - Variation of left and right aileron angle with stick position. NACA modified ailerons; aileron-deflection range, ±11°.

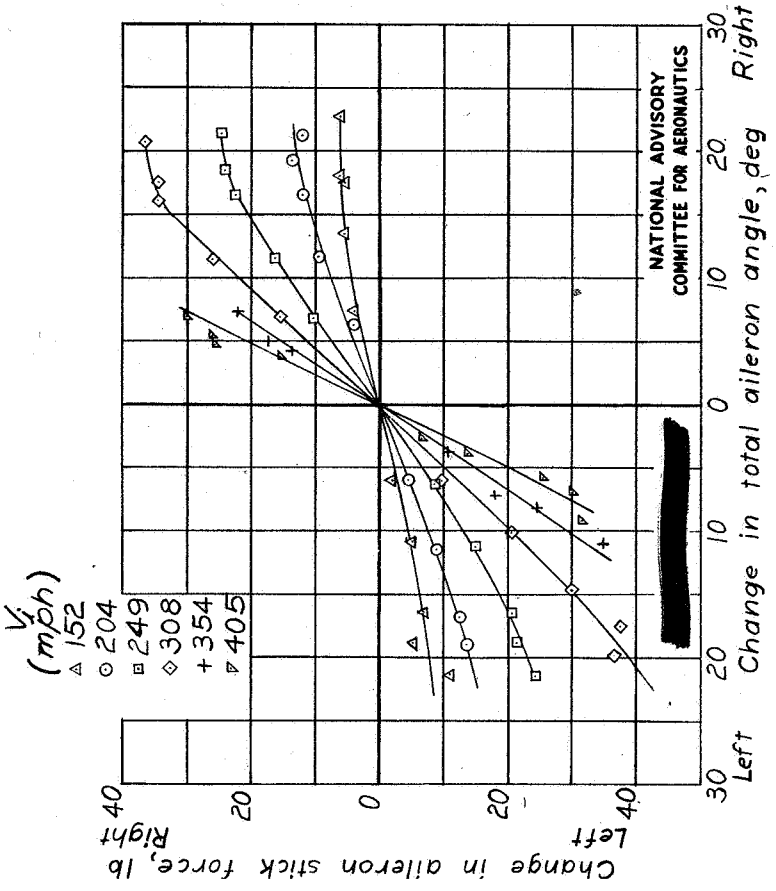

Figure 1 - Variation of change in aileron stick force with change in total aileron angle. NACA modified ailerons; aileron-deflection range, ±11°.

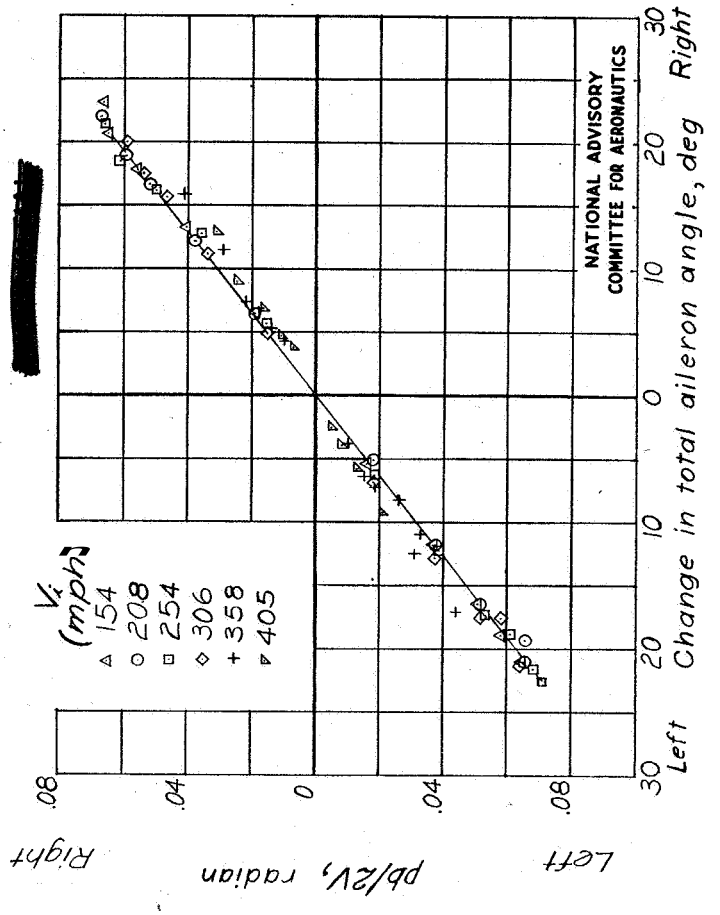

Figure 10. - Variation of helix angle pb/2V with change in total aileron angle. NACA modified ailerons; aileron-deflection range, ±11°.

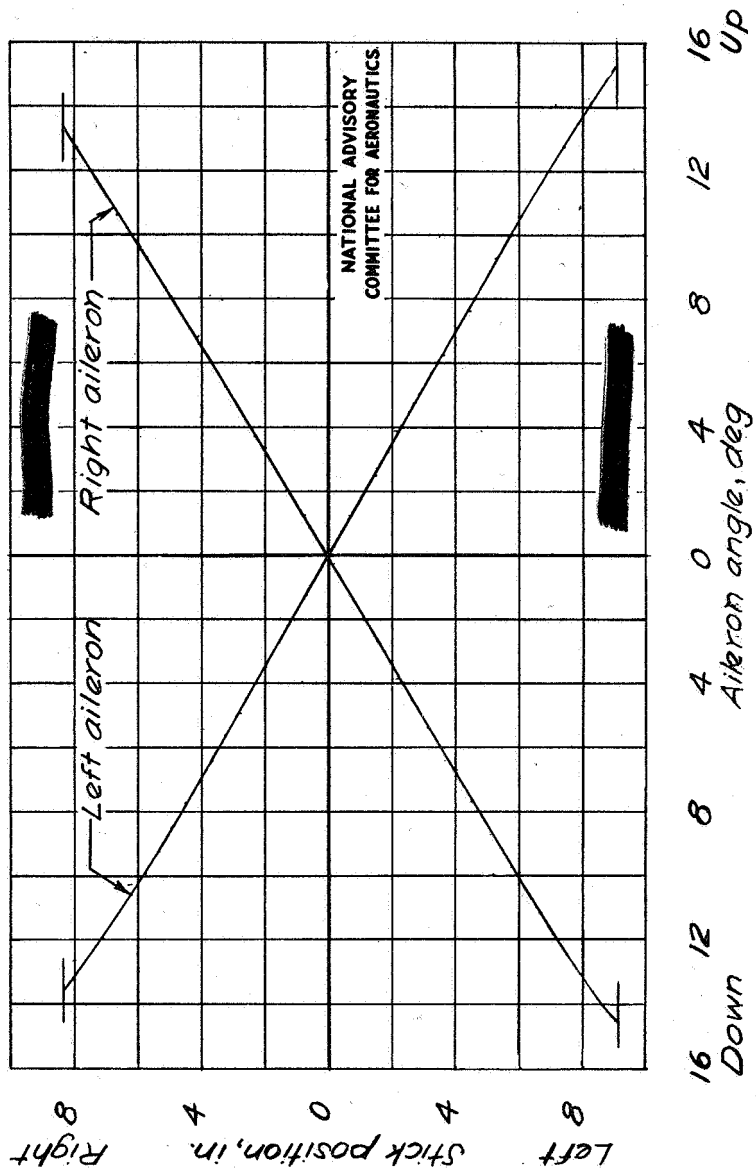

Figure 12. - Variation of left and right aileron angle with stick position. NACA modified ailerons; aileron-deflection range, ±15°.

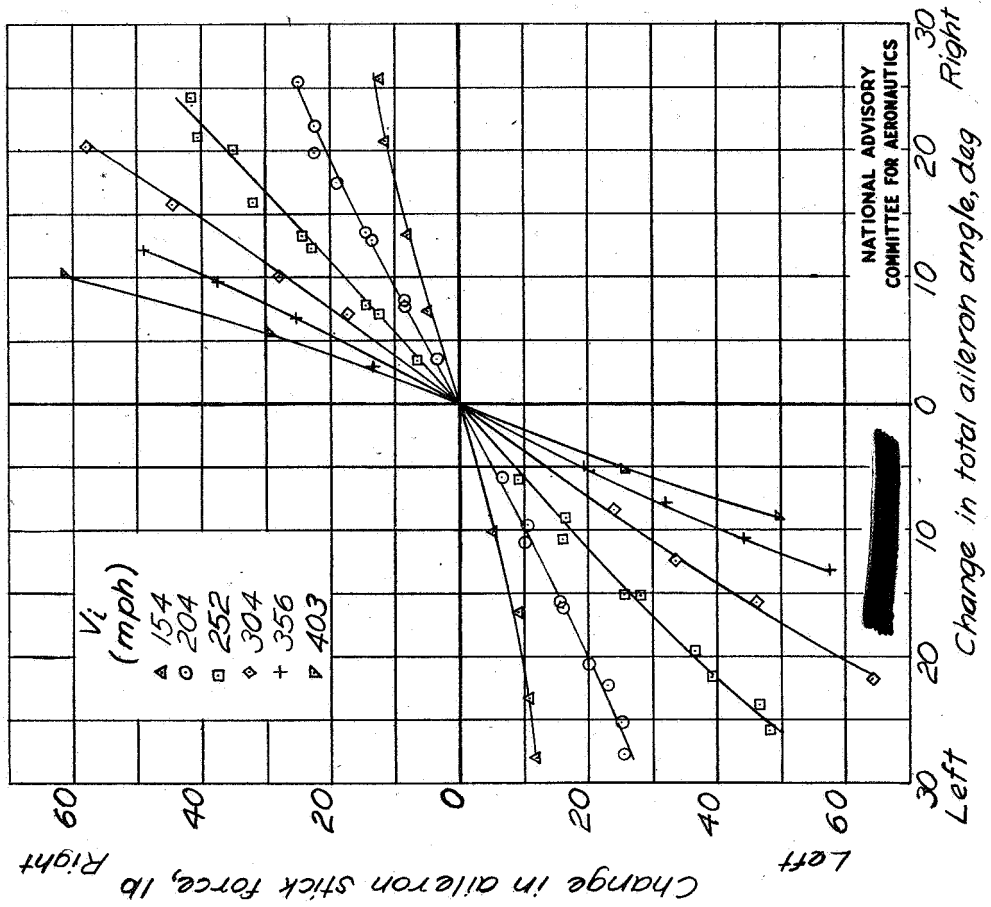

Figure 13 - Variation of change in aileron stick force with change in total aileron angle. NACA modified ailerons; aileron-deflection range, ±15°.

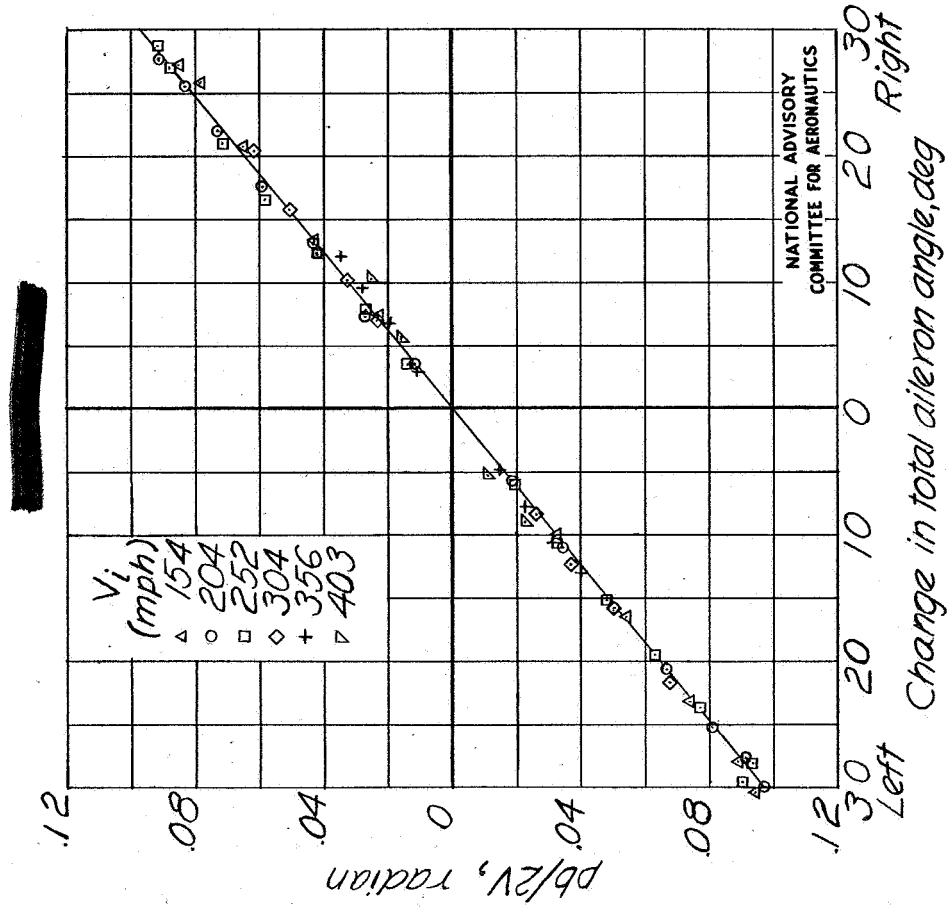

Figure 14 - Variation of helix angle pb/2V with change in total aileron angle. NACA modified ailerons; aileron-deflection range, ±15°.

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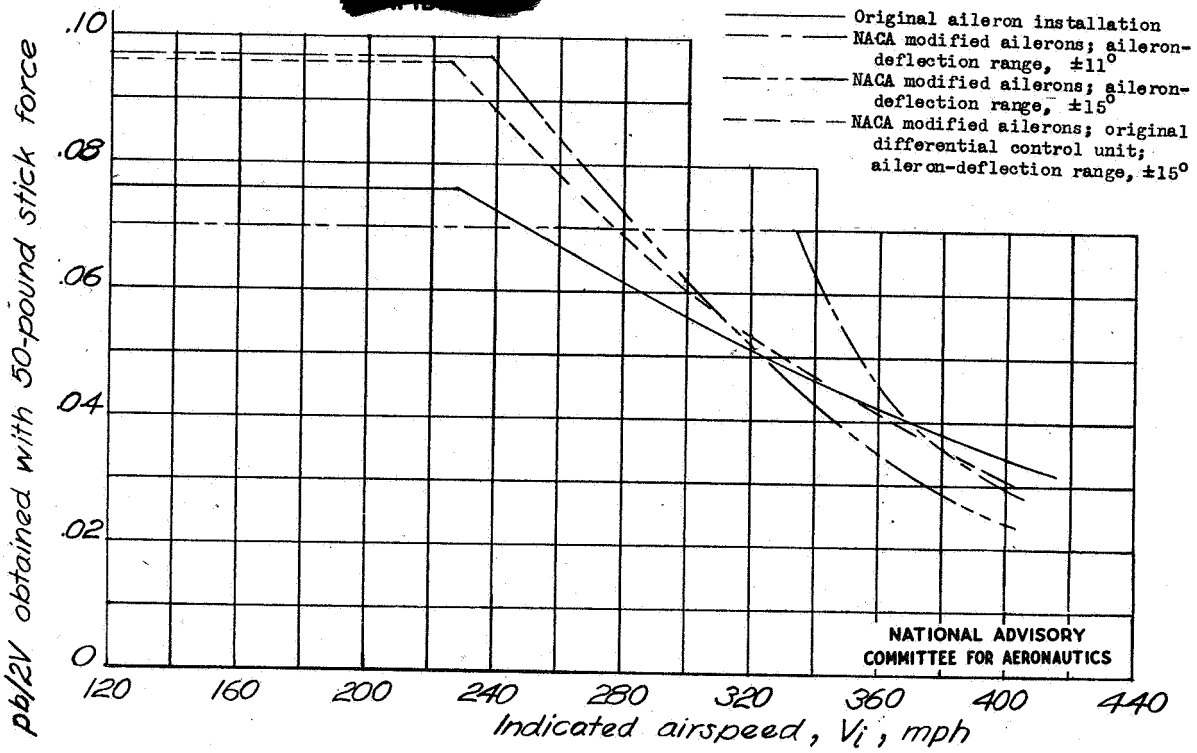
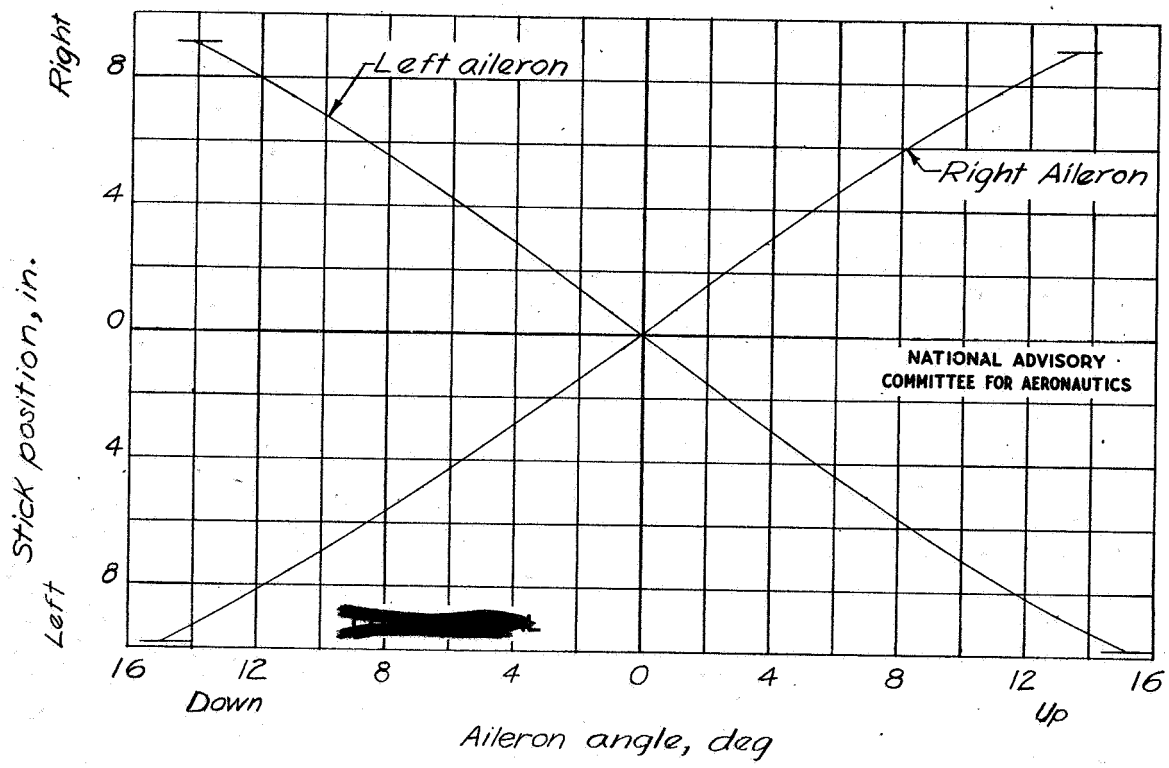


Figure 15. - Variation of helix angls pb/2V with indicated airspeed for a 50-pound stick force. Original aileron installation; NACA modified ailerons with defleation range of ±11°; NACA modified ailerons with deflection range of ±15°; and NACA modified ailerons with deflection range of ±15° and original differential control unit.



[redacted]

Figure 16. - Variation of left and right aileron angle with stick position. NACA modified ailerons; original differential control unit; aileron-deflection range, ±15°.

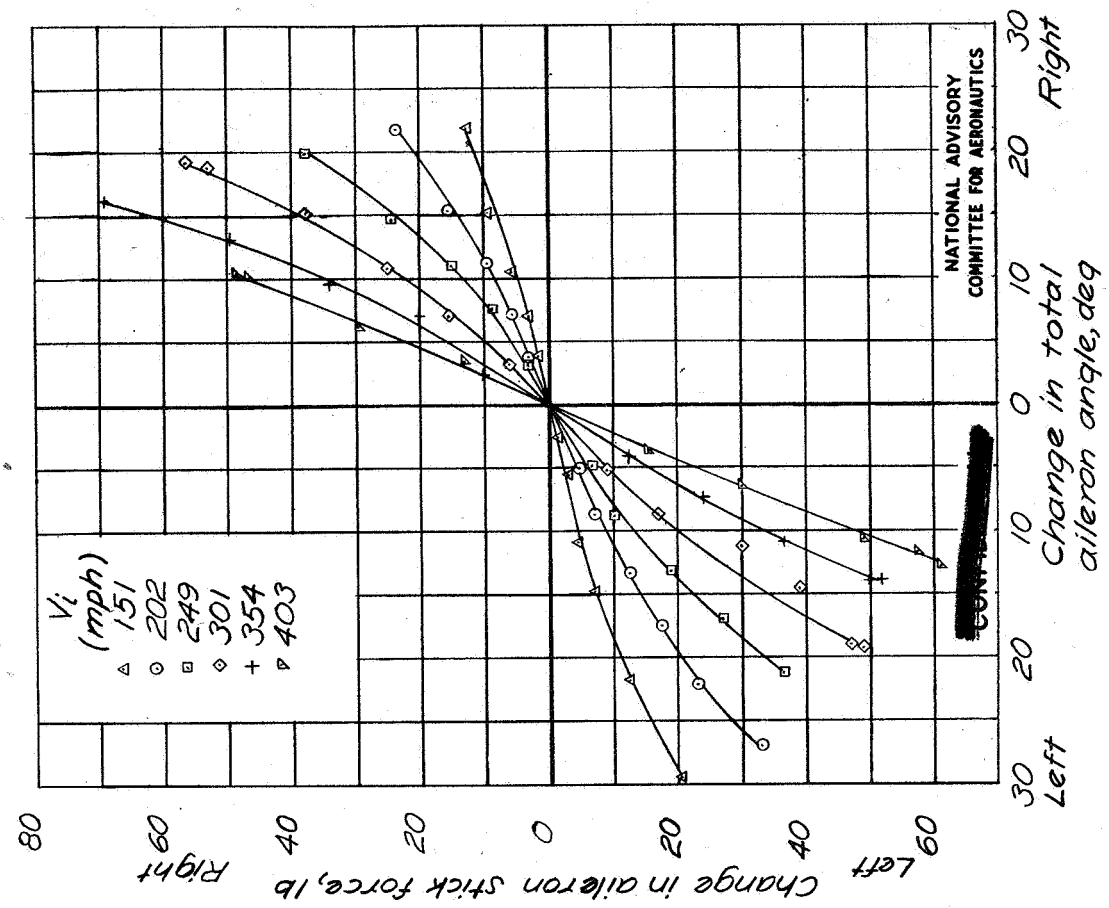


Figure 18. - Variation of change in aileron stick force with change in total aileron angle. NACA modified ailerons; original differential control unit; aileron-deflection range, ±15°.

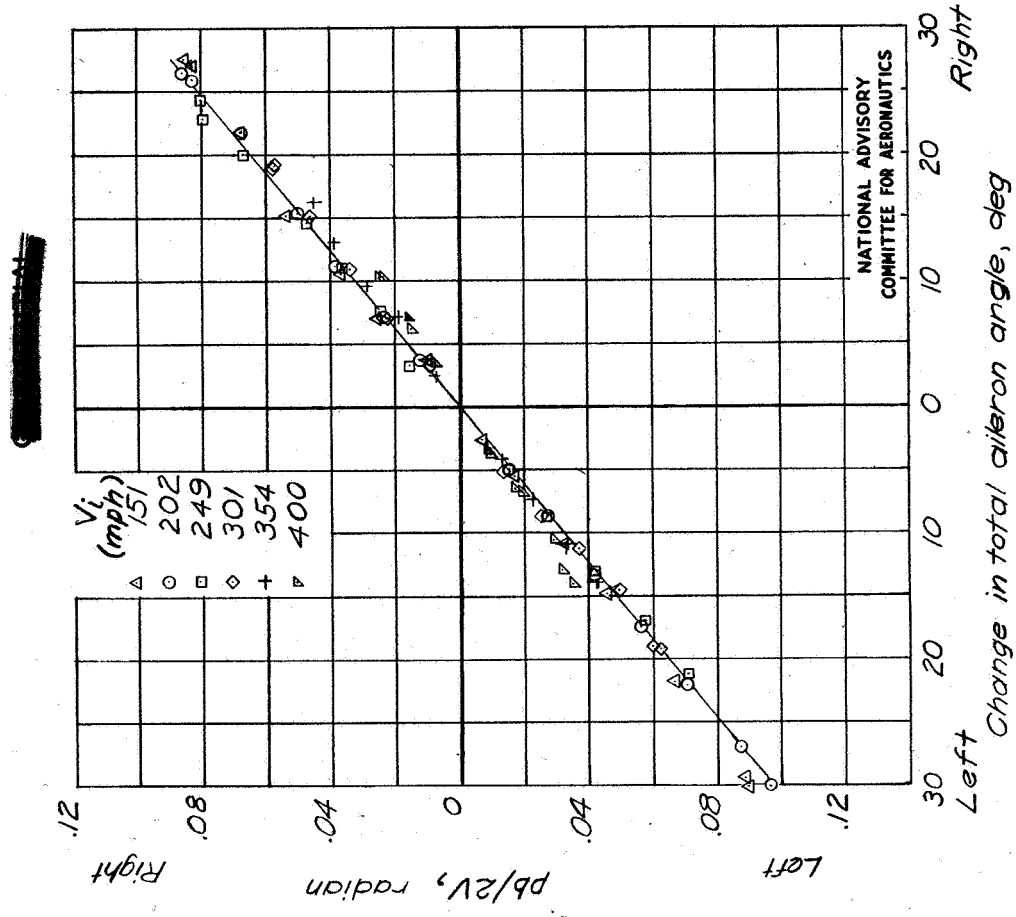


Figure 17. - Variation of helix angle pb/2V with change in total aileron angle. NACA modified ailerons; original differential control unit; aileron-deflection range, ±15°.

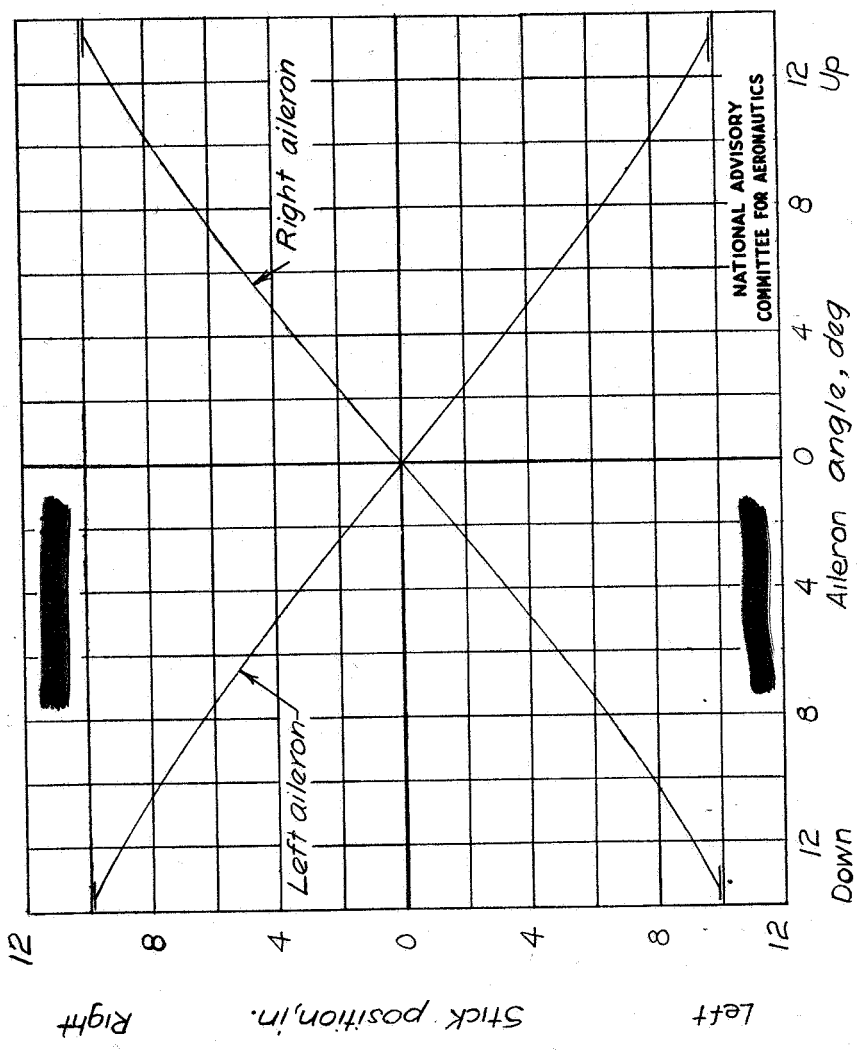


Figure 19. - Variation of left and right aileron angle with stick position. Metal NACA modified ailerons; modified differential control unit; aileron-deflection range, ±13.4°; normal rigging.

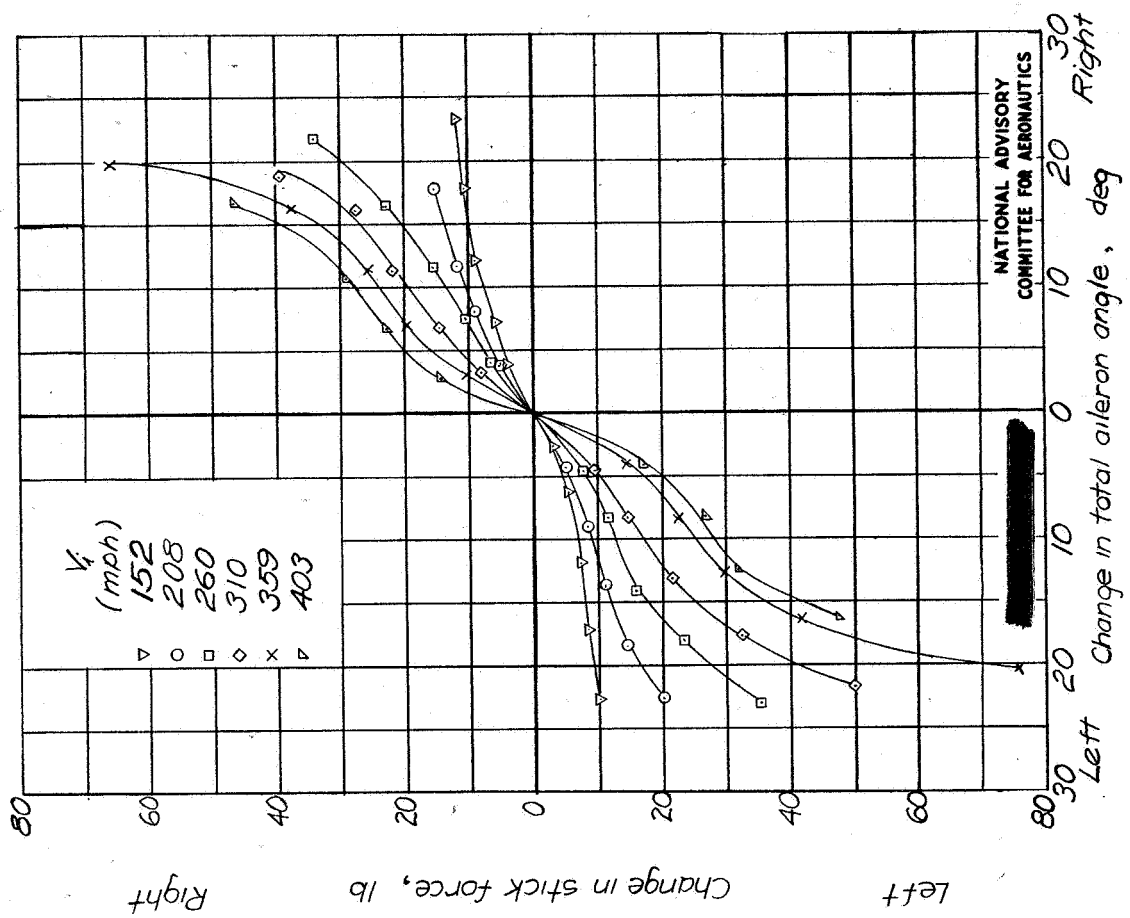


Figure 21. - Variation of change in aileron stick force with change in total aileron angle. Metal NACA modified ailerons; modified differential control unit; aileron-deflection range, ±13.4°; normal rigging.

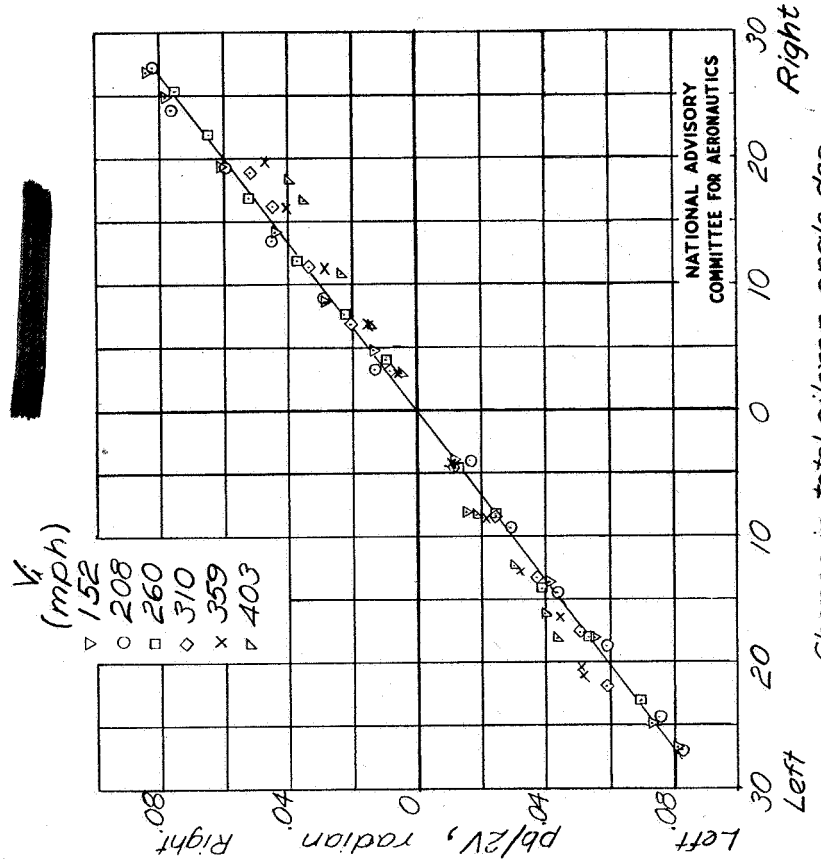


Figure 20. - Variation of helix angle pb/2V with change in total aileron angle. Metal NACA modified ailerons; modified differential control unit; aileron-deflection range, ±13.4°; normal rigging.

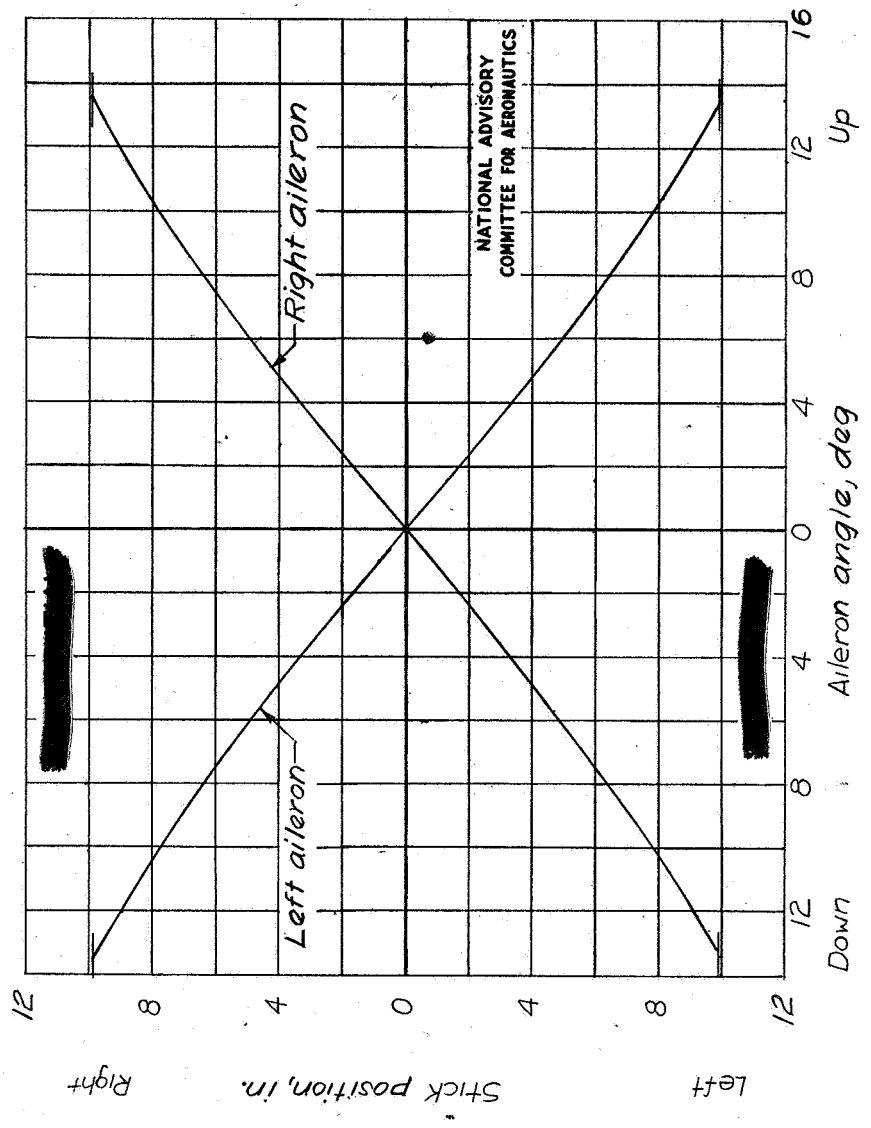


Figure 22. - Variation of left and right aileron angle with stick position. Metal NACA modified ailerons; modified differential control unit; aileron-deflection range, ±13.4°; $\frac{1}{16}$ - inch shims.

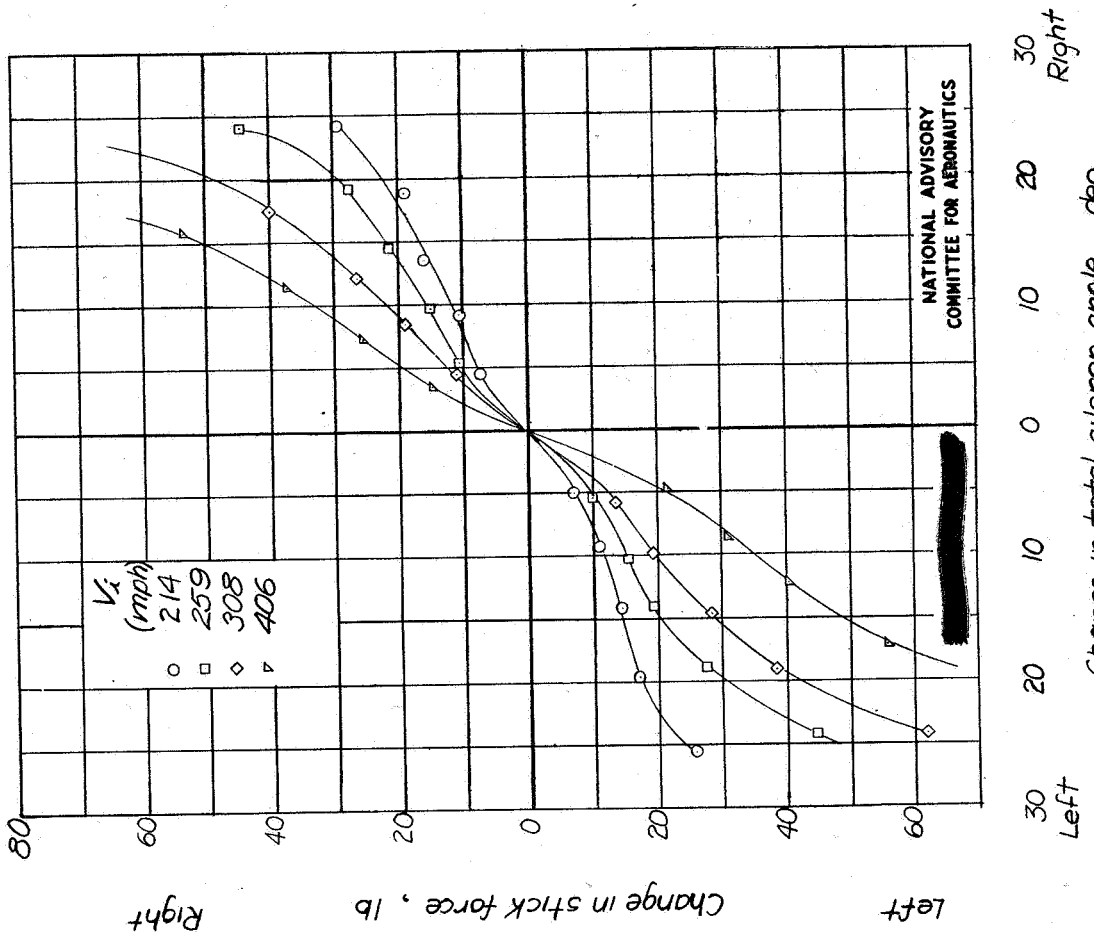


Figure 24. - Variation of change in aileron stick force with change in total aileron angle. Metal NACA modified ailerons; modified differential control unit; aileron-deflection range, ±13.4°; $\frac{1}{16}$-inch shims.

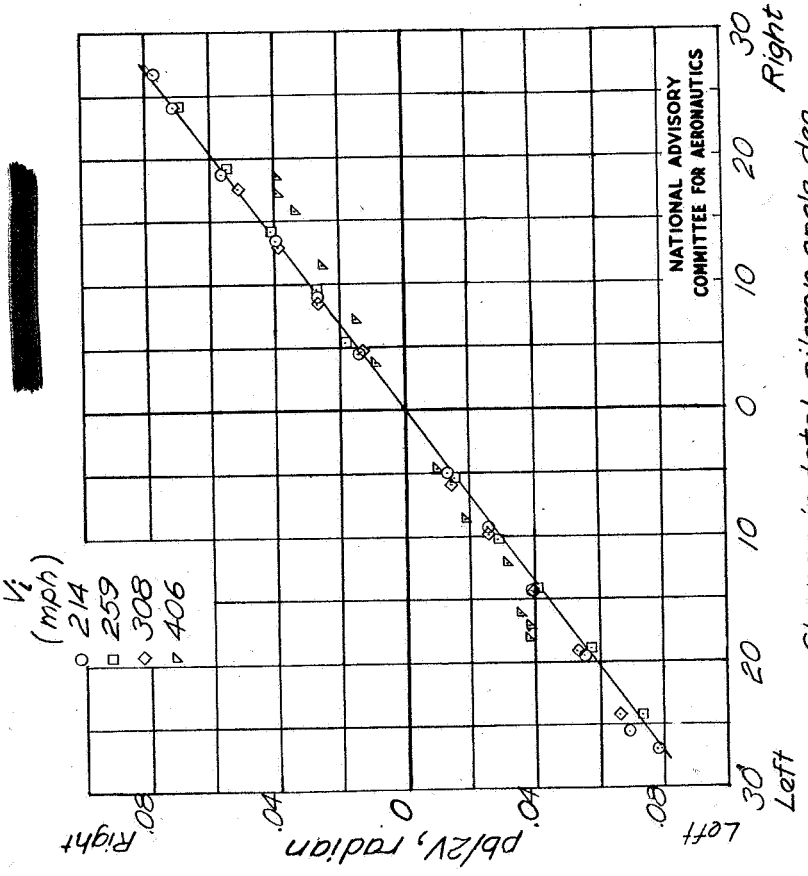


Figure 23. - Variation of helix angle pb/2V with change in total aileron angle. Metal NACA modified ailerons; modified differential control unit; aileron-deflection range, ±13.4°; $\frac{1}{16}$- inch shims.

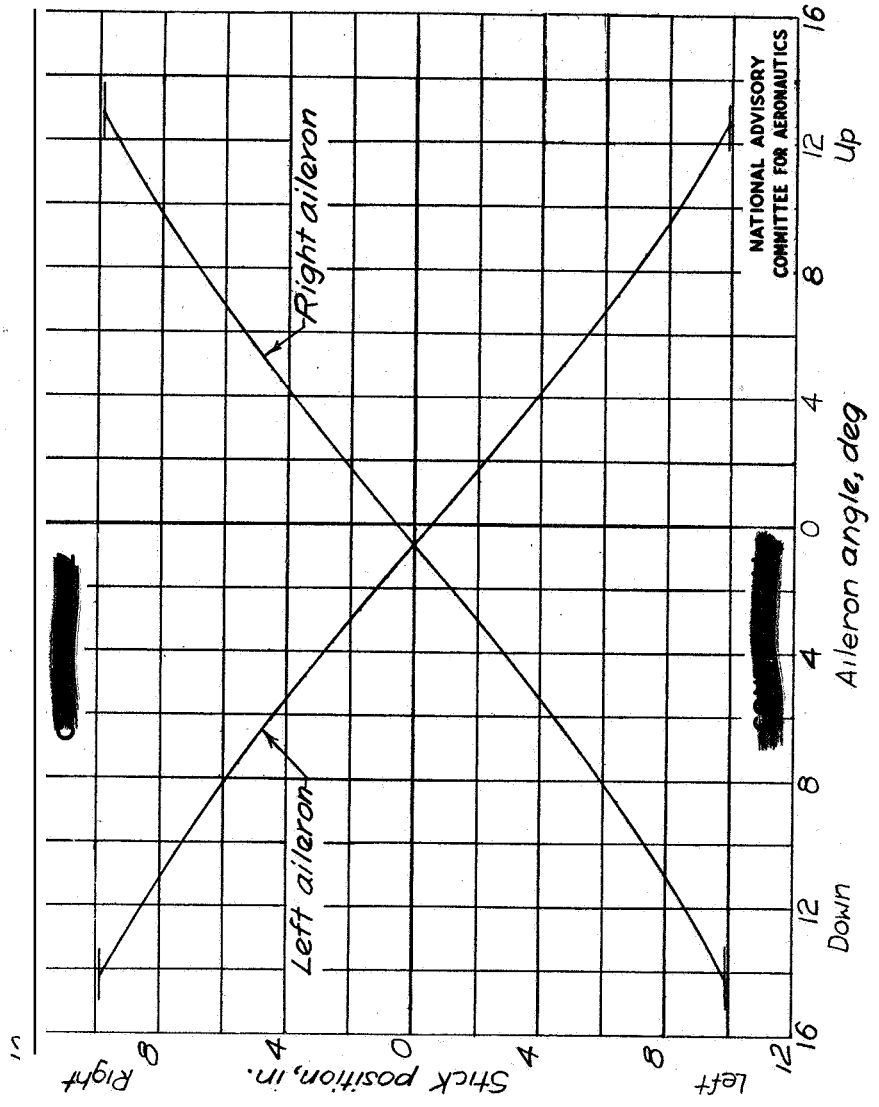


Figure 25. - Variation of left and right aileron angle with stick position. Metal NACA modified ailerons; modified differential control unit; aileron-deflection range, ±13.4°; ailerons drooped 0.6°.

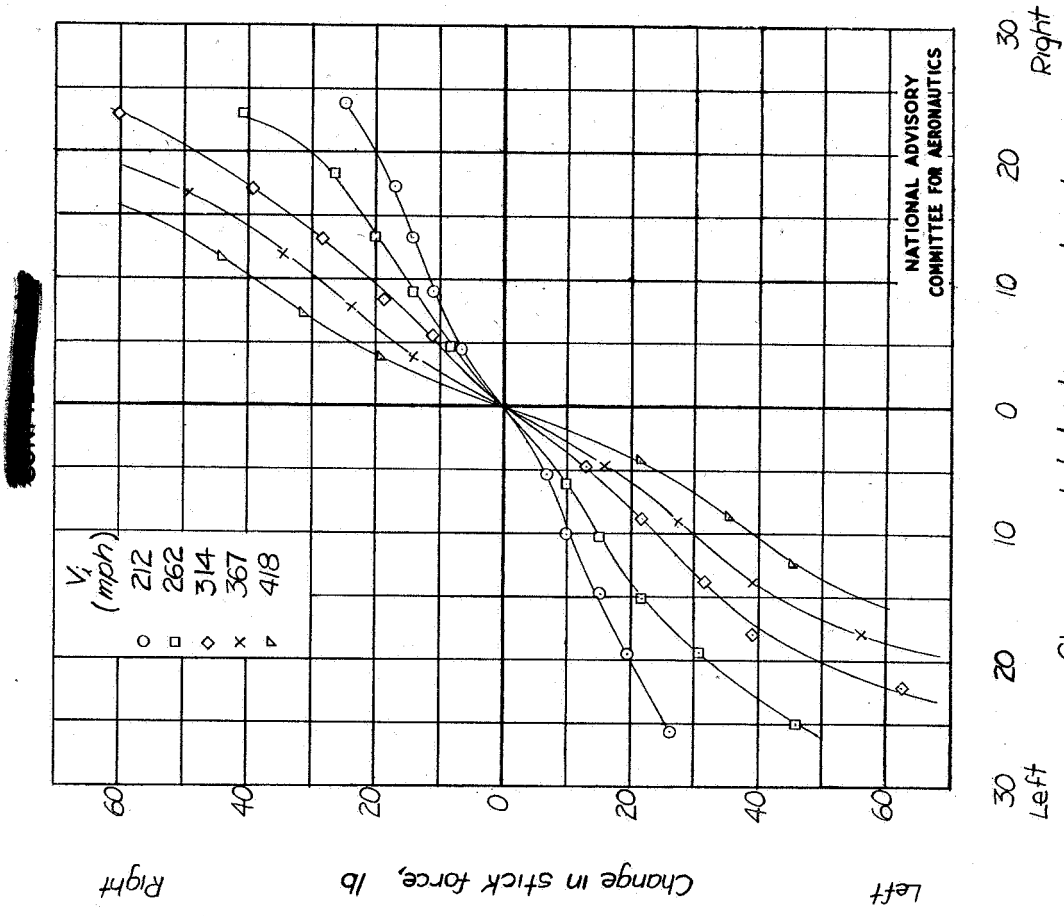


Figure 27. - Variation of change in aileron stick force with change in total aileron angle. Metal NACA modified ailerons; modified differential control unit; aileron-deflection range, ±13.4°; ailerons drooped 0.6°.

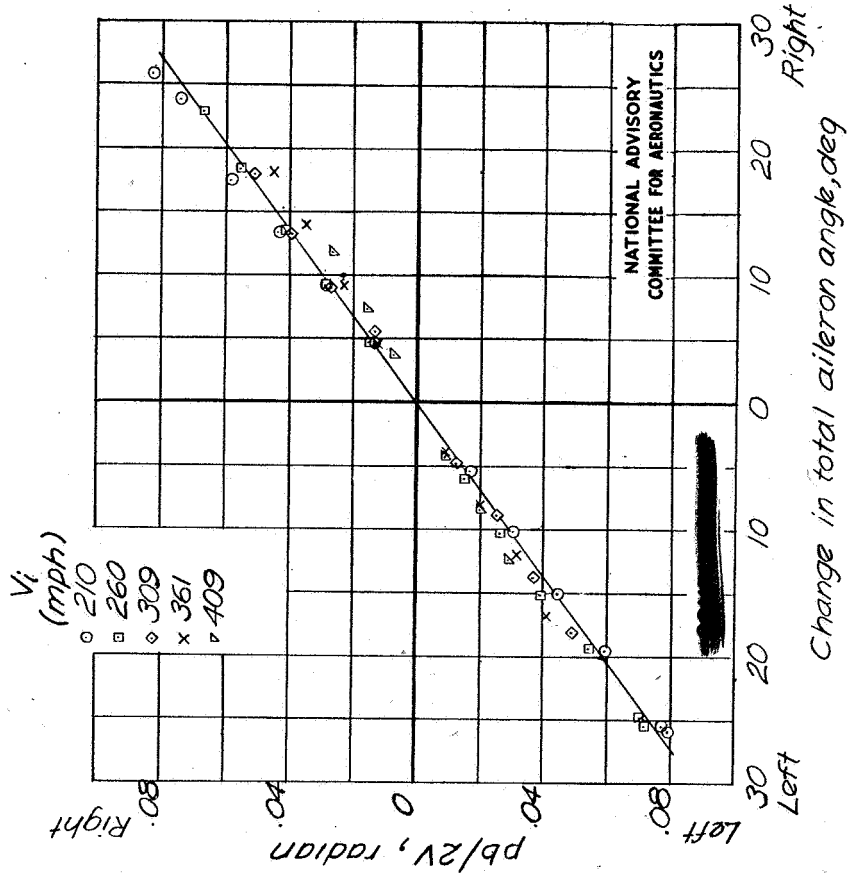


Figure 26. - Variation of helix angle pb/2V with change in total aileron angle. Metal NACA modified ailerons; modified differential control unit; aileron-deflection range, ±13.4°; ailerons drooped 0.6°.

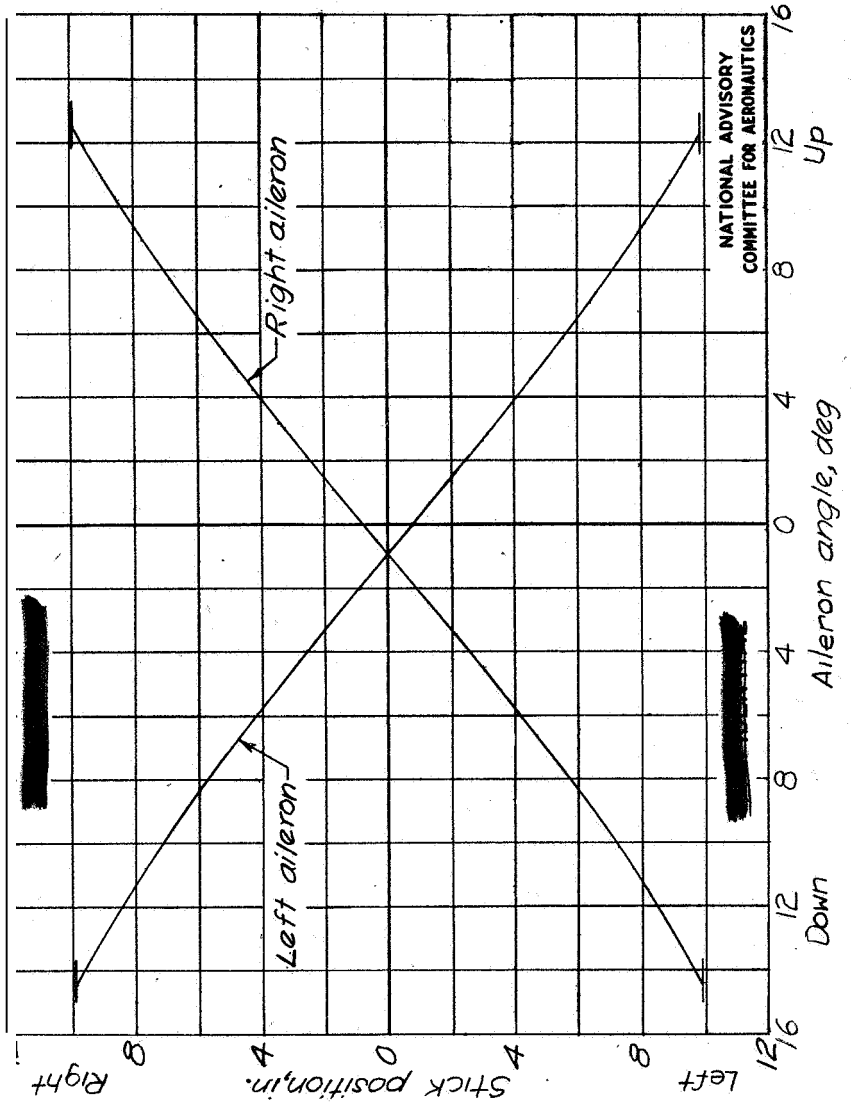


Figure 28. - Variation of left and right aileron angle with stick position. Metal NACA modified ailerons; modified differential control unit; aileron-deflection range, ±13.4°; ailerons drooped 0.95°.

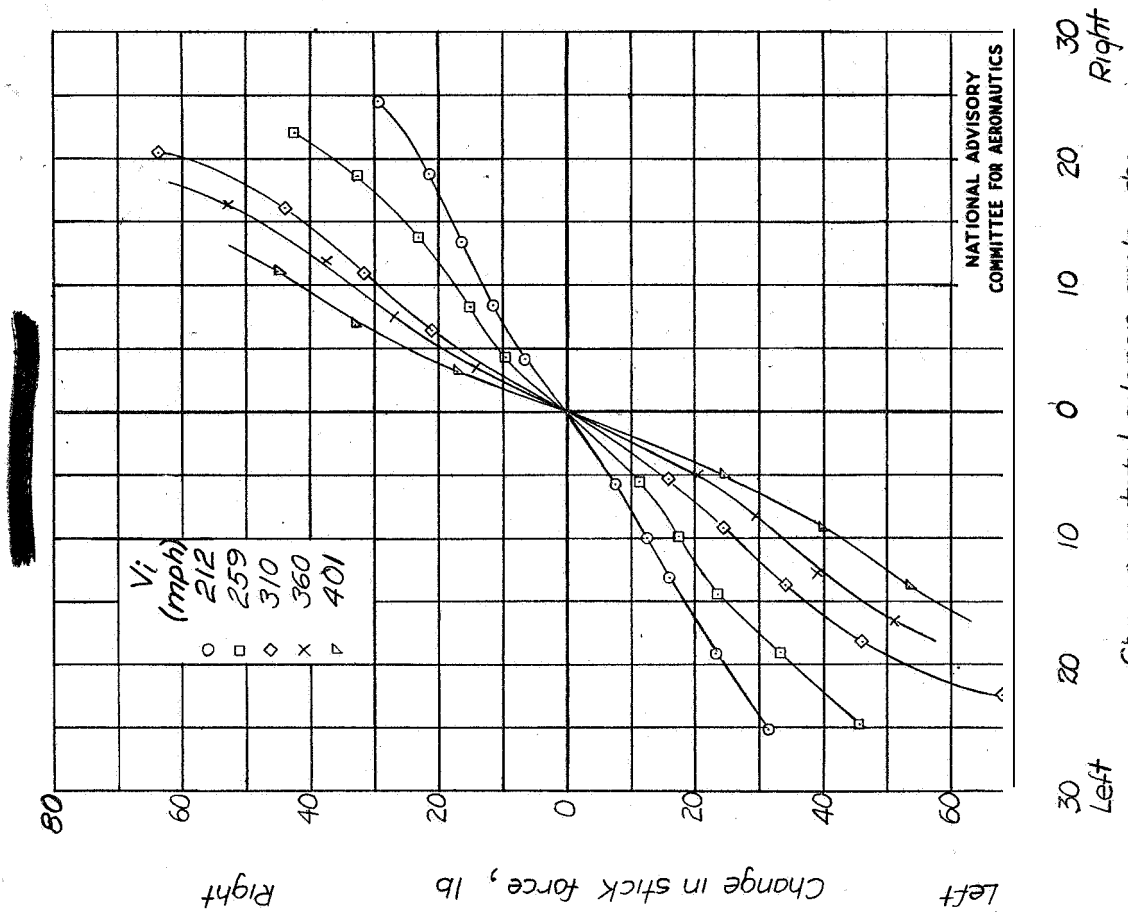
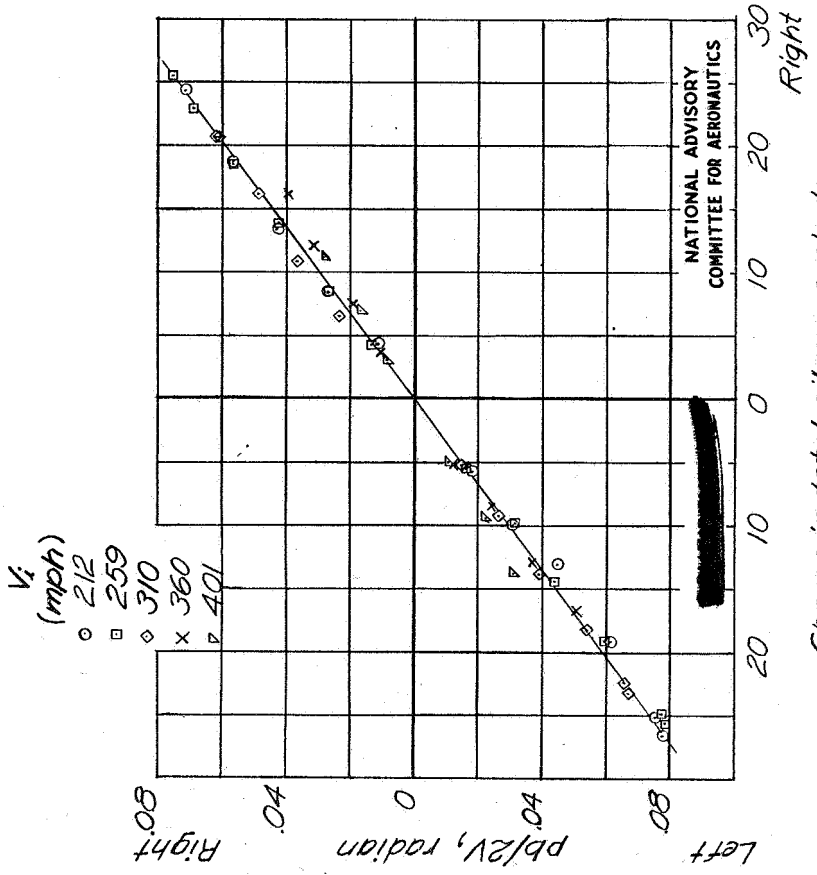


Figure 30. - Variation of change in aileron stick force with change in total aileron angle. Metal NACA modified ailerons; modified differential control unit; aileron-deflection range, ±13.4°; ailerons drooped 0.95°.



31 - Variation of helix angle pb/2V with change in total aileron angle. Metal NACA modified ailerons; modified differential control unit; aileron-deflection range, ±13.4°; ailerons drooped 0.95°.

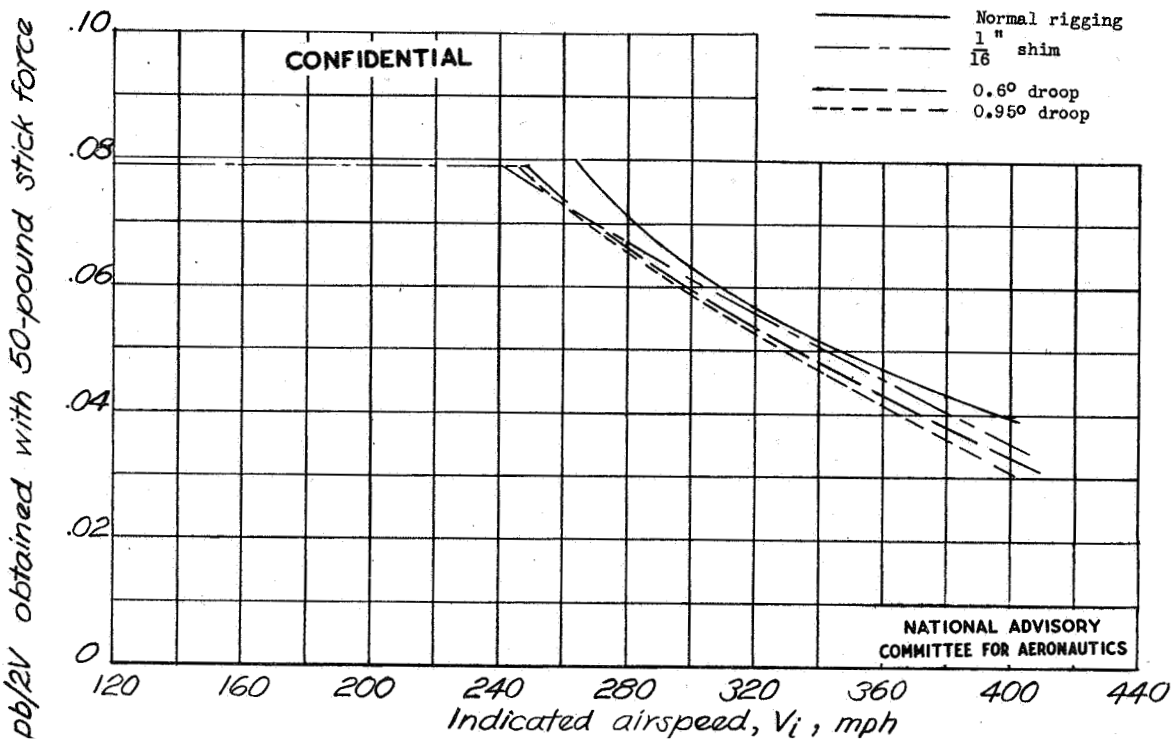


Figure 31. - Variation of helix angle pb/2V with indicated airspeed for 50-pound stick force. Metal NACA modified ailerons and modified differential control unit with various riggings.

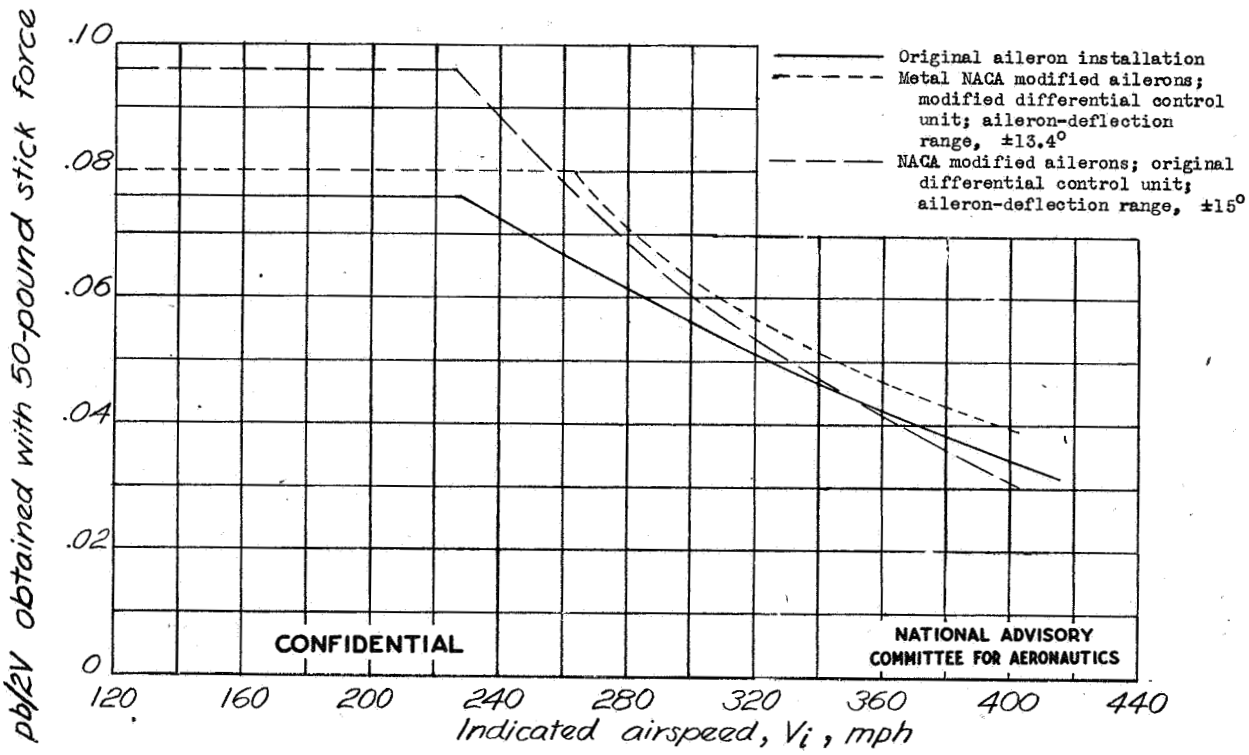


Figure 32. - Variation of helix angle pb/2V with indicated airspeed for 50-pound stick force. Original aileron installation; metal NACA modified ailerons with deflection range of ±13.4° and modified differential control unit; NACA modified ailerons with deflection range of ±15° and original differential control unit.

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ABSTRACT

Aileron characteristice of a fighter airplane were measured in aileron rolls from level flight with fixed rudder. Control balancing was concluded to be very complex for high-speed aircraft because of operating forces sensitivity to small rigging and balance contour changes. NACA aileron increasedaileron effectivenese at low epeeds with 50 lb stick preesure. Modified aileron increased efficiency at high epeeds but lacked effectiveness at slow epeeds. Modified aileron solves aileron overbalance and oscillation in high-speed divee with tested airplane.

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