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Technical Notes

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Aerodynamic Lift at Reynolds Numbers Below 7 × 10⁴

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Introduction

THESE wind tunnel tests were made to evaluate the lift and drag of rectangular planform wings at a Reynolds number lower than that attained by Schmitz[1] ($Re \geq 4.2 \times 10^4$). The tunnel-empty turbulence level was 0.02%, so tests could be made at a much lower turbulence level than that available to Schmitz,[1] who measured a turbulence factor of 1.06 with the relatively insensitive sphere test. To measure the aerodynamic forces at Reynolds numbers as low as 2×10^4, a sensitive two-component beam balance was built to have an accuracy of ±0.01 g (9.8×10^{-5} N). This was ten times more sensitive than the balance used by Schmitz.[1]

The lift and drag of thin flat and cambered plates were compared with a wing having a NACA 0012 profile. The final data presented are all for aspect ratio 6 rectangular planform wings having a chord of 31 mm. The wings were hung vertically, connected to the balance above the wind tunnel ceiling by a 3-mm-diam rod that was soldered to the midchord of the upper wing tip, which was approximately 8 chord lengths below the ceiling. The lower wing tip was approximately 12 chord lengths above the wind tunnel floor. The square test section had 0.813-m walls and a length of 3.66 m. The dynamic pressure was measured by a standard Betz micromanometer, accurate to 0.01 mm of water. The lowest test velocity was 10 m/s, corresponding to approximately 6 mm of water and a tunnel-empty turbulence level of 0.02%.

Discussion of Wind Tunnel Tests

At a Reynolds number of 2.07×10^4, Fig. 1 shows that a sharp leading edge, rather than a sharp trailing edge, governs the aerodynamic lift at low Reynolds numbers. By reversing the NACA 0012 wing so that its sharp trailing edge faces the flow, its lift coefficient at stall is increased from 0.455 to 0.67; even more significant, the initial lift-curve slope is increased 56%, from 0.041 to 0.064. However, all of the thin plates with a sharp leading edge had a greater initial lift-curve slope. The steepest lift-curve slope of 0.098 was attained by a 1.3% thin plate with a 5% circular arc camber, as shown in Fig. 1. It was also found that for aspect ratios greater than 5, this profile produced a continual increase in lift for $\Delta\alpha > 14$ deg, after local stall at $C_L \approx 1$, as shown in Fig. 1. This unusual increase in lift after stall was clearly a two-dimensional effect, similar to that of a turbine blade, since it did not occur for smaller aspect ratios.

As shown in Figs. 1 and 2, the thin wedge (1% leading edge and 4% trailing edge) had a higher lift coefficient at stall and a greater

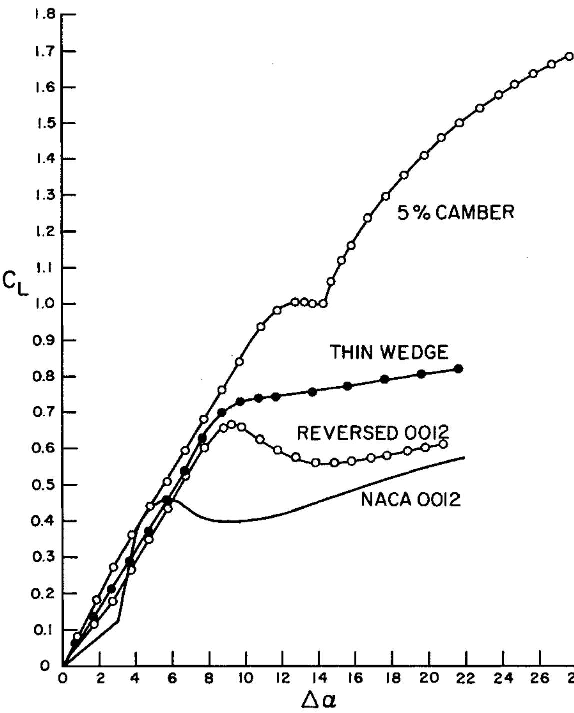

Fig. 1 Variation of lift coefficient (C_L) with angle of attack from zero lift ($\Delta\alpha$) for aspect ratio 6 rectangular planform wings at $Re = 2.07 \times 10^4$. The 5% camber is a thin (1.3%) plate bent to a circular arc. The thin wedge has 1% leading edge and 4% trailing edge thickness.

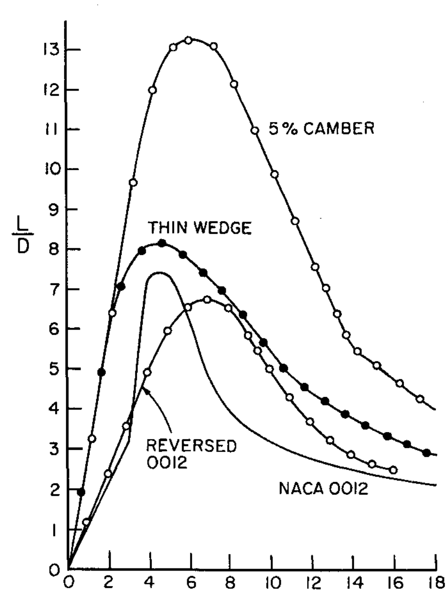

Fig. 2 Lift-drag ratios (L/D) corresponding to the wing-lift data shown in Fig. 1.

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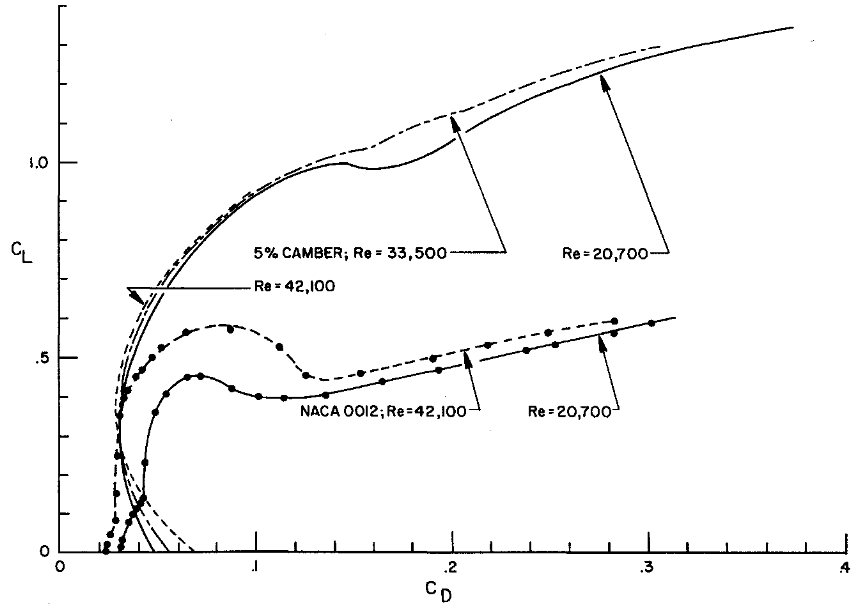

Fig. 3 Lift-drag polars for the NACA 0012 and the 5% camber rectangular planform wings (aspect ratio 6) in low turbulence flow at various Reynolds numbers.

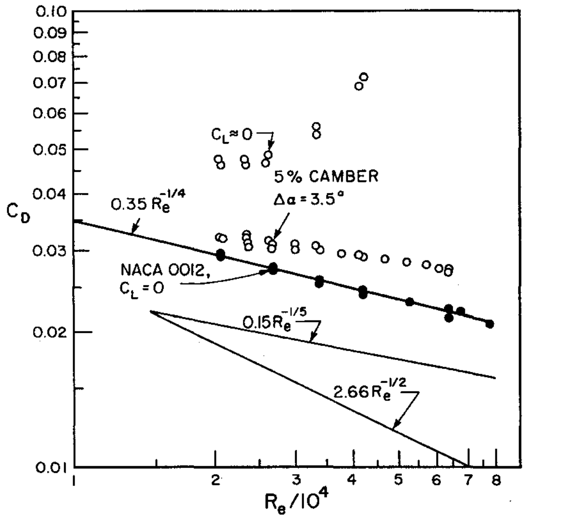

Fig. 4 Variation of drag coefficient (C_D) with Reynolds number for the wings in Fig. 3. The Blasius equation 2.66 $Re^{-1/2}$ is for laminar skin friction drag of a zero-thickness flat plate. The equation 0.15 $Re^{-1/5}$ is the corresponding approximation for turbulent skin friction.

lift-drag ratio than the NACA 0012 profile. This thin wedge developed the same lift as a thin 1% flat plate, with only 1.2% greater drag, again indicating that at low Reynolds number the aerodynamic lift is not as dependent on a sharp trailing edge as it is at higher Reynolds number.

At $Re = 2.07 \times 10^4$, the highest lift-drag ratio of 13.3 was developed by the 5% circular arc cambered plate, as shown in Fig. 2. Its lift-drag ratio increased with increasing Reynolds number, whereas the thin flat plates were shown to be relatively unaffected for $2 \times 10^4 < Re < 7 \times 10^4$. However, the NACA 0012 profile had very large increases in its lift-drag ratio and its initial lift-curve slope $(C_L/\alpha)_0$, produced by an increase in either Reynolds number or the turbulence level. For example, an increase of the tunnel-empty turbulence level from 0.02 to 0.10% increased the lift-drag ratio 25%, from 7.45 to 9.31, at $Re = 2.07 \times 10^4$. An increase of Reynolds number to 4.21×10^4 increased $(C_L/\alpha)_0$ from 0.041 to 0.061 and increased the lift-drag ratio 61% from 7.45 to 12, as measured in Fig. 3 by $(dC_D/dC_L) = \frac{1}{12}$. By comparison, the same increase in Reynolds number to 4.21×10^4 increased the 5% camber's lift-drag ratio only 13.5% from 13.3 to 15.1, as measured by $(dC_D/dC_L) = 0.0662$ in Fig. 3. Another effect produced by increasing the Reynolds number on the 5% camber was the elimination of the small local stall at $C_L \approx 1$ when $\Delta\alpha = 13$ deg, as shown in Fig. 1 for $Re = 2.07 \times 10^4$. This local stall at $C_L \approx 1$ was eliminated by increasing Reynolds number from 2.07×10^4 to 3.35×10^4. This is also indicated in Fig. 3 by the continual increase in C_L when $Re = 3.35 \times 10^4$. However, further tests at $Re = 2.07 \times 10^4$ showed that this continual increase for $C_L > 1$ was produced only by aspect ratios greater than 5 and by cambers less than 6.4%.

The sharp break in the lift-curve slope (C_L/α) of the NACA 0012 profile, seen at $C_L = 0.12$ in Fig. 1, was eliminated by increasing the Reynolds number because $(C_L/\alpha)_0$ continually increased with Reynolds number until the break in (C_L/α) finally vanished at $Re = 7 \times 10^4$ when $(C_L/\alpha)_0 = 0.08$.

Unlike the NACA 0012, the drag coefficient at zero lift for the 5% cambered plate actually increased with Reynolds number, as shown in Figs. 3 and 4. However, its minimum drag coefficient, which occurs in the range shown in Fig. 3 as $0.3 < C_L < 0.4$, decreases with Reynolds number but at a slower rate than that for the NACA 0012. The data shown in Fig. 4 for the 5% cambered plate correspond to $C_L \approx 0.35$ and closely approximates the minimum C_D, which is everywhere less than $C_L^2/6\pi$ greater than the corresponding C_D for the NACA 0012 at $C_L = 0$.

Conclusions

Schmitz showed that typical 12% thick airfoils with camber were not as satisfactory, when $Re < 8.4 \times 10^4$, as a thin (2.9%) plate bent to a 6% camber, with maximum camber at 40% chord. This 6% cambered plate developed more lift at all angles of attack when $Re \leq 8.4 \times 10^4$.

The present tests showed that the symmetrical NACA 0012 profile was satisfactory, for $Re > 7 \times 10^4$. However, for $Re < 7 \times 10^4$ a thin (1.3%) plate bent to a 5% circular arc camber had a greater lift-drag ratio and developed more lift at all angles of attack. This 5% cambered plate also produced an increasing lift at high angles of attack, accompanied by surprisingly high lift-drag ratios.

Reference

[1]Schmitz, F. W., "Aerodynamics of the Model Airplane," Redstone Arsenal Translation, N70-39001, RSIC-721, Redstone Arsenal, AL, Nov. 1967.