NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT No. 602

WIND-TUNNEL AND FLIGHT TESTS OF SLOT-LIP AILERONS

By JOSEPH A. SHORTAL

1937

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AERONAUTIC SYMBOLS

1. FUNDAMENTAL AND DERIVED UNITS

	Symbol	Metric		English	
		Unit	Abbreviation	Unit	Abbreviation
Length	l	meter	m	foot (or mile)	ft. (or mi.)
Time	t	second	s	second (or hour)	sec. (or hr.)
Force	F	weight of 1 kilogram	kg	weight of 1 pound	lb.
Power	P	horsepower (metric)		horsepower	hp.
Speed	V	kilometers per hour	k.p.h.	miles per hour	m.p.h.
		meters per second	m.p.s.	feet per second	f.p.s.

2. GENERAL SYMBOLS

W, Weight $=mg$

g, Standard acceleration of gravity $=9.80665$ m/s^2 or 32.1740 ft./sec.^{2}

m, Mass $=\frac{W}{g}$

I, Moment of inertia $=mk^2$. (Indicate axis of radius of gyration k by proper subscript.)

μ, Coefficient of viscosity

ν, Kinematic viscosity

ρ, Density (mass per unit volume)

Standard density of dry air, 0.12497 kg-m^{-4}-s^2 at 15° C. and 760 mm; or 0.002378 lb.-ft.$^{-4}$ sec.^{2}

Specific weight of "standard" air, 1.2255 kg/m^3 or 0.07651 lb./cu. ft.

3. AERODYNAMIC SYMBOLS

S, Area

S_w, Area of wing

G, Gap

b, Span

c, Chord

$\frac{b^2}{S}$, Aspect ratio

V, True air speed

q, Dynamic pressure $=\frac{1}{2}\rho V^2$

L, Lift, absolute coefficient $C_L=\frac{L}{qS}$

D, Drag, absolute coefficient $C_D=\frac{D}{qS}$

D_0, Profile drag, absolute coefficient $C_{D_0}=\frac{D_0}{qS}$

D_i, Induced drag, absolute coefficient $C_{D_i}=\frac{D_i}{qS}$

D_p, Parasite drag, absolute coefficient $C_{D_p}=\frac{D_p}{qS}$

C, Cross-wind force, absolute coefficient $C_C=\frac{C}{qS}$

R, Resultant force

i_w, Angle of setting of wings (relative to thrust line)

i_t, Angle of stabilizer setting (relative to thrust line)

Q, Resultant moment

Ω, Resultant angular velocity

$\rho\frac{Vl}{\mu}$, Reynolds Number, where l is a linear dimension (e.g., for a model airfoil 3 in. chord, 100 m.p.h. normal pressure at 15° C., the corresponding number is 234,000; or for a model of 10 cm chord, 40 m.p.s., the corresponding number is 274,000)

C_p, Center-of-pressure coefficient (ratio of distance of c.p. from leading edge to chord length)

α, Angle of attack

ϵ, Angle of downwash

α_0, Angle of attack, infinite aspect ratio

α_i, Angle of attack, induced

α_a, Angle of attack, absolute (measured from zero-lift position)

γ, Flight-path angle

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By JOSEPH A. SHORTAL
Langley Memorial Aeronautical Laboratory

1938—37——1

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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REPORT No. 602

WIND-TUNNEL AND FLIGHT TESTS OF SLOT-LIP AILERONS

By Joseph A. Shortal

SUMMARY

The slot-lip ailerons developed by the N. A. C. A. consist of a flap-type spoiler with an adjoining continuously open slot. The ailerons were developed in an investigation of the delayed response, or lag, of spoiler-type lateral controls. Tests of these slot-lip ailerons were made on wing models in the 7- by 10-foot wind tunnel, on a Fairchild 22 airplane in the full-scale wind tunnel and in flight, and on the Weick W1–A airplane in flight.

The tests showed that, although the slot-lip ailerons did not have the lag normally associated with plain spoilers, they were rather slow in developing the full amount of rolling moment and therefore imparted a sluggish motion to the roll of the airplane. The tests in the full-scale tunnel showed that the drag due to the open slot was excessive, but later tests in the 7- by 10-foot tunnel revealed that this drag could be somewhat reduced by modifying the slot shape.

In spite of their disadvantages, the N. A. C. A. slot-lip ailerons exhibited certain characteristics that are desirable for airplanes in which safety and simplicity of operation are considered of greater importance than high performance and a great degree of maneuverability. The slot-lip ailerons permit the use of a full-span flap; the slot may extend the angle-of-attack range with stability in roll; and the ratios of yawing moment to rolling moment are such as to be particularly satisfactory for the two-control operation of an airplane.

INTRODUCTION

Since the high wing loadings of many modern airplanes have necessitated the use of landing flaps to reduce the landing speed, considerable interest has been displayed in lateral-control devices with which a flap covering the entire wing span can be used. The spoiler type of control, located near the midchord, permits the free use of the trailing edge of the wing for full-span flaps. Wind-tunnel tests (reference 1) of wing models indicated that spoilers had desirable control characteristics, but flight tests (reference 2) revealed considerable lag between the control movement and the beginning of the wing motion in the desired direction. The slot-lip aileron, which consists of a spoiler with an adjoining continuously open slot, has been developed during the attempt to find a control device with the desirable characteristics of the spoiler and without its undesirable lag.

This lag, or the delay of the response motion of the airplane after a control movement, with various spoilers and spoiler-aileron combinations, was measured in the flight tests of reference 2. It was noticed that the pilots failed to detect any lag less than 0.10 second. This value, in seconds, seems to be an upper limit to the lag and is of particular interest. In the interpretation of model tests and the application of the results to airplanes, it seems that the lag should be expressed as the distance in wing chord lengths traveled by the airplane after the control is moved. With the lag expressed in this nondimensional form, the lag in seconds may be computed for a particular airplane and speed and compared with the 0.10-second limit, although this time limit may depend upon the reaction of the pilot and may vary with different pilots.

Another characteristic possessed by lateral-control devices is that of "sluggishness." The control may cause the wing to move in the desired direction immediately, but the moment produced by the control may not reach its maximum until the wing has traveled a considerable distance. As a result, the airplane motion will appear rather sluggish. It seems that all control devices are sluggish to a certain extent because the change in lift is not effected immediately. In the present report, sluggishness is defined as the distance in chords traveled by the airplane from the time the control is deflected until the maximum moment is produced. At the start of the investigation the upper allowable limit of sluggishness was not known but the tests have indicated that the control was satisfactory if the maximum moment was produced before the tested airplane traveled four chord lengths. This value is by no means fixed as it may be masked by such factors as the moment of inertia of the airplane and the indirect rolling moment induced by yawing motions.

The complete wind-tunnel and flight tests that have been made by the N. A. C. A. to determine the practicability of slot-lip ailerons are reported herein. The investigation was divided into the following phases:

1. An investigation in the 7- by 10-foot wind tunnel of the lag characteristics of spoilers and slot-lip ailerons. (See reference 3.)

2. The measurement in the 7- by 10-foot wind tunnel of the lateral-control and stability characteristics of a wing model equipped with slot-lip ailerons in several chordwise locations.

3. The determination of the effect of slot-lip ailerons on the lift and drag of a model wing and of an airplane.

4. A study in the 7- by 10-foot wind tunnel of the effect of various slot shapes on the wing section drag with a large-chord wing.

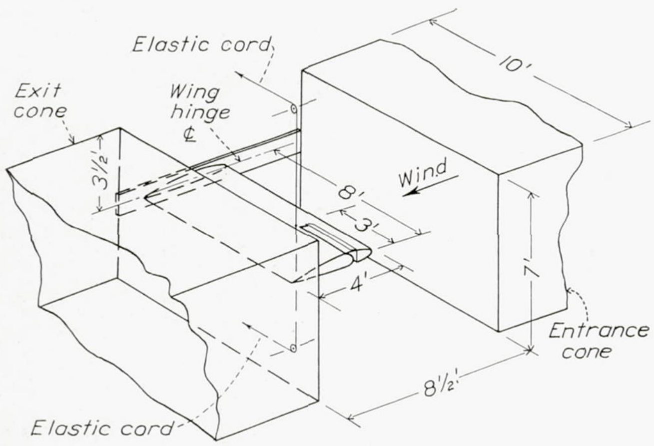


FIGURE 1.—Diagram of the lag set-up in the 7- by 10-foot tunnel.

5. Flight tests of an airplane equipped with slot-lip ailerons.

6. An analysis of the wind-tunnel and flight results to obtain a quantitative comparison of the response characteristics of slot-lip and ordinary ailerons.

LAG INVESTIGATION

The lag investigation was conducted in the open-jet 7- by 10-foot wind tunnel (reference 4). A Clark Y–15 wing of 4-foot chord and 8-foot span was hinged at one end to the side of the tunnel as shown in figure 1. The set-up thus simulated a 16-foot wing with one of the tunnel vertical boundaries as an imaginary plane of symmetry. The wing was restrained in roll by long elastic cords but was free to move to a new position of equilibrium when a moment was applied by a control device located at the free wing tip. A continuous record of the control motion and the wing motion was obtained by a recording instrument developed for flight tests. The tests consisted of deflecting the ailerons various amounts and recording the wing motion. The tunnel was operated at an air speed of 80 miles per hour for 0° angle of attack and at 40 miles per hour for 15° angle of attack. The corresponding wing lift coefficients were approximately 0.25 and 1.00.

RETRACTABLE SPOILERS

The retractable spoilers consisted of curved plates that slid in and out of the wing as indicated in figure 2. The spoiler chord and location are given as fractions of the wing chord c_w. The spoilers were of $0.10c_w$ chord and were tested successively at different locations between $0.15c_w$ and $0.83c_w$. Reference 2 had revealed that a retractable spoiler located $0.15c_w$ had considerable lag and reference 5, that a retractable spoiler located $0.83c_w$ was satisfactory. The tests reported in reference 6 indicated that the $0.30c_w$ location should give the optimum rolling and yawing moments. It was considered advisable, therefore, to investigate the variation of lag with spoiler location for the entire chordwise range. Some of the results are plotted in figure 2.

The results from some typical lag records are plotted in figure 3. It will be noticed that the retractable spoiler at $0.15c_w$ caused the wing to roll initially in the wrong direction before rolling in the desired direction. Included in the same figure for comparison is a response curve obtained with a flat plate attached to the trailing edge of the wing and deflected as an aileron; this curve is taken as representative of ordinary aileron action. The considerable difference in the response of the wing to these two devices is quite evident.

The results of figure 2 having indicated satisfactory response time with a spoiler at $0.83c_w$, tests were made to determine the effect of a split flap on the spoiler response. The curves of figure 4 show the time histories with and without a split flap deflected 60° and indicate greater lag with the flap deflected.

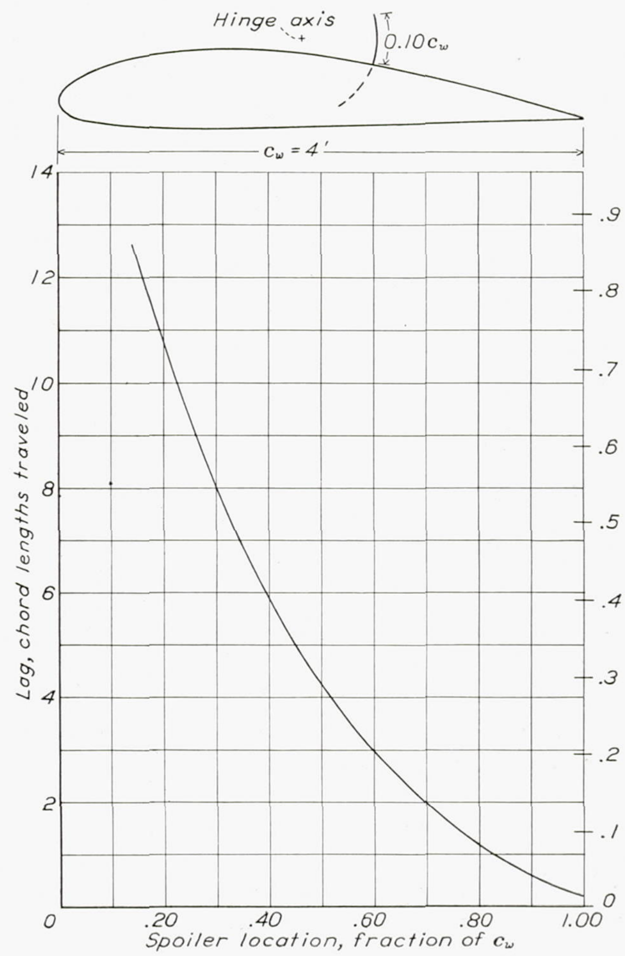


FIGURE 2.—Effect of spoiler location on lag. The 7- by 10-foot tunnel; C_L, 1.0; air speed, 40 m. p. h.

Inasmuch as satisfactory operation had been obtained in flight with combinations of ailerons and spoilers, it was considered of interest to measure the lag obtained

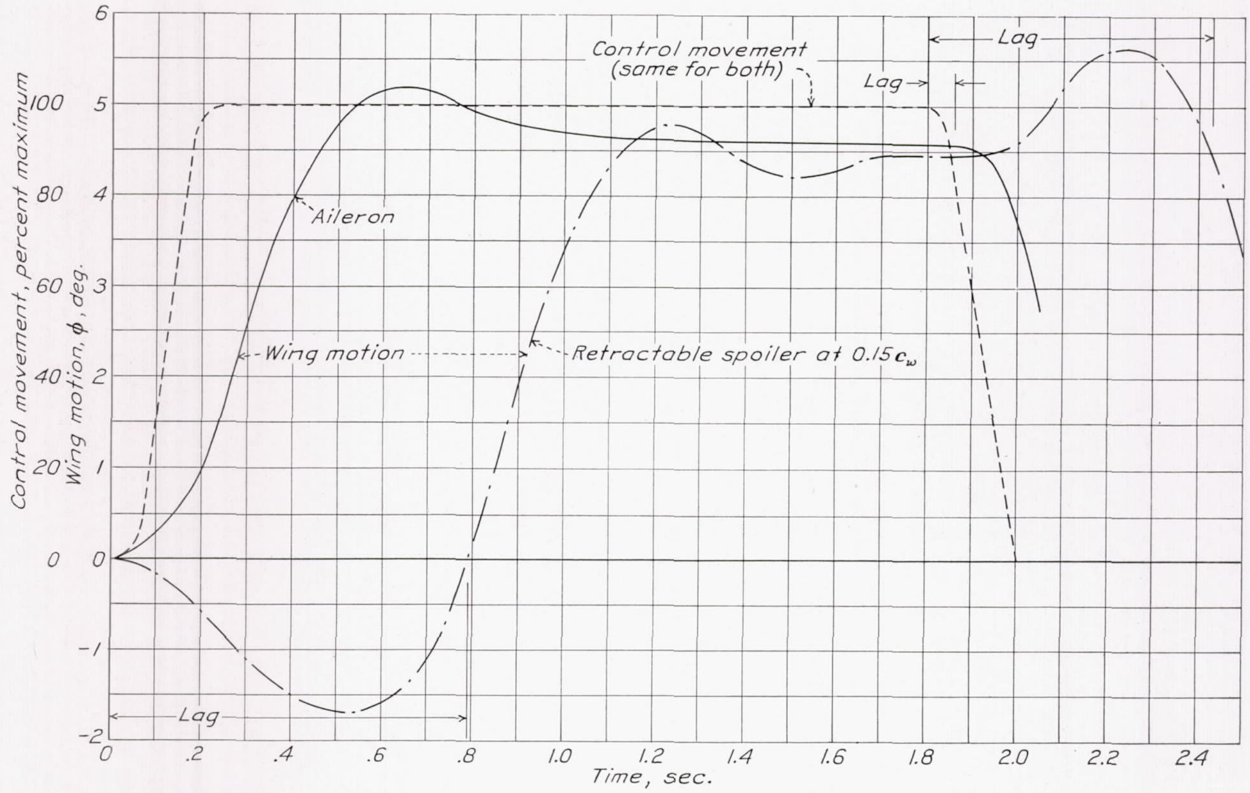


FIGURE 3.—Time history of wing motion with retractable spoiler at $0.15c_w$. The 7- by 10-foot tunnel; C_L, 1.0; air speed, 40 m. p. h.

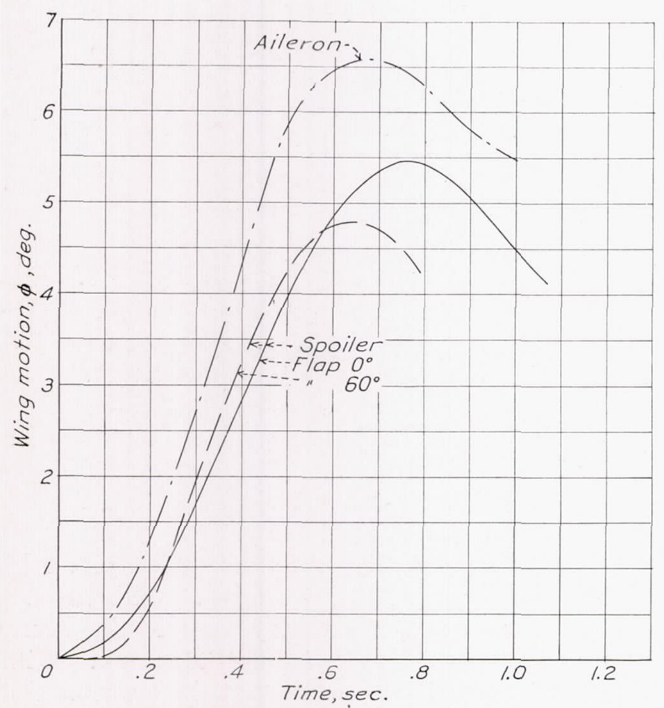


FIGURE 4.—Time histories of wing motion with retractable spoiler at $0.83c_w$ and with a split flap. The 7- by 10-foot tunnel; C_L, 1.0; air speed, 40 m. p. h.

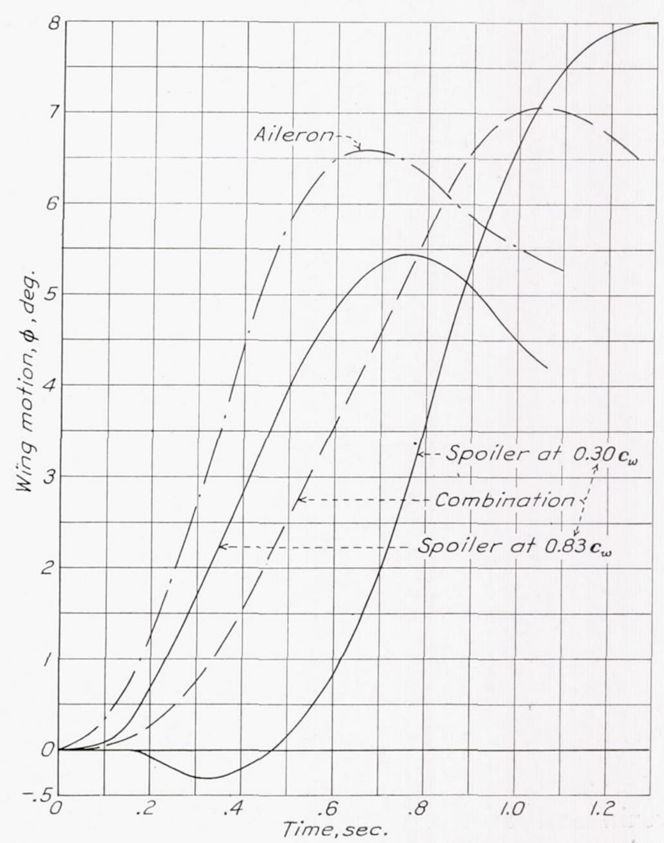


FIGURE 5.—Time histories of wing motion with combinations of spoilers. The 7- by 10-foot tunnel; C_L, 1.0; air speed, 40 m. p. h.

with a combination of two retractable spoilers. A representative time history is given in figure 5. The addition of the $0.83c_w$ spoiler counteracted the lag of

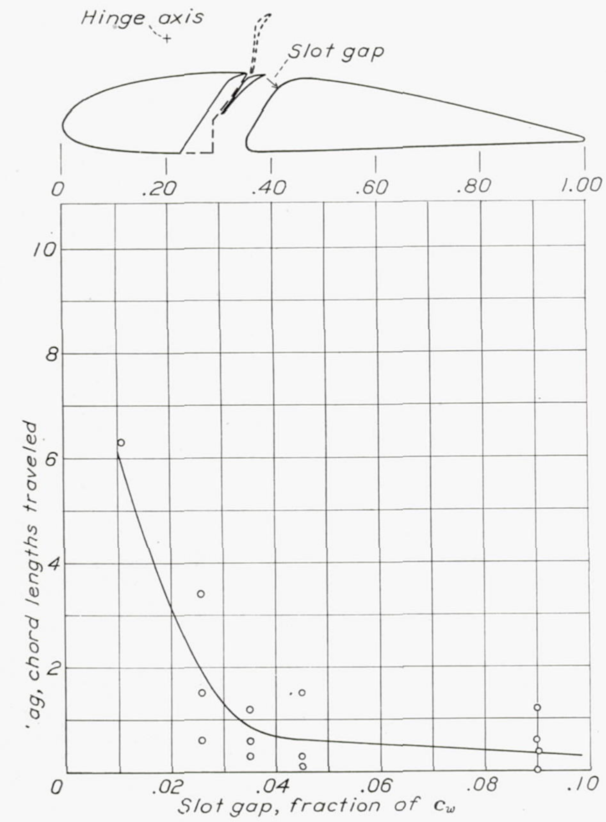


FIGURE 6.—Effect of slot size on lag of retractable spoiler and slot at $0.30c_w$. The 7- by 10-foot tunnel; C_L, 1.0; air speed, 40 m. p. h.

the $0.30c_w$ spoiler, but the response of the combination was not so rapid as that of the rearward one alone nor of the ordinary aileron.

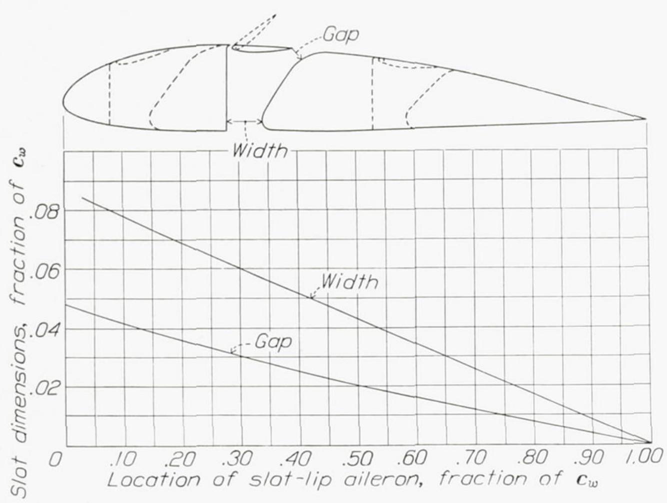


FIGURE 7.—Diagram of the slot-lip ailerons tested in the lag investigation.

It was believed that a slot adjoining the spoiler would relieve the low pressure existing behind the spoiler when it is first deflected. Lag measurements were made of several widths of slot behind a retractable spoiler located near $0.30c_w$. As shown in figure 6, a slot with an upper gap of about $0.035c_w$ reduced the lag from about 8 chord lengths to less than 1 chord length travel. The lower opening of the slot was later reduced to about $0.06c_w$ and to the shape shown by the dashed line without altering the response characteristics.

SLOT-LIP AILERONS

Although the retractable spoilers with a slot would probably give satisfactory control, the device appears structurally undesirable. A simpler arrangement consisting of a slot with the upper portion, or lip, hinged for control was given more consideration. This hinged lip was designated a "slot-lip aileron." Tests were made of various combinations of sizes for the upper and lower slot openings and with the aileron hinge-axis located

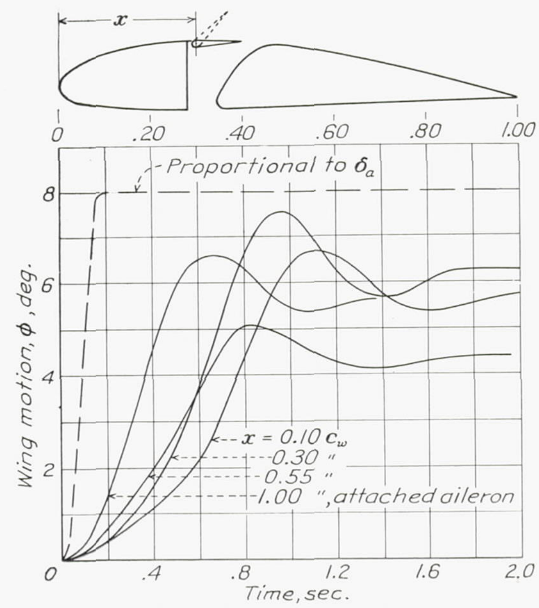


FIGURE 8.—Time histories of wing motion with slot-lip ailerons in various fore-and-aft locations. The 7- by 10-foot tunnel; C_L, 1.0; air speed, 40 m. p. h.

$0.10c_w$, $0.30c_w$, and $0.55c_w$ back from the leading edge. The slot sizes required to obtain an immediate response following control movement were determined for each location and the results are shown in figure 7. The particular shape used was similar to that of a previously developed low-drag slot. (See reference 7.) The chord, c_a, of the slot-lip aileron was $0.10c_w$.

The wing motions obtained with the final slots for each location of the slot-lip ailerons are compared with the aileron curve in figure 8. The curves show immediate response in all cases although the final motion builds up differently in each case.

The effect of the slot is clearly shown in figure 9 by the time histories of the wing motion. With the slot closed at the bottom, the wing moved in the wrong direction as before with a lag of about 0.5 second. With the upper slot opening sealed so that there was no slot with the aileron neutral but a considerable opening with the aileron deflected, the lag was reduced to about 0.3 second but was still unsatisfactorily large.

With the final slot-lip ailerons showing satisfactory lag characteristics, the hinge moments were measured. Some modification of the aileron and slot was necessary to obtain a curve of hinge moment against deflection which showed that the arrangement was not overbalanced at the start of control movement. The arrangements tested are reported in more detail in reference 3. The final hinge-moment curves are given in figure 10 at lift coefficients of 0.25 and 1.0. The hinge-moment tests were made with the wing used in the lag tests and at an air speed of 60 miles per hour. The hinge moments are given in the form of absolute coefficients C_h based on the aileron chord c_a and area S_a back of the hinge,

$$C_h = \frac{\text{hinge moment}}{qc_aS_a}$$

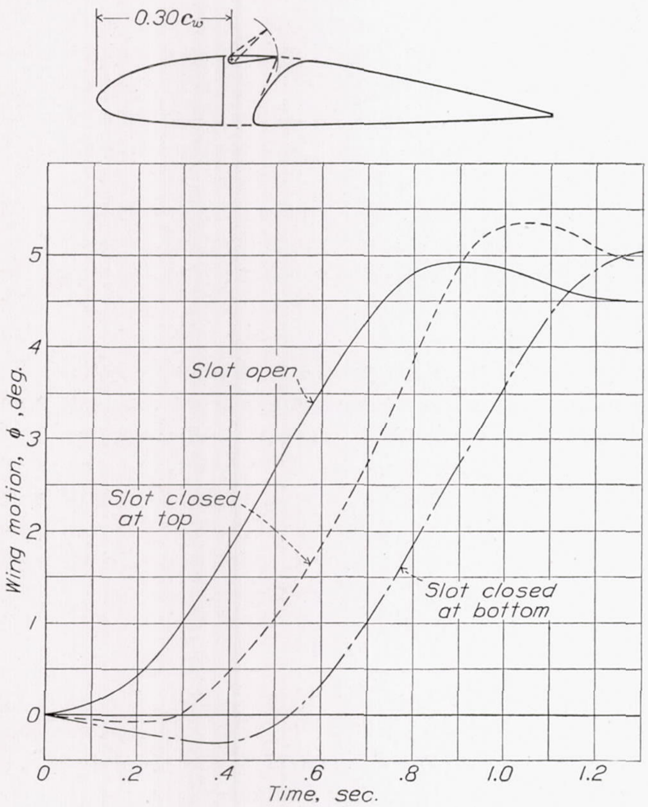


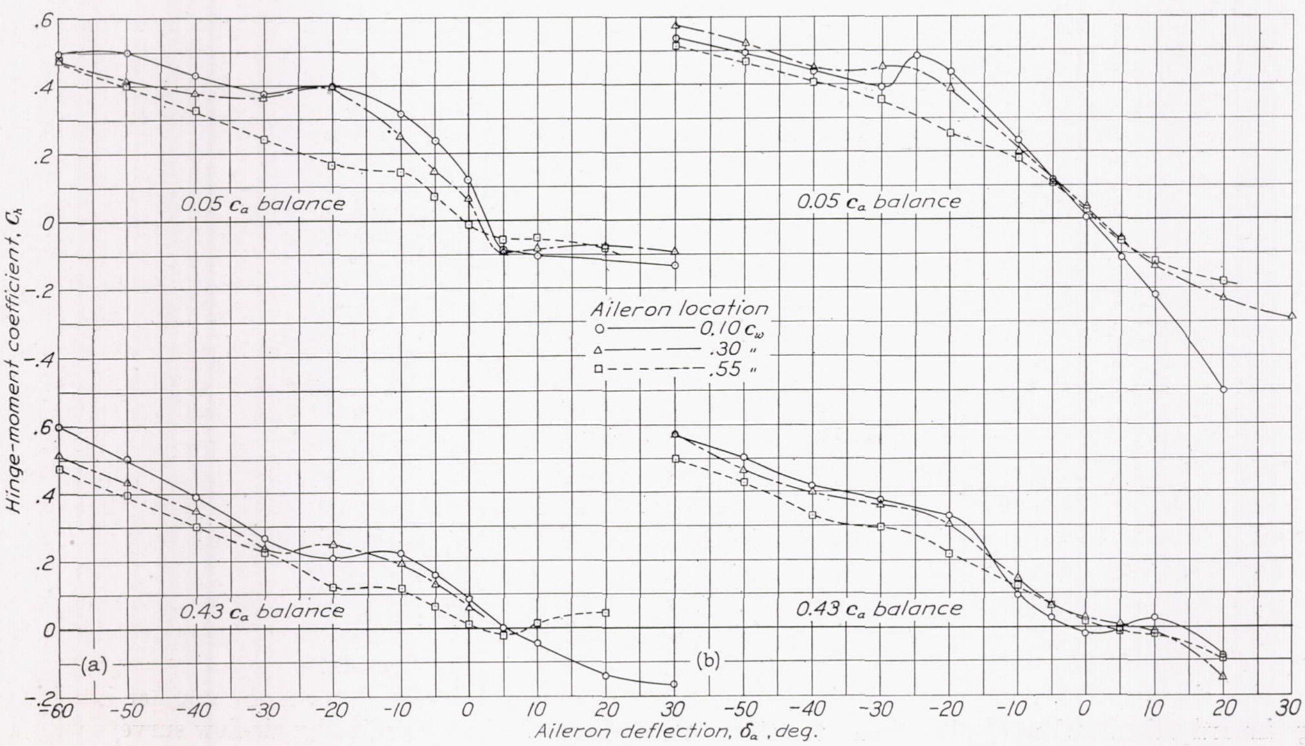
FIGURE 9.—Time histories of wing motion with slot-lip ailerons at $0.30c_w$, showing effect of the slot. The 7- by 10-foot tunnel; C_L, 1.0; air speed, 40 m. p. h.

ROLLING- AND YAWING-MOMENT TESTS

The lag investigation of slot-lip ailerons indicated the possibilities of their providing improved lateral control. A wing that had been used in the investigation reported in reference 8 was fitted with slot-lip ailerons and the rolling and yawing moments produced by these ailerons were measured. The effect of the slot-lip ailerons on lateral control, on lateral stability, and on lift and drag was determined with and without a split flap.

APPARATUS AND TESTS

The model was mounted on the 6-component balance of the open-throat 7- by 10-foot tunnel. (See reference 4.) The three force and the three moment components can be read independently and simultaneously in the form of coefficients for a standard-size model. The force-test tripod may be replaced by a special mounting that permits the model to rotate

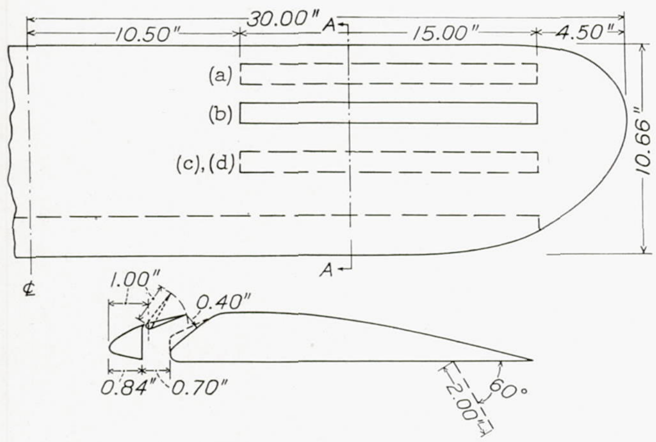


(a) = C_L = 0.25 (b) = C_L = 1.0

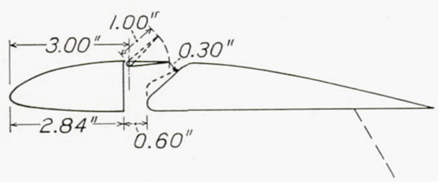
FIGURE 10.—Hinge-moment coefficients of slot-lip ailerons on the 4- by 8-foot wing in the 7- by 10-foot tunnel.

about the longitudinal wind axis passing through the midspan quarter-chord point. This apparatus is mounted on the balance and the rolling-moment coefficients are read directly during forced rotation tests.

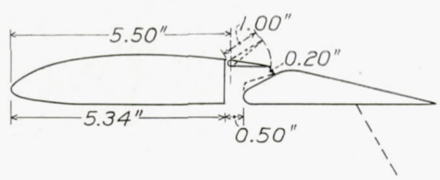
The model used in this part of the investigation was the one with large rounded tips used for the tests reported in reference 8. A Clark Y wing section was maintained throughout the span with no washout. The basic chord of the wing was 10.66 inches, the span was 60 inches, and the aspect ratio 6.0. A diagram of



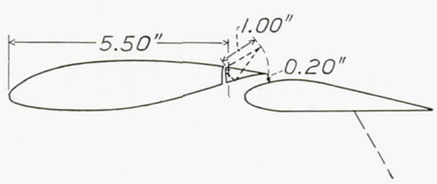
(a) Slot-lip aileron at 0.10 c_w.



(b) Slot-lip aileron at 0.30 c_w.



(c) Slot-lip aileron at 0.55 c_w.



(d) Slot-lip aileron at 0.55 c_w with special slot.

FIGURE 11.—Diagram of the Clark Y wing with slot-lip ailerons tested in the 7- by 10-foot tunnel.

the wing showing the ailerons and flap tested is given in figure 11. The split flap consisted of a sheet-steel strip screwed to the wing at an angle of 60°. The slot-lip ailerons were formed of brass with their upper surfaces conforming to the upper contour of the wing. The slot sizes and shapes were determined from the lag investigation. The modifications to the slots shown by dashed lines were found necessary during the tests and were made with wooden strips screwed to the wing. The slot shape shown as (d) was designed to reduce the drag of the slot by having the slot formed between two airfoil-shape sections.

The standard test procedure was followed at a dynamic pressure of 16.37 pounds per square foot corresponding to an air speed of 80 miles per hour at standard density. The Reynolds Number of the tests was 609,000, based on the average wing chord of 10 inches.

The lift, the drag, and the pitching moment were measured with the ailerons neutral; the rolling and the yawing moments were measured with the ailerons deflected various amounts. Tests were repeated with the split flap deflected 60°. Some of the tests were repeated with the wing yawed to determine the control characteristics while sideslipping. Rotation tests were made with the ailerons neutral when located in all positions along the wing chord to determine the effect of the slots on damping in roll. Rotation tests were then made with the ailerons deflected when located $0.10c_w$ from the leading edge to determine the effect of the deflected control on the damping.

RESULTS

The results are given in figures 12 to 18. The coefficients are obtained directly from the balance and refer to the wind (or tunnel) axes. The results as given have not been corrected for tunnel effects.

The results of the rotation tests are given in the form of a damping coefficient $\frac{dC_l'}{d\left(\frac{p'b}{2V}\right)}$ obtained from an average of the results of rotation tests in both directions at a rate of $\frac{p'b}{2V}=0.05$, where p' is the angular velocity in roll and V is the air speed.

Ailerons neutral.—The curves of lift and drag with flap and ailerons neutral are given in figure 12 (a) and with flap deflected 60° in figure 12 (b). The shape of the lift curves with flap neutral is somewhat affected by the slots. The forward slot locations are more effective than the rearward locations in delaying the stall over the adjacent portion of the wing span. This fact is revealed more clearly by the curves of damping in roll in the same figures, which show that damping is maintained to a higher angle of attack with the forward slots than with the rearward slots. The drag due to the slot-lip ailerons will later be discussed in more detail in connection with tests made at a larger value of the Reynolds Number.

The effect of the slots on the manner in which the wing stalled was studied by air-flow surveys with a fine silk thread attached to a thin sting. The effectiveness of the forwardly located slots is clearly shown in figure 13. The slot-lip ailerons were located in three different positions with the flap neutral and deflected 60°, and the wing was at an angle of attack of 22° (about 6° past maximum lift). The stalled area of the wing is shown by the shaded areas.

Effect of slot shape on control.—The slots first used with the slot-lip ailerons in the present tests were similar to the ones used in the lag investigation but were later modified as shown by the dashed lines in figure 11. The rolling- and yawing-moment coefficients obtained with the original and modified slots with the slot-lip ailerons located at 0.10, 0.30, and $0.55c_w$ from the leading edge are given in figure 18(a) with the right aileron deflected up 40° and the left aileron deflected down 12°, flap 0°. The rolling moments with the modified slot were superior to those with the original slot in most cases. Consequently, complete data have been given only for the tests with the modified slots. The effect of a more drastic change in slot shape was determined from tests of the slot-lip aileron shown in figure 11(d). In this case the slot was formed between two airfoil-shape sections, an arrangement that, it was believed, would result in reduced drag. A comparison of the relative control effectiveness of this aileron and of the modified slot-lip aileron of figure 11(c)

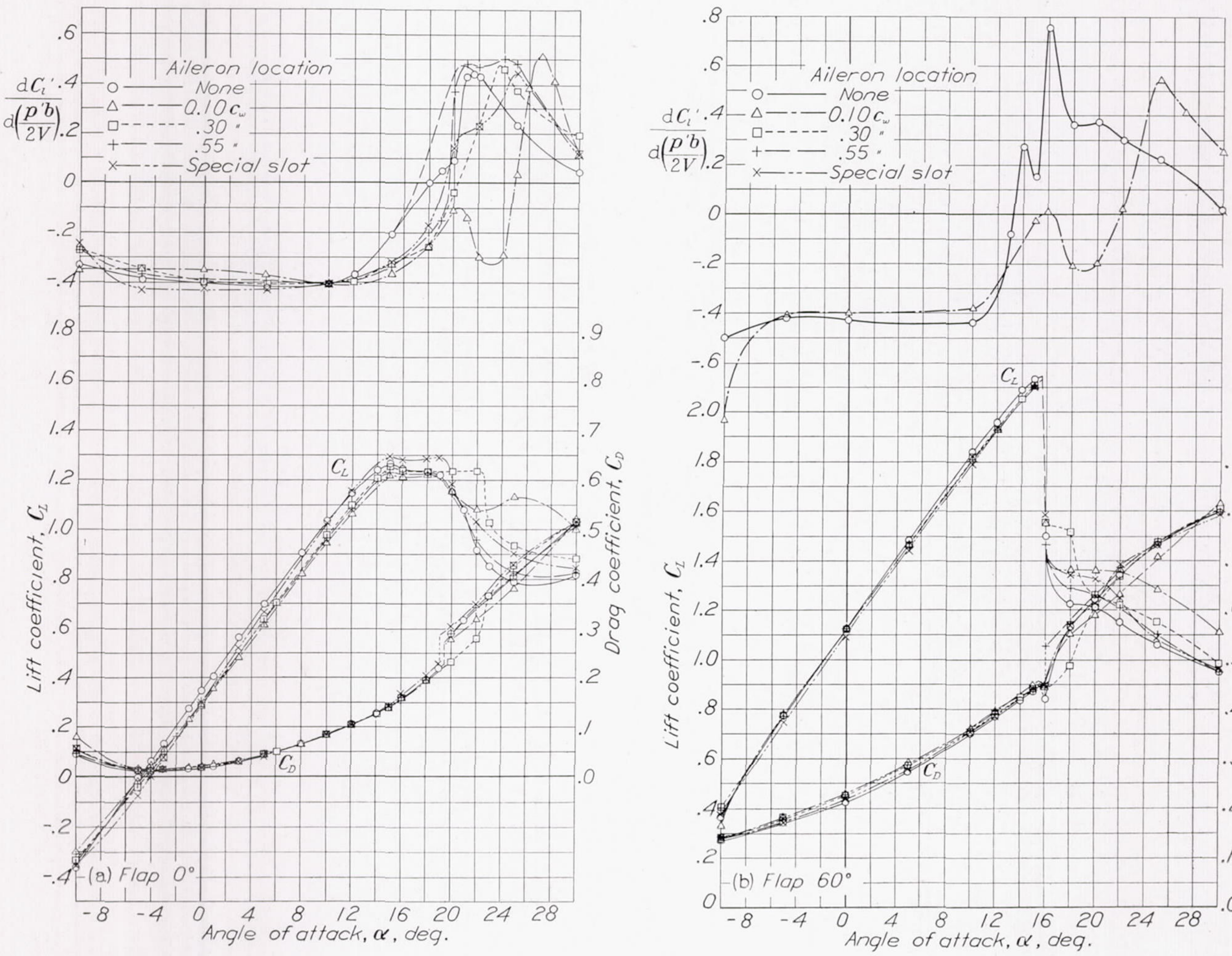


FIGURE 12.—Effect of slot-lip ailerons on lift, drag, and rate of change of rolling-moment coefficient with rate of rotation $\frac{dC_l'}{d\frac{p'b}{2V}}$. Ailerons neutral; 7- by 10-foot tunnel.

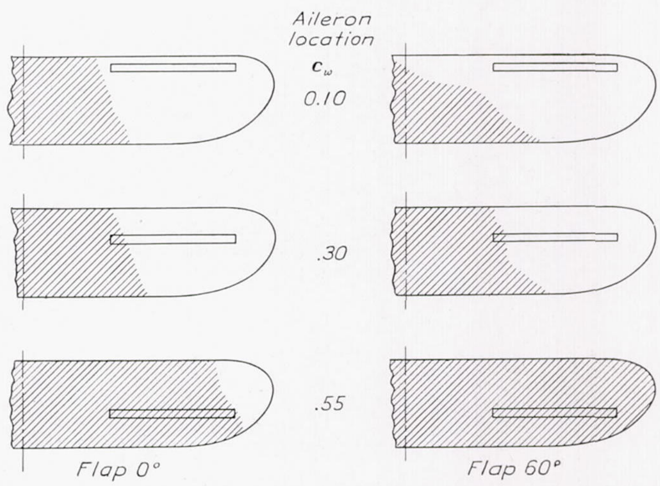


FIGURE 13.—Effect of slot-lip ailerons on air flow above the stall. (Shaded area is stalled.) Ailerons neutral; α, 22°.

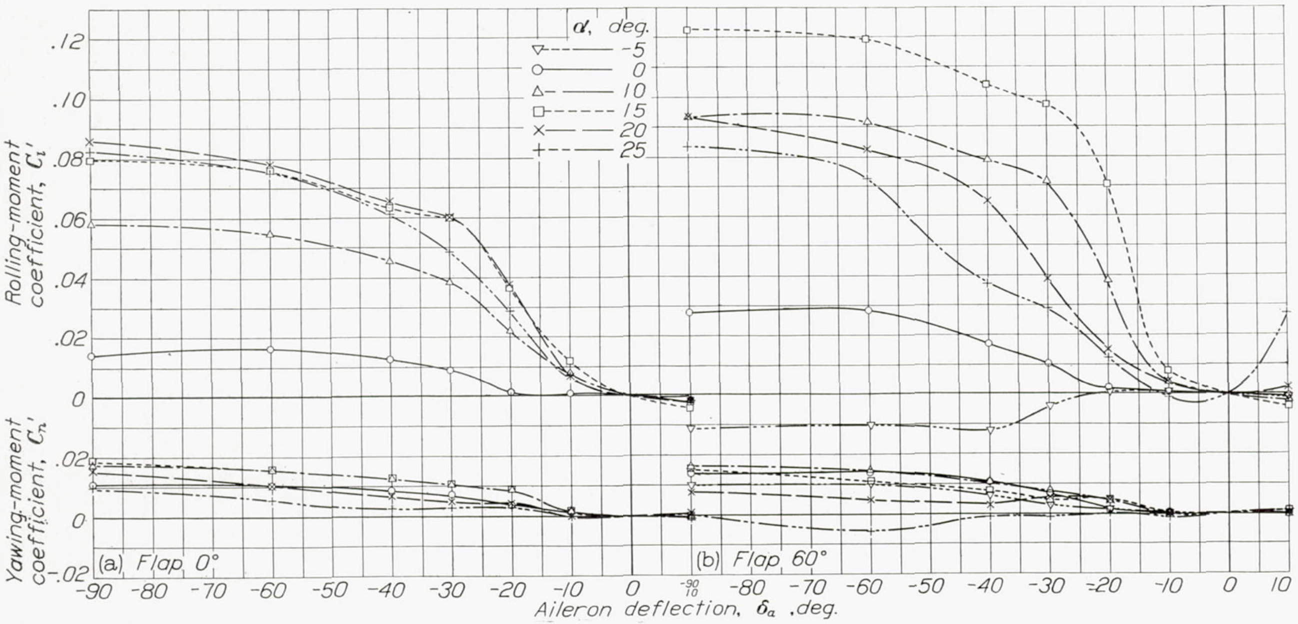


FIGURE 14.—Rolling- and yawing-moment coefficients due to slot-lip ailerons at $0.10c_w$.

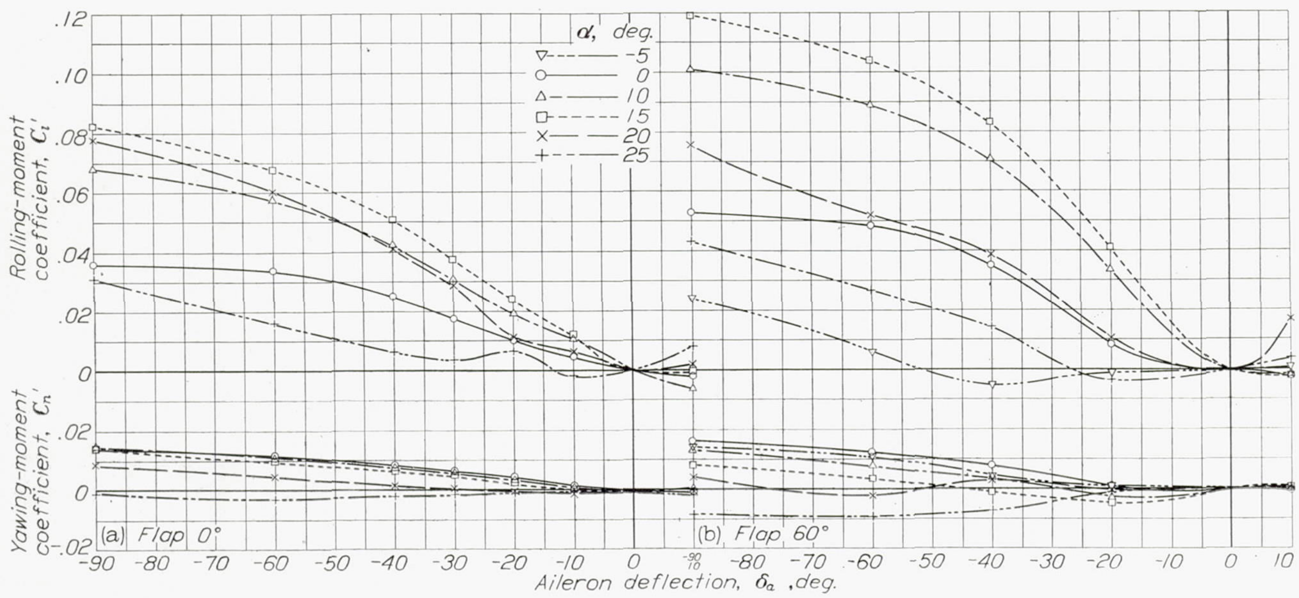


FIGURE 15.—Rolling- and yawing-moment coefficients due to slot-lip ailerons at $0.30c_w$.

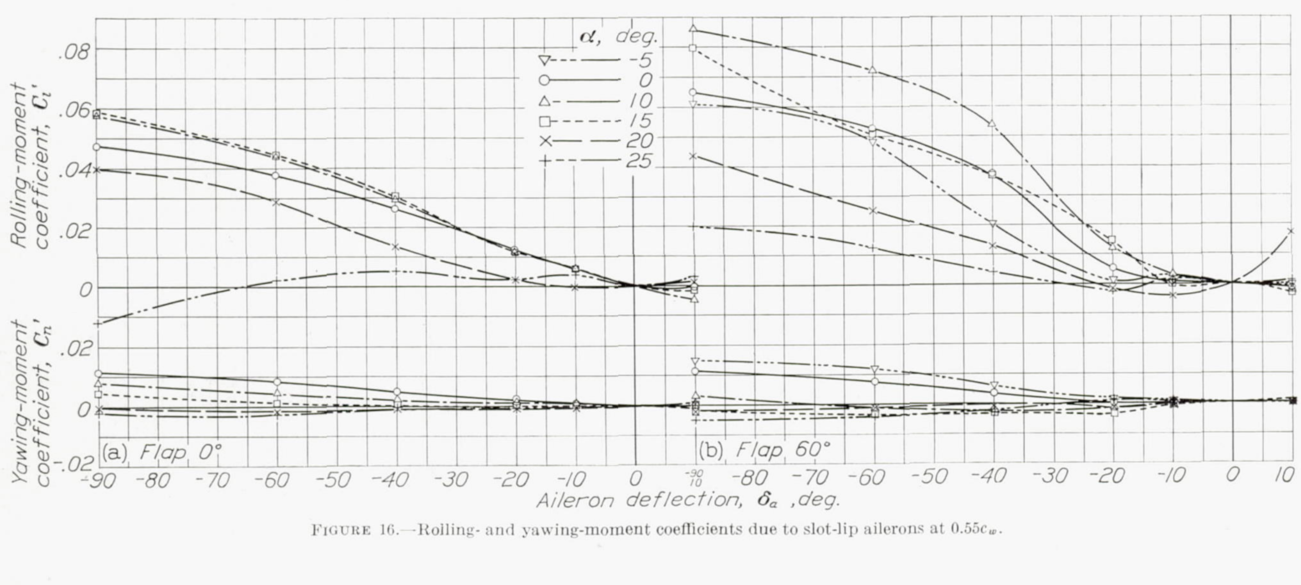


FIGURE 16.—Rolling- and yawing-moment coefficients due to slot-lip ailerons at $0.55c_w$.

may be made from figures 16(a) and 17(a). Although the aileron with the special slot gave higher rolling moments above 20° deflection, the variation of this moment with aileron deflection was not uniform. With the flap deflected, the difference between the two slot shapes was even greater, as may be seen by comparing figures 16(b) and 17(b).

Comparison of slot-lip ailerons and spoilers.—A direct comparison between slot-lip ailerons and plain spoilers was made by testing the slot-lip ailerons in certain conditions with the slot both open and completely sealed. The results are given in figure 19 and show the effect of the slot on the rolling- and yawing-moment coefficients. The ailerons as spoilers were deflected upward 60° in all cases and were located at 0.10, 0.30, and $0.55c_w$. With the slots open the rolling moments are appreciably higher below the stall but are definitely lower above the stall. The yawing-moment coefficients are lower with the slots open.

Effect of slot-lip aileron deflection.—For a satisfactory control device it is desirable that the curve of rolling moment against control deflection have no discontinuities. Owing to the importance of this requirement, the results of all the slot-lip ailerons tested in this part

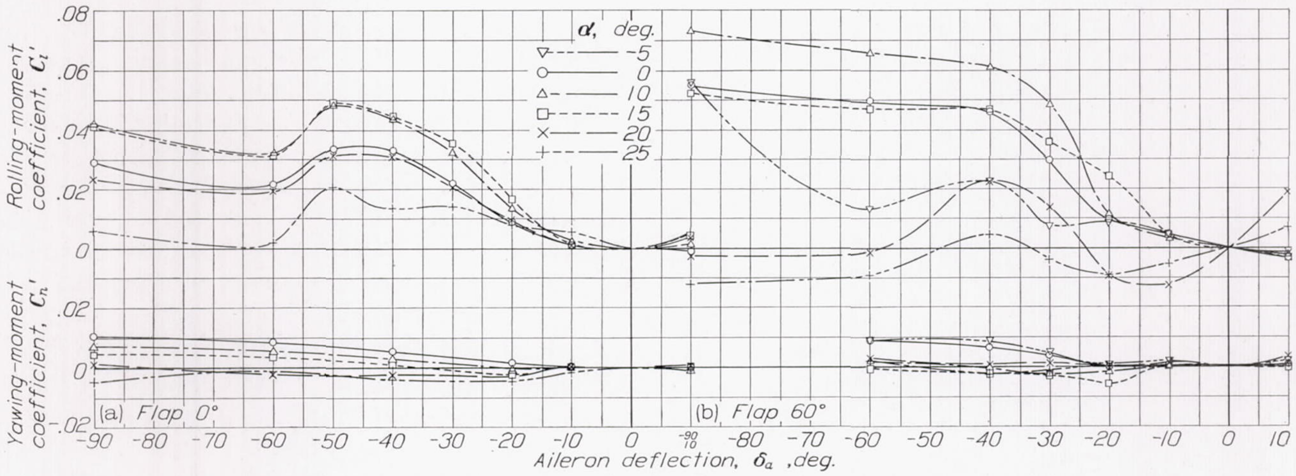


FIGURE 17.—Rolling- and yawing-moment coefficients due to slot-lip ailerons at $0.55c_w$ with special slot.

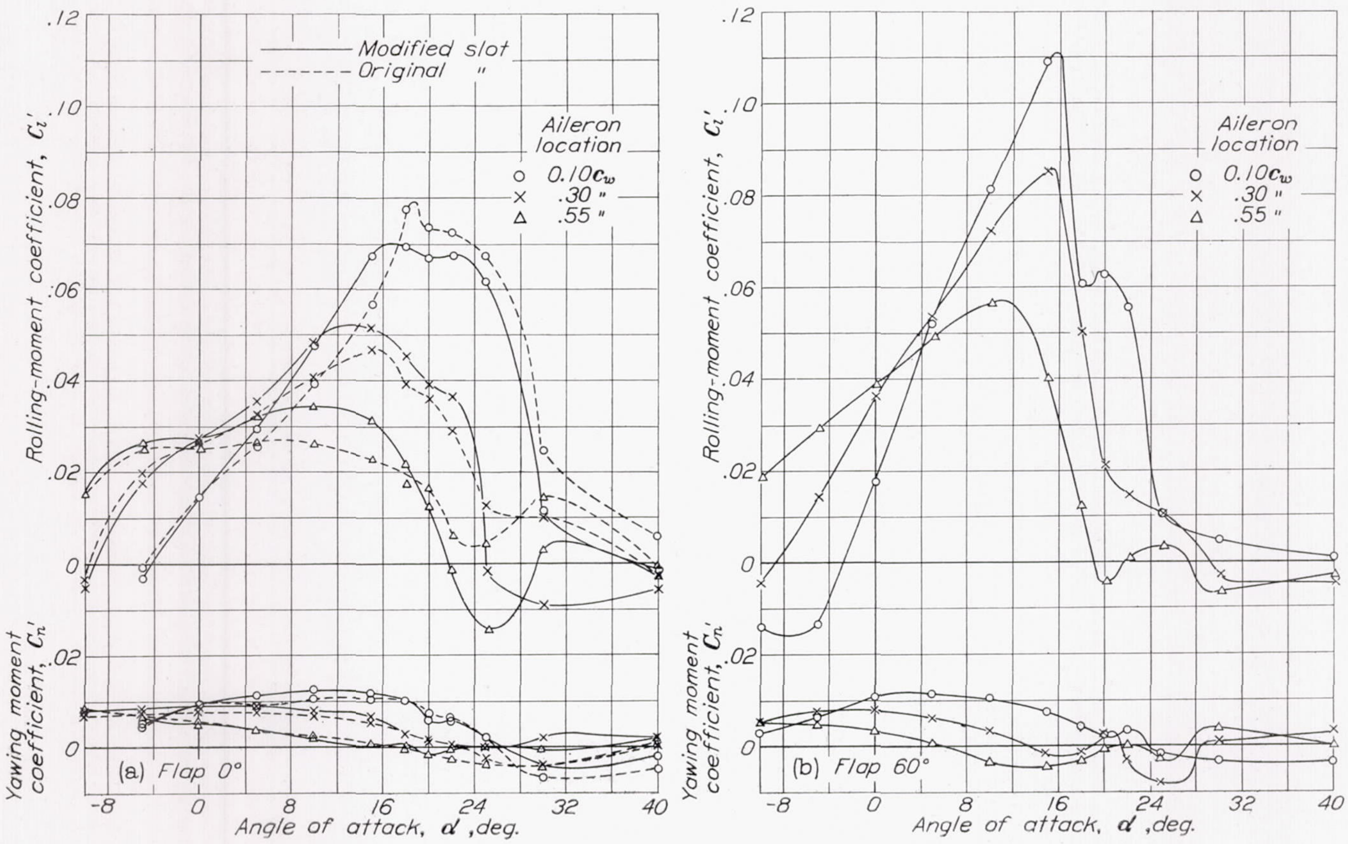


FIGURE 18.—Effect of slot-lip aileron location on rolling- and yawing-moment coefficients, δ_a up 40°, down 12°.

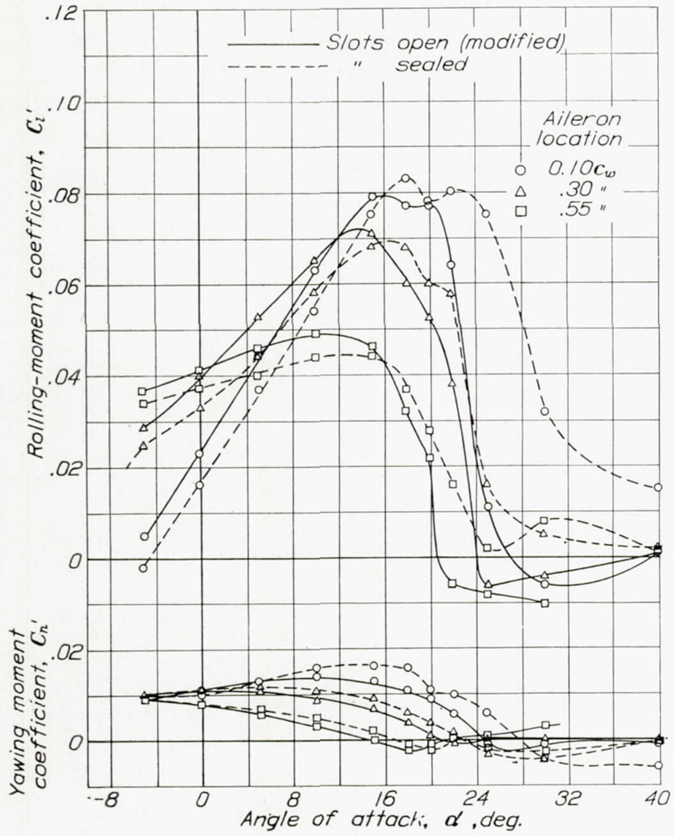


FIGURE 19.—Effect of slot-lip aileron location on rolling- and yawing-moment coefficients, δ_a up 60°; flap, 0°.

of the investigation have been plotted against aileron deflection in figures 14 to 17. With the slot-lip ailerons at the $0.10c_w$ location, the rolling moments are relatively low at 10° aileron deflection, particularly with the flap deflected. With the ailerons at either $0.30c_w$ or $0.55c_w$, however, the moments vary uniformly with aileron deflection except with the flap deflected and the aileron at $0.55c_w$. With the special slot, the rolling moments are low at 10° and 20° deflection but rise to rather high values beyond 30° deflection. In most of the cases given, the rolling moments with the slot-lip aileron deflected downward are opposite in sign to the moments with the ailerons deflected upward. This characteristic allows the use of a differential aileron linkage with some control obtained from the downwardly deflected aileron.

Effect of flap deflection.—With the split flap deflected 60°, the rolling moments produced by the slot-lip ailerons were considerably higher at a given angle of attack than with the flap neutral. Rolling- and yawing-moment coefficients are given in figure 18(b) for the slot-lip ailerons located at the three locations tested with aileron deflection of 40° up, 12° down, with the split flap deflected 60°. Large rolling moments were given by the ailerons at the $0.10c_w$ location at angles of attack near the stall, but these moments rapidly diminish as the angle of attack is reduced.

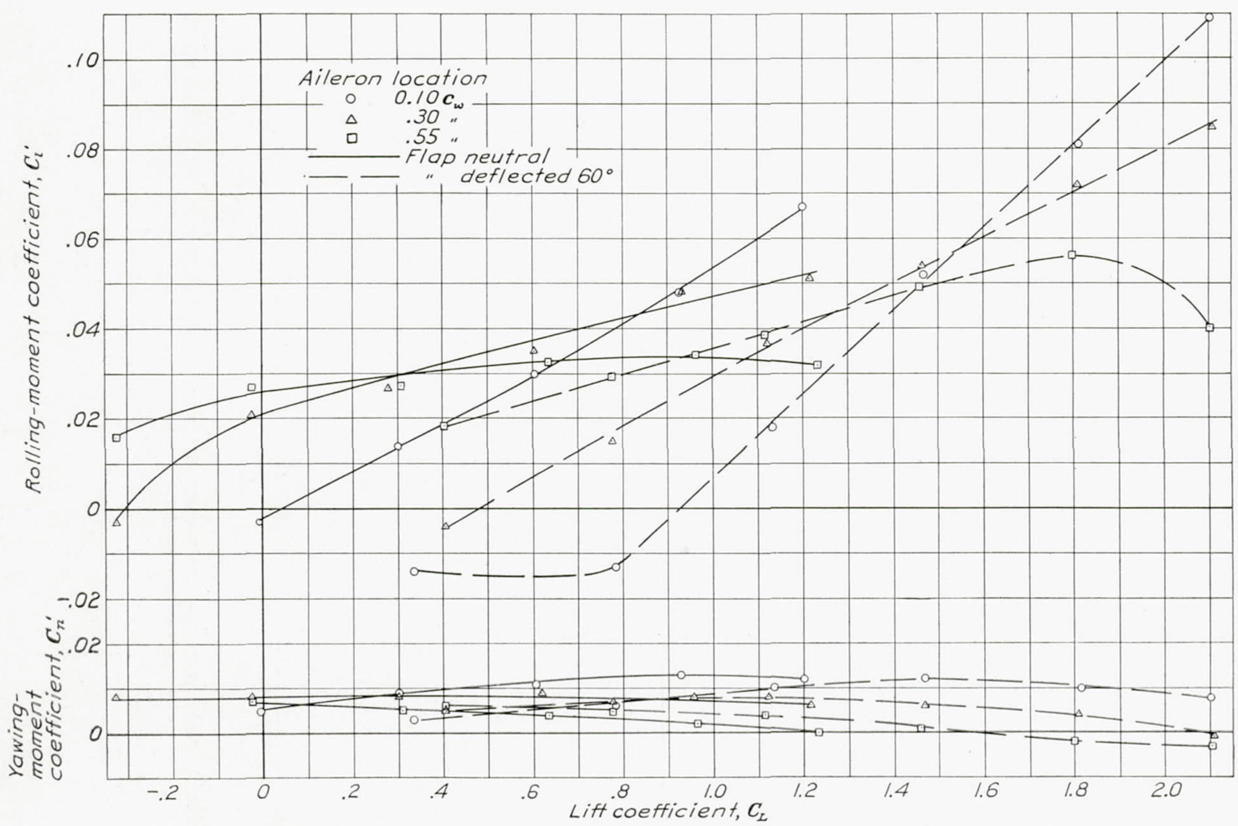


FIGURE 20.—Variation of rolling- and yawing-moment coefficients with lift coefficient for slot-lip ailerons in various locations, δ_a up 40°, down 12°.

A more conclusive comparison of the moments obtained with and without a flap may be made from figure 20 with C_n' and C_l' plotted against C_L. With the flap deflected 60° the rolling moments reached zero at higher values of lift coefficient than with the flap retracted. These values of lift coefficient at which the rolling-moment coefficients vanish are given in figure 21 for various aileron deflections. This characteristic limits the forward location of the ailerons because it is necessary to have control maintained to the highest speed at which the airplane will be flown with the flap deflected. If the corresponding lift coefficient is 0.5, the slot-lip aileron cannot be located farther forward than $0.30c_w$ and still give control.

Effect of deflected ailerons on damping in roll.—With a wing rotating about the longitudinal axis, the downgoing wing is at a higher angle of attack than the center of the wing. If the curve of aileron rolling

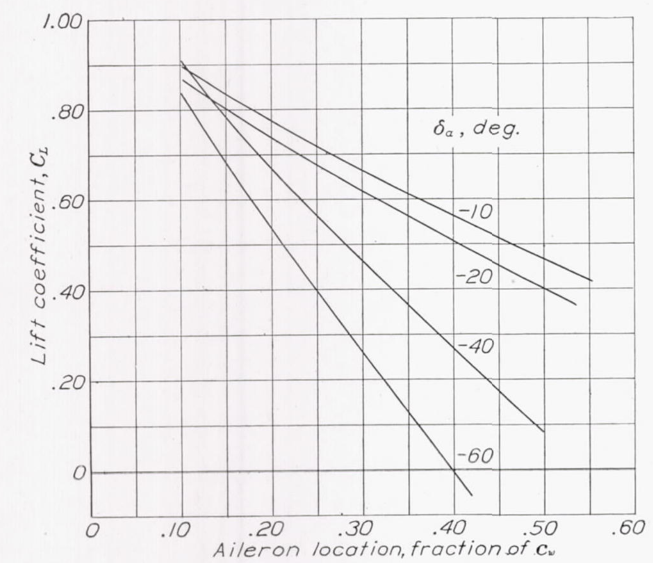


FIGURE 21.—Lift coefficients at which rolling-moment coefficient vanishes when flap is deflected 60°.

moment against angle of attack has a positive slope, the rolling moments obtained with the wing rotating should be higher than those measured in static tests. This increase in rolling effectiveness may be expressed as a reduction in damping in roll. The reduction in damping was checked by rotation tests made with slot-lip ailerons at $0.10c_w$, deflected 40° up, 10° down, and with the split flap both neutral and deflected. The measured values and an approximate curve for the values for the intermediate locations have been included in figure 22.

Choice of slot-lip aileron location.—In the discussion of slot-lip aileron location, it has been shown that the rolling moments are highest at angles of attack near the stall with the forward location. With the aileron in this location, control is not available at high speed with a flap deflected. Control under these conditions is only possible with the location at least as far from the leading edge as $0.30c_w$. Another interesting consideration is the yawing moment accompanying the rolling moment. With ordinary ailerons the induced yawing moment contributes practically the entire yawing moment and the coefficient C_{n_i} is obtained from

$$C_{n_i}=0.20\ C_L C_l'$$

for a rectangular wing of aspect ratio 6 with equal up-and-down aileron deflection. (See reference 9.) In

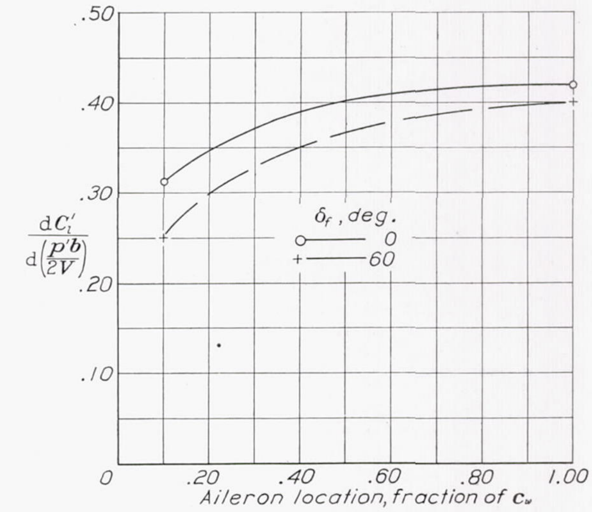


FIGURE 22.—Effect of slot-lip aileron location on damping in roll, δ_a up 40°.

figure 23 are plotted the ratios of yawing moments to rolling moments for the slot-lip ailerons in the three tested positions. Included in the same figure is the theoretical ratio for equal up-and-down deflection of ordinary ailerons. It will be seen that the slot-lip ailerons produced a large profile yawing moment of the same sign as the rolling moment, which was reduced by

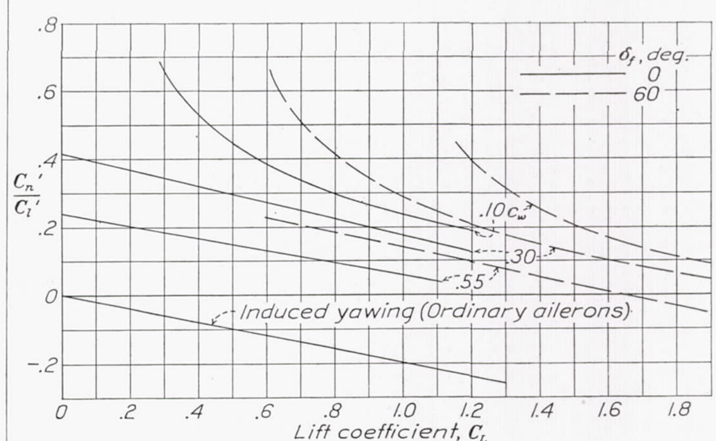


FIGURE 23.—Ratios of yawing moment to rolling moment for slot-lip ailerons.

the induced yawing moment until, at high lift coefficients with the flap down, the yawing moment was negative or adverse with the slot-lip aileron in the rearward location. It appears from reference 10 that, for two-control operation of an airplane, an aileron giving rolling moments accompanied by yawing moments of the same sign (favorable) and about one-fifth the magnitude seems to be the most desirable, although the rate

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of application of the control and the airplane characteristics influence the desirable ratio. With the slot-lip

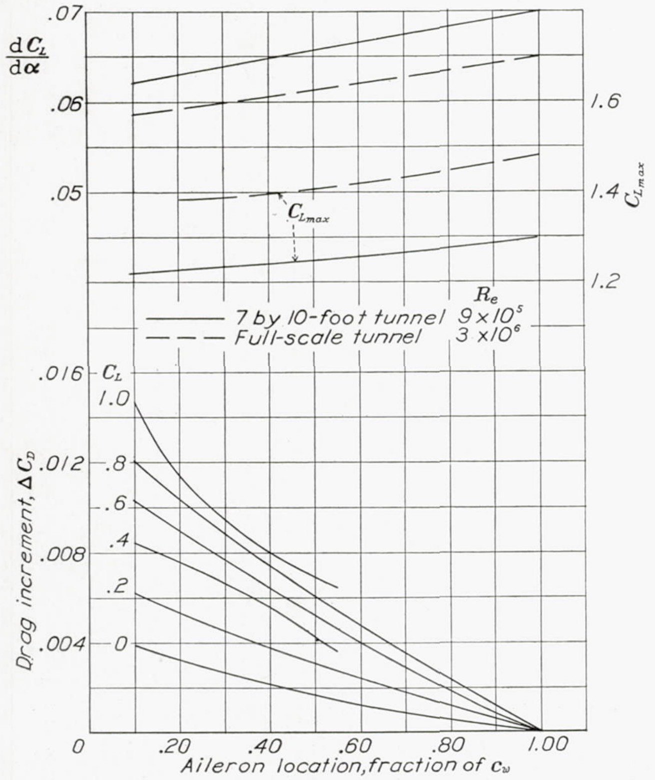


FIGURE 24.—Effect of slot-lip aileron location on ΔC_D, $dC_L/d\alpha$, and $C_{L_{max}}$.

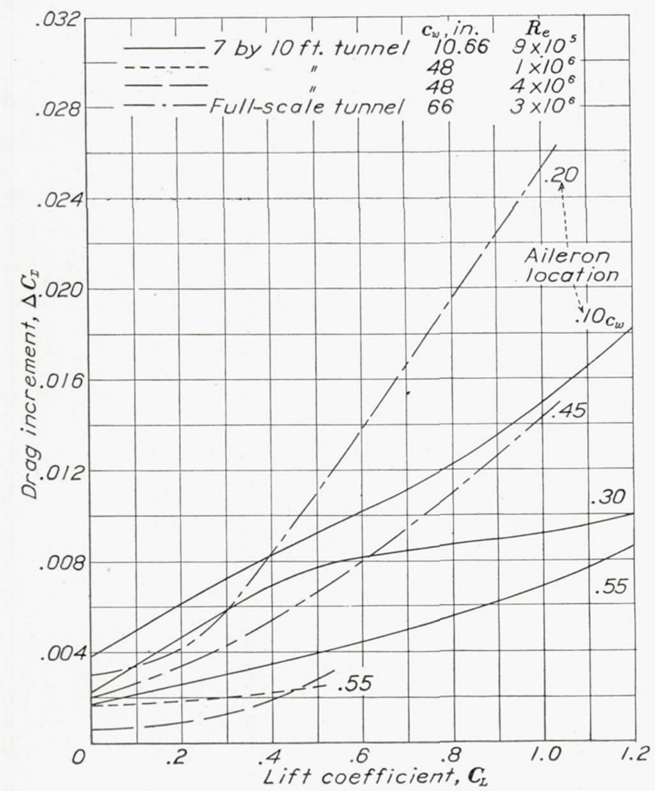
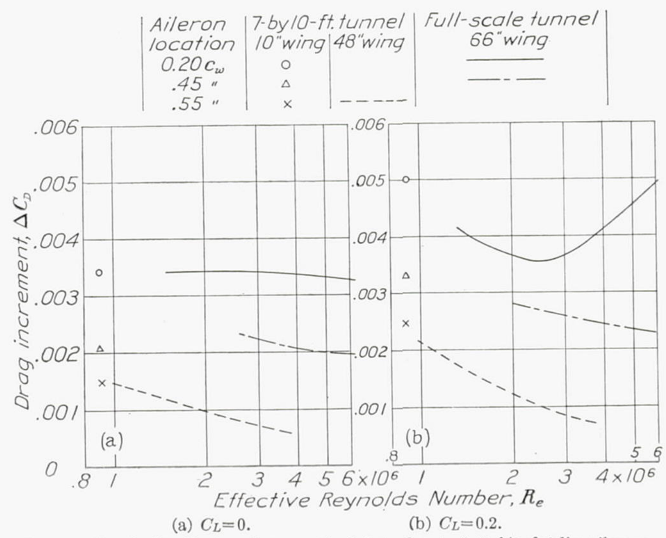


FIGURE 25.—Increments of drag due to 0.50 $b/2$ slot-lip ailerons.

aileron at $0.30c_w$, the ratio of C_n'/C_l' varies from about 0.05 at maximum lift with the flap deflected to about 0.40 at high speed, flaps neutral. With the aileron in the $0.55c_w$ location, the ratio becomes negative at the landing condition, whereas at the $0.10c_w$ location the ratio becomes excessively large at high speed. Consideration of lateral stability dictates a forward location; the lowest drag is obtained with the rearward location. The $0.30c_w$ location would seem to be the most desirable for a slot-lip aileron used as the sole means of lateral control, except for the effect of the slots on the drag of the wing.

LIFT AND DRAG EFFECTS DUE TO SLOT-LIP AILERONS

The effect of slot-lip ailerons on the lift and the drag is of particular importance for high-performance airplanes. Previous tests have shown that at low angles of attack practically all slots reduce the lift and increase the drag. It has also been shown that a given size of slot has less drag when located rearward on the wing



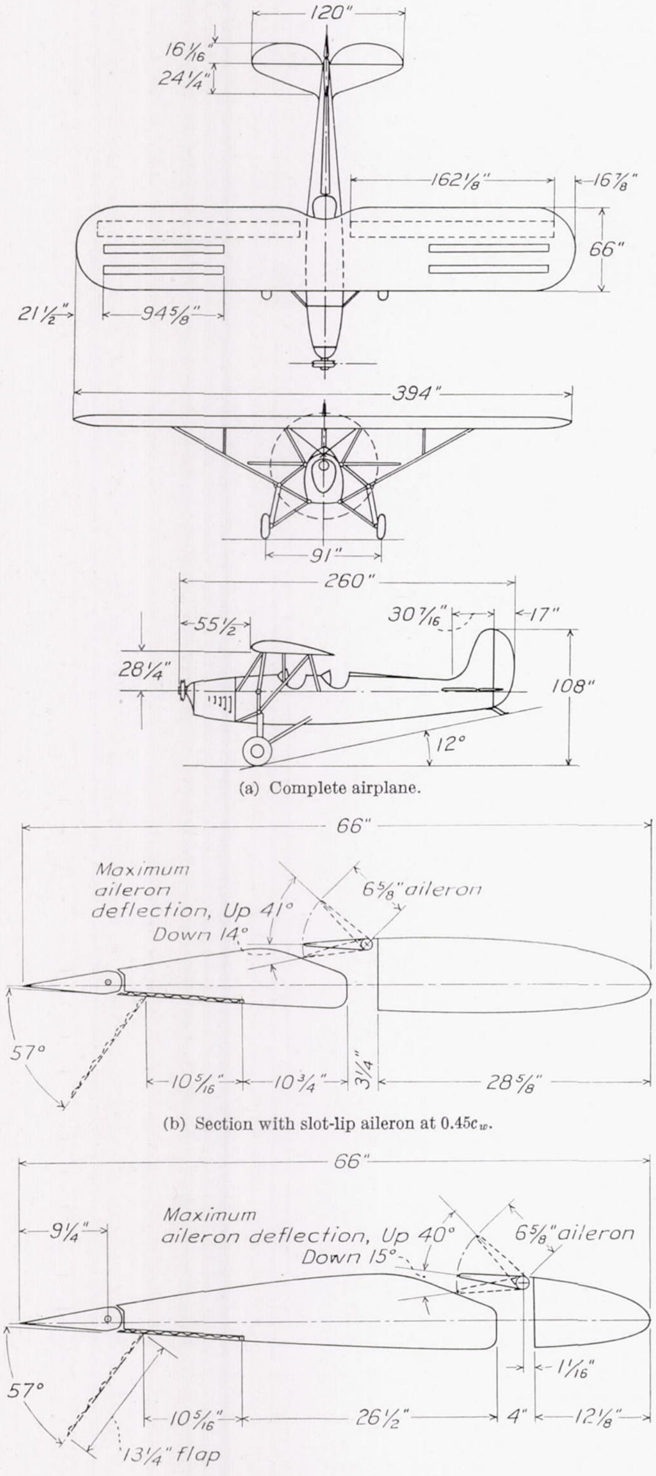
(a) $C_L=0$. (b) $C_L=0.2$.

FIGURE 26.—Scale effect on increment of drag due to 0.50 $b/2$ slot-lip ailerons.

than when located forward. In the present investigation the slots were made as narrow as possible without causing lag. Because the effect of the slots on the drag was large, considerable attention was given to its measurement and to means for reducing it. The effect of the slots on the drag was determined with slot-lip ailerons on a small-scale wing model in the 7- by 10-foot tunnel and on an actual airplane in the full-scale tunnel. The airplane was equipped with slot-lip ailerons in two locations, one ($0.20c_w$) selected for its control and stability characteristics and the other ($0.45c_w$) selected for its smaller effect on lift and drag.

TESTS IN THE 7- BY 10-FOOT TUNNEL

The tests of the small model in the 7- by 10-foot tunnel mentioned in the last section are interesting because they indicate certain trends. It would, however, be misleading to attempt to predict the performance of an airplane from the low-scale tests. The values of increments of drag due to the slot-lip ailerons have been computed for the slot-lip ailerons in the three locations tested from polar curves plotted from the data given in figures 12(a) and 12(b) and from additional check tests. The average values of ΔC_D are given in figures 24, 25, and 26 and are compared with values from other tests at large values of the Reynolds



(a) Complete airplane.

(b) Section with slot-lip aileron at $0.45c_w$.

(c) Section with slot-lip aileron at $0.20c_w$.

FIGURE 27.—Fairchild 22 airplane with slot-lip ailerons. The N. A. C. A. 2412 wing section.

Number. The Reynolds Numbers given are the effective Reynolds Number determined for each tunnel from reference 11. The effects of slot-lip aileron location on the slope of the lift curve $dC_L/d\alpha$ and on maximum lift are shown in figure 24 and compared with values from tests in the full-scale tunnel. Because of the different test aspect ratios and different Reynolds Numbers, the actual values do not agree but the reductions in the values due to the slots are comparable. The values at the $1.00c_w$ location are taken from the case with no slot or aileron.

TESTS IN THE FULL-SCALE TUNNEL

In order to determine the practicability of slot-lip ailerons from actual flight tests and to determine their drag at large scale, tests were made of a Fairchild 22 airplane equipped with a wing modified to permit the installation of slot-lip ailerons with their hinge axes at either 0.20 or $0.45c_w$ positions. The F-22 airplane is a two-place, externally braced, parasol-type mono-

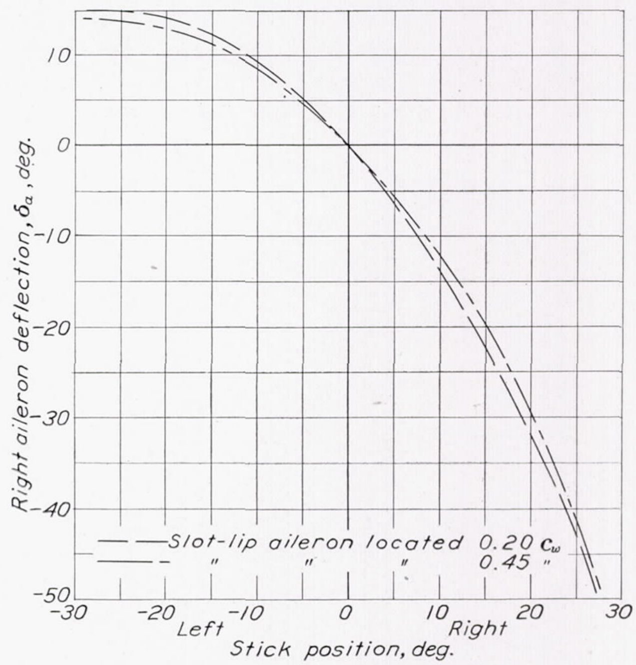


FIGURE 28.—Slot-lip aileron deflections for Fairchild 22 airplane.

plane. A three-view drawing of the airplane as tested in flight is shown in figure 27(a). Section drawings of the wing showing the slot-lip ailerons in the two positions on the N. A. C. A. 2412 wing used are shown in figure 27(b) and (c). The allowable aileron motions are shown in figure 28 for both positions. In the tests in the full-scale tunnel the wing was mounted on a slightly different fuselage for convenience.

The airplane with the horizontal tail surfaces and propeller removed was mounted on the balance in the full-scale tunnel as shown by figure 29. A description of the wind tunnel and balances is given in reference 12. The ailerons were locked in their neutral position and lift, drag, and pitching moments were measured with the slot-lip ailerons first in the $0.20c_w$ location, then in the $0.45c_w$ location, and finally without the slot-lip ailerons. When the slot was not in use, the openings were covered with metal plates shaped to conform to the wing profile. A photograph (fig. 30) shows the wing with the slot open in the $0.45c_w$ position and with the front position slot covered by a metal plate.

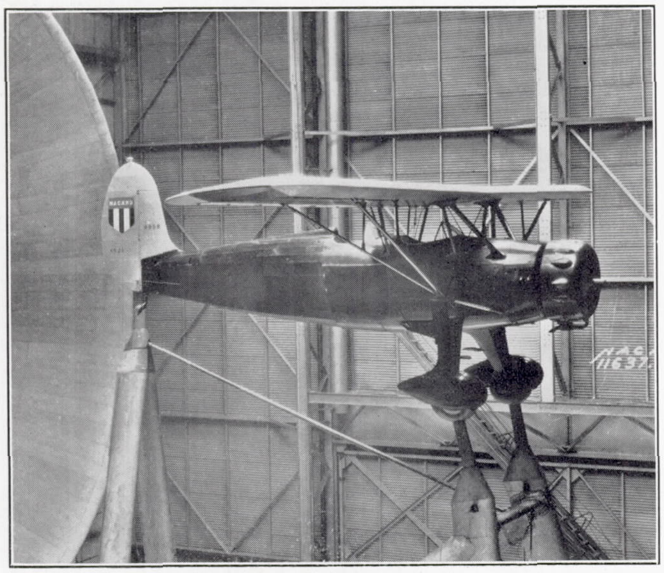


FIGURE 29.—The Fairchild 22 airplane with slot-lip ailerons mounted for test in the full-scale tunnel.

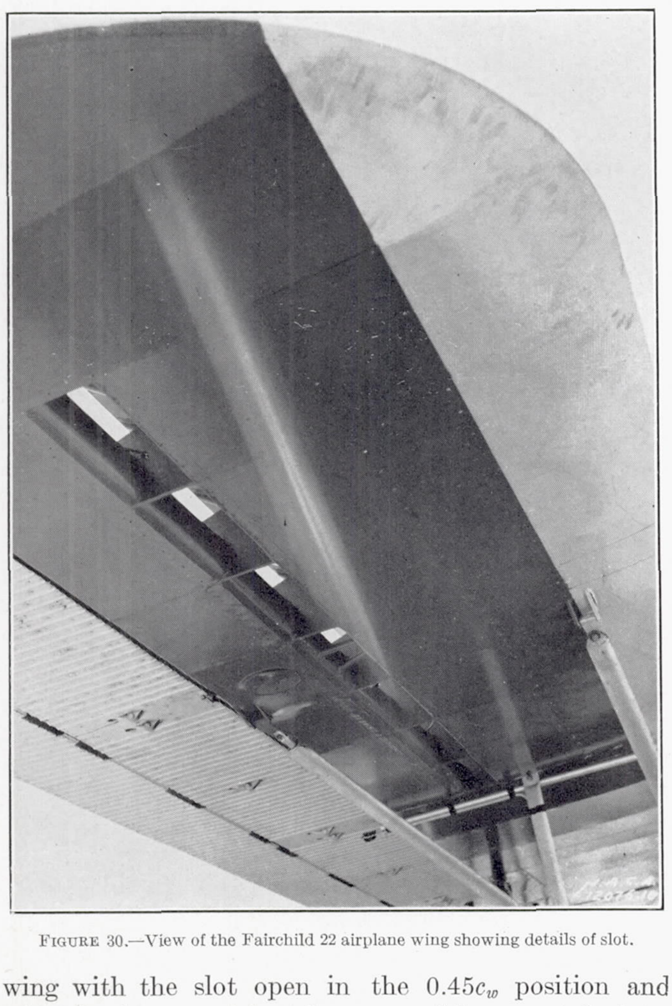


FIGURE 30.—View of the Fairchild 22 airplane wing showing details of slot.

The tests were made with the flap both neutral and deflected and covered a range of angles of attack from −8° to 24° at a tunnel air speed of about 56 miles per hour. Scale-effect tests to determine the minimum drag were made over a speed range from 30 to 120 miles per hour with the flap neutral.

All the results have been corrected for tare and wind-tunnel effects. The lift, the drag, and the pitching-moment coefficients are plotted in figure 31 against angle of attack. The effect of the slot-lip ailerons on the lift is clearly shown: The maximum lift and

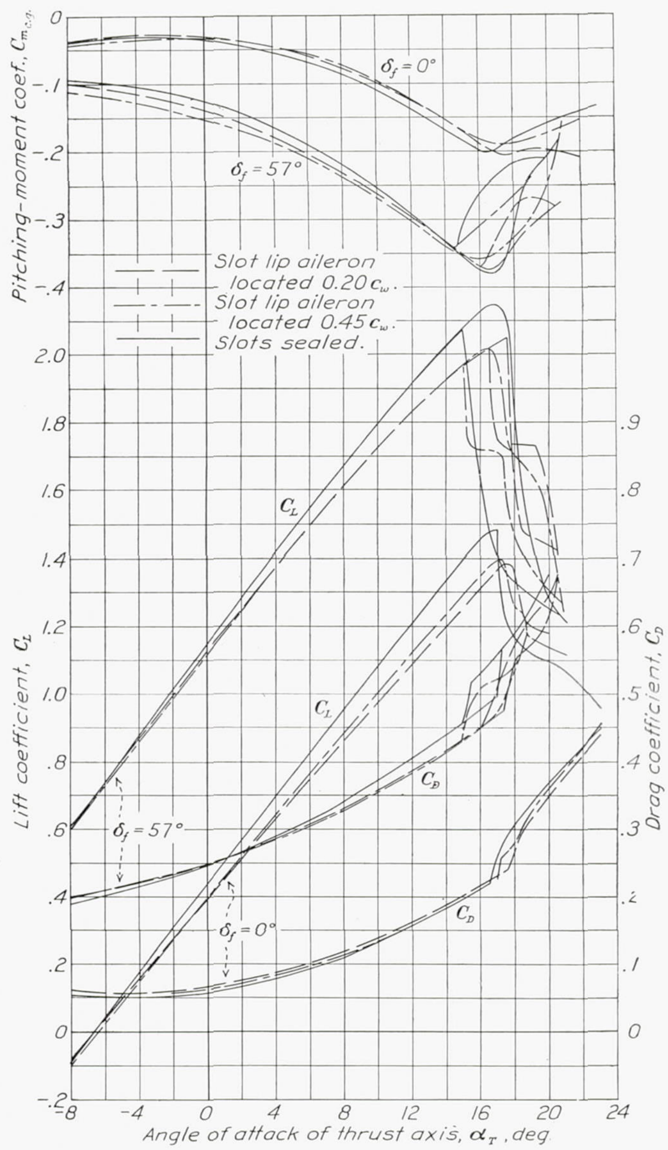


FIGURE 31.—Lift, drag, and pitching-moment coefficients of the Fairchild 22 airplane with slot-lip ailerons. The full-scale tunnel; air speed, 56 m. p. h.; propeller and horizontal tail surfaces removed; angle of wing setting, 4.4°.

the slope of the lift curve are reduced, but the stall is somewhat delayed, as in the wing model tests. The pitching-moment coefficients are only slightly affected by the slot-lip ailerons. The effect of the flap on the pitching moments is not conclusive since the horizontal tail surface was not in place and the additional downwash at a given angle of attack with the flap deflected would, no doubt, reduce the difference between the results with flap neutral and flap deflected.

The effect of the slot-lip ailerons on drag is clearly shown in figure 32, which is a plot of drag increment

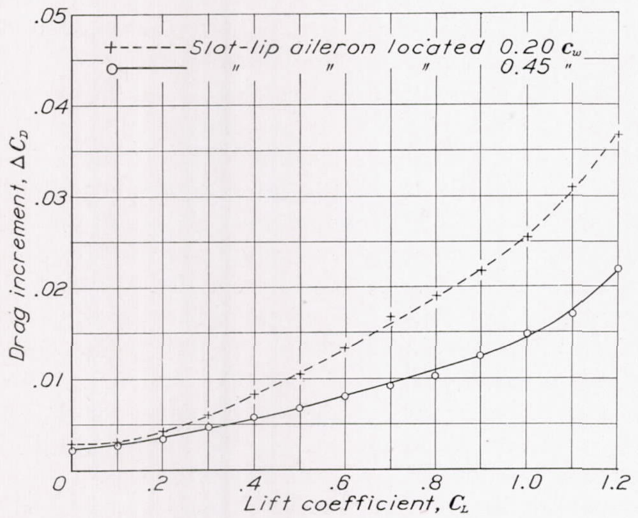


FIGURE 32.—Increase in drag due to slot-lip ailerons on the Fairchild 22 airplane in the full-scale tunnel. Air speed, 56 m. p. h.

ΔC_D against lift coefficient for the slot-lip ailerons in the two locations. With the particular shape of slot used the drag increment increases appreciably with lift coefficient. The effect of air speed on the drag coefficient is shown in figure 33(a) for minimum drag and in figure 33(b) for drag at a lift coefficient of 0.2. The effect of air speed or effective Reynolds Number on the drag increment is shown in figure 26. The scale effect is much greater at high lift coefficients than at the minimum drag attitude. The points of figure 26 taken from interpolated results of small-scale tests agree fairly well with the large-scale tests. Figure 25, however, shows poor agreement between large-scale and small-scale tests at lift coefficients above 0.2.

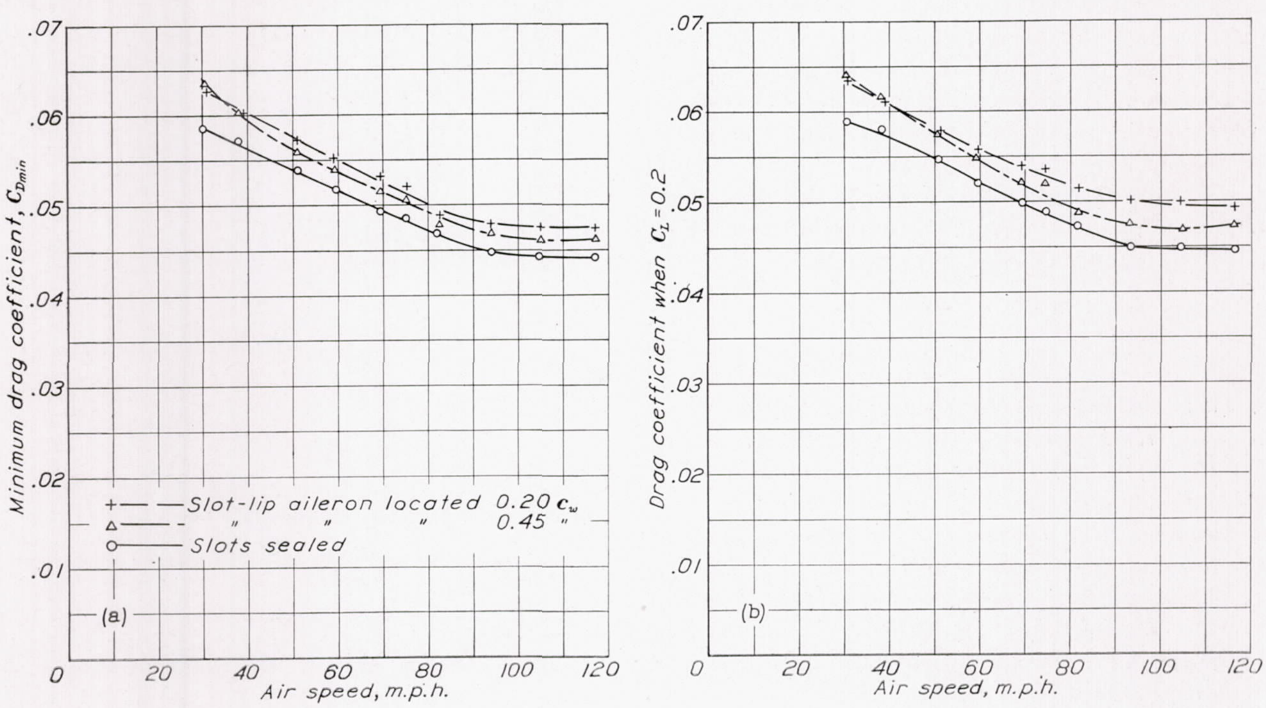
The effect of the slot-lip ailerons as tested in the full-scale tunnel on the Fairchild 22 airplane is more clearly shown by computing the estimated performance of the airplane. The following table gives the estimated power-on performance characteristics based on the tunnel results.

ESTIMATED PERFORMANCE OF F-22 AIRPLANE WITH SLOT-LIP AILERONS IN TWO LOCATIONS

Slot location	V_{min} (m. p. h.)		V_{max} $\delta_f = 0°$ (m. p. h.)	Maximum rate of climb (ft./min.)	Maximum angle of climb (deg.)
	$\delta_f = 0°$	$\delta_f = 56°$			
0. 20c_w	53. 08	43. 75	122. 6	625. 0	4. 7
0. 45c_w	52. 91	44. 12	125. 0	675. 0	5. 7
No slot	51. 37	42. 75	129. 4	772. 5	6. 3

SLOT-DRAG INVESTIGATION

An investigation of the drag of slots used with slot-lip ailerons was conducted in the 7- by 10-foot wind tunnel. A wing of N. A. C. A. 23012 section with a chord of



(a) $C_{D_{min}}$. (b) C_D at C_L=0.2.

FIGURE 33.—Scale effect on drag coefficients of Fairchild 22 airplane with slot-lip ailerons tested in the full-scale tunnel.

4 feet and a span of 8 feet was mounted on the regular balance between end planes that spanned the jet vertically as shown in figure 34. With an air speed of 80 miles per hour, the effective Reynolds Number was high enough to overlap the Reynolds Number of the tests

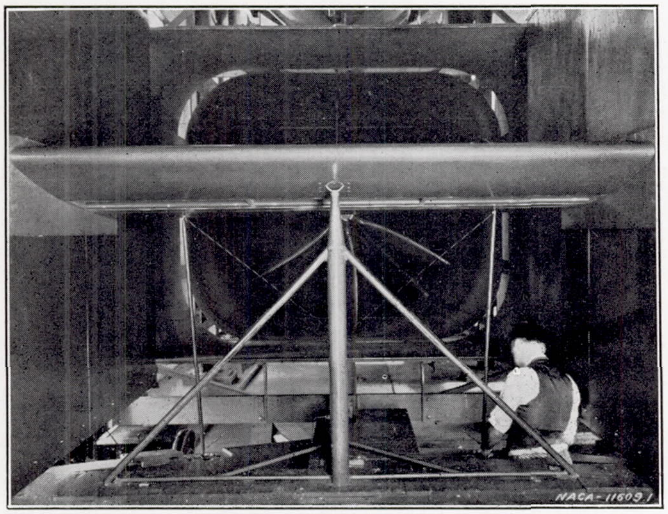


FIGURE 34.—The N. A. C. A. 23012 wing of 4-foot chord and 8-foot span with slots at $0.55c_w$ mounted between end planes in the 7- by 10-foot tunnel.

in the full-scale tunnel. The full-span slots were all located about $0.55c_w$.

Tests were made of the wing with no slots, with slot-lip ailerons of the type previously tested, and with several modifications. The lift, the drag, and the pitching-moment coefficients were obtained at an air speed of 80 miles per hour for all slots and at air speeds of 20, 40, and 60 miles per hour for certain conditions.

The results of the plain-wing tests at 80 miles per hour corrected for tunnel effects are plotted in figure 35. The values of the drag coefficient were corrected for tares and for static-pressure gradient by the usual methods and for deflection of the tunnel air stream by the following equation from reference 13:

$$\Delta C_{D_i}=0.25\frac{c}{h}C_L^2$$

where c/h is the ratio of the wing chord to the height of the jet. With the corrections applied, the profile drag of the plain wing agrees with values obtained in the variable-density tunnel at the same effective Reynolds Number. The accuracy of the equation in correcting for the air-stream deflection depends on the nature of the spillage of air from the open test section of the tunnel. In the 7- by 10-foot tunnel the exit cone is of the same size as the entrance cone and part of the deflected air stream at high lift coefficients flows below the exit cone. In such a condition the theoretical corrections do not hold. The theoretical correction for angle of attack was insufficient to correct the results to infinite aspect ratio, so an arbitrary correction was applied to give a lift-curve slope of $dC_L/d\alpha_0$ of 0.101. The pitching-moment coefficient at zero lift C_{m_0} agreed with the results from tests in the variable-density tunnel, but the aerodynamic-center location was slightly ahead of the location found in the variable-density tunnel although it agreed with previous tests in the 7- by 10-foot tunnel of the same airfoil section. The errors due to tunnel effects are eliminated by presenting the results of the tests with various slots mainly in terms of variation from the plain-wing tests.

The type of slot used with the previously tested slot-lip ailerons was tested first for comparison. (See fig. 11(c).) The increments of drag obtained have been plotted in figures 25 and 26 for comparison with the previous tests. The increments as given are one-half the measured increments for comparison with the other one-half span slots. It will be seen (fig. 26) that the increments agree with the previous tests in the 7- by 10-foot tunnel at low values of the Reynolds Number at values of the lift coefficient of 0 and 0.2. There appears to be a large favorable scale effect for the slot location tested as compared with the tests of the more forward locations in the full-scale tunnel. A direct comparison is given in figure 25 of the drag increments from partial-span slots. Differences in the low-scale tests, which agree at zero lift but do not agree at other lifts, are partly due to the additional induced drag accompanying the distorted span load distribution of the lift. In addition, the scale effect at high lift coefficients differs from that at low lift coefficients. For this reason, the low-scale tests are of little value in predicting the drag at high lift coefficients.

The results of the present tests are given in table I, which shows: A diagram of each slot tested; increments

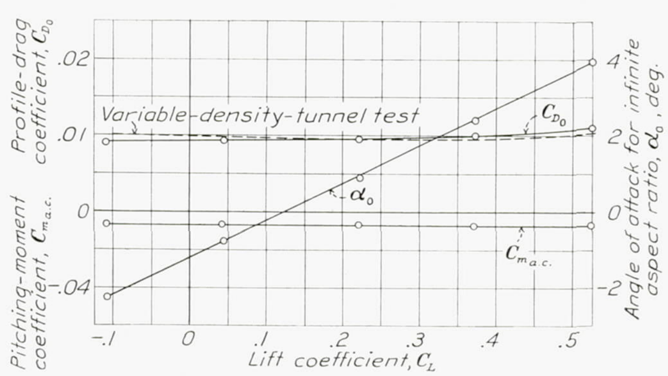


FIGURE 35.—Aerodynamic characteristics of the 4- by 8-foot wing of N. A. C. A. 23012 section mounted between end planes in the 7- by 10-foot tunnel. Effective Reynolds Number, 4,090,000; aerodynamic-center location: ahead of quarter-chord point $0.030c_w$, above chord $0.084c_w$.

of profile drag at $C_L=0$, 0.2, 0.4, and 0.5; slope of the lift curve $dC_L/d\alpha_0$; shift of the angle of attack of zero lift, $\Delta\alpha_{L_0}$; pitching-moment coefficient at zero lift, C_{m_0}; and the approximate aerodynamic-center location in the fraction of c_w from the quarter-chord point of the wing. The values in the table are from the tests at 80 miles per hour. Only a few arrangements will be discussed.

The original slot 1 gave a rather low increment of drag ($\Delta C_D=0.0013$) at zero lift but gave a high increment ($\Delta C_D=0.0052$) at $C_L=0.5$. With the surface in the rear of the slot reduced in thickness to allow smoother air flow, as in slot 5, the drag coefficient at $C_L=0.5$ increased to 0.0084 without appreciably affecting the drag at $C_L=0$. The rounding of the slot entrance so as to offer less resistance to the air, as in slot 11, reduced the drag coefficient at $C_L=0.5$ to 0.0034 but increased that at $C_L=0$ to 0.0038. It seemed, therefore, that the sharp-edge entry was desirable for high-speed conditions and further attempts were made to reduce the drag at $C_L=0.5$. Since the blunt shape of slot 1 gave less drag than the pointed shape of slot 4, slots 12 and 15 were tested, in which the lower opening was variable in size and the rear face was extremely blunt. Then the slot was filled in, as in 16, and the small opening ahead of the slot-lip aileron was sealed, as in slot 18; the drag increments were reduced to 0.0033, which is a substantial reduction from the original value of 0.0052 at $C_L=0.5$. If the slot size can be reduced as in slot 21, the drag coefficient is reduced to 0.0028. With the slot sealed on the bottom, as in slot 14, the drag increment was only 0.0011; and when sealed only at the top, as in slot 20, the drag increment was only 0.0008. With either surface sealed, however, the lateral control obtained with the slot-lip aileron was no longer satisfactory because of lag. It therefore seems that, although an appreciable reduction in drag due to the original form of the slot-lip ailerons is obtainable, the drag increments would still be considered excessive for high-performance airplanes.

FLIGHT TESTS

After the wind-tunnel tests had indicated that the slot-lip ailerons should give satisfactory lateral control, it seemed desirable to obtain flight tests of the device. The pilots' reactions to the aileron control as well as instrument records of the airplane motion produced by the ailerons were obtained. The airplane as tested in flight with the slot-lip ailerons deflected in the $0.45c_w$ location is shown in figure 36. Four conditions were investigated:

The hinge axis located at $0.20c_w$, flap neutral.
The hinge axis located at $0.20c_w$, flap deflected.
The hinge axis located at $0.45c_w$, flap deflected.
The hinge axis located at $0.45c_w$, flap neutral.

METHODS

The flight tests consisted of three phases. First, the angular velocity in roll and yaw and the control position were recorded on high-speed film during a maneuver in which the ailerons were fully deflected to determine the response. Second, somewhat slower records were obtained with the controls fully deflected at different air speeds. Third, the control obtained with partial aileron deflection at a given air speed was determined. In addition, the force required to deflect the ailerons under different conditions was measured. Graphical differentiation of the angular-velocity records gave the angular acceleration produced.

RESULTS

Time histories showing the response of the airplane to the moment produced by the slot-lip ailerons in the $0.20c_w$ location are given in figure 37(a) with the flap both neutral and deflected. It will be seen that the wing starts to roll in the desired direction immediately but is decidedly slow in attaining maximum angular acceleration. Similar records with the ailerons in the $0.45c_w$ location are shown in figure 37(b). With the ailerons in the rearward location, the maximum acceleration is attained sooner than with them in the forward location.

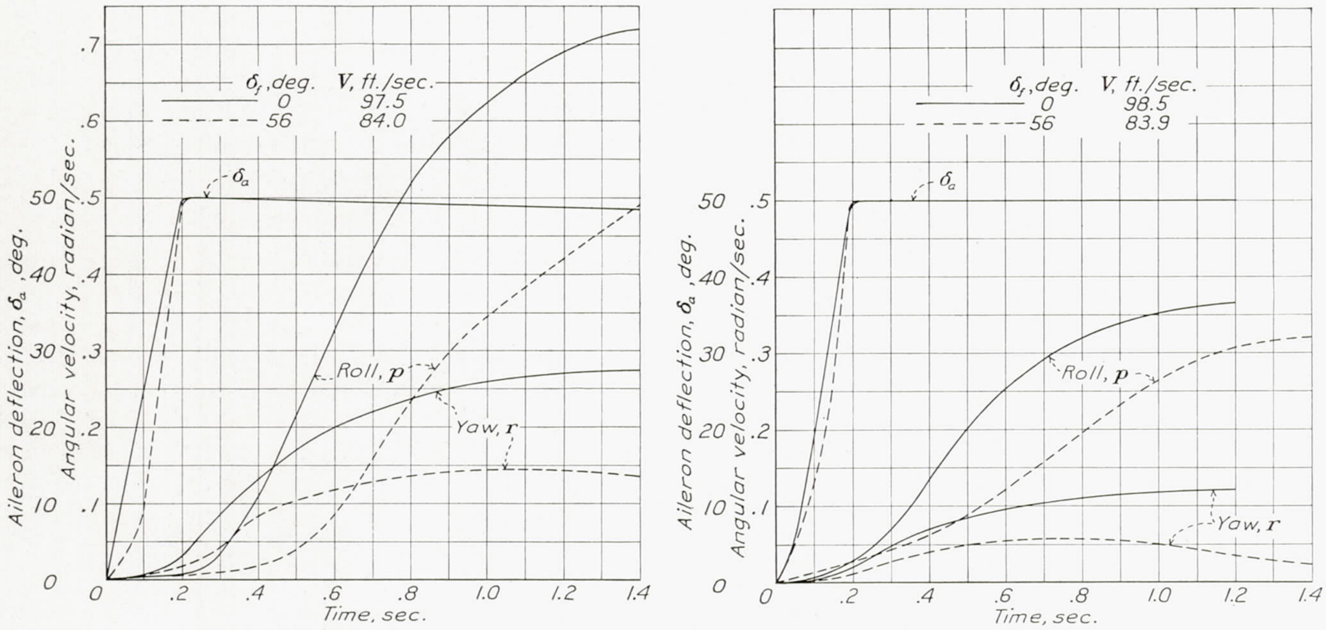
The effect of aileron deflection on angular velocity and acceleration in roll and in yaw is shown in figure 38.

FIGURE 36.—The Fairchild 22 airplane with slot-lip ailerons as tested in flight.

For satisfactory operation the motions produced by control deflection should not depart excessively from a linear variation with deflection. With the flap neutral this characteristic is obtained, but with the flap deflected the control may be too weak for low aileron deflections.

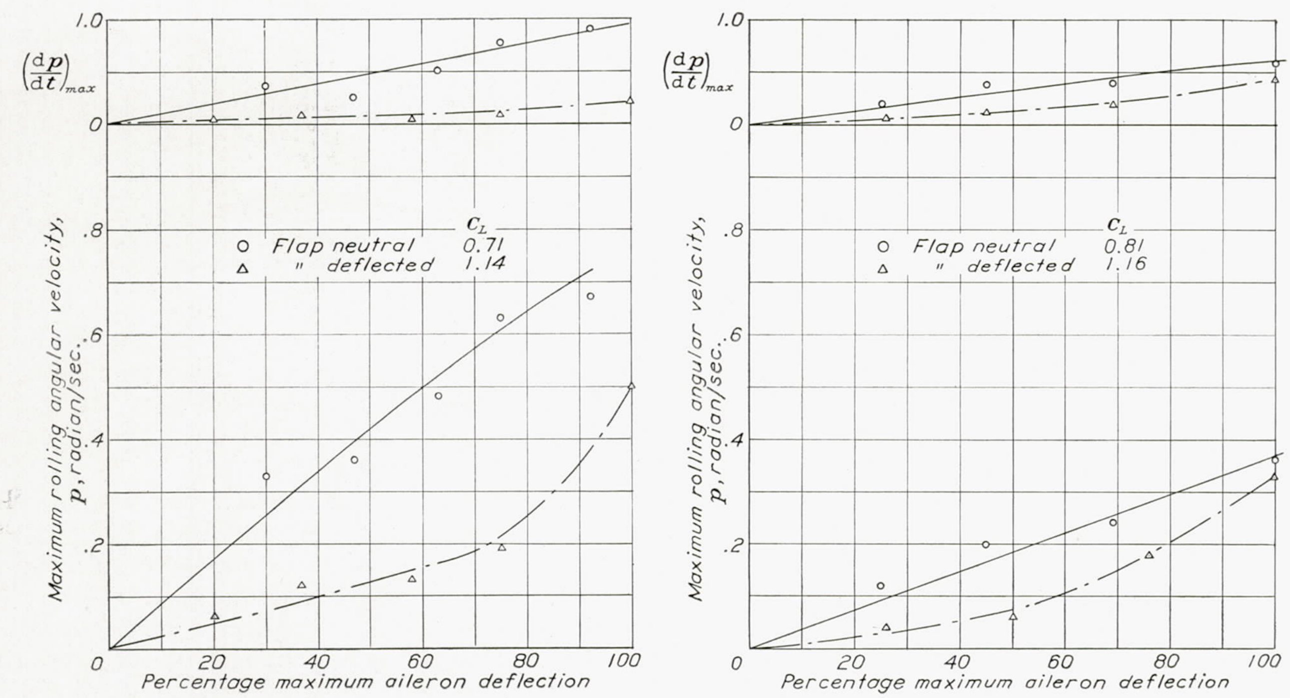
The variation of control effectiveness with air speed is shown in figure 39. Normally, the angular velocity and acceleration decrease with air speed but, with the slot-lip aileron in the forward location with the flap deflected, the velocity and acceleration decrease with an increase of air speed. In fact, this characteristic seems to be one that limits the forward location of the slot-lip aileron. The slot-lip aileron should be so located as to give good control up to the highest speed flown with flap down. Reference to figure 21 will show the lift coefficient at which control vanishes for various aileron deflections and locations as determined from the wind-tunnel tests.

The stick forces required for maximum deflection of the slot-lip ailerons are given in the following table. The pilots considered all the forces rather heavy and the force of 19.8 pounds excessive with the flap deflected and the aileron in the forward location.



(a) Slot-lip ailerons at $0.20c_w$. (b) Slot-lip ailerons at $0.45c_w$.

FIGURE 37.—Time history of airplane motion with slot-lip ailerons on the Fairchild 22 airplane.



(a) Slot-lip ailerons at $0.20c_w$. (b) Slot-lip ailerons at $0.45c_w$.

FIGURE 38.—Variation of maximum rolling angular velocity and acceleration with aileron deflection for slot-lip ailerons on the Fairchild 22 airplane.

Aileron location	Flap condition	Air speed (ft./sec.)	Stick force (lb.)
$0.20c_w$	Neutral	88	8.4
$0.20c_w$	do	132	10.8
$0.20c_w$	Deflected	71	14.5
$0.20c_w$	do	108	19.8
$0.45c_w$	Neutral	79	6.4
$0.45c_w$	do	131	12.0
$0.45c_w$	Deflected	64	8.3
$0.45c_w$	do	83	8.8

The pilots reported that the control action was weak for all flight conditions with the slot-lip ailerons and that the sluggishness was definitely objectionable for both locations, although less so at the rearward location. With the flaps deflected, the sluggishness was worse than with them neutral. The actual magnitude of the sluggishness for the different conditions has been computed and is discussed in the next section.

ANALYSIS OF RESULTS

LAG AND SLUGGISHNESS

In the present analysis of wind-tunnel and flight tests in which dynamic lift is produced, an attempt has been made to determine the sluggishness produced by certain control devices. In the case of slot-lip ailerons it is conceivable that the sluggishness might be greater than with ordinary ailerons because the vortices shed from the slot-lip ailerons located at midchord act on the wing for a longer time. In addition, the wing travels a greater distance before the final flow pattern, involving separation over certain regions, is established.

Wind-tunnel tests.—In the wind-tunnel tests of the lag investigation a half-span wing was restrained in roll by an elastic cord but was free to roll to a new position of equilibrium after a rolling moment was applied by certain control devices. (See fig. 1.) The equation of motion of the wing thus restrained and acted upon may be expressed by

$$\frac{dp}{dt}=L_0+pL_p+\phi L_\phi \qquad (1)$$

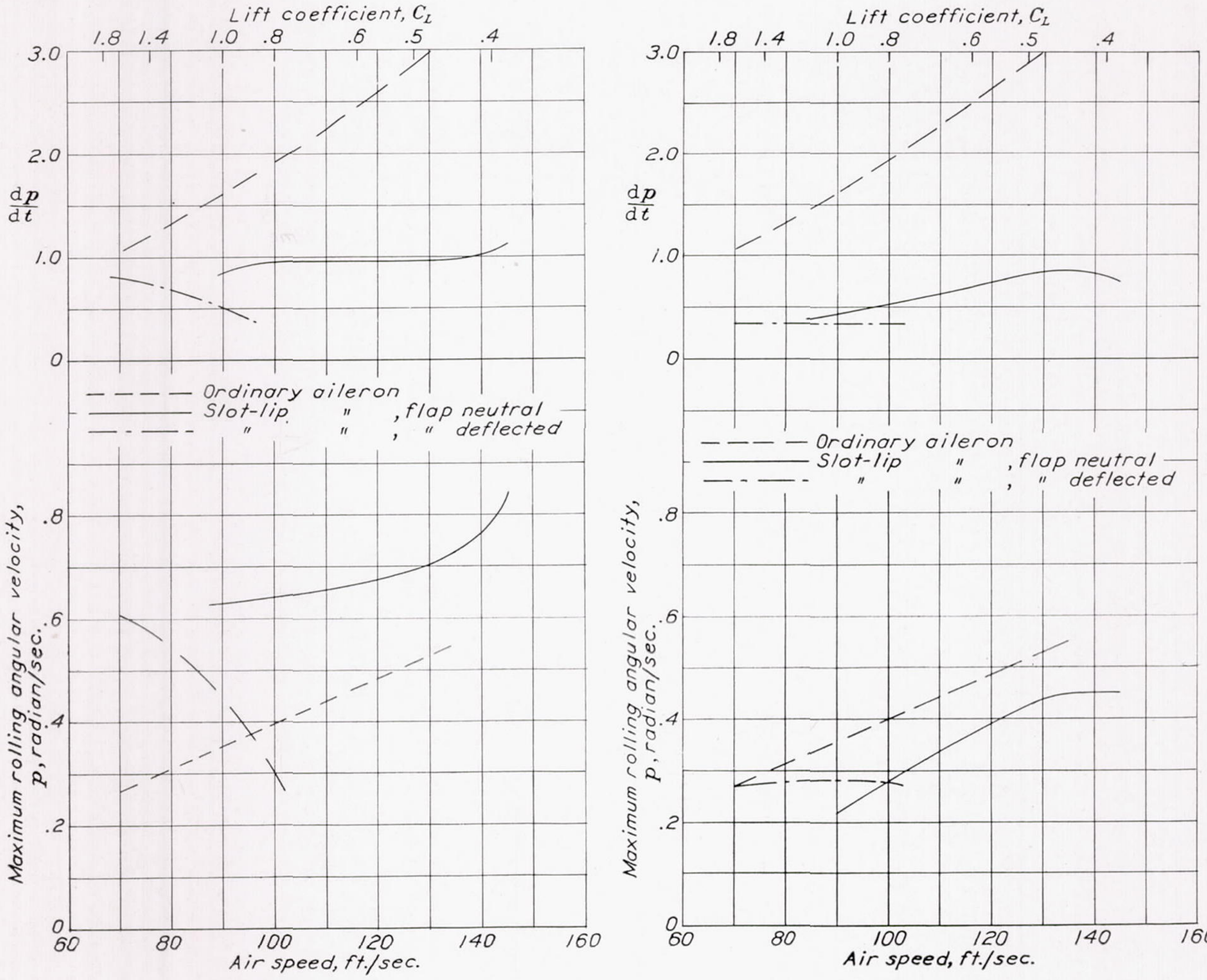
where dp/dt is the rolling angular acceleration.

L_0, the applied rolling moment.

pL_p, the damping moment that depends on the angular velocity in roll, p.

and ϕL_ϕ, the restraining moment due to the elastic cords that depends on the angular deflection ϕ. The coefficients L_p and L_ϕ contain I_X, the moment of inertia about the axis of rotation, so that L_0 is expressed as acceleration. The variations with time of the angular deflection ϕ and of the control deflection δ_a were simultaneously recorded on the same film. The values of the angular velocity p were determined by graphical differentiation of the ϕ curves and the angular accelerations dp/dt were determined by graphical differentiation of the p curves. The analysis consisted of determining values of L_0 from the determined values of ϕ, p, and dp/dt by equation (1) and comparing the values with those expected from the particular aileron deflections. A typical curve of δ_a and of ϕ against time is shown in figure 40 with the computed values of p and dp/dt for the wing motion due to a slot-lip aileron located $0.30c_w$ from the leading edge.

The values of L_0 computed for the case shown in figure 40 and the component parts of the moment are



(a) Slot-lip aileron at $0.20c_w$. (b) Slot-lip aileron at $0.45c_w$.

FIGURE 39.—Variation of maximum rolling angular velocity and acceleration with air speed for slot-lip ailerons on the Fairchild 22 airplane.

shown in figure 41. The static moment, L, curve has been included as a function of control deflection, assuming the maximum static moment equal to the maximum value of L_0. Dividing L_0 by the static moment at any instant gives a measure of the sluggishness. Because the sluggishness varies directly as the

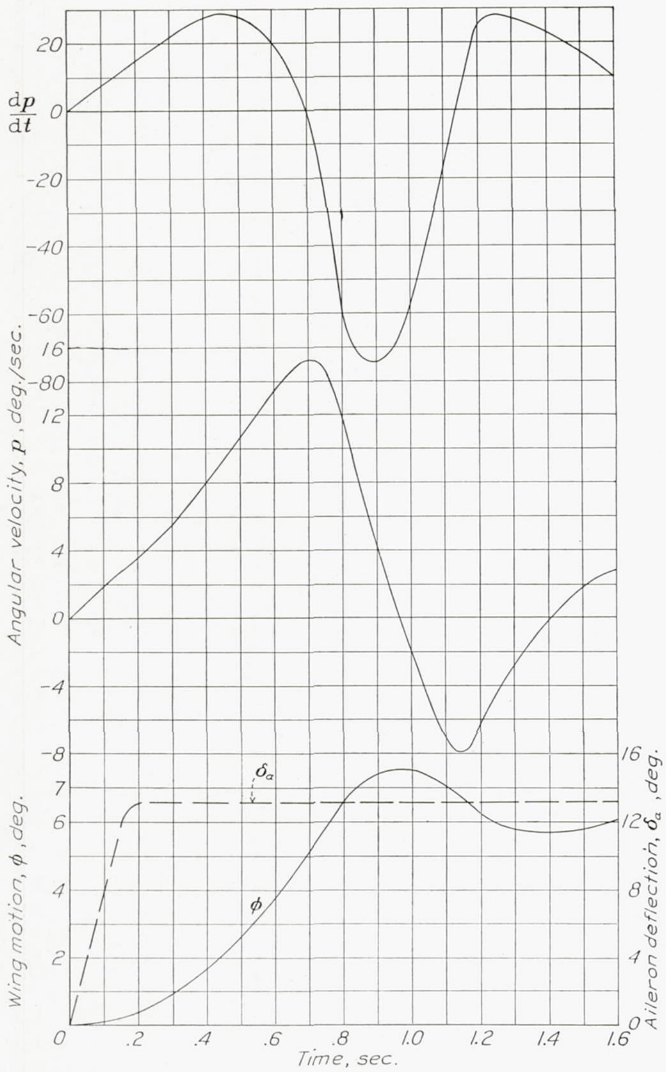


FIGURE 40.—Time history of motion of wing with slot-lip ailerons at $0.30c_w$. The 7- by 10-foot tunnel.

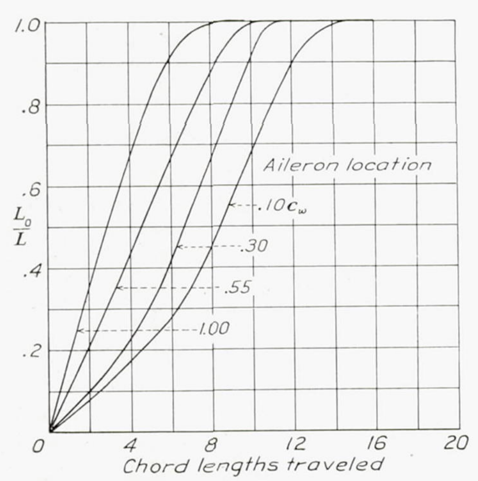


FIGURE 42.—Ratios of effective moment to static moment for various slot-lip ailerons in the 7- by 10-foot tunnel.

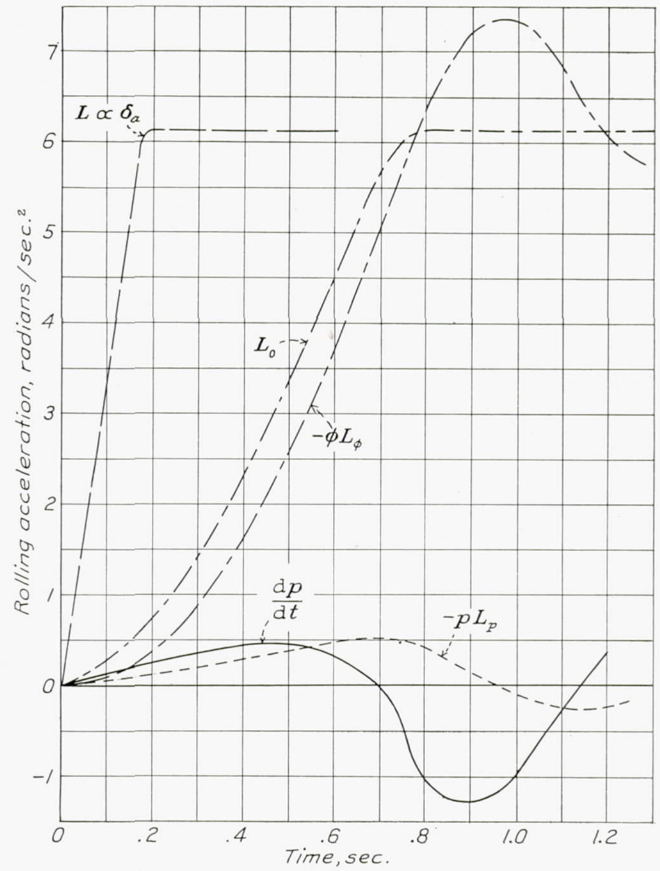


FIGURE 41.—Analysis of test in the 7- by 10-foot tunnel of a slot-lip aileron at $0.30c_w$.

$$L_0=\frac{dp}{dt}-pL_p-\phi L_\phi$$

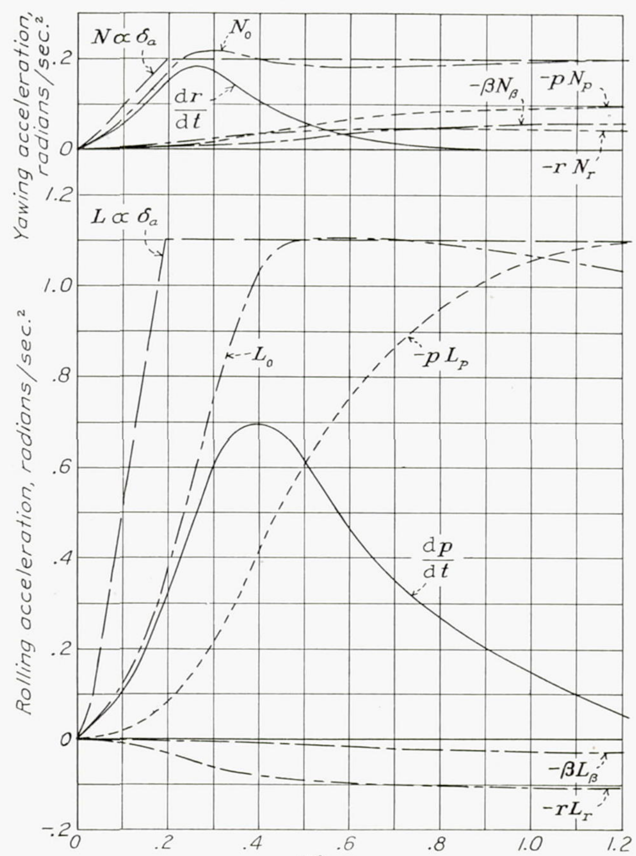


FIGURE 43.—Analysis of aileron control with slot-lip aileron at $0.45c_w$. δ_f, 0°; C_L, 0.827; air speed, 98.5 ft./sec.; flight test.

$$N_0=\frac{dr'}{dt}-r'N_r'-p'N_p'-\beta N_\beta \qquad L_0=\frac{dp'}{dt}-p'L_p'-r'L_r'-\beta L_\beta$$

wing chord and inversely as the air speed, the values of time have been converted to the nondimensional form of distance traveled in terms of chord lengths by multiplying by V/c. The sluggishness in terms of L_0/L was computed for slot-lip ailerons in several locations and for an attached aileron as shown in figure 42.

Flight tests.—The method used in analyzing the flight tests was essentially the same as the one used with the wind-tunnel tests. Flight records of simultaneous values of rolling and yawing angular velocities and of the control deflection were obtained. The angular accelerations were graphically determined and, from computed values of the resistance coefficients or derivatives, the moment acting on the airplane at each instant was derived. The derivatives L_p, L_r, L_β, N_p, N_r, and N_β of the equations of motion

$$\frac{dp}{dt}=L_0+pL_p+rL_r+\beta L_\beta \text{ (rolling)} \qquad (2)$$

$$\frac{dr}{dt}=N_0+pN_p+rN_r+\beta N_\beta \text{ (yawing)} \qquad (3)$$

were determined for the particular cases as in reference 14, considering the effects on the derivatives of the slot-lip ailerons and of the flap. The derivatives contain the proper values of I_X and I_Z so that L_0 and N_0 are expressed as accelerations.

The values of dp/dt and dr/dt were determined by graphical differentiation of the curves of p and r.

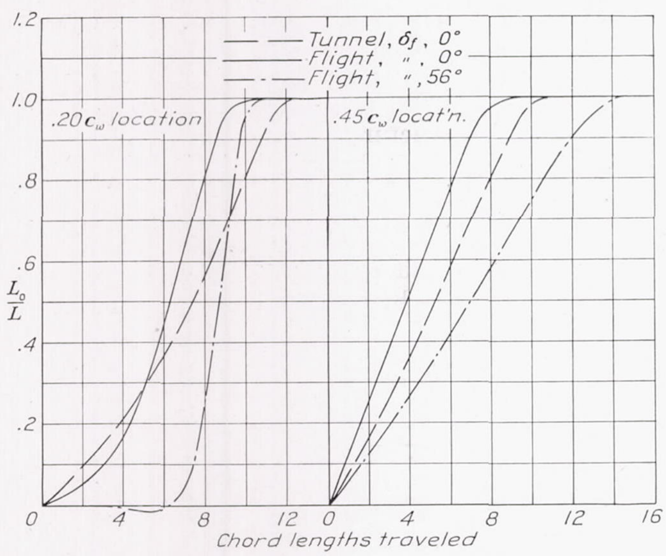


FIGURE 44.—Comparison of flight and tunnel measurements of sluggishness of slot-lip ailerons.

The values of the angle of sideslip β were determined by summing the outward sideslip due to centrifugal force and the inward sideslip due to the banked attitude. With positive r, the outward acceleration due to centrifugal force is

$$-\frac{dv}{dt}=V_0 r$$

Integrating,

$$\left(\frac{v}{V}\right)_0=-\int r dt$$

The inward acceleration is

$$\frac{dv}{dt}=g \sin \phi=g\phi$$

where ϕ is the angle of bank. Integrating,

$$v=g\int \phi dt$$

or

$$\left(\frac{v}{V}\right)_1=\frac{g}{V}\int \phi dt$$

Then the angle of sideslip is

$$\beta=\left(\frac{v}{V}\right)_0+\left(\frac{v}{V}\right)_1=-\int r dt+\frac{g}{V}\int \phi dt$$

The values of $\int r dt$ and $\int \phi dt$ were determined by graphical integration.

The values of L_0 and N_0 were determined from equations (2) and (3). The interrelation of the various

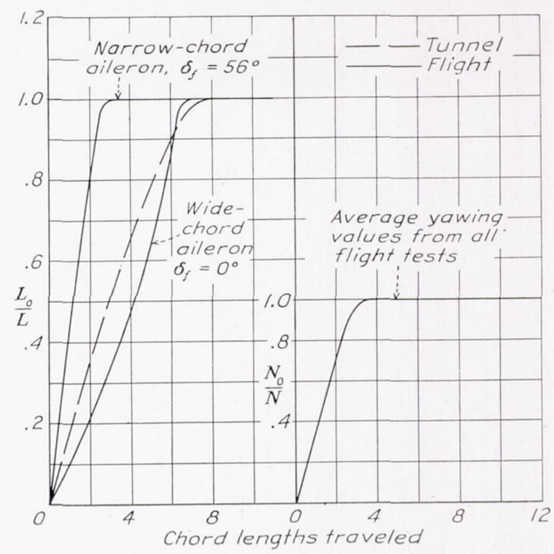


FIGURE 45.—Comparison of flight and tunnel measurements of sluggishness of ordinary ailerons.

components for a typical case of a slot-lip aileron on the F–22 airplane is shown in figure 43. All the values are given in terms of acceleration. The values of L and N are given in proportion to the aileron deflection with maximum values equal to the maximum values of L_0 and N_0. A measure of the sluggishness was taken as the ratios of L_0/L and N_0/N. The outlined procedure was followed in analyzing the flight records for the cases listed in the following table for the F–22 airplane.

Aileron	Location	δ_f (deg.)	C_L	V (ft./sec.)	c_w (ft.)
Slot-lip	0.20c_w	0	0.85	97.5	5.5
Do	0.20c_w	56	1.15	84.0	5.5
Do	0.45c_w	0	.83	98.5	5.5
Do	0.45c_w	56	1.14	84.0	5.5
Narrow, ordinary	T. E.	0	1.00	87.0	5.5
Do	do	56	1.75	66.5	5.5
Wide, ordinary	do	0	1.10	95.0	4.5

The ratios of L_0/L have been determined for each tabulated case and are plotted in figures 44 and 45. For comparison, the corresponding values found by interpolation from the wind-tunnel tests have been included in the same figures. The wind-tunnel tests, however, were made only with the flap neutral.

DISCUSSION

With the ordinary ailerons (fig. 45) the full static rolling moment was reached, for the average case, after the airplane had traveled about 4 chord lengths. In the case of the wide-chord ailerons with the flap down, the full moment was not produced until about 7 chord lengths had been traveled; with the narrow aileron, flap neutral, substantially instantaneous response was obtained. The accuracy of the method used in determining the sluggishness depends largely upon the accuracy with which the flight records of aileron motion and airplane motion can be synchronized. The difference between the two extremes and the average of between 3 and 4 chord lengths might easily be attributed to errors in interpreting the flight records. As the response to all the ordinary ailerons tested was satisfactory to the pilots, it follows that any device which gives a moment that is uniformly produced and with the maximum in about 4 chord lengths distance is satisfactory on this airplane. The wind-tunnel tests of the ordinary aileron showed greater sluggishness than did the flight tests.

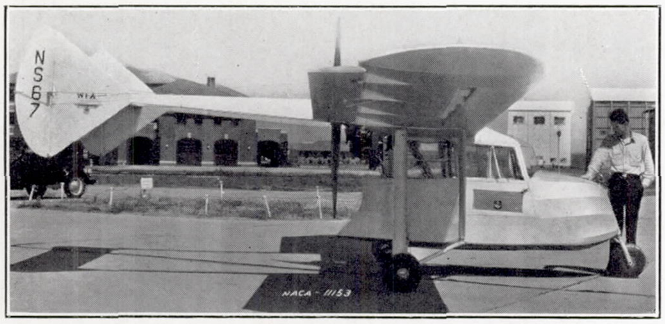


FIGURE 46.—The W1-A airplane with slot-lip ailerons and slotted flaps.

With the slot-lip ailerons at $0.20c_w$ location (fig. 44) the rolling moment is built up in a nonuniform manner, the maximum being reached in about 10 chord lengths. With the flap deflected, the moment actually lags for 6 chord lengths, the rolling motion of the airplane being indirectly produced by the positive yawing moment due to the ailerons. The wind-tunnel test gave a more uniform curve but with the maximum reached at 12 chord lengths. The sluggishness of these ailerons is considered excessive for the F–22 airplane. With the slot-lip ailerons at $0.45c_w$, the moments built up uniformly to a maximum in 8 chord lengths with flap 0° and in 14 chord lengths with flap deflected. The tunnel test showed a maximum in about 10 chord lengths with flap neutral. As in the case of the ordinary ailerons, the wind-tunnel tests showed greater sluggishness than the flight tests. The sluggishness in flight with the slot-lip aileron, flap neutral, was not appreciably greater than that with the wide-chord ordinary aileron, flap deflected.

The yawing moments, as shown in figure 45, reach their maximum fairly rapidly in all cases and may be considered practically instantaneous.

The results of this analysis agree qualitatively with the pilots' reports of the action of the slot-lip ailerons on the F–22 airplane. The pilots reported that the slot-lip ailerons in either location were more sluggish than ordinary ailerons and were worse with flap deflected than with flap neutral. The $0.45c_w$ location was, however, better than the $0.20c_w$ location. In addition to being sluggish, the aileron action was reported to be very weak. In an effort to find an explanation of this weak action, the moments determined in the analysis have been converted to coefficient form and are given in the following table with corresponding coefficients obtained by interpolation from the wind-tunnel force tests.

Aileron location	Flap deflection	Tunnel			Flight			
	δ_f (deg.)	C_l'	C_n'	δ_a (deg.)	C_l'	C_n'	δ_a for C_l' (deg.)	δ_a for C_n' (deg.)
$0.20c_w$	0	0.0475	0.0105	−40	0.0388	0.0084	−33	−31
$0.20c_w$	56	.0310	.0085	−40	.0199	.0082	−29	−39
$0.45c_w$	0	.0410	.0050	−40	.0239	.0032	−25	−32
$0.45c_w$	56	.0385	.0050	−40	.0219	.0033	−31	−32

The coefficients in flight are seen to be considerably lower than the wind-tunnel values. One reasonable explanation of this difference is that the ailerons in flight may not have been deflected the indicated 40° because of structural flexure. In the last two columns are given the necessary aileron deflections corresponding to the moments produced. The effective deflection was only about 32°.

Another determination of the sluggishness of slot-lip ailerons has been made possible by recent tests of the W1–A airplane made by the N. A. C. A. for the Bureau of Air Commerce. The W1–A airplane (fig. 46) has slot-lip ailerons located $0.30c_w$. (See fig. 47.) With the stable three-wheel landing gear, the large dihedral angle of the wings, and the slot-lip aileron so located as

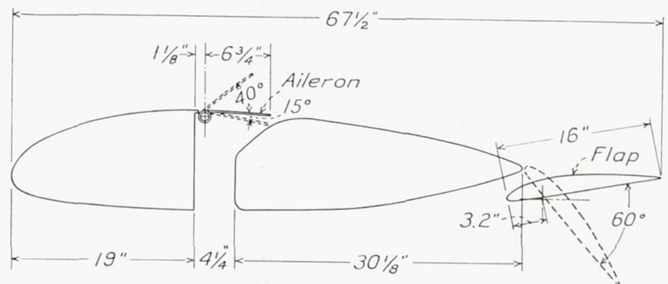


FIGURE 47.—Section of the W1-A airplane wing showing details of slot-lip aileron and slotted flap.

to give a good ratio of yawing moment to rolling moment, it was believed that the airplane could be flown satisfactorily with adequate directional as well as lateral control by means of the slot-lip ailerons alone. The pilots reported that a good degree of control was obtained with the slot-lip ailerons with neither lag nor sluggishness in their action. Successful flights were later made with the rudder locked neutral, leaving only the slot-lip ailerons for both directional and lateral control. The control was equally good with the slotted flap deflected for landing.

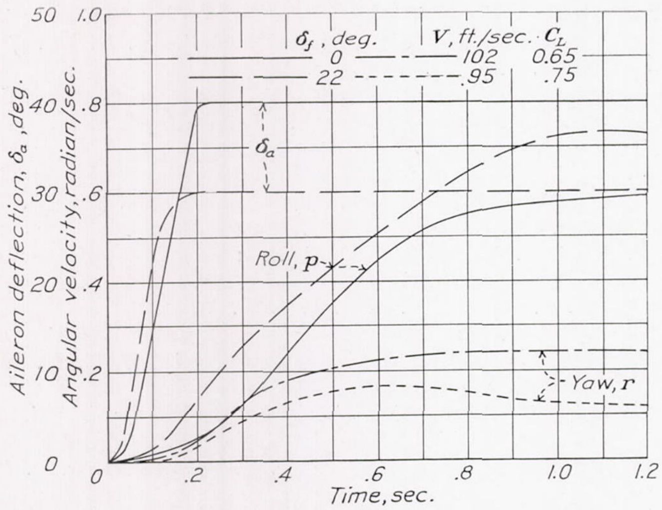


FIGURE 48.—Time history of W1-A airplane motion due to slot-lip ailerons.

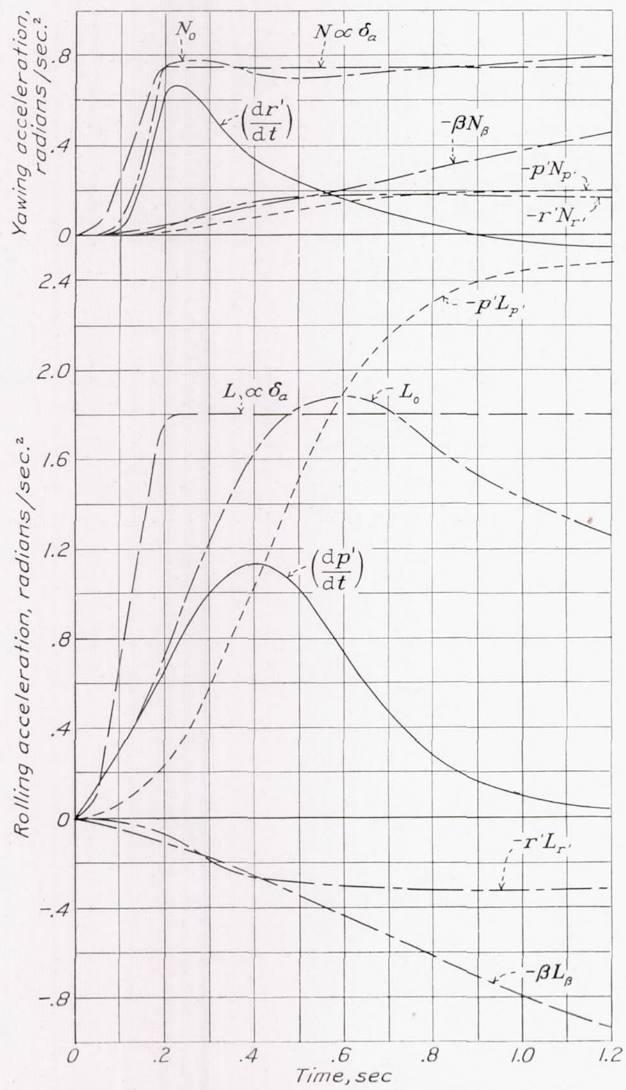


FIGURE 49.—Analysis of flight test of W1-A airplane with slot-lip ailerons at $0.30c_w$. δ_f, 0°; C_L, 0.55.

$$N_0=\frac{dr'}{dt}-r'N_r'-p'N_p'-\beta N_\beta \qquad L_0=\frac{dp'}{dt}-p'L_p'-r'L_r'-\beta L_\beta$$

Inasmuch as these results seemed to be in disagreement with the results of the tests of the F–22 airplane, detailed records of the airplane motion following a deflection of the slot-lip ailerons were made and are given in figure 48. An analysis of the motions has been made using estimated resistance derivatives and moments of inertia for the W1–A airplane. The results of the analysis are given in figure 49. It will be readily seen that an appreciable part of the rolling angular velocity was indirectly obtained from the large favorable yawing moment, as evidenced by the large values of βL_β. As in the previous analysis of the F–22 tests, the values of L_0/L and N_0/N were computed and are given in figure 50 with the flap both neutral and deflected. Comparison with figure 44 shows that the curve for L_0/L with the flap neutral lies between the curves from the F–22 tests of slot-lip ailerons located at $0.20c_w$ and $0.45c_w$. It therefore seems that the apparent discrepancy between the results of the F–22 tests and the W1–A tests is explained by the large dihedral of the W1–A, which indirectly contributed a large proportion of the roll.

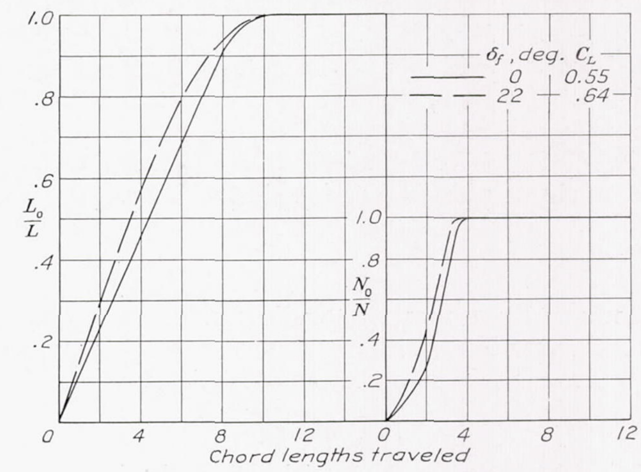


FIGURE 50.—Sluggishness of slot-lip ailerons on W1–A airplane.

With the special slotted flap of the W1–A deflected 22½°, the sluggishness was appreciably less than that for the F–22 with the split flap deflected 56°. In fact, with the W1–A airplane, the sluggishness was slightly less with the flap deflected than with it retracted. It seems, therefore, that the sluggishness may be critically affected by the particular type of flap used.

CONCLUSIONS

1. For airplanes similar to the ones tested, the lag with single retractable spoilers or ailerons varies with the position along the wing chord from a negligible value near the trailing edge to nearly 1 second for a position near the leading edge. Unless the device is located within 20 percent of the wing chord from the trailing edge, the lag will be objectionably large (more than 0.10 second).

2. With a proper combination of spoiler and slot, such as the N. A. C. A. slot-lip aileron, the lag with

spoiler at any location may be reduced to a negligible value although the sluggishness may be excessive. This sluggishness may be in the order of 4 chord lengths distance traveled by the airplane for ordinary ailerons located at the trailing edge and about 12 chord lengths for slot-lip ailerons located near the leading edge of the wing.

3. The added airplane drag with slot-lip ailerons is considered excessive for high-performance airplanes, being in the order of 10 percent of the wing drag at high speed and about 35 percent of the wing profile drag in the climbing attitude.

4. One advantage of the slots as used for the slot-lip ailerons lies in the extension of the usable angle-of-attack range of an airplane by delaying the stall of the outer portions of the wing and thus maintaining damping in roll. This effect becomes of small importance when the slot is located farther back than 50 percent of the wing chord.

5. For airplanes in which increased safety and simplicity of control is of more importance than high speed, high rate of climb, and high maneuverability, the slot-lip ailerons located between 30 and 40 percent of the wing chord might be desirable, particularly when used on an airplane having considerable dihedral.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., *June 11, 1937.*

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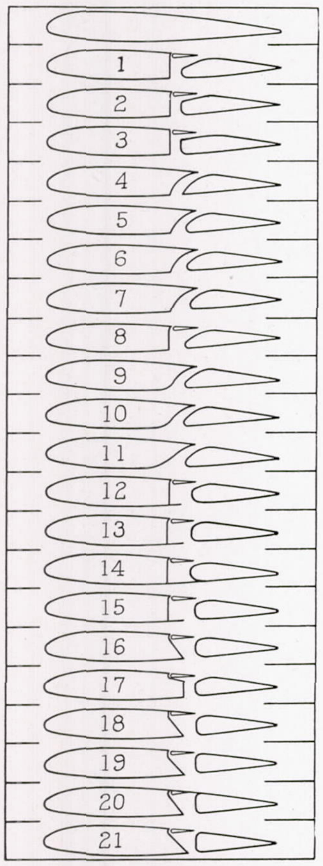
TABLE I

SUMMARY OF DRAG INVESTIGATION OF VARIOUS SLOTS IN A 4- BY 8-FOOT N. A. C. A. 23012 WING IN THE 7- BY 10-FOOT WIND TUNNEL

[Air speed, 80 m. p. h.]

Slot designation	ΔC_D for $C_L=$ 0	0.2	0.4	0.5	$\frac{dC_L}{d\alpha_0}$	$\Delta\alpha_{L_0}$	C_{m_0}	a. c. [1]
	0	0	0	0	0.101	0	−0.007	0.030
1	.0013	.0014	.0034	.0052	.091	0	−.007	.030
2	.0014	.0016	.0038	.0052	.091	0	−.007	.030
3	.0018	.0026	.0064	.0085	.086	0	−.008	.034
4	.0014	.0023	.0071	.0078	.084	−.1	−.007	.034
5	.0016	.0019	.0060	.0084	.084	−.1	−.007	.034
6	.0018	.0023	.0061	.0090	.084	−.1	−.007	.034
7	.0018	.0026	.0056	.0093	.084	−.1	−.007	.034
8	.0020	.0018	.0055	.0071	.086	0	−.008	.034
9	.0043	.0058	.0068	.0068	.095	.8	−.007	.015
10	.0041	.0045	.0050	.0053	.101	.9	−.007	.000
11	.0038	.0038	.0037	.0034	.103	.9	−.011	.000
12	.0015	.0020	.0041	.0053	.086	0	−.007	.040
13	.0015	.0013	.0028	.0042	.092	0	−.008	.032
14	.0011	.0008	.0008	.0011	.100	−.1	−.008	.028
15	.0012	.0016	.0037	.0050	.086	0	−.007	.040
16	.0016	.0015	.0030	.0040	.090	−.1	−.009	.036
17	.0015	.0019	.0035	.0055	.092	−.1	−.008	.036
18	.0016	.0013	.0022	.0033	.092	−.1	−.009	.036
19	.0014	.0013	.0025	.0036	.103	−.1	−.008	.036
20	.0012	.0008	.0008	.0008	.092	−.1	−.008	.026
21	.0012	.0010	.0023	.0028	.095	−.1	−.008	.034

[1] Values are approximate aerodynamic-center location in fractions of c_w ahead of wing quarter-chord point.

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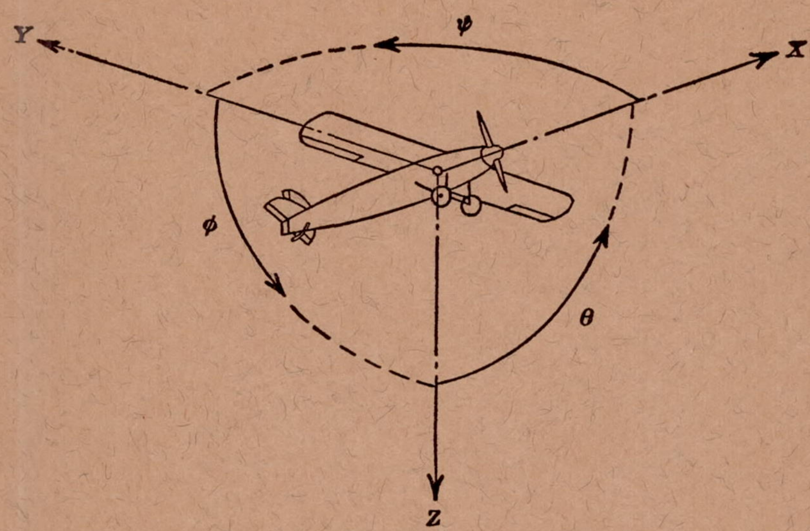

Positive directions of axes and angles (forces and moments) are shown by arrows

Axis		Force (parallel to axis) symbol	Moment about axis			Angle		Velocities	
Designation	Symbol		Designation	Symbol	Positive direction	Designation	Symbol	Linear (component along axis)	Angular
Longitudinal	X	X	Rolling	L	$Y \longrightarrow Z$	Roll	ϕ	u	p
Lateral	Y	Y	Pitching	M	$Z \longrightarrow X$	Pitch	θ	v	q
Normal	Z	Z	Yawing	N	$X \longrightarrow Y$	Yaw	ψ	w	r

Absolute coefficients of moment

$C_l=\frac{L}{qbS}$ (rolling) $C_m=\frac{M}{qcS}$ (pitching) $C_n=\frac{N}{qbS}$ (yawing)

Angle of set of control surface (relative to neutral position), δ. (Indicate surface by proper subscript.)

4. PROPELLER SYMBOLS

D, Diameter
p, Geometric pitch
p/D, Pitch ratio
V', Inflow velocity
V_s, Slipstream velocity
T, Thrust, absolute coefficient $C_T=\frac{T}{\rho n^2 D^4}$
Q, Torque, absolute coefficient $C_Q=\frac{Q}{\rho n^2 D^5}$
P, Power, absolute coefficient $C_P=\frac{P}{\rho n^3 D^5}$
C_s, Speed-power coefficient $=\sqrt[5]{\frac{\rho V^5}{P n^2}}$
η, Efficiency
n, Revolutions per second, r.p.s.
Φ, Effective helix angle $=\tan^{-1}\left(\frac{V}{2\pi r n}\right)$

5. NUMERICAL RELATIONS

1 hp. = 76.04 kg-m/s = 550 ft-lb./sec.
1 metric horsepower = 1.0132 hp.
1 m.p.h. = 0.4470 m.p.s.
1 m.p.s. = 2.2369 m.p.h.
1 lb. = 0.4536 kg.
1 kg = 2.2046 lb.
1 mi. = 1,609.35 m = 5,280 ft.
1 m = 3.2808 ft.