REPORT No. 449

WING CHARACTERISTICS AS AFFECTED BY PROTUBERANCES OF SHORT SPAN

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SUMMARY

The drag and interference caused by short-span protuberances from the surface of an airfoil have been investigated in the N. A. C. A. variable-density wind tunnel at a Reynolds Number of approximately 3,100,000, based on the chord length of the airfoil. The effects of variations of the protuberance span length, span position, and shape were measured by determining how the wing characteristics were affected by the addition of the various protuberances.

The results indicate that the central sections of a rectangular wing are more sensitive to the addition of protuberances than the outer sections. A very short protuberance in the midspan position may cause a disproportionately large reduction in maximum lift. At low values of the lift coefficient the drag due to the protuberances increases approximately as the total length for protuberances of equal height, but at higher lift coefficients induced interference effects appear so that short-span protuberances produce disproportionately large drag increases. An example is included to show how airfoil theory and a knowledge of the section characteristics may be applied to estimate induced interference effects. The adverse effects of protuberances are shown to be greatly reduced by simple fairings.

INTRODUCTION

The National Advisory Committee for Aeronautics is conducting in the variable-density wind tunnel a series of fundamental investigations dealing with aerodynamic interference. The investigations will, it is hoped, lead to the discovery of the sources of adverse interference effects and provide data that may be applied to the solution of practical problems of design. Some of the investigations deal with the effects of protuberances from the surfaces of bodies. The data obtained from these investigations are applicable to the prediction of the effects of projecting objects such as fittings, tubes, wires, rivet heads, joints, filler caps, and inspection plates protruding from the main surfaces.

Variations of the height and the chord position of protuberances extending along the entire span of an airfoil have been investigated to determine how the airfoil section characteristics are affected. These results have been published. (Reference 1.) Tests have also been made to investigate the effects of protuberances from the surface of a body of revolution. (Reference 2.) Because the protuberances found on actual airplane wings usually extend over only short portions of the span, it is necessary to consider the effects of short-span protuberances. The investigation with which this report deals was therefore made to study the effects of short-span protuberances and to form a basis for the practical application of the airfoil section data reported in reference 1.

Most of the present investigation was confined to the effects of protuberances of one height at one position along the chord of a symmetrical airfoil section. The variables considered were the protuberance length along the span, position along the span, and the number and shape of the protuberances. The generality of the results was tested by investigating the effects on the aerodynamic characteristics of a cambered airfoil of protuberances simulating lift or landing-wire fittings of a type sometimes found on airplanes. The tests were made during March and April, 1932.

TESTS

The tests necessary for this investigation were made in the N. A. C. A. variable-density wind tunnel at one value of the Reynolds Number, approximately 3,100,000. This tunnel and the methods employed for testing are described in detail in reference 3. The tests herein reported were made in the usual way except that the symmetrical airfoil used with most of the tests was provided with the special mounting described in reference 1.

For most of the tests a standard 5 by 30 inch duralumin airfoil having the symmetrical N. A. C. A. 0012 section (reference 1) was used. This airfoil was tested with different protuberance arrangements in order to determine the effects of varying the protuberance span length, span position, and shape. The various protuberances were of one height, 0.0125c, and were placed on the upper surface of the airfoil at the single position on the profile shown in Figure 1, 0.05 of the chord behind the leading edge. A strip of metal to form the protuberances was placed in the slot shown in Figure 1, which extended along the entire span of the airfoil. The portions of the strip which were not needed to form protuberances were carefully filed to the airfoil surface and polished to present a continuous smooth surface. Protuberances having various lengths were thus formed at the mid-span position by progressively filing off the ends of the

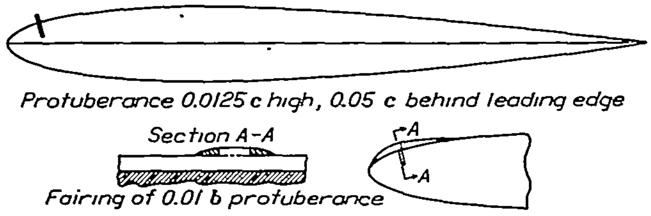

FIGURE 1.—N. A. C. A. 0012 profile showing protuberances

remaining protuberance. The airfoil was also tested with short protuberances placed at positions along the span corresponding approximately to those of the interplane struts on single-bay and two-bay biplanes. The protuberances that will be referred to as faired protuberances were produced, as indicated in Figure 1, by forming over the protuberance a plaster-of-Paris

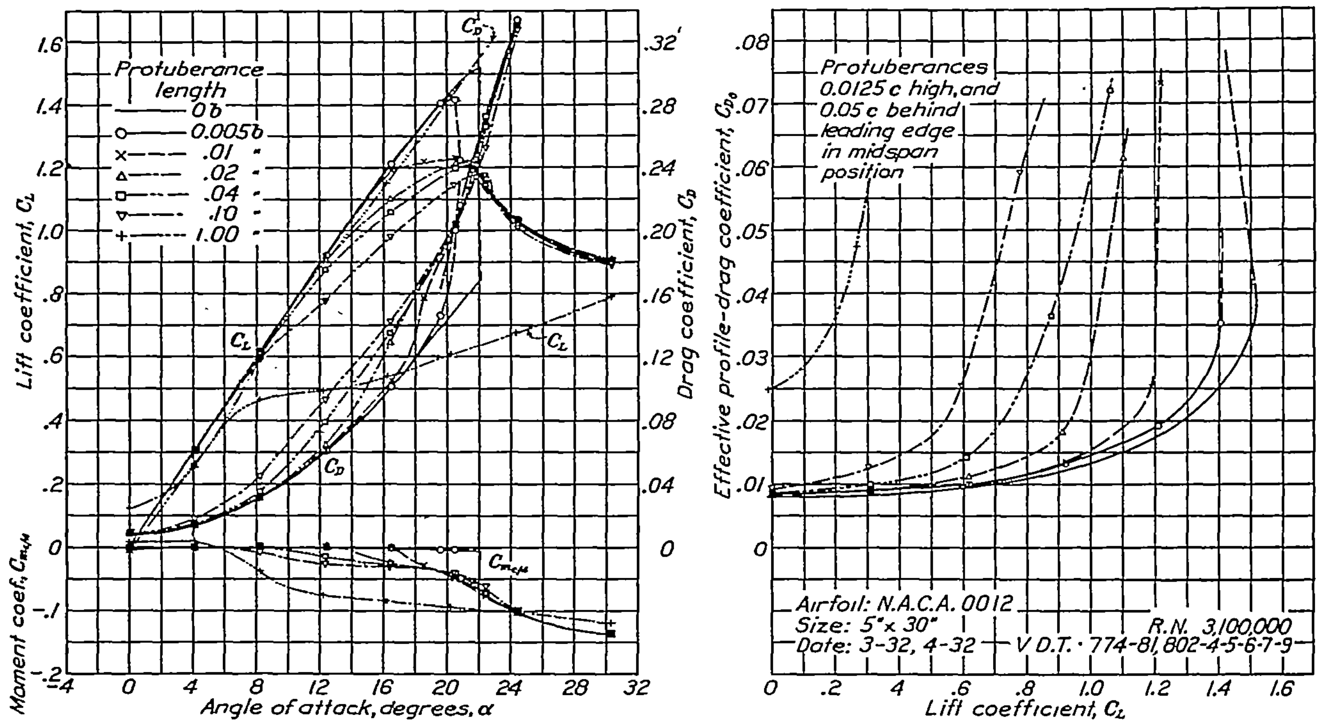

FIGURE 3.—The characteristics of an airfoil having a protuberance on the upper surface at mid span

fairing, the cross section of which approximated a small half-airfoil section on the surface of the main airfoil.

Two tests were also included of an N. A. C. A. 4412 airfoil with protuberances simulating the interplane wire fittings sometimes found on single and two bay biplanes. These protuberances and their arrangement on the airfoil are shown in Figure 2.

RESULTS

The results are presented in the form of curves of lift coefficient C_L, drag coefficient C_D, and moment coefficient about a point on the chord one-quarter of

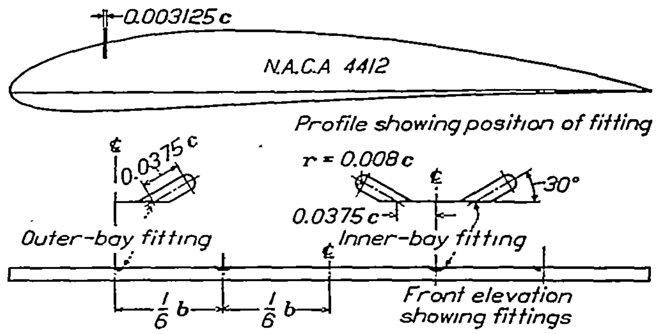

FIGURE 2.—Fitting arrangements on N. A. C. A. 4412 airfoil

the chord behind the leading edge $C_{m_{c/4}}$ plotted against angle of attack. These results, which are corrected for tunnel-wall effects (reference 3), thus represent the characteristics of an airfoil of aspect ratio 6. Curves are also given representing the effective profile-drag coefficient C_{D_0} plotted against the lift coefficient C_L. The effective profile-drag coefficient is that obtained by deducting from the total drag coefficient the usual induced-drag coefficient of a rectangular airfoil of aspect ratio 6. (Reference 3.) The effective profile drag therefore includes any additional induced drag due to the protuberance over that of a plain rectangular airfoil operating at the same lift coefficient.

DISCUSSION

Protuberance length.—The results obtained by varying the protuberance length are shown in Figure 3. The characteristics of the airfoil with midspan protuberances of various lengths between one-tenth span (0.10*b*) and five one-thousandths span (0.005*b*) are compared in this figure with the characteristics of the plain airfoil and the characteristics of the airfoil having the full-span protuberance, taken from reference 1. The variation of drag and maximum lift with protuberance length, however, is shown more advantageously in Figure 4 where the effective profile-drag coefficients, corresponding to various angles of attack, and the maximum lift coefficient are plotted against protuberance length.

Referring to the curve in Figure 4 representing the variation of the maximum lift coefficient with protuberance length, it will be seen that as the protuberance length is increased from zero the maximum lift at first drops very sharply, then at an approximately constant rate. Apparently, a protuberance of length 0.01*b* is sufficiently large to disturb the entire flow over the central portion of the airfoil at large angles of attack.

The curves of effective profile-drag coefficient in Figure 4 indicate that at the small angles of attack which correspond to the small lift coefficients the additional drag due to the protuberance is approximately proportional to the protuberance length. The effect of a short-span protuberance on the drag of a wing at very low lift coefficients may therefore be approximated from the section characteristics of an airfoil with a full-span protuberance. At higher angles of attack corresponding to higher lift coefficients, however, the moderately short protuberances produce disproportionately large adverse effects. These effects may be attributed in part to an additional drag resulting from induced interference. The increase in induced drag caused by the protuberance over that of a plain rectangular airfoil appears on the plot as an increased effective profile drag.

Induced interference.—Short-span protuberances that reduce the lift coefficients of the airfoil sections near the center of a rectangular wing tend to increase the departure from the elliptical span load distribution, and thus to increase the induced drag. This effect is said to be due to induced interference. If the aerodynamic characteristics of all the sections of a wing are known, airfoil theory may be applied to estimate its span load distribution, and hence the induced interference drag.

The span load distribution for a wing having a short-span protuberance may be approximated as follows: For a given angle of attack of the wing, a more or less arbitrary curve is drawn representing a span load distribution that is thought to approximate the true one. From this assumed span load distribution, the downwash is found at a number of stations along the span. The effective angle of attack at each station is then obtained as the difference between the geometric angle of attack at the station and the downwash angle. From the effective angle of attack at each station and the experimentally determined airfoil section characteristics for the section at that station, the lift coefficient for the section at each station is obtained. A check span load distribution is thus derived, from which,

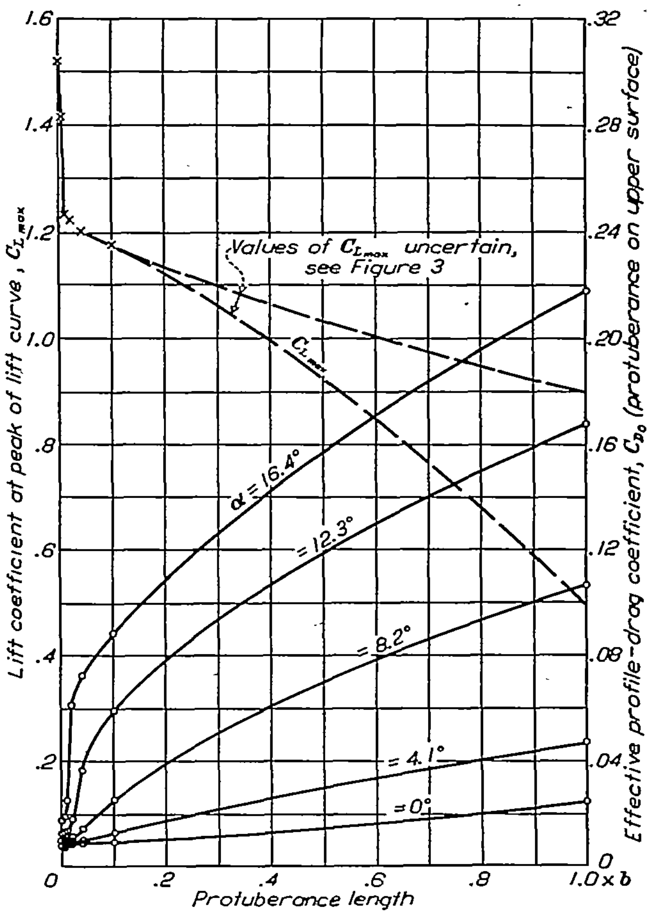

FIGURE 4.—Variation of lift and drag with protuberance length

together with the span load distribution curve originally assumed, a more nearly accurate span load distribution curve may be estimated. Thus, a curve approximating the actual span load distribution may be determined, as shown in Figure 5, by continuing the process through successive approximations until a check distribution is reached that agrees with the assumed curve from which it was derived.

Figure 5 illustrates the application of this method to the approximation of the span load distribution for the N. A. C. A. 0012 airfoil with the 0.10*b* protuberance in the midspan position for an angle of attack of 15°. Figure 6 shows some of the results.

In the derivation of the check span load distribution, the following equation for the downwash w_1 at any station y_1 was used:

$$w_1=\frac{1}{4\pi}\int_{-s}^{s}\frac{\frac{dK}{dy}dy}{y_1-y}. \qquad \text{(Reference 4)}$$

where K is the circulation at any point along the span, y is the distance of any point out from the center line along the span, and s is the length of the semispan. This equation was put in a more convenient form by

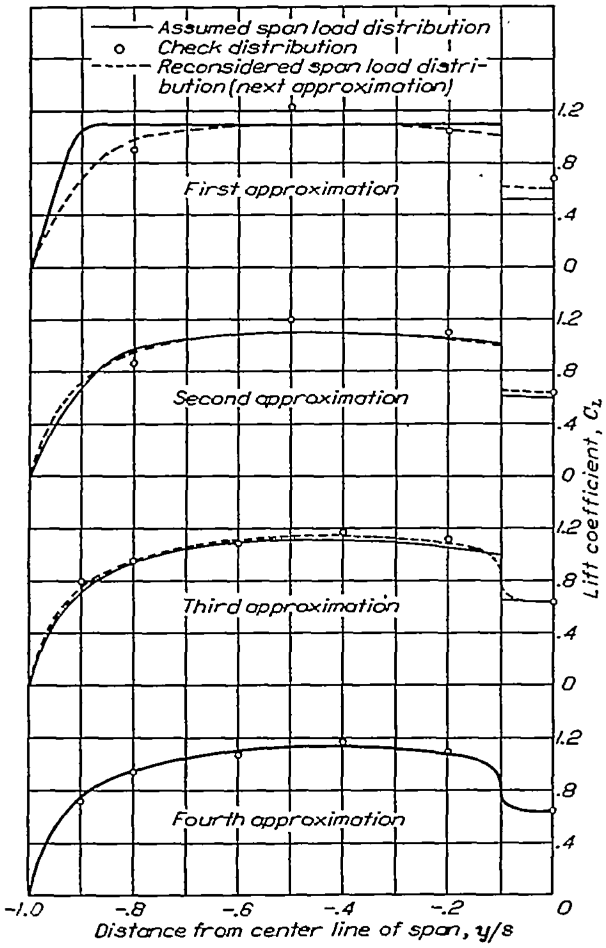

FIGURE 5.—Approximation of span load distribution for a wing with 0.10b protuberance at midspan position. $\alpha=15°$

substituting $\frac{C_L}{2}cV$ for K where c is the chord length and V is the free-stream velocity, thus:

$$\frac{w_1}{V}=\frac{c}{8\pi}\int_{-s}^{s}\frac{\frac{dC_L}{dy}dy}{y_1-y}$$

However, because $\frac{\frac{dC_L}{dy}}{y_1-y}$ approaches infinity as y approaches y_1, $\frac{w_1}{V}$ was determined by expanding the equation for the downwash to the more useful form:

$$\frac{w_1}{V}=\frac{c}{8\pi}\int_{-s}^{y_1-\Delta}\frac{\frac{dC_L}{dy}dy}{y_1-y}+\frac{c}{8\pi}\int_{y_1+\Delta}^{s}\frac{\frac{dC_L}{dy}dy}{y_1-y}$$
$$+\frac{c}{8\pi}\left[\left(\frac{dC_L}{dy}\right)_{y_1-\Delta}-\left(\frac{dC_L}{dy}\right)_{y_1+\Delta}\right]$$

where Δ is a small distance as compared with the span. The first two terms were integrated graphically. The third term resulted from evaluating

$$\frac{c}{8\pi}\int_{y_1-\Delta}^{y_1+\Delta}\frac{\frac{dC_L}{dy}dy}{y_1-y}$$

after expressing the span load distribution between the limits $y_1-\Delta$ and $y_1+\Delta$ by the equation $C_L=a+by+cy^2$, the constants a, b, and c being expressed in terms of the slopes of the span load distribution curve at $y=y_1-\Delta$ and $y=y_1+\Delta$.

Difficulties resulting from uncertainty in regard to the exact form of the loading curve along the portions of the span near the ends of the protuberance were avoided by calculating independently the downflow resulting from those portions of the lift grading curve. The downflow resulting from each small portion of the curve between $y=h-\Delta$ and $y=h+\Delta$, where h is the value of y at the ends of the protuberance, was evaluated approximately by considering the downflow to be induced by a finite vortex at $y=h$, the strength of which is the difference between the vorticity at $y=h-\Delta$ and $y=h+\Delta$. This part of the downflow at the station y_1 due to each vortex is then given by

$$\frac{w_1}{V}=\frac{c}{8\pi}\frac{C_{L_{h-\Delta}}-C_{L_{h+\Delta}}}{h-y_1}$$

When working through the successive approximations shown in Figure 5, the method was found to require some care and judgment in order to converge rapidly to an acceptable solution. The judgment was required for the estimation of each succeeding approximate loading curve from considerations of the character of the preceding loading curve and its check distribution. It was noticed, in developing this method, that the use of the check distribution as the succeeding approximation might lead to successively divergent loading curves.

From the span load distribution, the lift coefficient C_L and the induced-drag coefficient C_{D_i} were calculated from the following equations (reference 4):

$$C_L=\frac{1}{2s}\int_{-s}^{s}C_L\,dy$$

$$C_{D_i}=\frac{1}{2s}\int_{-s}^{s}\frac{w}{V}C_L\,dy$$

The value of C_L calculated for this example was 0.97 as compared with the test value of 0.91, the discrepancy being 7 per cent.

The calculated C_{D_i} was 0.0670, which corresponds to an increase of 26 per cent over that of the wing without a protuberance at the same lift coefficient.

The total drag coefficient of the wing was calculated as follows: The average values of effective angle of attack for the portions of the wing with and without the protuberance were found from Figure 6(c) to be 20.5° and 9.9°, respectively. At these effective angles of attack, the profile-drag coefficients for the corresponding airfoil sections were read from the section characteristics in reference 1. They were 0.296 and 0.0125, respectively. They were each multiplied by the portions of the span their corresponding profiles occupied (0.1 and 0.9) and added to the calculated induced-drag coefficient to obtain the total calculated drag coefficient. The value obtained was 0.108, which was 14 per cent low as compared with the test value of 0.1250.

The differences between the calculated and the experimentally determined values may be due in part to the fact that the section characteristics used in the computations are average section characteristics derived from tests of rectangular airfoils of normal aspect ratio and not true infinite aspect ratio characteristics. Such calculations may be of value, nevertheless, in connection with the interpretation of experimental results, and should also be of assistance in predicting certain interference effects.

Protuberance arrangements.—The results of the tests of the airfoil with the short protuberances at various positions along the span are presented in Figures 7 and 8. It is evident from the lift curves that protuberances distributed along the span away from the center have a smaller adverse effect on the maximum lift than a protuberance of the same total length at center span. The greater effect of the protuberance at the center might be expected, because the central sections of a rectangular airfoil near maximum lift operate at higher effective angles of attack than the outer sections. Protuberances near the center therefore tend to start the burble at a lower angle of attack.

Considering now the effects of the distributed protuberances on the drag in the range of the lift coefficient corresponding to high-speed flight, the results of Figures 7 and 8 indicate that the additional drag due to the protuberances depends approximately directly on their total length. Although this agrees with the results of Figure 4, from which it was concluded that the additional drag was proportional to the protuberance length, it should be mentioned here that all the results tend to indicate that at very low lift coefficients protuberances of length 0.01*b* or less may produce relatively larger than proportional adverse effects. If very short protuberances do produce serious disturbing effects, such objects as small protruding rivet heads on an airplane wing might be expected to reduce substantially the performance of the airplane. Full-scale tests should therefore be made to investigate the effects of a large number of such short-span protuberances.

The effect of the distributed protuberances on the drag at higher values of the lift coefficient might be estimated by applying the airfoil theory previously described as applied to a midspan protuberance. Experimental results (figs. 7 and 8) indicate, as might be expected, that the distributed protuberances do not increase the drag at higher lifts as much as a single protuberance of the same total length at the center of the airfoil.

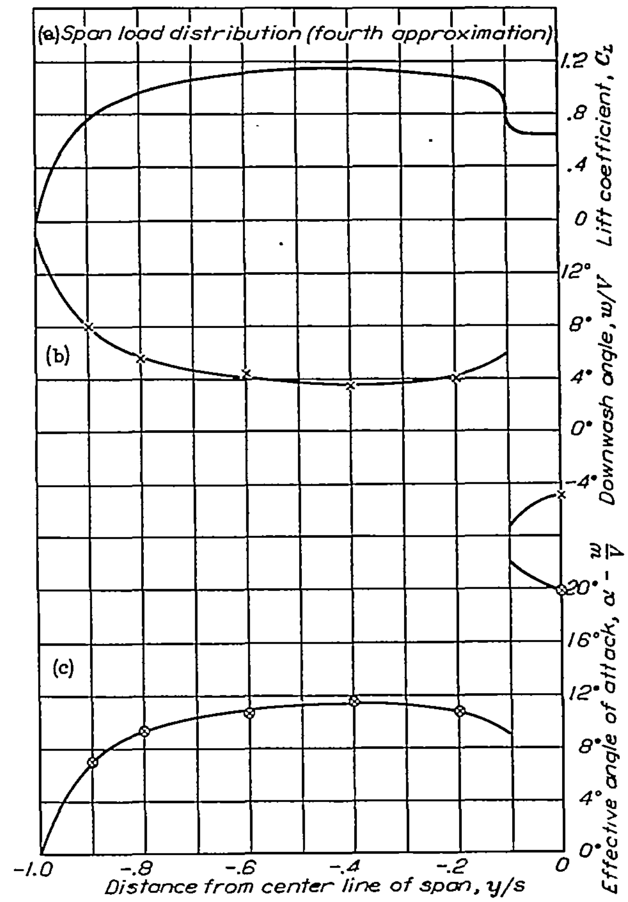

FIGURE 6.—Results of interference calculated for a wing with 0.10b protuberance at midspan position. $\alpha = 15°$

Practical applications.—From practical considerations, it is desirable to know whether or not the adverse effects of protuberances may be eliminated by fairing them into the wing surface, and if the effects of actual protuberances can be predicted from the results of tests of these simplified protuberances. The results shown in Figure 8 indicate that the adverse effects of short-span protuberances may be largely eliminated within the working range of angles of attack by applying simple fairings as shown in Figure 1. The maximum lift of the airfoil with the faired protuberances, however, was not so high as that of the plain airfoil. The results in reference 1, dealing with the fairing of full-span protuberances, indicated that the adverse effect of a

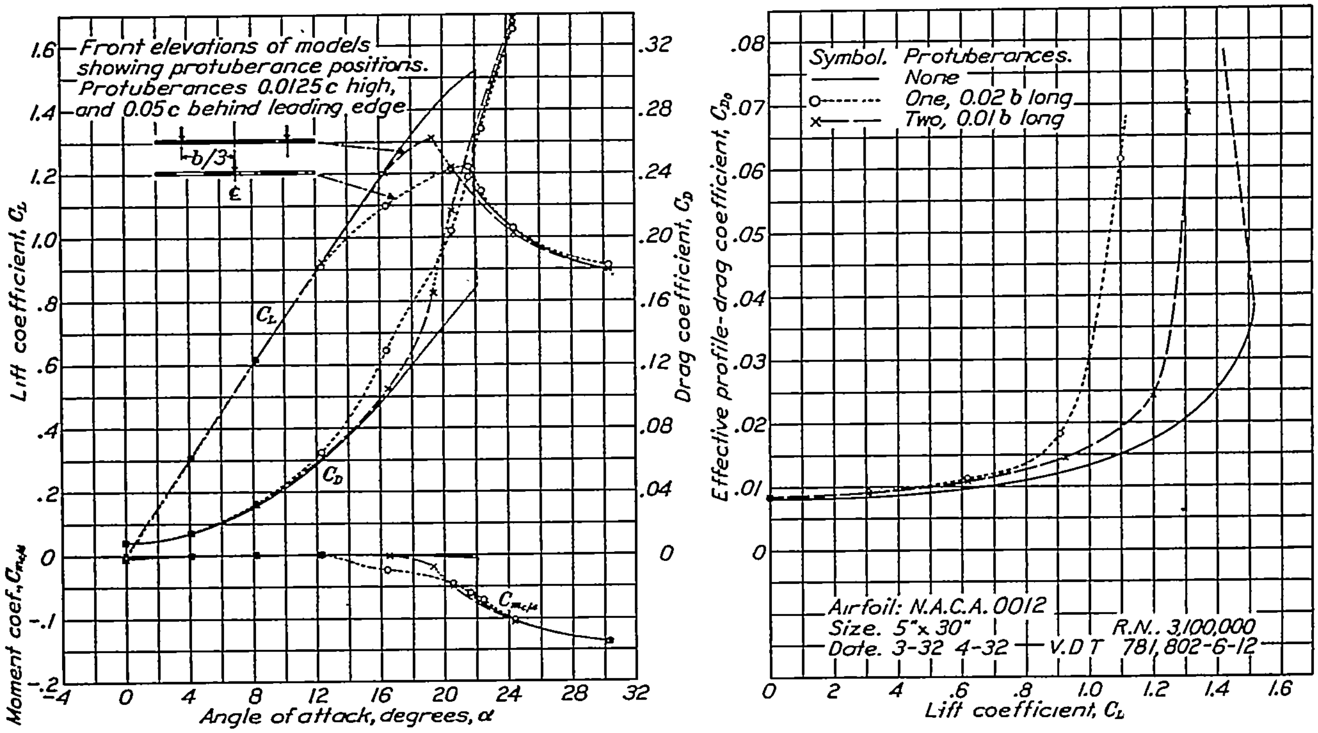

FIGURE 7.—The characteristics of an airfoil with protuberance arrangements having same total length on upper surface

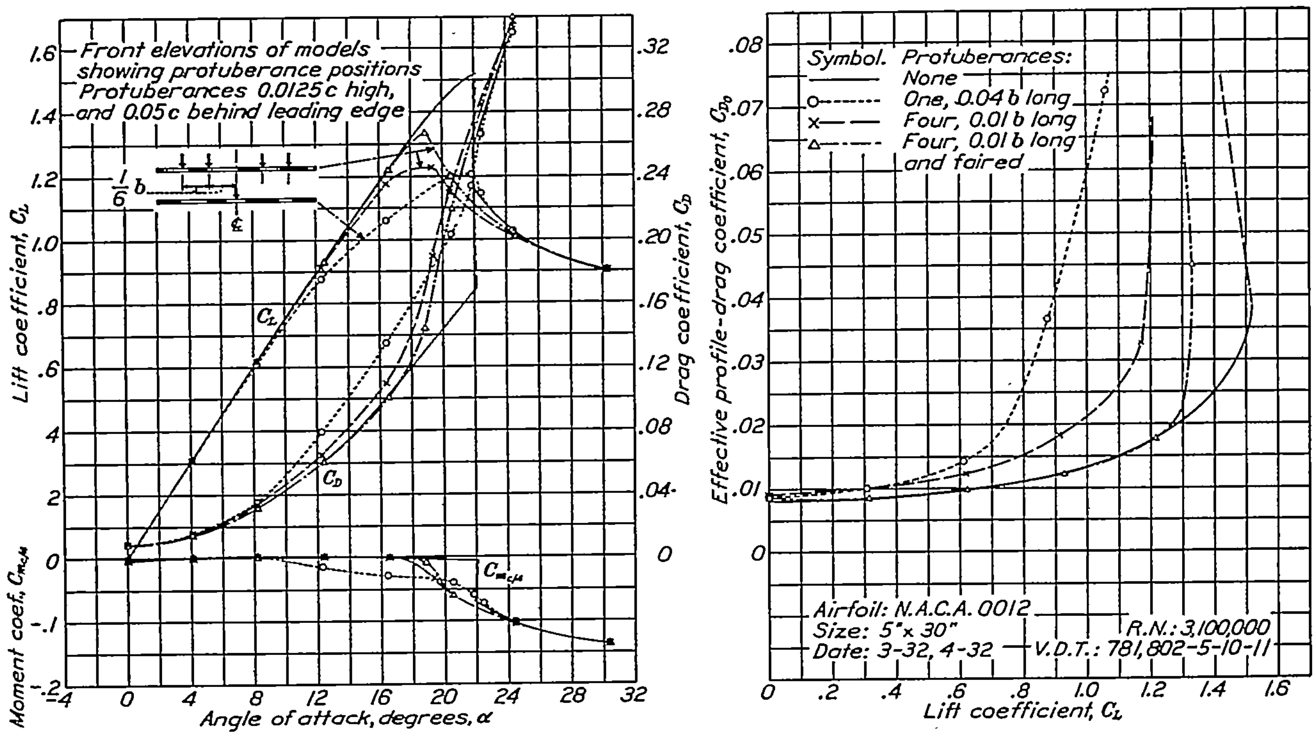

FIGURE 8.—The characteristics of an airfoil with various protuberance arrangements having same total length on upper surface

protuberance on maximum lift was practically eliminated by a simple fairing unless the protuberance was very near the leading edge. In all probability, therefore, fairings over short-span protuberances from positions on the wing near or behind the front-spar position would also eliminate any adverse effects on the maximum lift coefficient.

The applicability of the results to a practical instance of a wing with protuberances was investigated by testing an airfoil having the N. A. C. A. 4412 section with protuberances simulating lift or landing-wire fittings. (Fig. 2.) The results of these tests are presented in Figure 9. They indicate that within the usual flying range of lift coefficients, the protuberances produce no marked loss of lift and therefore no marked induced interference, although at very high lifts the inner-bay fittings do show an effect on the lift. The drag curve then shows a definite interference-drag effect. The effect of protuberances on the drag of a wing, from the practical designer's standpoint, is of greatest importance in the high-speed range of lift coefficients where the induced interference effects may be neglected. In this range, the drag due to the fittings would be approximated as follows: The increase in profile drag due to a protuberance of equivalent height, and at the same position along the chord as the fittings (0.15*c* behind the leading edge), is taken from the section characteristics of reference 1. If the equivalent height of the fitting is taken as 0.0125*c* (the average height is 0.0124*c*) and a value of the lift coefficient of 0.2 is assumed, the increase in profile-drag coefficient is found to be 0.0366. Then if the fittings are considered as occupying the portions of the span between the extremities of each projection, the portion of the span occupied by the two outer-bay fittings is 0.019*b*, and by the outer-bay and inner-bay fittings is 0.056*b*. Then applying the conclusion that the effect of short-span protuberances at low lifts is proportional to the total length of the protuberances, the increase in drag coefficient resulting from the two outer-bay protuberances is found to be 0.0007, and for the outer and inner-bay protuberances, 0.0020. The agreement between these predicted drag increases and those shown by the test results in Figure 9, 0.0008 and 0.0020, respectively, is good.

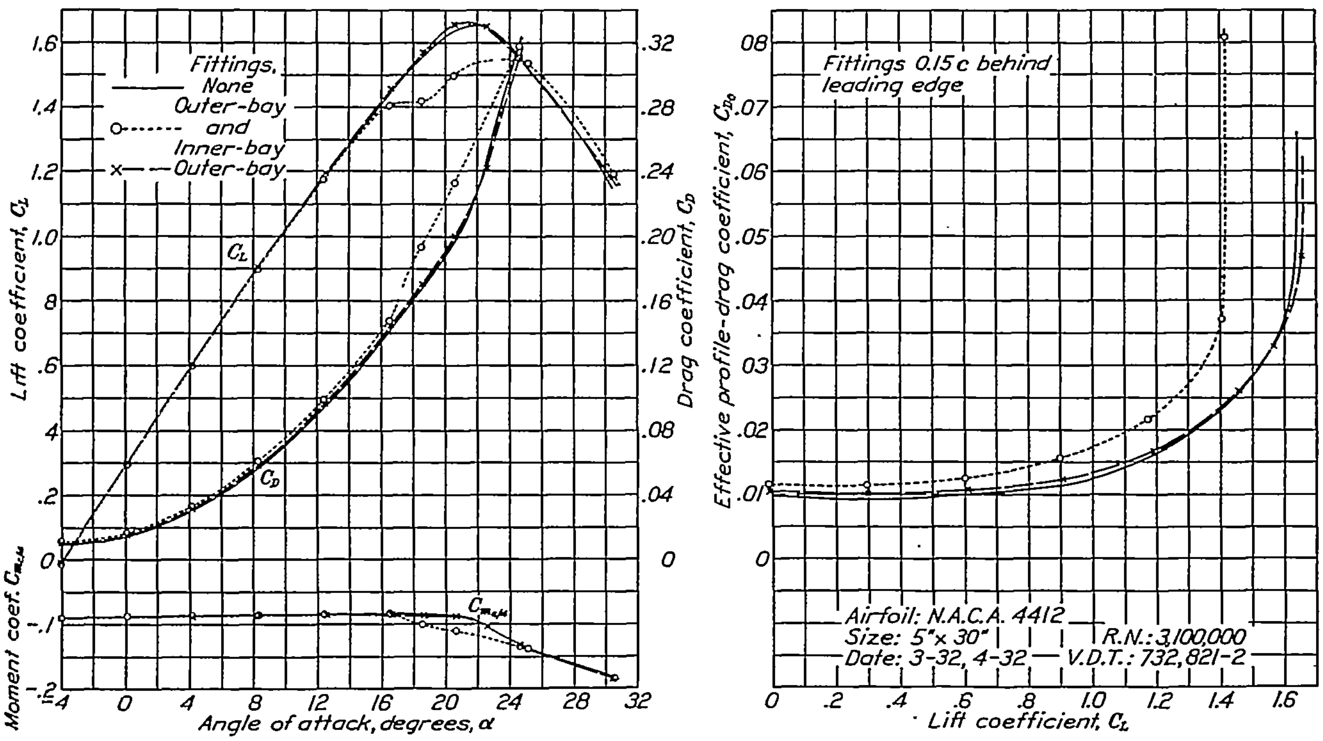

FIGURE 9.—N. A. C. A. 4412 airfoil with various fitting arrangements on upper surface

CONCLUSIONS

1. At low values of the lift coefficient corresponding to the high-speed flight condition, the effect on drag of partial-span protuberances is approximately proportional to their total length. This conclusion, however, may not apply to a large number of very small protuberances, such as rivet heads, on an airplane wing. Full-scale tests should be made to investigate the effects of a multiplicity of small protuberances.

2. At higher values of the lift coefficient induced interference effects may become important if the protuberance is of the type that alters the airfoil section lift. Under these conditions short-span protuberances may produce disproportionately large effects, which for rectangular wings are greatest when the disturbing protuberances are near the midspan position.

3. Small protuberances near the midspan position may produce serious adverse effects on the maximum lift coefficient.

4. A simple fairing over a small protuberance practically eliminates its adverse effects.

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS,
LANGLEY FIELD, VA., *October 24, 1932.*

REFERENCES

1. Jacobs, Eastman N.: Airfoil Section Characteristics as Affected by Protuberances. T. R. No. 446. N. A. C. A., 1932.
2. Abbott, Ira H.: The Drag of Two Streamlined Bodies as Affected by Protuberances and Appendages. T. R. No. 451, N. A. C. A., 1932.
3. Jacobs, Eastman N., and Abbott, Ira H.: The N. A. C. A. Variable-Density Wind Tunnel. T. R. No. 416, N. A. C. A., 1932.
4 Glauert, H.: The Elements of Aerofoil and Airscrew Theory. Cambridge University Press (London), 1926.