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THE EFFECT OF SURFACE IRREGULARITIES ON WING DRAG

III - ROUGHNESS

By Manley J. Hood
Langley Memorial Aeronautical Laboratory

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SUMMARY

Tests have been made in the N.A.C.A. 8-foot high-speed wind tunnel of the drag caused by roughness on the surface of an airfoil of N.A.C.A. 23012 section and 5-foot chord. The tests were made at speeds from 80 to 500 miles per hour at lift coefficients from 0 to 0.30.

For conditions corresponding to high-speed flight, the increase in the drag was 10 percent of the profile drag of the smooth airfoil for the roughness produced by spray painting and 63 percent for the roughness produced by 0.0037-inch carborundum grains. About one-half the drag increase was caused by the roughness on the forward one-fourth of the airfoil. Sandpapering the painted surface with No. 400 sandpaper made it sufficiently smooth that the drag was no greater than when the surface was polished. In the lower part of the range investigated the drag due to roughness increased rapidly with Reynolds Number.

INTRODUCTION

The form drag of airplanes has been reduced so much by improvements in streamlining that skin-friction drag often constitutes a major portion of the total drag. It is therefore important that skin friction be reduced as much as possible. One method of reducing skin friction is to eliminate irregularities, such as rivet heads and roughness, from surfaces exposed to air flow.

Previous tests have shown that rivet heads (reference 1), certain arbitrary protuberances (references 2 and 3), and roughness (references 4 and 5) greatly increase wing drag.

Tests have been made in the N.A.C.A. 8-foot high-speed wind tunnel to provide more complete data for the effect on wing drag of various surface irregularities common to airplane wings. The surface irregularities investigated included rivet heads and spot welds (reference 6), lap joints (reference 7), manufacturing discrepancies (reference 8), and surface roughness, the subject of the present paper.

Most of the surface-roughness tests were made with an N.A.C.A. 23012 airfoil of 5-foot chord. The effect of the following surface finishes on the drag of this airfoil was determined:

0.0037-inch carborundum grains.

0.0013-inch carborundum grains.

0.0005-inch carborundum grains.

Sprayed paint.

Sandpapered paint.

Polished paint.

The drag was determined with the entire surface covered with each of these finishes and also with various percentages of the surface, starting from the leading edge, polished. With the surface of the airfoil in the desired condition, the drag was determined at lift coefficients from 0 to 0.30 and air speeds from 80 to 500 miles per hour, corresponding to Reynolds Numbers from 3,000,000 to 18,500,000.

Supplementary tests to investigate scale effect were made using an N.A.C.A. 23012 airfoil of 2-foot chord.

APPARATUS

The tests were conducted in the N.A.C.A. 8-foot high-speed wind tunnel. The turbulence of the air flow in the closed circular test section of this wind tunnel is so small that sphere tests have shown virtually the same critical Reynolds Number in the tunnel as in free air (reference 9).

The airfoils used for these tests had the N.A.C.A.

23012 section (reference 10) and had active spans of 6 feet. Figure 1 shows the 5-foot airfoil mounted in the wind tunnel. Detailed descriptions of the airfoils and their arrangement in the wind tunnel are given in reference 6.

Photomicrographs of samples of the different surface finishes, all to the same magnification, are shown in figure 2. The carborundum-covered surfaces were produced by spraying carborundum grains mixed with thin shellac onto the polished airfoils. The common designations of the grain sizes are:

Average grain size, k(in.)	Carborundum Company's designation
0.0037	180
.0013	FF
.0005	800-RA

From figure 2 it is apparent that the 0.0005-inch grains were piled on top of each other in such a manner that the degree of roughness was not equivalent to the grain size, as was the case with the larger grains. The photomicrographs also indicate that the shellac used to hold the grains was sufficiently thin that the effective size and shape of the grains were not appreciably changed. The sizes of the grains were determined from measurements made with a microscope and from measurements of the photomicrographs. The density (spacing) of the grains varied somewhat over the airfoils but the photomicrographs represent average conditions. The spray-painted surface was produced by spraying a lacquer-base primer-surfacer onto the airfoil, probably a little rougher than is common practice. The sandpapering was done with No. 400 sandpaper lubricated with water. No attempt was made to limit the sandpapering strokes to any one direction but chordwise strokes predominated. The surface was polished by rubbing with a polish of the type used in polishing automobiles, waxing, and rubbing with a soft cloth. The polished surface was comparable with that of a new automobile.

METHODS

The lift, the drag, and the pitching moment of the airfoils with each surface condition were determined at $-1.25°$, $-0.15°$, and $0.95°$ angle of attack, corresponding to lift coefficients of approximately 0, 0.15, and 0.30, respectively. The tests at lift coefficients of 0.15 and 0.30 were made at speeds varying from 80 to 370 and from 80 to 270 miles per hour, respectively, the upper limit in each case producing a wing loading of approximately 50 pounds per square foot. For the tests at zero lift the speed was varied from 80 to about 500 miles per hour, at which speed compressibility effects were so large that the drag coefficient was increasing rapidly as speed was increased.

Each type of roughness was applied to the entire surface of the airfoils at first and then removed in steps starting from the leading edge and working rearward as the tests proceeded. After the roughness had been removed, the surface was polished.

At the high speeds attained in the N.A.C.A. 8-foot high-speed wind tunnel the dynamic pressure $(q = \frac{1}{2} \rho V^2)$ used in computing force and moment coefficients departs considerably from the impact pressure as shown by a pitot-static tube. The method by which the dynamic pressure, air speed, and Reynolds Number in the test section are computed is presented in reference 6.

RESULTS

The tunnel effects on the characteristics of airfoils that are as large, relative to the tunnel diameter, as the two tested are considerable and, since these effects have not yet been completely determined for this wind tunnel, no corrections have been applied. None of the results are, therefore, presented as absolute drag coefficients. The results are, instead, presented in terms of increases in drag coefficient, which should be little altered by tunnel effects.

According to the subsequent discussion, the results of these tests should be applied on the usual Reynolds Number basis but, for expediency, the drag results are shown in terms of Mach number M, (the ratio of the air speed to the speed of sound in the air) because, at the higher speeds employed in the tests, compressibility effects cause drag coefficients to vary so rapidly with M that comparisons are preferably made at equal values of this parameter. The air speeds quoted are not actual test air speeds at the reduced densities existing in the wind tunnel but are speeds that, at sea level in a standard atmosphere, would produce values of M equal to the test values. The Reynolds Numbers are the averages of the actual Reynolds Numbers for the various test runs. None of the Reynolds Numbers departs from those averages enough to affect the results appreciably.

Increases in the drag coefficient C_D of the 5-foot airfoil caused by 0.0037-inch, 0.0013-inch, and 0.0005-inch grains and by spray painting are shown in figure 3. The increases were derived by deducting the drag coefficients of the polished airfoil from the coefficients of the airfoil with the various degrees of roughness at equal Mach numbers. The drag of the sandpapered airfoil was the same as the drag of the polished airfoil within the limits of measurement. In order to aid in visualizing the magnitude of the drag increases, the approximate percentage increases at one Reynolds Number, using full-scale wind-tunnel results from reference 10 extrapolated and corrected for tip effects as base values, are shown for a few representative points.

Figure 4 shows the effect of removing the roughness and polishing various percentages of the surface starting at the leading edge. This figure applies directly to a speed of 230 miles per hour and a lift coefficient of 0.15, but curves showing the same phenomenon at other speeds and lift coefficients would be quite similar.

None of the degrees of roughness tested had any appreciable effect on lift or pitching moment within the range of the tests, which included the usual high-speed and cruising range of lift coefficients.

PRECISION

Only increases in drag coefficient are reported herein. For the reasons discussed in reference 6, random errors in these increases probably do not exceed ±0.0001, corresponding to ±1.4 percent of the drag of the smooth airfoil, except at speeds below 100 and above 400 miles per hour, where the errors may be twice this value. Systematic errors are thought to be small enough so that their effect on the results is not important.

DISCUSSION

From figure 3 it is evident that even a small degree of roughness increases the wing drag sufficiently to have serious adverse effects on high-speed performance and economy. Even the roughness due to spray painting may increase the drag 10 to 14 percent in the high-speed and cruising range. Except at the lowest speeds, 0.0013-inch roughness increases the drag considerably more than 3/32-inch brazier-head rivets (reference 6).

In the range of these tests, the drag increases caused by surface roughness vary considerably with scale (fig. 3). At the lower speeds the drag due to roughness decreases rapidly as speed is reduced and the curves indicate that, for each degree of roughness, there is a speed or Reynolds Number below which that roughness has no effect on drag. Conversely, it is indicated that for every speed or Reynolds Number there is a limiting "permissible roughness," which will cause no increase in drag. The existence of such a permissible roughness has been shown by other tests (references 11 and 12). Estimating permissible roughness from the results herein reported involves questionable extrapolations but, nevertheless, the results do indicate about the same order of magnitude of permissible roughness as is tabulated for a flat plate with turbulent boundary layer in reference 11; even though in the case of the airfoil the conditions are different in that part of the boundary layer is laminar, the air speed varies over the surface, and the pressure gradients are large.

Because of the large adverse scale effect on the drag of rough surfaces, it is essential that experimental investigations of the effects of surface roughness be made at large scale. Degrees of roughness large enough to have serious effects under flight conditions may have no effect whatsoever under the conditions of small-scale tests.

The variation of drag with speed (fig. 3) above about 300 miles per hour cannot be attributed entirely to scale effect because compressibility effects may be large enough to predominate at these speeds. At lower speeds, however, compressibility effects are negligible so the variation in drag can be attributed entirely to scale effect and the results may be applied on the usual basis of Reynolds Number.

The effects of roughness on airplane wings can be estimated only approximately from the results of these tests because the effects depend on grain shape and grain spacing as well as grain size. The variation of drag with grain density is so great (reference 13) that the results of tests using similar grains may not agree when the usual methods of applying the roughness are used.

According to Reynolds' principles of similitude, the drag coefficients of similar wings having different chords but acting at equal Reynolds Numbers would be equally increased by roughnesses of equal size and arrangement <u>with respect to wing chord</u>. The tests made of the 2-foot and 5-foot airfoils with equivalent degrees of roughness showed poor agreement at equal Reynolds Numbers. It was difficult, however, to obtain equal grain densities with the method of application employed and, as previously mentioned, the drag of rough surfaces is quite sensitive to changes in grain density. Tests in which Reynolds Number and speed were independently varied have been made in the British compressed-air tunnel (reference 14) and permit a comparison of drag values by the use of only one model. These tests show, as expected, that Reynolds' principles apply to rough surfaces. In the application of the results herein reported, the grain size and arrangement should therefore be considered in terms of wing chord. For this reason grain size is shown on the figures in terms of wing chord as c/k as well as in inches.

Figure 4 indicates that, with the entire surface of the airfoil roughened, about one-half the total drag increase is due to the roughness on the forward 25 percent. In preliminary tests in the N.A.C.A. 8-foot high-speed wind tunnel, it was found that a slight roughness on the leading edge of an airfoil, caused by erosion due to running the tunnel with dirt in the air stream, increased the minimum drag of the airfoil 10 percent. It is obvious that roughness on the forward part of a wing increases the drag more than the roughness farther back and that it is, therefore, of the greatest importance to keep the forward part of wings smooth.

CONCLUSIONS

The principal conclusions derived from the results of the tests can be summarized as follows:

1. Surface roughness increased the drag of the 5-foot-chord airfoil by the following amounts at 230 miles per hour and at a lift coefficient of 0.15:

	Percent
0.0037-inch grains - - - -	63
0.0013-inch grains - - -	44
0.0005-inch grains - - - -	7
Sprayed paint - - - - - - - -	14

2. Sandpapering the spray-painted surface with No. 400 sandpaper made it aerodynamically smooth so that the drag was as low as that of a highly polished surface.

3. The drag due to the degrees of roughness tested decreased rapidly as speed was decreased below about 200 miles per hour.

4. Polishing the front 25 percent of the airfoil reduced the drag increase caused by roughness about 50 percent.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., December 1, 1937.

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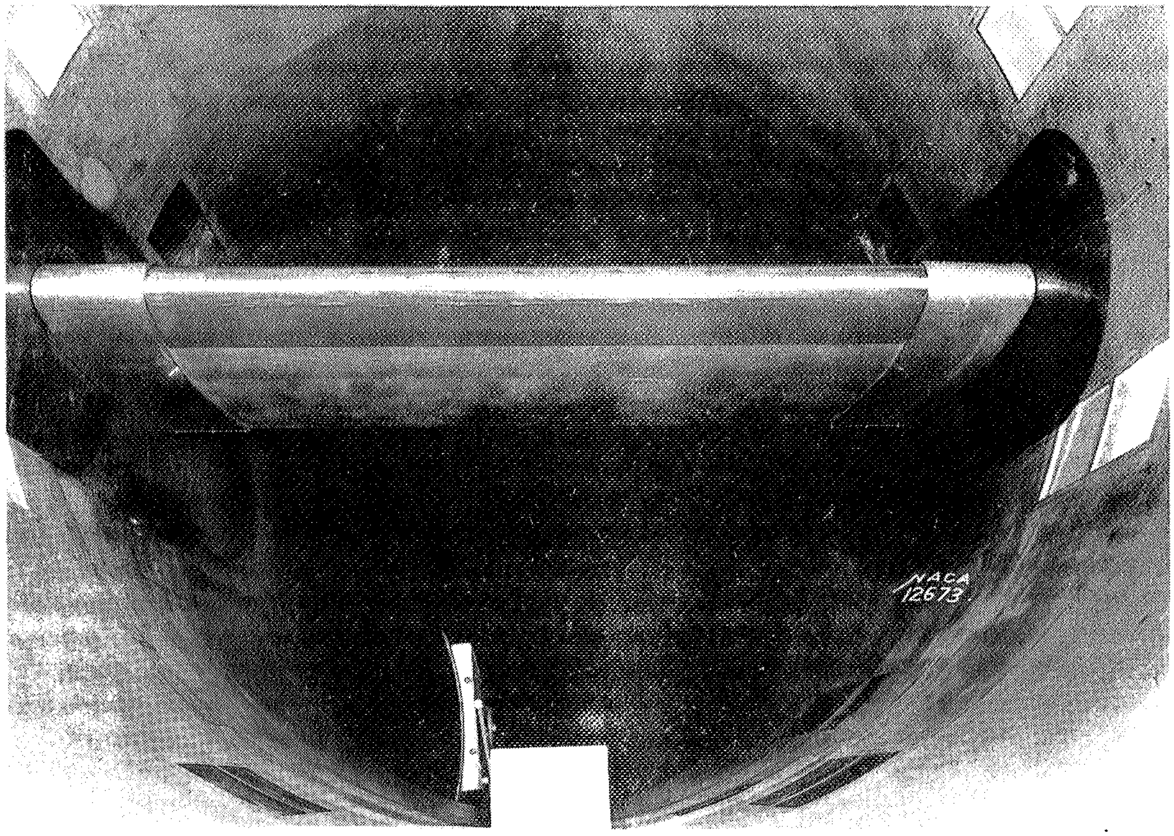
FIGURE LEGENDS

Figure 1.- Airfoil of 5-foot chord with forward 20 percent polished, mounted in wind tunnel.

Figure 2.- Photomicrographs of surface roughness.

Figure 3.- Increase in drag of airfoil of 5-foot chord due to surface roughness. c, chord; k, grain size.

Figure 4.- Reduction of drag by removing roughness from forward part of airfoil. C_L, 0.15; V, 230 m.p.h.; chord, 5 ft.; average, R, 10,200,000; c, chord; k, grain size.



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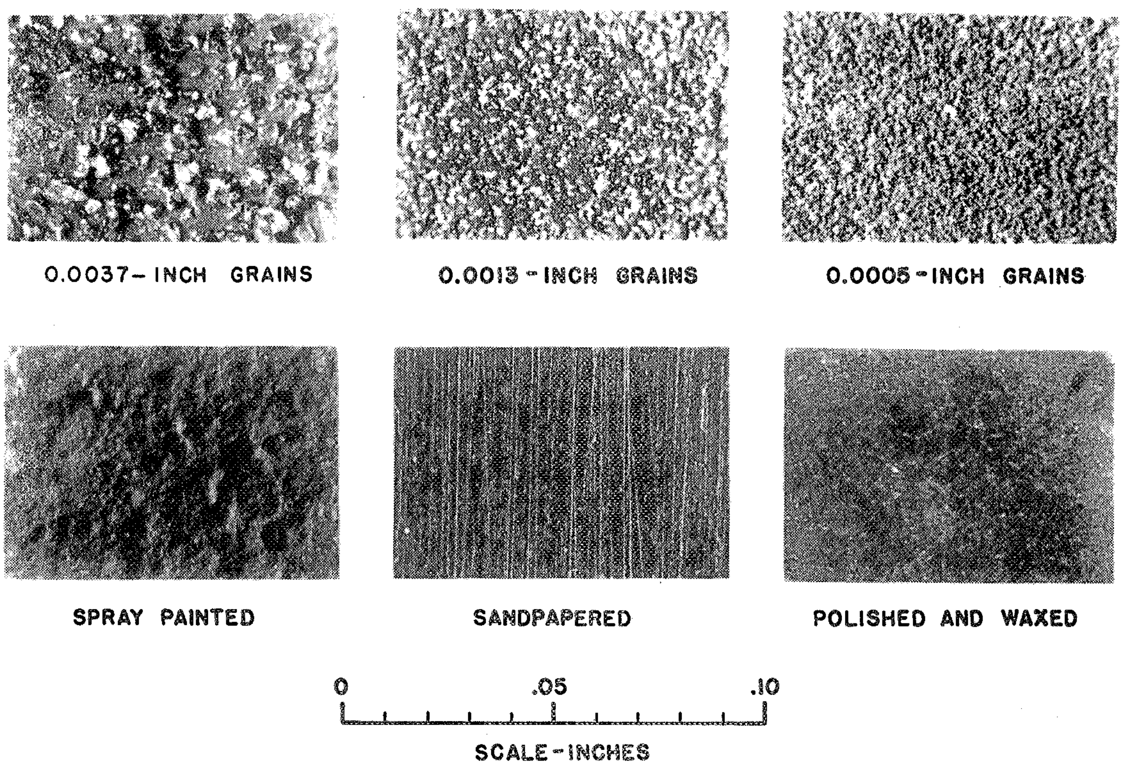

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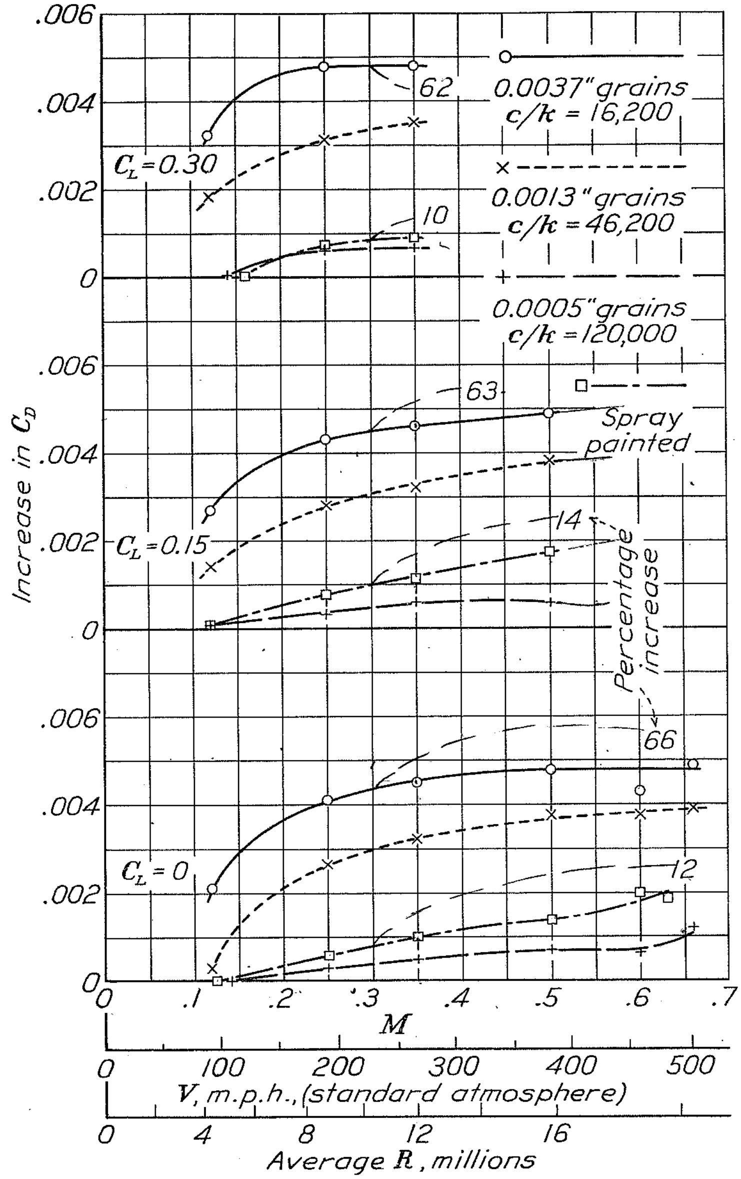

Figure 3

Figure 4