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RESEARCH MEMORANDUM

EXPERIMENTAL INVESTIGATION OF THE EFFECTS OF VORTEX GENERATORS ON THE MAXIMUM LIFT OF A 6-PERCENT-THICK SYMMETRICAL CIRCULAR-ARC AIRFOIL SECTION

By William J. Bursnall

Langley Aeronautical Laboratory
Langley Field, Va.

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

An experimental investigation was made in the Langley low-turbulence tunnel of the effectiveness of several configurations of vortex generators in increasing the maximum lift of a 6-percent-thick symmetrical circular-arc airfoil section. Lift measurements at a Reynolds number of 2.0×10^6 and a Mach number less than 0.2 indicated that none of the configurations tested substantially increased the maximum lift of the circular-arc section (the greatest increase was less than 0.1).

Although the generators decreased the extent of local separation from the leading edge at the lower angles of attack, the majority of the configurations failed to produce vortices at the angles of attack just below stall because the generators were enveloped by the separated region. Even for vortex generators swept forward of the leading edge of the airfoil, the vortices which were produced throughout the angle-of-attack range were not sufficiently strong to effect a reattachment of the strong separation from the leading edge at the higher angles of attack.

INTRODUCTION

The use of thin airfoil sections has been found to be advantageous on high-speed aircraft, but the maximum lift coefficient obtainable with most airfoils of this type is limited to relatively low values because the stall occurs at a relatively low angle of attack as a result of poor boundary-layer flow conditions near the leading edge.

A method of increasing the maximum lift of airfoils, based on directly altering the boundary-layer flow, is presented in reference 1. In this method, a row of small auxiliary airfoils or vortex generators is mounted perpendicular to the airfoil surface and along the span. This system utilizes the induced vortex generated at the tip of the small lifting airfoil as a means of mixing the high-energy air of the main stream and the low-energy air in the boundary layer. This mixing, therefore, alters the boundary-layer velocity distribution such that separation is prevented or, at least, delayed. It is shown in reference 1 that the maximum lift coefficient of the NACA 23012 airfoil section may be increased by approximately 30 percent as a result of delaying the stall (due to turbulent boundary-layer separation from the trailing edge) to a higher angle of attack by means of vortex generators.

The effectiveness of vortex generators as a fluid mixing device and in preventing the separation of turbulent boundary layers has been demonstrated in a number of cases (ref. 2), but the effectiveness of the generators in reducing the extent of the separated boundary layer near the leading edge of airfoils was not known. Consequently, it was decided to investigate the effects of several arrangements of vortex generators on the maximum lift characteristics of a thin, sharp-nosed airfoil section.

The experimental investigation was conducted in the Langley low-turbulence tunnel. Lift measurements were made of a 6-percent-thick symmetrical circular-arc airfoil section at a Reynolds number of 2.0×10^6 and a Mach number less than 0.2 for both the plain airfoil and for the airfoil equipped with several configurations of vortex generators. In addition, limited pressure-distribution and boundary-layer velocity profile measurements were made on the plain airfoil and on one vortex-generator configuration; limited tuft surveys were also made on several generator configurations. These studies are presented and analyzed herein.

SYMBOLS

$b/2$ vortex-generator semispan, measured from generator tip to surface of basic airfoil, in.

c airfoil chord, in.

c_g vortex-generator chord, in.

c_l section lift coefficient

H_o free-stream total pressure, lb/sq in.

p	local static pressure, lb/sq in.
q_o	free-stream dynamic pressure, lb/sq in.
S	pressure coefficient, $\frac{H_o - p}{q_o}$
u	local velocity inside boundary layer, fps
U	local velocity outside boundary layer, fps
x	chordwise coordinate, in.
y	coordinate above airfoil surface (normal to airfoil surface), in.

APPARATUS AND TESTS

Wind tunnel and model.- The experimental investigation was conducted in the Langley low-turbulence tunnel. The test section was 3 feet by 7.5 feet and the model, when mounted, completely spanned the 3-foot dimension. Lift measurements were made by taking the difference between the pressure reaction on the floor and ceiling of the tunnel. A more complete description of the tunnel and the method of obtaining and reducing the data may be found in reference 3.

All measurements were made on a 24-inch-chord machined steel model of a 6-percent-thick symmetrical circular-arc airfoil section. The model was painted with lacquer and sanded with No. 400 carborundum paper to obtain a smooth surface. The ordinates of the airfoil section are presented in table I.

Rectangular airfoils of two sizes $\left(\frac{b}{2} = 1 \text{ in. and } c_g = 1 \text{ in.}; \frac{b}{2} = 2 \text{ in. and } c_g = 1.5 \text{ in.}\right)$ were used as vortex generators. These airfoils were made of mahogany and machined approximately to the ordinates of the NACA 6415 airfoil section (ref. 4). The generators were attached to the basic airfoil in various configurations as shown in figure 1 and described in table II.

Tests.- Lift measurements were made of the plain airfoil and the various configurations of vortex generators at a Reynolds number of 2.0×10^6. The Mach number of all tests was less than 0.2. The lift data were corrected for tunnel-wall effects according to the methods of reference 5. Chordwise pressure distributions and boundary-layer velocity profiles were measured at an angle of attack of 6° on the forward portion of the plain airfoil and on one configuration of vortex generators. Vertical surveys of static and total pressure were made with multitube pressure rakes which consisted of four static-pressure tubes and four total-pressure tubes. The tubes were made of steel hypodermic tubing having an outside diameter of 0.040 inch and a wall thickness of 0.003 inch. The total-pressure tubes were flattened at the ends until the opening at the mouth of the tube was 0.006 inch. Tube heights less than 0.1 inch from the surface were measured with a micrometer microscope and tube heights greater than 0.1 inch were measured with a scale graduated in hundredths of an inch. One static-pressure tube was kept on the surface of the airfoil to measure the chordwise pressure distribution, and the vertical surveys of static and total pressure were combined to give the velocity distribution through the boundary layer. It should be emphasized that these measurements can be considered as only qualitative because the vortices and separated flow tended to cause fluctuations in both local speed and local direction of the flow resulting in indeterminable errors in the pressure measurements.

The over-all effects of the generators on the flow for some of the configurations were studied qualitatively by means of short wool tufts placed on the airfoil surface, on the tips of the generators, and on small masts attached to the surface of the model.

RESULTS AND DISCUSSION

The subsequent discussion considers the effectiveness of the various vortex-generator configurations with respect to their influence on the maximum lift of the airfoil.

Effectiveness of a single row of vortex generators near the leading edge.- Criteria for the placement of vortex generators in relation to the separation point were recommended in reference 2. For the present investigation of leading-edge separation, however, these criteria are not applicable. It was considered necessary to place the generators as close to the leading edge as was convenient for mounting purposes in order to permit the mixing action to be effective over as much of the separated region as possible.

The first configuration tested (configuration I) was composed of generators of 1-inch chord and 1-inch semispan placed with their quarter chord 1 inch (0.0416c) behind the leading edge of the circular-arc airfoil section and spaced every 2 inches along the span. Figure 2 presents the lift curves measured for the plain airfoil and for configurations I(a) to I(d) with the vortex generators at angles of attack of 10°, 15°, 20°, and 25°. The faired line of configuration I(a) in figure 2 is based on the slopes of the other lift curves. The vortex generators proved to be relatively ineffective in increasing the maximum lift of the basic airfoil. The increase in lift coefficient amounted to less than 0.1 and was very slightly changed by varying the angle of attack of the generators.

In the absence of an appreciable increase in maximum lift coefficient, it was decided to determine the flow changes brought about by the vortex generators before testing any other configurations. For this purpose, chordwise surveys were made of the surface pressures and the boundary-layer profiles over the forward part of the plain airfoil and configuration I(b) at an angle of attack of 6°. The surface pressure distributions are presented in figure 3 as plots of pressure coefficient S against chordwise position x/c. A diagram defining the three spanwise stations at which both the surface pressure and boundary-layer measurements of configuration I were made is also shown in figure 3. The pressure-distribution data indicate that, at an angle of attack of 6°, the generators have probably been effective in increasing the peak pressures of the distribution and, consquently, decreasing the extent of separated flow near the leading edge of the airfoil. The extent of these changes cannot be determined because the presence of the generators did not permit measurements in this region.

The boundary-layer velocity-profile data are presented in figure 4. Plots of the velocity ratio u/U through the vertical distance y/c are shown superposed on the chordwise position scale x/c. Thus, the development of the boundary layer is shown as the flow progresses from the leading edge toward the trailing edge of the airfoil. Figure 4 shows that, at an angle of attack of 6°, the reduction of the extent of separated flow indicated by the pressure-distribution measurements is quite pronounced. The effectiveness of the generators in reducing the size of the separated flow, however, depends upon the spanwise survey position relative to the generator. One possible explanation of the spanwise variation of generator effectiveness is a localized channel-flow effect of the geometry of the generator installation. Although the primary factor tending to reduce the extent of separated flow is the mixing brought about by the vortex motion, the local accelerations at position 3 due to the converging section between the generators may be sufficient to reduce further the extent of separated flow. Similarly, the decelerations at position 1 may be such that the mixing action is not as fully effective.

In an effort to increase the spanwise effectiveness of the vortex mixing, the spanwise spacing was reduced to 1 inch (configuration II). No apparent gain was found in the maximum lift (fig. 5(a)), and it was concluded that the lift was limited by turbulent separation near the trailing edge brought about by the increased pressure peaks near the leading edge.

Effectiveness of the addition of a second row of generators to delay turbulent separation.- Configuration I was modified by the addition of a second row of vortex generators of a larger size $\left(\frac{b}{2} = 2 \text{ in.}\right.$ and $\left.c_g = 1.5 \text{ in.}\right)$ at the 0.35c station and designated configuration III. It was believed that this second row of generators would inhibit the turbulent separation that seemed to be indicated near the trailing edge. The maximum lift (fig. 5(a)) was not substantially improved in this case nor was it improved by moving the second row of vortex generators forward to 0.25c as in configuration IV (fig. 5(a)). The spacing of the forward row of generators was reduced as in configuration II in order to obtain better spanwise mixing at the forward part of the airfoil. The second row was retained at 0.25c. This configuration (configuration V), however, reduced the maximum lift (fig. 5(a)) to a value below that of the plain airfoil. Tufts placed at the tip of several generators on the forward row indicated that these airfoils ceased to generate vortices just before the angle of attack for maximum lift so that the stall still occurred as a result of separation from the leading edge of the airfoil. Thus, the separated region enveloped the vortex generators and it seemed apparent that larger vortex generators were needed.

Effectiveness of larger vortex generators.- The use of the larger vortex generators $\left(\frac{b}{2} = 2 \text{ in. and } c_g = 1.5 \text{ in.}\right)$ in configurations VI, VII, and VIII either did not increase the maximum lift of the airfoil or increased it only slightly (fig. 5(b)). It was found that the auxiliary airfoils still failed to generate vortices of sufficient strength at the higher angles of attack to bring about reattachment of the separated boundary layer near the leading edge. Although the generators were able to reduce the size of the separated region of flow at the lower angles of attack, it appeared from limited tuft surveys that, once an angle of about 9° was reached, the separated region enveloped the auxiliary airfoils and a vortex was no longer generated.

Effectiveness of sweeping forward the front row of generators.- In the final configurations (configurations IX and X), the front row of auxiliary airfoils was mounted at the leading edge of the basic airfoil with the generators swept forward 40°. The introduction of sweep was intended to start the vortex and its subsequent mixing as close to the leading edge as possible. The latter configurations, however, proved to be no more effective than the others in regard to the maximum lift characteristics (fig. 5(c)). Even though the forward row of generators produced vortices throughout the angle-of-attack range, as indicated by tufts, these vortices were not sufficiently strong to effect a reattachment of the leading-edge separation at the higher angles of attack.

CONCLUDING REMARKS

An experimental investigation was made in the Langley low-turbulence tunnel of the effectiveness of several configurations of vortex generators in increasing the maximum lift of a 6-percent-thick symmetrical circular-arc airfoil section. Lift measurements at a Reynolds number of 2.0×10^6 and a Mach number less than 0.2 indicated that none of the configurations tested substantially increased the maximum lift of the circular-arc section (the greatest increase was less than 0.1).

Although the generators decreased the extent of local separation from the leading edge at the lower angles of attack, the majority of the configurations failed to produce vortices at the angles of attack just below the stall because the generators were enveloped by the separated region. Even for vortex generators swept forward of the leading edge of the airfoil, the vortices which were produced throughout the angle-of-attack range were not sufficiently strong to effect a reattachment of the strong separation from the leading edge at the higher angles of attack.

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

REFERENCES

1. McCurdy, W. J.: Investigation of Boundary-Layer Control of an NACA 16-325 Airfoil by Means of Vortex Generators. Rep. M-15038-3, United Aircraft Corp. Res. Dept., Dec. 3, 1948.

2. Taylor, H. D.: Summary Report on Vortex Generators. U.A.C. Rep. R-05280-9, United Aircraft Corp. Res. Dept., March 7, 1950.

3. Von Doenhoff, Albert E. and Abbott, Frank T., Jr.: The Langley Two-Dimensional Low-Turbulence Pressure Tunnel. NACA TN 1283, 1947.

4. Jacobs, Eastman N., Ward, Kenneth E., and Pinkerton, Robert M.: The Characteristics of 78 Related Airfoil Sections From Tests in the Variable-Density Wind Tunnel. NACA Rep. 460, 1933.

5. Abbott, Ira H., Von Doenhoff, Albert E., and Stivers, Louis S., Jr.: Summary of Airfoil Data. NACA Rep. 824, 1945. (Supersedes NACA ACR L5C05.)

TABLE I

ORDINATES OF THE 6-PERCENT-THICK SYMMETRICAL

CIRCULAR-ARC AIRFOIL SECTION

[Stations and ordinates given in percent of airfoil chord]

Station	Upper and lower ordinates
0	0
5	.572
10	1.082
15	1.533
20	1.922
25	2.252
30	2.521
35	2.731
40	2.880
45	2.970
50	3.000
55	2.970
60	2.880
65	2.731
70	2.521
75	2.252
80	1.922
85	1.533
90	1.082
95	.572
100	0

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TABLE II

VORTEX-GENERATOR CONFIGURATIONS

[See fig. 1]

Configu-ration	Generator $c_g/4$ location on airfoil, percent	Spacing, in.	Semispan, b/2, in. (*)	Chord, c_g, in.	Generator angle of attack, deg
I(a) (b) (c) (d)	4.16	2	1	1	10 15 20 25
II	4.16	1	1	1	15
III	4.16 35.00	2 3	1 2	1 1.5	15 10
IV	4.16 25.00	2 3	1 2	1 1.5	15 10
V	4.16 25.00	1 3	1 2	1 1.5	15 10
VI(a) (b)	4.16	1.5	2	1.5	10 15
VII	5.20 35.00	3 3	2 2	1.5 1.5	10 10
VIII	5.20 25.00	3 3	2 2	1.5 1.5	10 10
IX	(**)	2.25	2	1.5	15
X	(**) 35.00	2.25 3	2 2	1.5 1.5	15 10

*Semispan measured from the tip to the surface of the basic airfoil.

**Generators swept forward 40° with leading edge of the generator root at the leading edge of basic airfoil.

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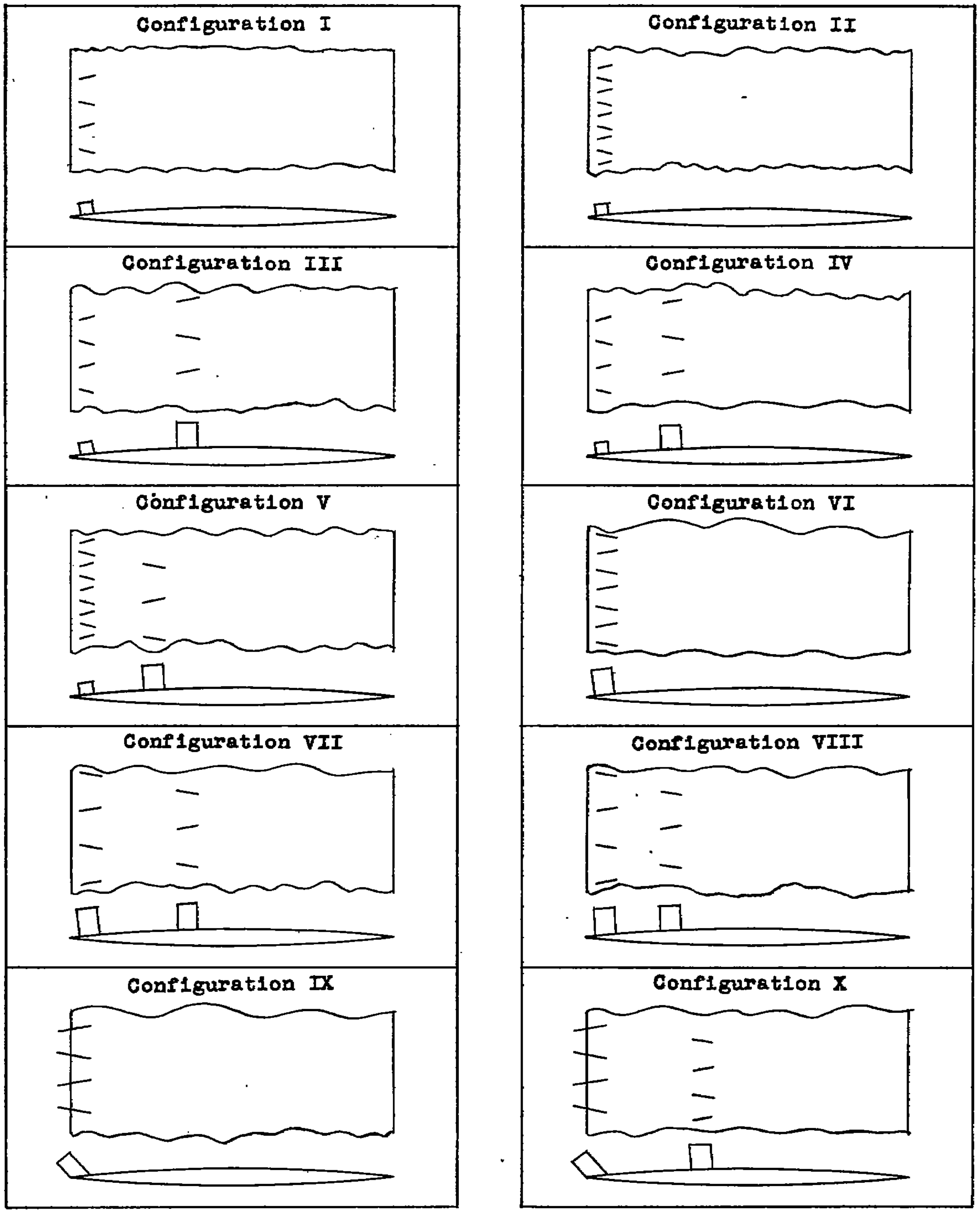


Figure 1.- Vortex-generator test configurations shown approximately to scale.

[redacted]

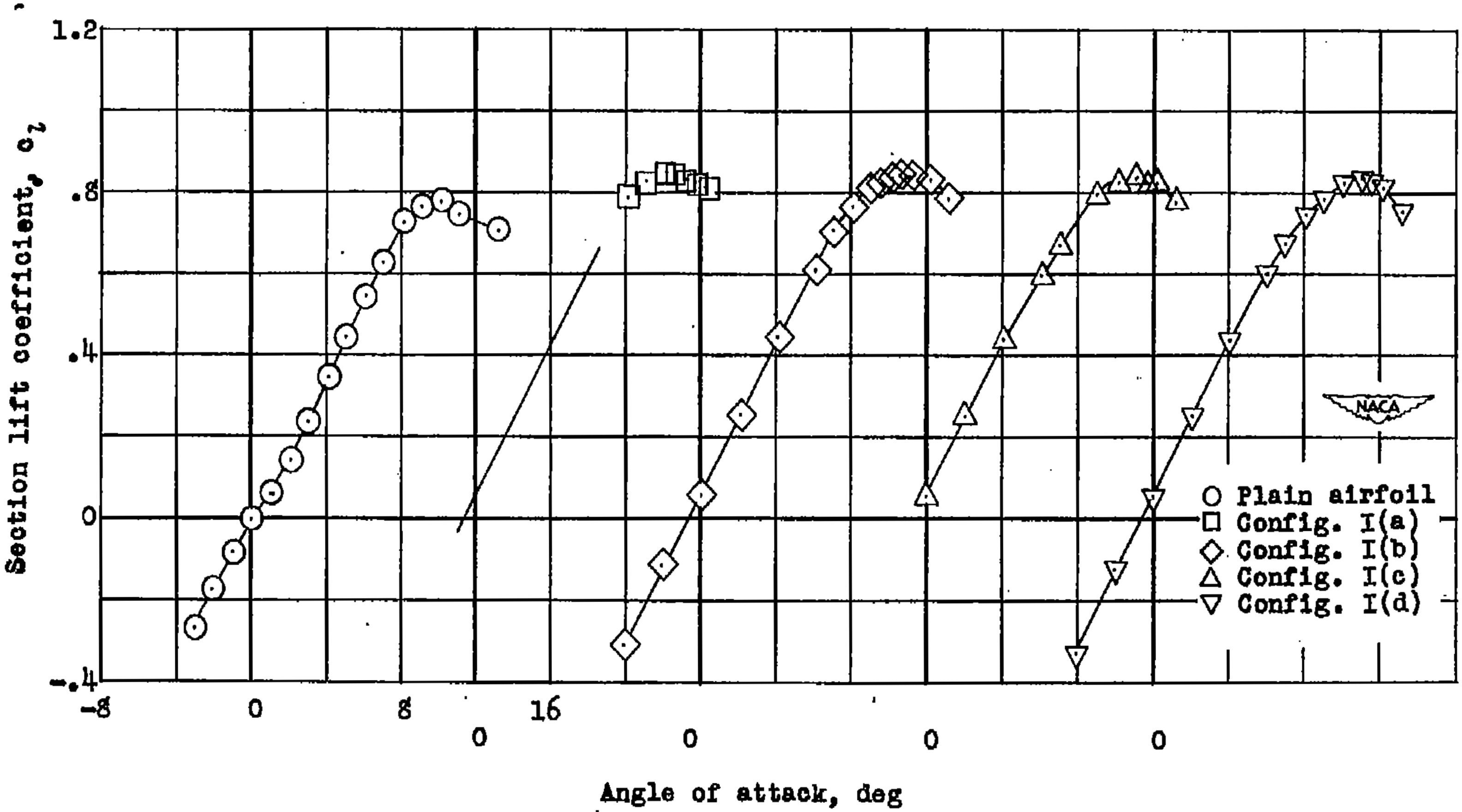


Figure 2.- Variation of lift coefficient with angle of attack of a 6-percent-thick symmetrical circular-arc airfoil section with and without vortex generators (configuration I).

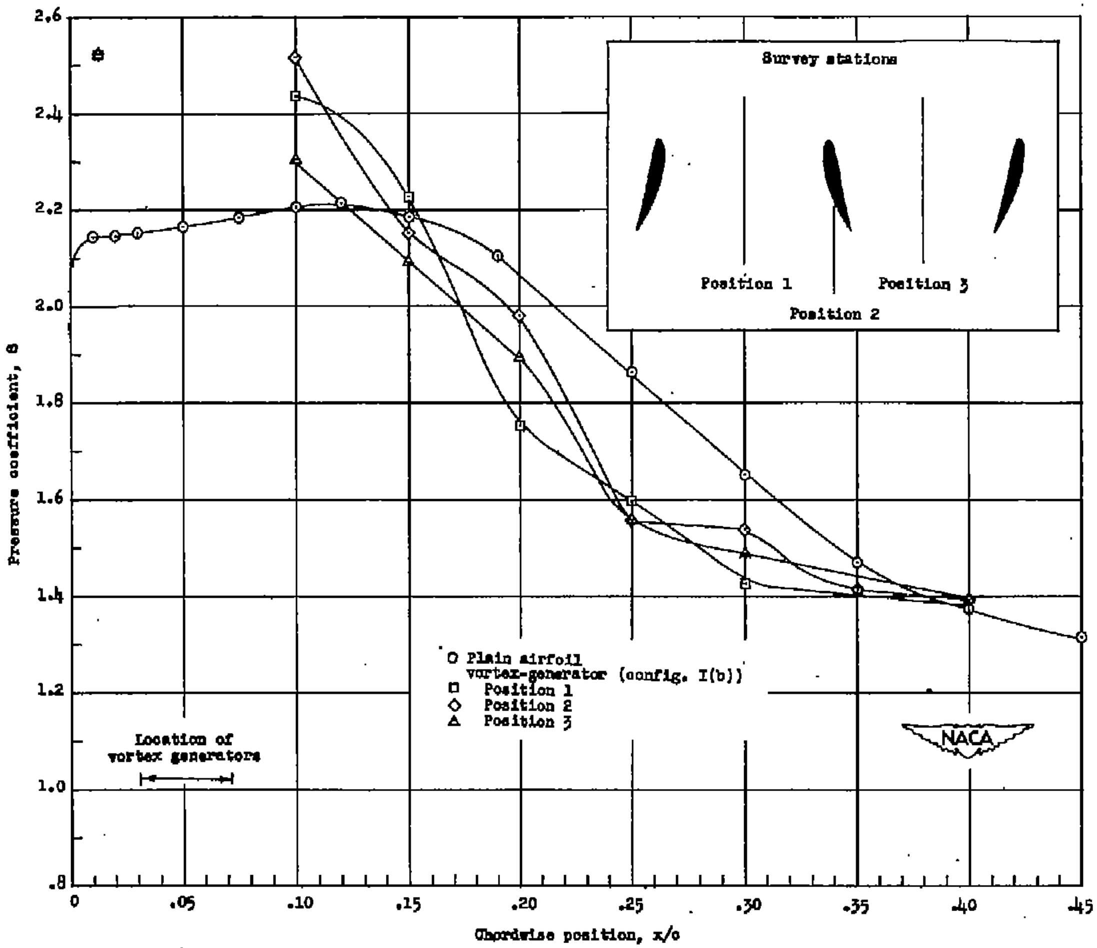


Figure 3.- Chordwise surface pressure distribution on a 6-percent-thick symmetrical circular-arc airfoil section with and without vortex generators at an angle of attack of 6° and a Reynolds number of 2.0×10^{6}.

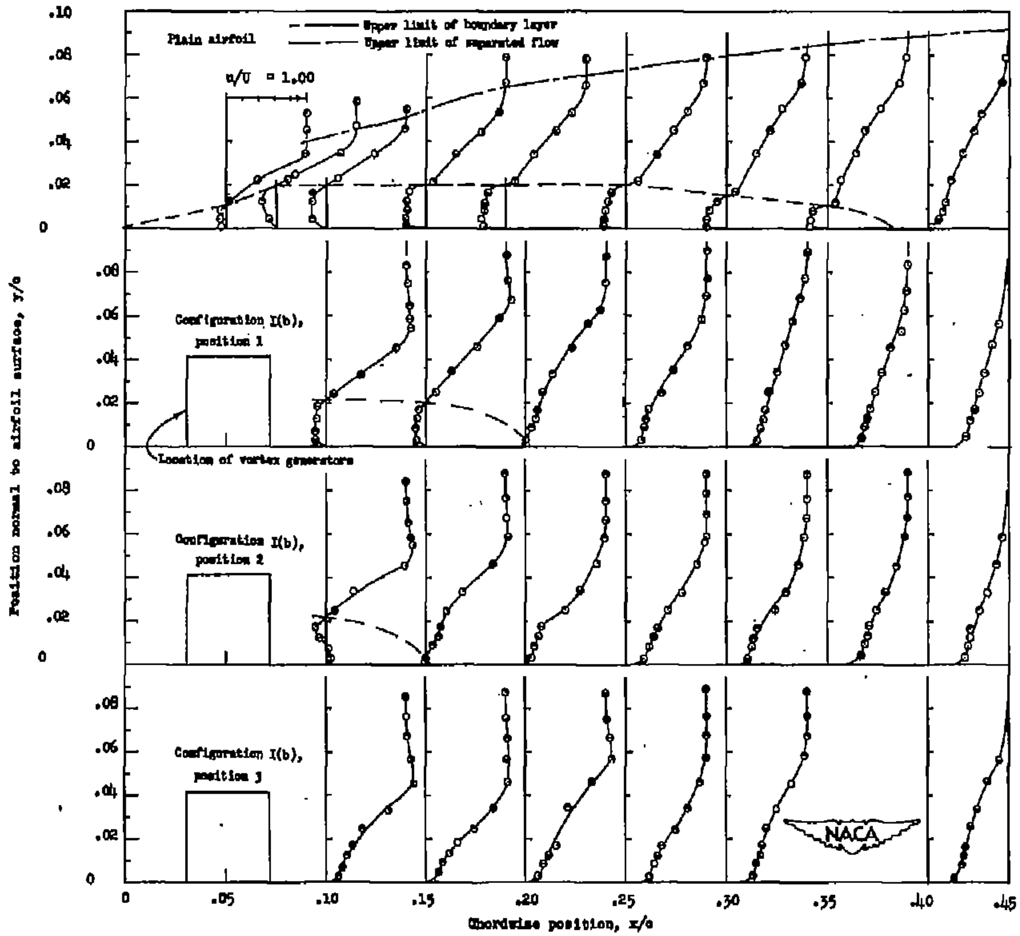
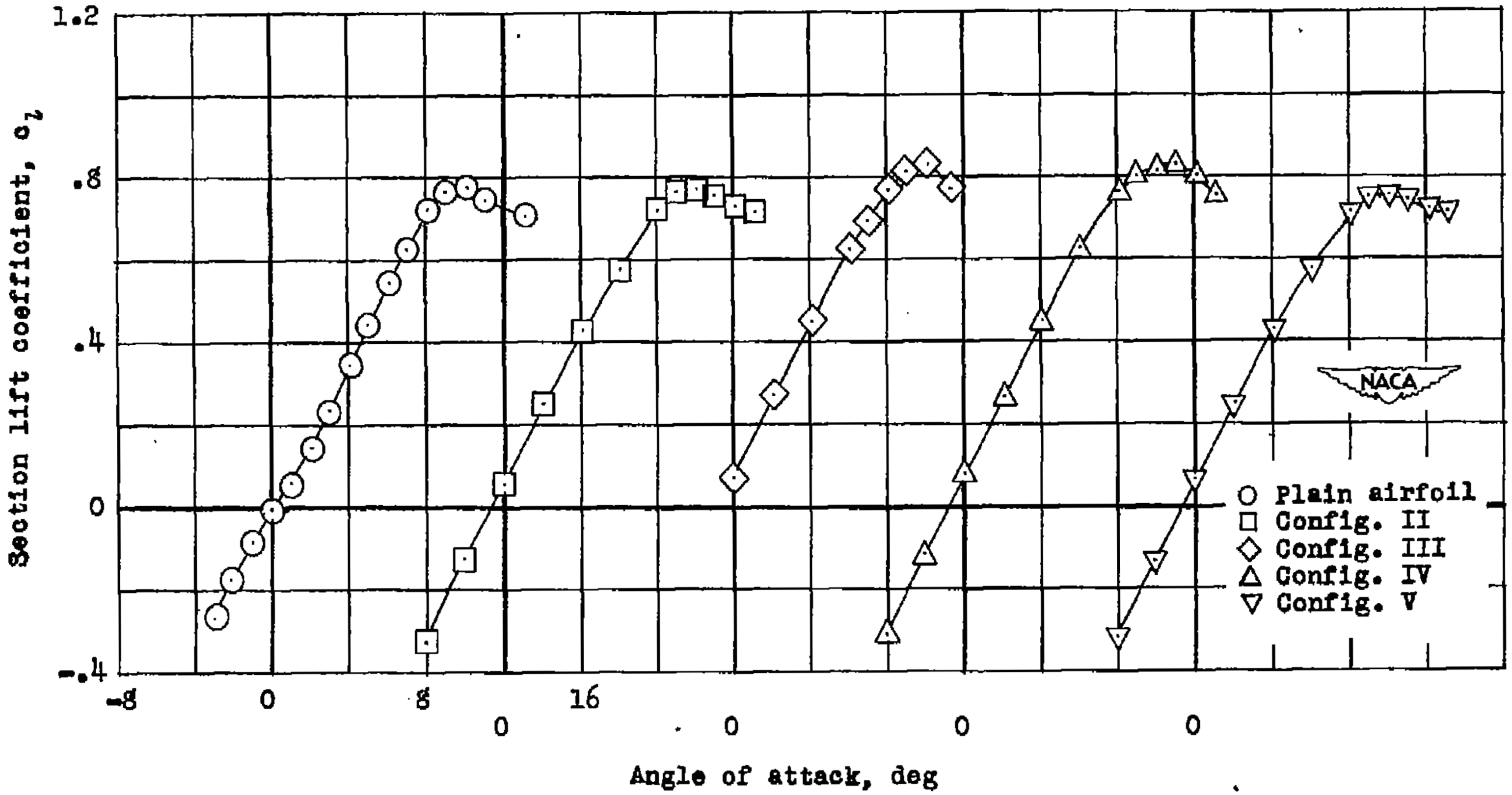
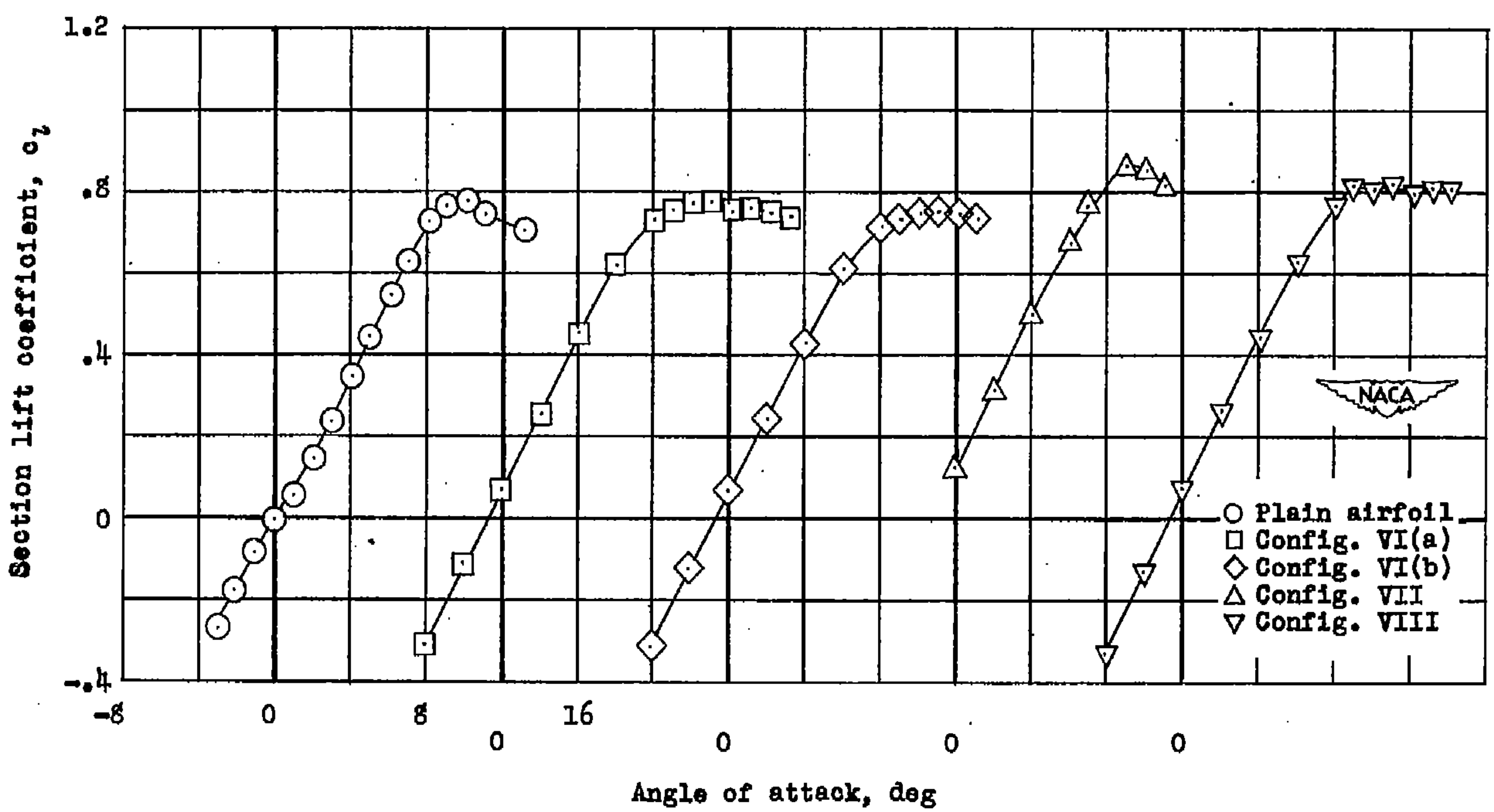


Figure 4.- Development of the boundary layer on the upper surface of a 6-percent-thick symmetrical circular-arc airfoil section at an angle of attack of 6° and a Reynolds number of 2.0×10^{6} as encountered on the plain airfoil and as modified by the presence of configuration I(b) vortex generators.



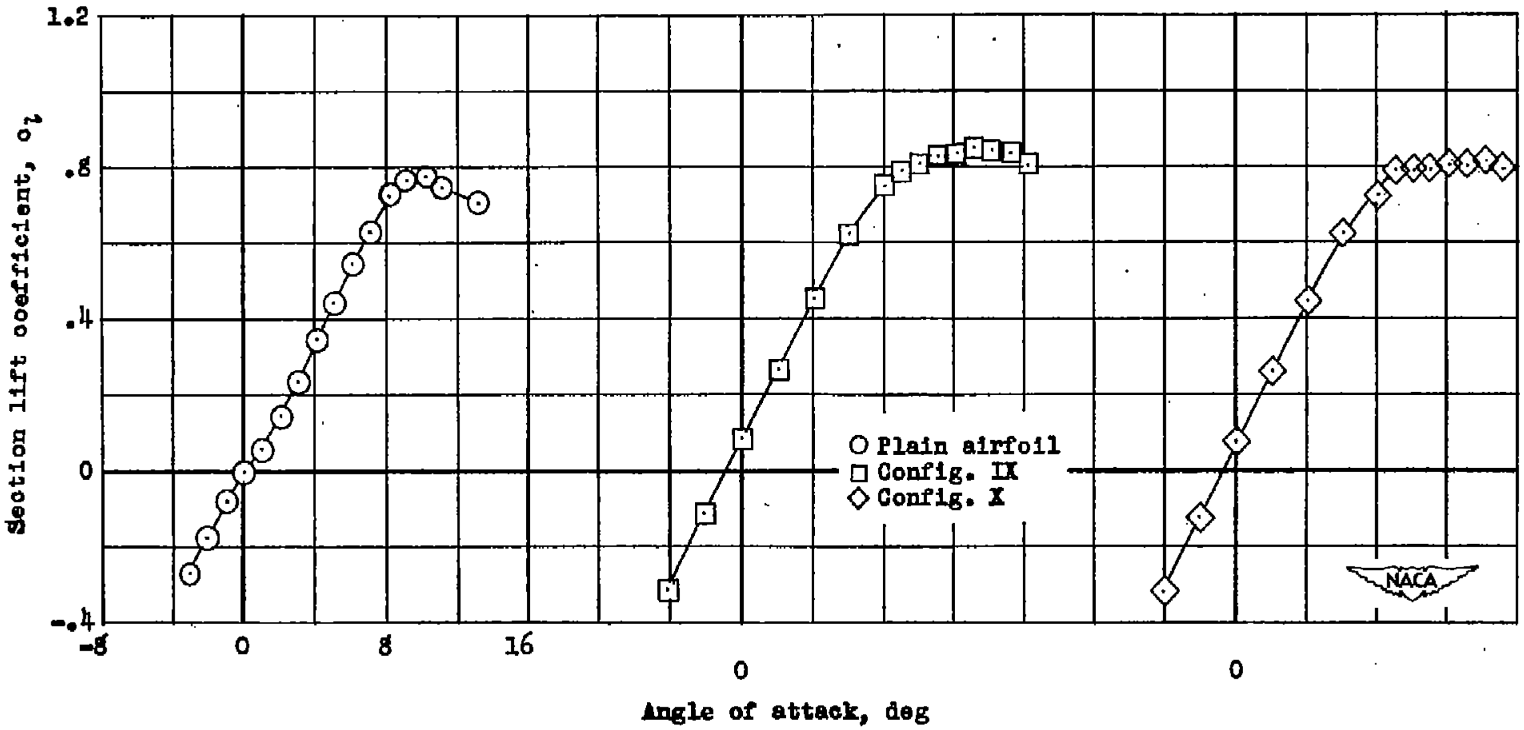
(a) Plain airfoil and airfoil with vortex-generator configurations II, III, IV, and V.

Figure 5.- Variation of lift coefficient with angle of attack for a 6-percent-thick symmetrical circular-arc airfoil section equipped with various vortex-generator configurations.



(b) Plain airfoil and airfoil with vortex-generator configurations VI(a), VI(b), VII, and VIII.

Figure 5.- Continued.



(c) Plain airfoil and airfoil with vortex-generator configurations IX and X.

Figure 5.- Concluded.