NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3536

A LIMITED FLIGHT INVESTIGATION OF THE EFFECT OF THREE VORTEX-GENERATOR CONFIGURATIONS ON THE EFFECTIVENESS OF A PLAIN FLAP ON AN UNSWEPT WING

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SUMMARY

Limited flight tests of a fighter airplane have been conducted to determine the effect of three vortex-generator configurations on the effectiveness of a plain flap. Vortex generators consisting of rectangular airfoils mounted on the upper surface of the airplane wing at the 63-percent-chord station produced some increase in airplane lift coefficient at a given angle of attack, no increase in drag with flaps deflected 19°, and no increase in maximum normal-force coefficient. These vortex generators mounted at the 75-percent-chord station in another test produced no increase in either airplane lift coefficient or maximum normal-force coefficient. A third generator configuration consisting of larger tapered airfoils mounted at the 63-percent-chord station of the airplane wing produced a considerable increase in lift coefficient for a given angle of attack at the 19° flap deflection in a glide but at the expense of increased drag. The effect of these generators was equivalent to a further increase in flap deflection to 27°. No improvement in flap effectiveness was obtained with any of the generators tested for flaps deflected 45°.

The results, therefore, indicated that the vortex-generator configurations tested provided only a little advantage over the use of the flaps alone. Since the vortex generators tested were effective in increasing lift coefficient at moderate flap deflections, they might be used to increase the effectiveness of ailerons.

INTRODUCTION

Extensive separated flow over the top surface of a deflected plain flap prevents much of the potential lift from being obtained. Large gains in flap effectiveness would therefore result if the flow could be made to follow the top surface of the flap.

Vortex generators have been used with success in eliminating or reducing separation in diffusers, as shown, for example, by the results given in references 1 and 2. No information appears to be available on the effectiveness of vortex generators in preventing or delaying separation over a plain flap. Limited flight tests of a fighter airplane have been conducted to determine the effects of three vortex-generator configurations on the performance of a plain flap on an unswept wing. The tests were made at several indicated airspeeds covering a range from stall to 140 miles per hour and were initiated at a pressure altitude of 7,000 feet.

SYMBOLS

a_z	normal acceleration, g units
c	airplane wing chord, ft
C_L	lift coefficient
C_N	normal-force coefficient
g	acceleration due to gravity, ft/sec^2
p	static pressure, lb/sq ft
q	dynamic pressure, lb/sq ft
R	gas constant, 1,716 ft-lb/slug-$^\circ$R
S	wing area, sq ft
T	temperature, $^\circ$R
V	velocity, ft/sec
W	airplane weight, lb
α	angle of attack of fuselage reference line, deg
γ	flight-path angle, positive in climb, deg
θ	attitude angle, positive with nose-up inclination of airplane, deg

TEST CONDITIONS AND APPARATUS

The Airplane and Flap Modification

The tests were conducted on a World War II propeller-driven fighter. The characteristics of the airplane are shown in table I. The airplane flap extended from 8.9 to 59.5 percent of the wing semispan. The corresponding flap-chord ratio varied from 0.238 at the inboard station (excluding the extended leading edge of the wing) to 0.245 at the outboard station. The airplane flap was slightly modified for these tests by cementing a thin balsa fairing to the flap to eliminate a surface discontinuity of about 1/8 inch which is exposed when the flap is deflected. (See fig. 1.)

Vortex Generators and Configurations

The four different vortex-generator conditions tested are as follows: no vortex generators (basic configuration), vortex generators of rectangular plan form mounted at the 0.63c station (configuration 1), vortex generators of rectangular plan form mounted at the 0.75c station (configuration 2), and vortex generators of tapered plan form mounted at the 0.63c station (configuration 3). Details of the vortex generators and their arrangements are shown in figure 2 and table II. Photographs of the generators installed on the wing of the airplane are shown in figures 3 to 6. The vortex generators were constructed of an acrylic-base plastic and were cemented to the airplane wing surface in front of the flap at 75 percent of the airplane wing chord for configuration 2 and at 63 percent of the wing chord for configurations 1 and 3. The generators were filed to an approximate airfoil shape with a flat lower surface and a rounded nose. They were arranged so that adjacent vanes would produce counterrotating vortices.

Instrumentation

Standard NACA recording instruments were used to measure impact pressure, static pressure, and temperature for determining flight-path angle, and an inclinometer was used for recording attitude angle. Normal acceleration was measured to permit evaluation of the maximum normal-force coefficient.

A boundary-layer survey was made at the 0.63-chord and 0.44-semispan station to determine approximately the thickness of the boundary layer by using a static-pressure orifice on the surface and three total-pressure tubes mounted 0.23, 1.22, and 1.75 inches above the surface. In another survey a total-pressure tube referenced to the free-stream total pressure was mounted about $2\frac{1}{16}$ inches above the wing surface at the 0.74-chord and 0.45-semispan station to determine whether the boundary layer at this location was thicker or thinner than the span of the vortex generators.

Wool tufts were attached to the upper surface of one flap and were photographed by a 16-millimeter gun camera installed in the fuselage.

Flight Conditions

Level-flight tests and steady glides were made at as nearly constant speed as possible. The speeds for the basic configuration and configuration 3 covered a range from about 10 miles per hour above stall to 140 miles per hour indicated airspeed. The speeds for configurations 1 and 2 were limited to about 10 and 20 miles per hour indicated airspeed above stall. A constant low power (15 inches of mercury manifold pressure) was used for all glides. The level-flight and glide runs were initiated at an altitude of 7,000 feet and the duration of each run was approximately 1 minute. Stalls were obtained by gradually reducing airspeed in a glide.

Tests with the flap partially deflected were made during the first part of the flights and were followed by tests with the flaps full down. The flap was set at a deflection angle of 30° on the ground prior to take-off in an attempt to obtain more accurate settings than could be made by the pilot in flight. Complete retraction of the flap was not permitted because of the balsa fairing on the flap. After the tests were completed, however, it was learned from motion pictures of the flap (which were taken to study air flow) that the flap did not remain in the position at which it was set on the ground. This flap movement probably occurred because of a dissimilarity of the test airplane from the standard production model which prevented full hydraulic pressure from holding the flap fixed in a partially deflected position. With the use of structural details and tufts which could be identified on the wing and flap, a comparison of the pictures taken during the flight tests with pictures taken during a calibration made after completion of the tests showed that the flap angles varied from 16° to 21° for the flaps partially deflected and from 45° to 46° for the flaps full down. Although motion pictures were not made for all glide and level-flight runs, it is believed that the flap angles for those runs not photographed were reliably estimated from the nature of the variations of flap deflection and the order of the runs photographed.

The flap was not photographed during the stalls and the flap angle could not be as reliably estimated for this maneuver with flaps partially deflected as for the glide and level-flight maneuvers. The angle has been assumed to be 19° for partially deflected flaps except for the stall with configuration 3. The flap for this configuration was set at 30° by the pilot in flight with the use of a reference line on the flap after the tests with flaps down were completed. The angle for flaps full down is considered to be 45° as the deflection was always nearly constant because of the holding action of the high hydraulic pressure. All tests were made under smooth air conditions with the landing gear down.

METHOD OF EVALUATION

The flight-path angle of the airplane was determined from the readily derived relation

$$\gamma = \sin^{-1}\left(-\frac{RT}{gp}\frac{1}{V}\frac{\Delta p}{\Delta t}\right)$$

where Δp corresponds to the change in pressure in a steady glide for the time interval Δt, approximately 60 seconds. The values of T, p, and V are average values determined from several equal time intervals during the glide in which V is held nearly constant and the variation of T and p is small. This relation is valid in the absence of any vertical air motion and of any vertical gradient of wind velocity; in view of the smooth air conditions of the tests, this assumption appears to be reasonable.

The angle of attack α and the airplane lift coefficient C_L for the steady flight runs were computed as follows:

$$\alpha = \theta - \gamma$$

and

$$C_L = \frac{W \cos \gamma}{qS}$$

In these computations also, the quantities taken are average values for the time interval Δt. The time interval Δt over which the average values were taken was sufficiently long and the change in airspeed between the beginning and end of the run was sufficiently small so that the average acceleration during the interval was very small. The average inclinometer angle therefore could be taken to represent the mean attitude angle θ directly.

In the stalls only the normal-force-coefficient variation with time was determined from the relation:

$$C_N = \frac{Wa_z}{qS}$$

Values of C_L and α could not be determined with the instrumentation used under the changing conditions of the stall.

The variation of the flap angle from 16° to 21° for the various glide and level-flight tests with the flaps partially deflected required that the results be corrected to a common flap deflection for comparison of the tests. The lift coefficients were corrected to a flap deflection of 19° by assuming a lift-coefficient variation of 0.014 per degree of flap deflection. Although this value is considered to be approximately correct, a considerable deviation from this value would have little effect on the results because of the comparatively small deviations in flap deflection from 19°. The flaps were considered to be deflected 45° for the tests with the flaps full down and no correction was made as the flaps appeared to remain nearly constant (45° to 46°) for this flap position.

DISCUSSION OF RESULTS

Boundary-Layer Thickness

The results of the boundary-layer survey made at about the 0.63-chord and 0.44-semispan station on the basic wing (no generators) indicated that the boundary layer was less than $1\frac{1}{4}$ inches thick in the level-flight condition for the flaps deflected 19° and 45° and less than $1\frac{3}{4}$ inches thick for the low-power glides at both of these flap settings. The span of the vortex generators, 2 inches, was therefore appreciably greater than the boundary-layer thickness at this wing location and very likely over the spanwise extent of configurations 1 and 3 for the steady level-flight and glide maneuvers below the stall. These ratios of span to boundary-layer thickness are in the range found to be optimum for diffuser applications in reference 2.

At the more rearward location of 0.74 chord, the total-pressure tube mounted $2\frac{1}{16}$ inches above the wing surface and 1/2 inch ahead of the leading edge of the generators for configuration 2 showed a total-pressure loss at this location for all flight conditions investigated;

this condition indicated that the generators for this configuration were submerged in the boundary layer.

Lift Curves

The variations of airplane lift coefficient with angle of attack for flaps deflected 19° and 45° are presented in figure 7 for the basic airplane in a steady glide and in level flight. Because of the increased power used for level flight, the slope of the lift curve was about 0.077 per degree for this condition as compared with 0.074 per degree for the glides.

The faired lift curves for the basic configuration (fig. 7) are compared with the results obtained from the three vortex-generator configurations in figure 8. With the flaps full down, none of the vortex-generator configurations had any appreciable effect on lift coefficient at a given angle of attack except that there seemed to be a slight loss in lift coefficient for configuration 2 in the glide condition.

With the flaps deflected 19°, vortex-generator configurations 1 and 3 resulted in some increase in lift coefficient at a given angle of attack over that of the basic airplane. The increment was about the same for configuration 1 in the level-flight and glide tests and for configuration 3 in the level-flight tests. A somewhat larger increment in lift coefficient for a given angle of attack was obtained with vortex-generator configuration 3 for this flap setting in the steady glides. For configuration 3, there was an increase in lift coefficient of about 0.09 for the glide condition. Vortex-generator configuration 2 had no effect at this flap setting.

Although the vortex-generator configurations tested were not able to increase the maximum lift capabilities of the airplane, the increase which was obtained with flaps partially deflected indicates that vortex generators may be suitable for improving the effectiveness of ailerons. An increase in aileron effectiveness would be desirable because of the decrease in aileron deflection required for a given rolling moment and the resulting decrease in stick force.

Normal-Force Coefficient at Stall

With flaps full down, none of the vortex-generator configurations had any appreciable effect on the average normal-force coefficient of the airplane just prior to stall. With flaps deflected 19°, vortex-generator configurations 1 and 2 also had no appreciable effect on normal-force coefficient. The effect of vortex-generator configuration 3 on the maximum normal-force coefficient of the airplane with flaps deflected 19° is not known because no stall tests were made under these conditions. The normal-force coefficient for configuration 3 and for flaps deflected 30° was only about 1 percent less than that for the basic configuration with flaps full down.

Glide Angle

The flight-path angle obtained in the steady glides is plotted against angle of attack in figure 9 for the various airplane and vortex-generator configurations. This flight-path angle actually represents the ratio of thrust minus drag to lift since some power (about 15 inches of mercury manifold pressure) was maintained in the glides. Part of the scatter seen in the data of figure 9 is probably due to inaccuracy in repeating the power setting in the glides at various airspeeds. The scatter is not consistent with differences in flap deflection. Also shown in figure 9 is a curve interpolated from the data of figures 8 and 9 for the flap of the basic configuration deflected to give the same lift coefficient as that obtained with vortex-generator configuration 3 and flaps deflected 19°.

The flight-path angle for each flight test shown in figure 9 is an indication of the drag of the test configuration, the propeller thrust being assumed to be nearly the same for each glide. A study of figures 8 and 9 reveals that the only vortex-generator arrangement showing an improvement in flap effectiveness, that is, an increase in lift with no increase in drag, is configuration 1 for a flap-deflection angle of 19°. Although both configuration 1 and configuration 3 indicated some increase in lift at a flap deflection of 19° (fig. 8), configuration 3 also indicates an increase in drag about equal to the interpolated value of drag for the basic configuration with the flap angle increased to provide the same lift increment. Configuration 3 therefore had about the same effect as a further increase in flap deflection (about 8°).

Flow Over the Flap

Tuft studies indicated that the flow over the top surface of the flap when fully deflected was completely separated and was not affected by the vortex generators.

For the basic configuration with the flap deflected 19°, the flow followed the top surface of the flap a short distance, became unsteady, and separated. Little change in the flow from the basic configuration was noted for configurations 1 and 2, which were tested over a limited low range of airspeed, and for configuration 3 at low speeds. Some change, however, was noted for configuration 3 with flaps deflected 19°

at 140 miles per hour indicated airspeed. Only a small amount of unsteady and separated flow was evident at this speed, the flow being especially smooth on the outboard portions of the flap. The flow was steadier for the glide than for level flight at this airspeed.

CONCLUSIONS

Flight tests have been conducted to determine the effect of three vortex-generator configurations on the effectiveness of a plain flap on an unswept wing. None of the generator configurations improved the effectiveness of the flaps deflected 45°. With the flaps deflected 19°, two of the vortex-generator configurations caused some increase in lift at a given angle of attack but it amounted to less than half of the gain resulting from further deflection of the flap to the full-down position. One of these vortex-generator configurations apparently caused no increase in drag. The vortex-generator configuration that caused the largest increase in lift also increased the drag by approximately the same amount as that which would result from increasing the flap deflection sufficiently to give the same lift increment as was obtained with the generators. The vortex generators tested, therefore, provided only a little useful improvement in flap effectiveness.

Although none of the vortex generators tested increased the maximum lift capabilities of the airplane, the increase which was obtained with flaps partially deflected indicates that vortex generators may be suitable for improving the effectiveness of ailerons which operate at moderate deflections.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., July 6, 1955.

REFERENCES

1. Wood, Charles C.: Preliminary Investigation of the Effects of Rectangular Vortex Generators on the Performance of a Short 1.9:1 Straight-Wall Annular Diffuser. NACA RM L51G09, 1951.

2. Taylor, H. D.: Summary Report on Vortex Generators. Rep. R-05280-9, United Aircraft Corp. Research Dept., Mar. 7, 1950.

TABLE I

CHARACTERISTICS OF TEST AIRPLANE

Wing:	
Airfoil section	NAA-NACA low drag airfoil
Span, ft	37.03
Dihedral, deg	5
Incidence (root), deg	1
Aerodynamic twist, deg	-2.8
Area (total), sq ft	240.1
Mean aerodynamic chord, ft	6.63
Aspect ratio	5.71
Taper ratio	0.462
Root thickness ratio	0.15
Tip thickness ratio	0.12
Wing flaps:	
Type	Plain
Area (both), sq ft	32.22
Span (each), in.	112.94
Chord:	
Inboard (wing station 19.84), in.	23.60
Outboard (wing station 132.78), in.	17.30
Motion (down), deg	47
Horizontal tail:	
Span, ft	13.18
Area, sq ft	41.0
Weight at take-off, lb	8,622

TABLE II

VORTEX-GENERATOR CONFIGURATIONS

	Configuration		
	1	2	3
Vortex-generator designation (see fig. 2)	A	A	B
Vortex-generator area, sq in.	4	4	8
Chordwise location on wing	0.63c	0.75c	0.63c
Angle of attack, deg	15	15	20
Spacing between vortex generators, in.	4	4	6
Number of vortex generators used	56	56	36

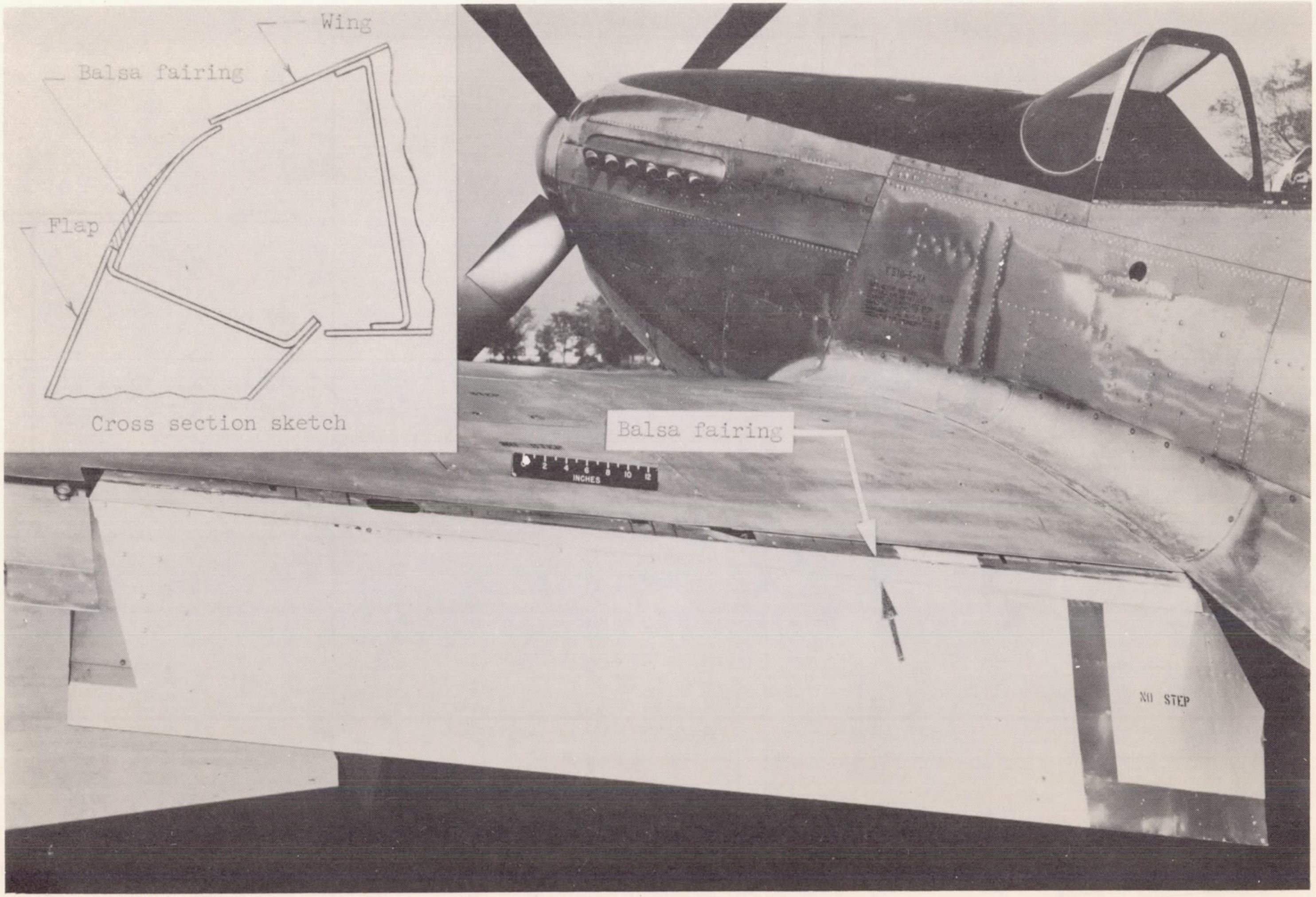

Figure 1.- Basic airplane with modified flap.

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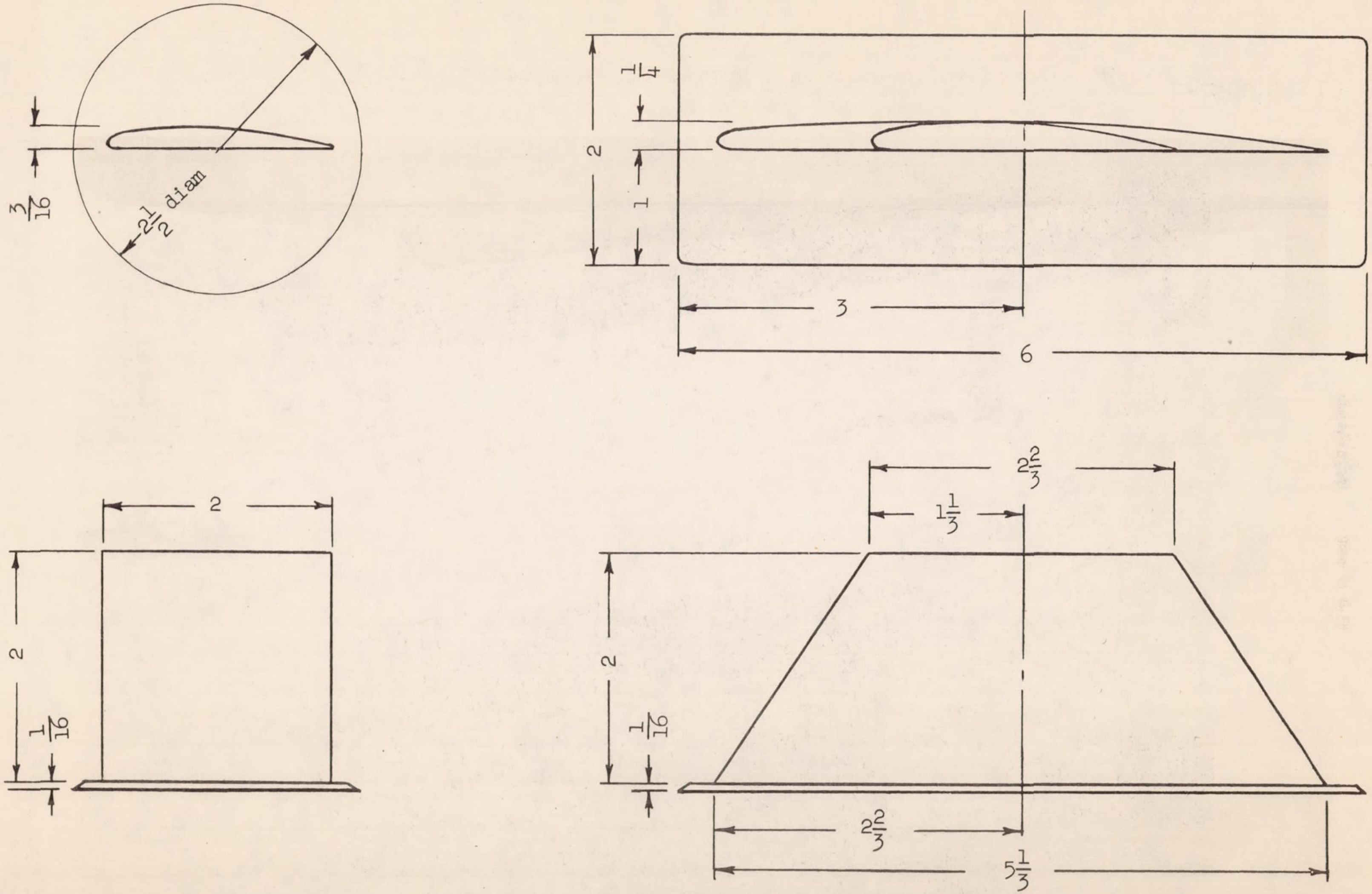

Vortex generators A used in configurations 1 and 2

Vortex generators B used in configuration 3

Figure 2.- Details of vortex generators. All dimensions are in inches.

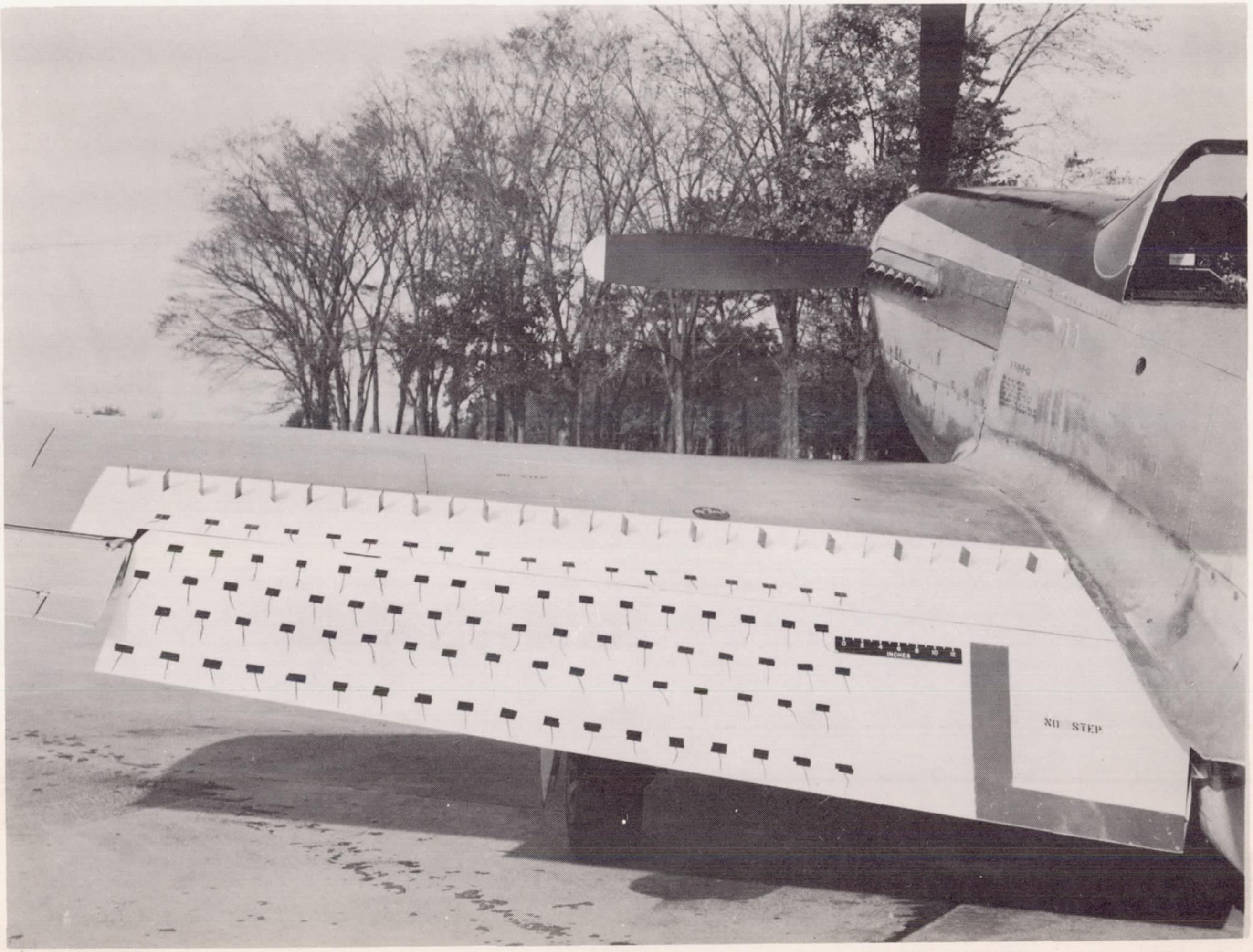

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Figure 3.- Vortex-generator configuration 1 mounted on airplane wing.

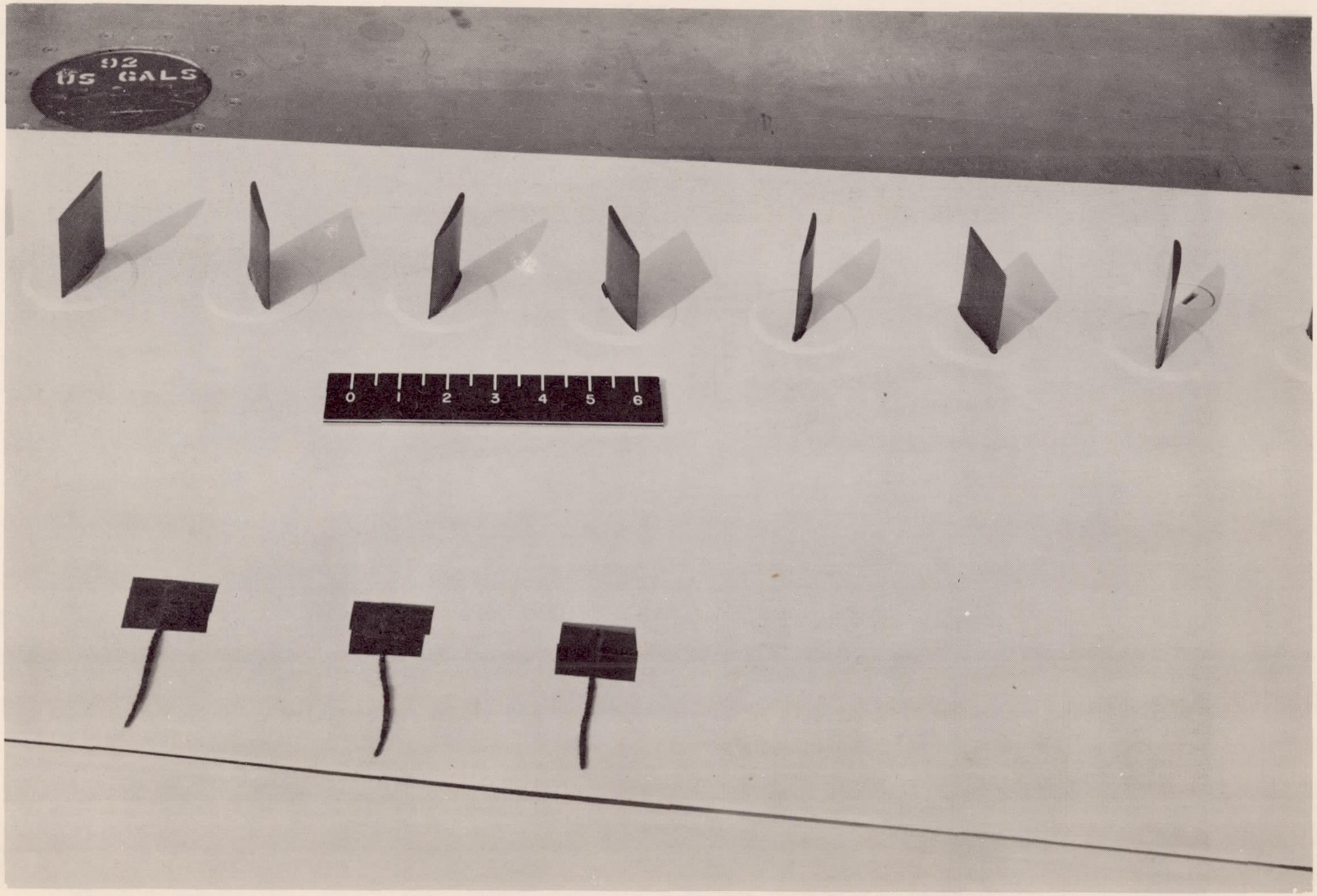

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Figure 4.- Closeup view of vortex-generator configuration 1 mounted on airplane wing.

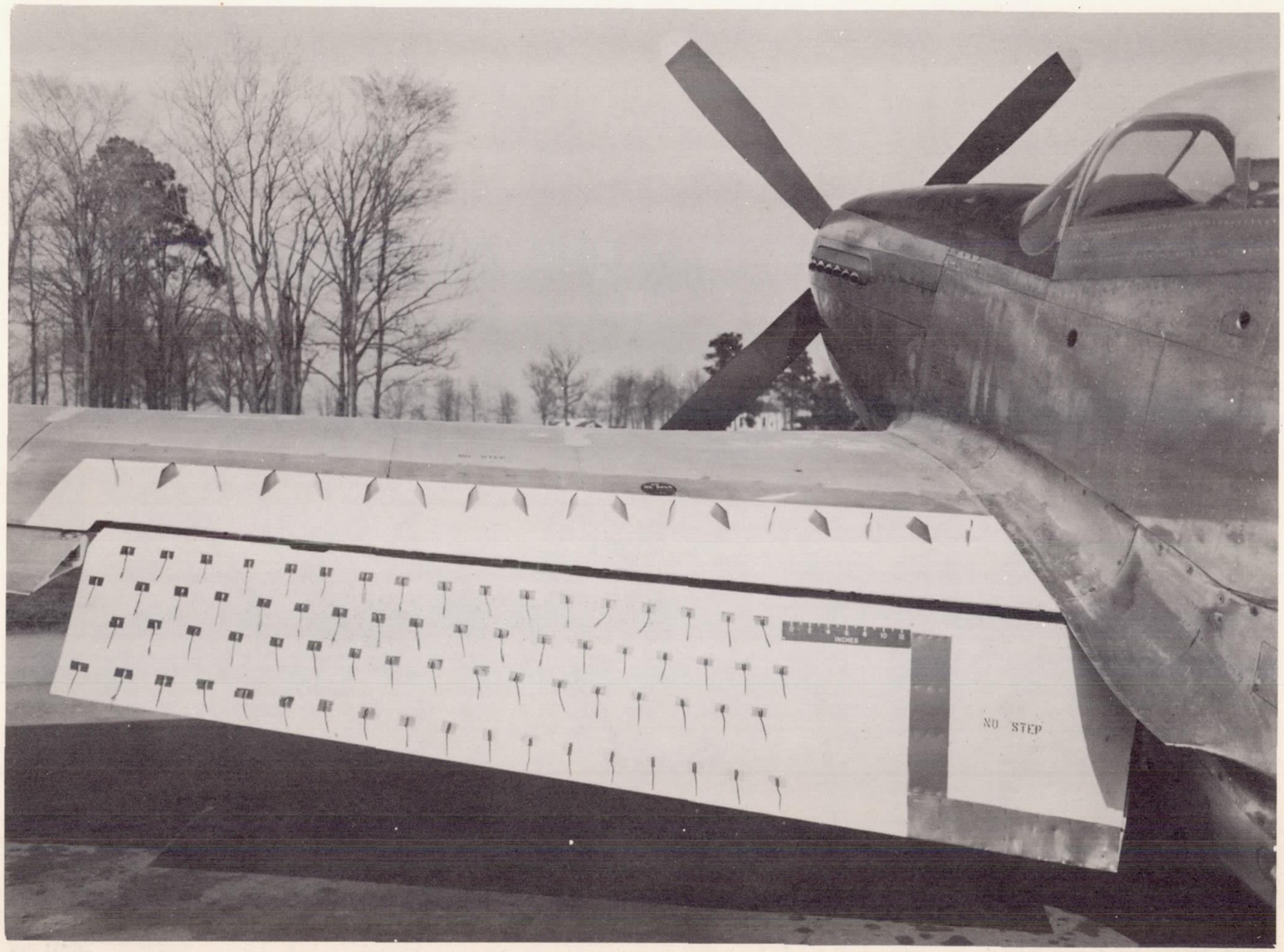

Figure 5.- Vortex-generator configuration 3 mounted on airplane wing. Flaps full down.

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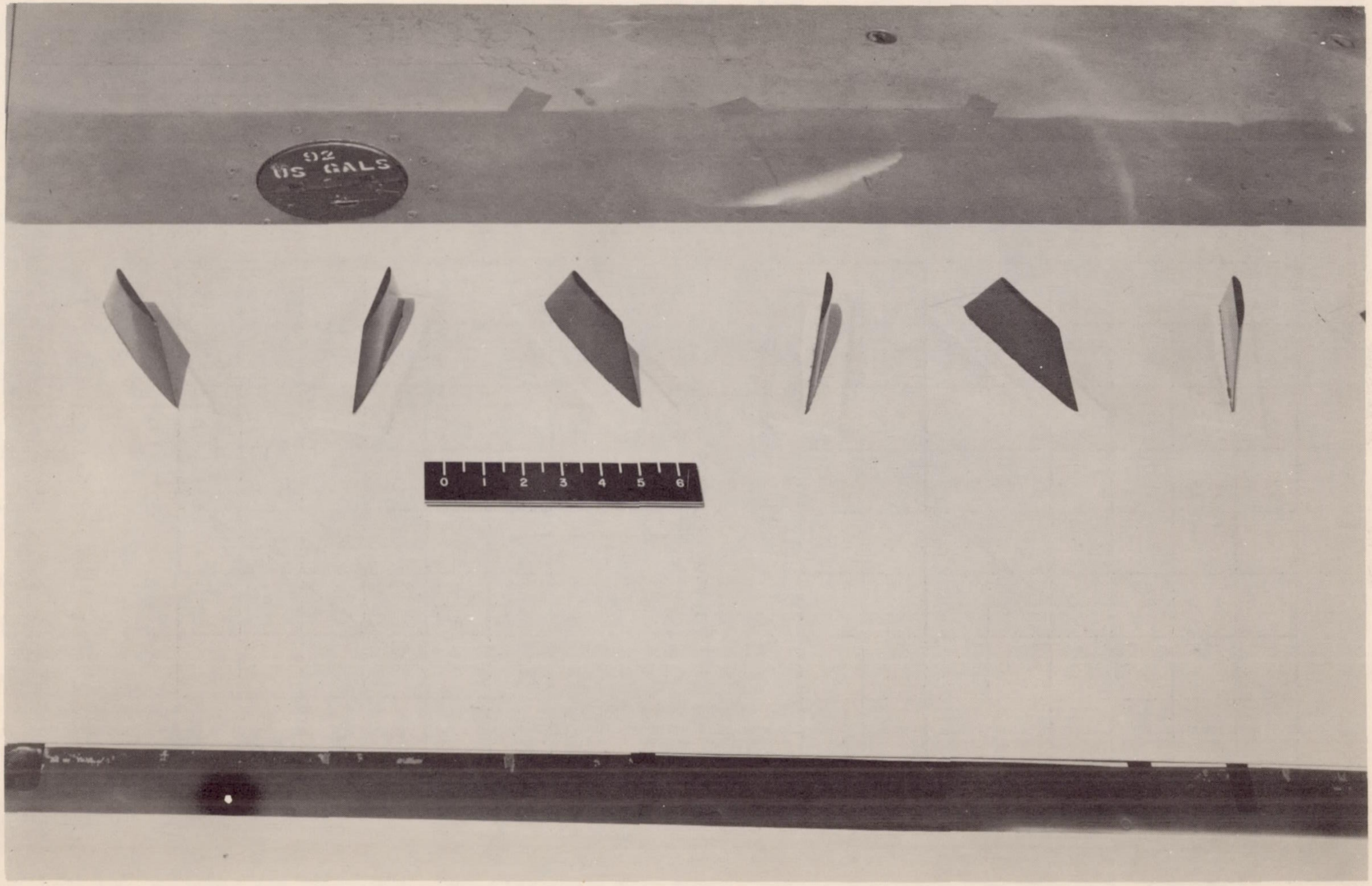

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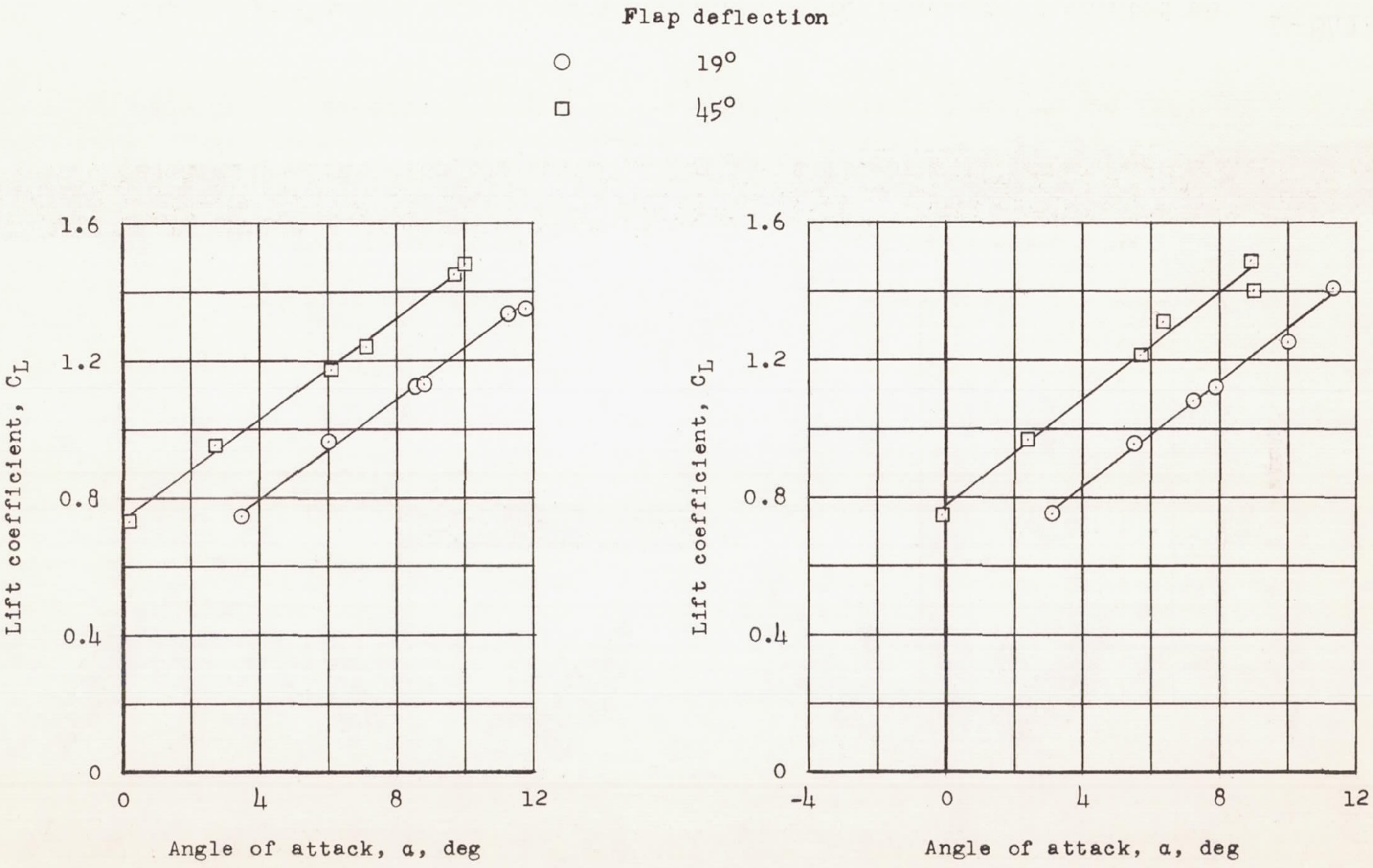
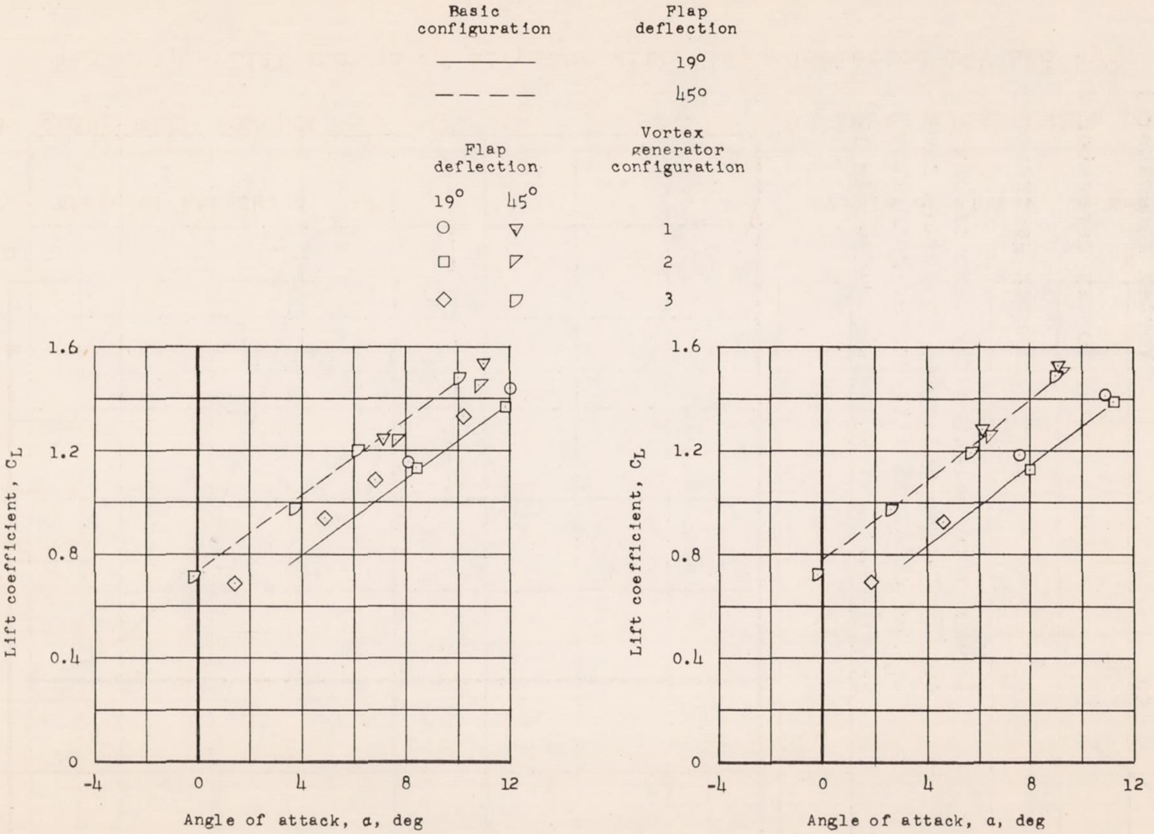
Figure 6.- Closeup view of vortex-generator configuration 3 mounted on airplane wing.



(a) Steady glide with low power.

(b) Level flight with power required.

Figure 7.- Lift curves of airplane with flaps deflected 19° and 45°.



(a) Steady glide with low power. (b) Level flight with power required.

Figure 8.- Effects of three vortex-generator configurations on lift curves of the airplane with flaps deflected 19° and 45°.

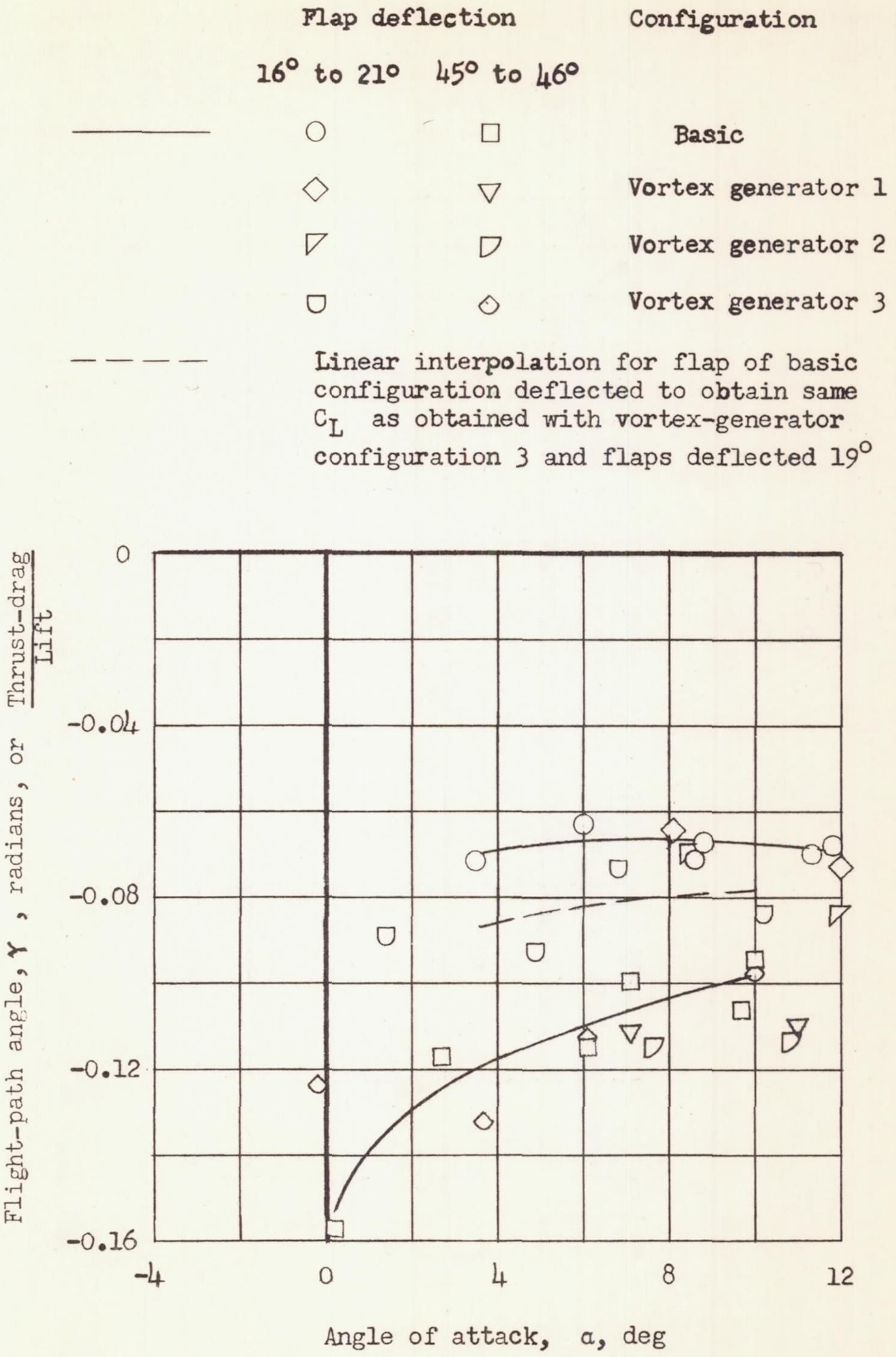


Figure 9.- Effects of vortex-generator configurations on flight-path angle in low-power glides. Flaps deflected approximately 19° and 45°.

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