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5.2 Drag Reduction Through Higher Wing Loading

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Introduction

The wing typically accounts for almost half of the wetted area of today's production light airplanes and approximately one-third of the total zero-lift or parasite drag. Thus the wing should be a primary focal point of any attempts to reduce drag of light aircraft with the most obvious configuration change being a reduction in wing area. Other possibilities involve changes in thickness, planform, and airfoil section.

This paper will briefly discuss the effects of reducing wing area of typical light airplanes, constraints involved, and related configuration changes which may be necessary.

Constraints and Benefits

The wing area of current light airplanes is determined primarily by stall speed and/or climb performance requirements. Table I summarizes the resulting wing loading for a representative spectrum of single-engine airplanes. The maximum lift coefficient with full flaps, a constraint on wing size, is also listed. Note that wing loading (at maximum gross weight) ranges between about 10 and 20 psf, with most 4-place models averaging between 13 and 17. Maximum lift coefficient with full flaps ranges from 1.49 to 2.15.

Clearly if $C_{L_{max}}$ can be increased, a corresponding decrease in wing area can be permitted with no change in stall speed. If total drag is not increased at climb speed, the change in wing area will not adversely affect climb performance either and cruise drag will be reduced.

Though not related to drag, it is worthy of comment that the range of wing loading in Table I tends to produce a rather uncomfortable ride in turbulent air, as every light-plane pilot is well aware. The only way to reduce this gust sensitivity is to increase wing loading.

Typically, wing loading tends to increase as performance (cruise speed) increases. This is particularly evident in Table II which presents data for twin-engine aircraft. But gust response is proportional to the ratio of calibrated cruise speed to wing loading ($V_c/(W/S)$) and thus improvements in ride due to higher wing loading are partially, if not completely, offset by higher cruise speed.

It is also evident in Table II that even though wing loading is higher than for single-engine aircraft, it is translated directly into higher stall speeds. Twin-engine high lift systems produce virtually the same $C_{L_{max}}$ as shown in Table I for single-engine airplanes. Thus there appears to be an equal potential for reduction in wing area of single- and twin-engine aircraft by employing improved high lift systems. How to achieve higher $C_{L_{max}}$ for light aircraft is discussed later.

But assuming for a moment that improvements in $C_{L_{max}}$ are available, making higher wing loading possible for a given airplane or class of airplanes, it is important to consider how the wing area should be reduced. The easiest and most tempting way is by reducing span. Not only does this leave the inboard wing structure, mechanisms, and wing-body junction unchanged, but it reduces wing bending moments making possible a lighter wing. But reducing the span increases the span loading, thus reductions in parasite drag through a decrease in wing area are countered by an increase in induced drag.

On the other hand, reducing wing area by a decrease in wing chord decreases parasite drag almost in direct proportion to chord decrease, and if span remains constant there is virtually no change in induced drag. From an aerodynamic point of view this is most desirable, but it introduces possible structural and weight problems because aspect ratio increases while spar thickness and internal volume decrease if the same airfoil section is used.

To understand the potential and the constraints of drag reduction through wing area reduction, consider the following simplified analysis.

Assuming that the parasite drag coefficient and span efficiency factor remain unchanged, the parasite drag is directly proportional to wing area and induced drag is inversely proportional to the square of the span. Then the wing drag at any given flight condition may be written as

$$D_W = D_{P_R} \frac{b\,c}{b_R c_R} + (D_{W_R} - D_{P_R}) \frac{b_R^2}{b^2} \tag{1}$$

where D_{P_R} is the reference wing profile drag; D_{W_R} is the total drag of the reference wing. The span and chord are denoted as b and c with a subscript R indicating reference values. For simplicity an untapered wing is assumed.

Normalizing equation (1) with respect to the original reference wing drag, D_{W_R}, gives

$$D = \frac{D_W}{D_{W_R}} = P \frac{bc}{b_R c_R} + (1 - P) \frac{b_R^2}{b^2} \tag{2}$$

where $P = \frac{D_{P_R}}{D_{W_R}}$, the ratio of parasite drag to total drag.

If only the wing chord is reduced, then the change in total normalized wing drag is

$$dD = P \frac{dc}{c_R} \qquad (3)$$

Thus the percent reduction in total wing drag is equal to the percent reduction in chord length times the original ratio of parasite to total wing drag. Clearly, the benefits of wing area reduction increase with air speed.

Consider a typical light airplane with the following characteristics:

Gross weight = 2800 pounds

Aspect ratio = 7.4

Wing area = 174 ft^2

Drag coefficient of body and empennage, $C_{D_{o_{BVH}}} = 0.017$

Wing parasite drag coefficient, $C_{D_{o_W}} = 0.009$

Airplane efficiency factor, e = 0.75

Cruise altitude = 8,000 ft

If only the chord is reduced, then,as shown in Reference 1, the resulting normalized total airplane drag, D_T, is shown in Figure 1. Although substantial drag reductions are possible, constraints are imposed by the requirement to cruise at a reasonably low lift coefficient and stall margin, and to keep stall speeds low enough for good takeoff and landing performance. Even with these constraints, however, significant reductions in wing area, cruise drag, and gust response are possible for today's general aviation fleet.

To analyze the effect of reducing span while holding chord constant, differentiate equation (2) with respect to span b. Then

$$dD = \frac{1}{b_R} \left[P - 2(1 - P) \frac{b_R^3}{b^3} \right] db \qquad (4)$$

For a decrease in span to result in a net decrease in drag the condition $\frac{dD}{db} > 0$ for $b = b_R$ must be satisfied.

This is true only if

$$P > \frac{2}{3} \qquad (5)$$

In other words, a reduction in drag by reducing span can be achieved only if parasite drag is more than double the induced drag at the flight condition in question. While this may be satisfied during high speed cruise, it is rarely true during a climb. And when $P < 2/3$ a reduction in span increases induced drag more than it decreases parasite drag. For a tapered wing, P must be even larger than the value given in (5) to achieve drag reduction.

The limit to favorable span reduction is found by solving for the value of $\frac{b}{b_R}$ which yields $\frac{dD}{db} = 0$, assuming $P > 2/3$. Again from equation (4) it is easily shown that

$$\frac{dD}{db} = 0$$

when $$\left(\frac{b}{b_R}\right)^3 = \frac{2(1 - P)}{P} \qquad (6)$$

Equation (6), plotted in Figure 2, establishes the boundary of favorable span reduction of a constant chord wing as a function of the reference wing parasite drag ratio, P.

Technical Developments

It is clear that wing area reduction can be achieved only if corresponding increases in $C_{L_{max}}$ can be designed into light airplanes in a practical manner. Several recent developments indicate that this is a very real possibility.

One promising development is a new family of general aviation airfoil sections. Two members of the family, the GA(W)-1 and GA(W)-2, have been defined at this time. As shown in Reference 2, the characteristics of these airfoils are:

- high $C_{L_{max}}$ compared to conventional airfoils (see Figure 3)
- gentle stall characteristics
- fairly thick section. The GA(W)-1 is 17% thick. This helps to maintain spar depth with reduced chord lengths.
- very little increase in C_{D_o} at climb lift coefficients (see Figure 4). This combined with decreased wing area offers the potential of significant increase in single-engine climb performance of twins.

Another interesting development is the recognition of the efficiency of spoilers for roll control on light airplanes. Among other features, spoilers permit the use of full-span, or at least increased span, flaps. This will increase $C_{L_{max}}$ with no change in airfoil or flap geometry. Several light airplanes are now using this concept: the advanced technology light twin (ATLIT), a modified Seneca; the Redhawk, a modified

Cessna Cardinal; the RSTOL Seneca, a modification kit developed by Robertson Aircraft Corporation; and the Mitsubishi MU-2 .

Another method of increasing $C_{L_{max}}$ is to increase the Fowler action of conventional single-slotted flaps. This can be done with very little increase in complexity or weight. Figure 5 shows the very large values of $C_{L_{max}}$ (2-D) which can be obtained with a GA(W)-1 airfoil using a 30% chord single-slotted Fowler flap.

Flight Test Results

Additional confirmation of the ability to increase $C_{L_{max}}$ through both airfoil design and flap design has been demonstrated in the Redhawk and ATLIT programs.

Table III, from Reference 3, shows maximum lift coefficients obtained on the Redhawk by using a 30% chord single-slotted Fowler flap. Note that the flap covers only 47% of the wing span.

The ATLIT, using full-span, 30% chord single-slotted flaps, and a GA(W)-1 basic airfoil, generated the high lift data shown in Table IV. Clearly, significant increases in $C_{L_{max}}$ are possible for this class of airplane.

Finally, Table V shows drag data generated during flight test of the Redhawk. The most significant result is that parasite drag was reduced 10.5% by reducing wing area, thickness, and span. This is a significant reduction, and it illustrates in flight that a reduction in wing area can be an effective and practical means of reducing drag.

References

1. Roskam, Jan, "Opportunities for Progress in General Aviation Technology," AIAA Paper No. 75-292, presented at AIAA 11th Annual Meeting and Technical Display, Washington, D. C., February 24-26, 1975.

2. McGhee, R. J., and Beasley, W. D., "Low Speed Aerodynamic Characteristics of a 17-Percent-Thick Airfoil Section Designed for General Aviation Applications," NASA TN D-7428, December 1973.

3. Kohlman, David L., "Flight Test Results for an Advanced Technology Light Airplane Wing," SAE Paper No. 740368, presented at Business Aircraft Meeting, Wichita, Kansas, April 2-5, 1974.

Table I. Wing Loading and $C_{L_{max}}$ for Typical Single-Engine Aircraft

Aircraft	W/S ~ PSF	$C_{L_{max}}$
Cessna 150	10.2	1.73
Cessna 172	13.2	2.15
Cessna 182	16.9	2.03
Cessna 210	21.7	2.01
Beech C23	16.8	1.89
Beech V35B	18.8	1.85
Grumman Tiger	17.1	1.92
Bellanca 300A	20.6	1.64
Mooney M20E	15.4	1.85
Piper PA-28-140	13.4	1.73
Piper PA-28-180	14.4	1.51
Piper PA-28-200R	15.6	1.49
Piper PA-32	19.5	1.92

Table II. Wing Loading and $C_{L_{max}}$ for Typical Twin-Engine Aircraft

Aircraft	W/S ~ PSF	$C_{L_{max}}$
Beech Baron	25.6	1.42
Beech Duke	31.8	1.64
Beech Queen Air	29.9	1.78
Cessna 310	30.7	2.02
Cessna 402	32.2	2.02
Cessna 421	35.2	1.86
Piper Seneca II	21.9	1.80
Piper Navaho PA-31-350	30.6	1.66
Piper Navaho PA-31P-425	34.1	1.93

Table III. Comparison of Stall Speeds and Maximum Lift Coefficients

Configuration	Redhawk		Cardinal	
	V_s, mph	$C_{L_{max}}$	V_s, mph	$C_{L_{max}}$
Cruise	79.6	1.40	64.7	1.35
Kruger flaps only	69.8	1.82	-	
Fowler flaps 10°	71.2	1.75	-	
Fowler flaps 10° and Kruger flaps	62.8	2.25	-	
Fowler flaps 40° (30° for Cardinal)	64.4	2.14	55.0	1.84
Fowler flaps 40° and Kruger flaps	56.0	2.83	-	

Notes:

1. Gross weight = 2500 lb
2. Redhawk c.g. location 7.2% m.a.c. (109 in.)
3. Cardinal c.g. location 19% m.a.c. (109.3 in.)

Table IV. ATLIT Preliminary Stall Data

f	V_{S_o} ~ MPH	$C_{L_{max}}$
0	76	1.81
10°	66	2.40
20°	61.5	2.77
30°	59.3	2.98
40°	59.4	2.97

Gross weight = 4200 lb

Aft c.g. location

Table V. Comparison of Drag Characteristics Determined from Flight Test

		C_{D_p}	$C_{D_p} S_w$
Cardinal	Cruise	0.0267	4.67
	Full Flaps	0.0462	8.08
Redhawk	Cruise	0.0380	4.18
	Full Fowler and Kruger Flaps	0.0788	8.67

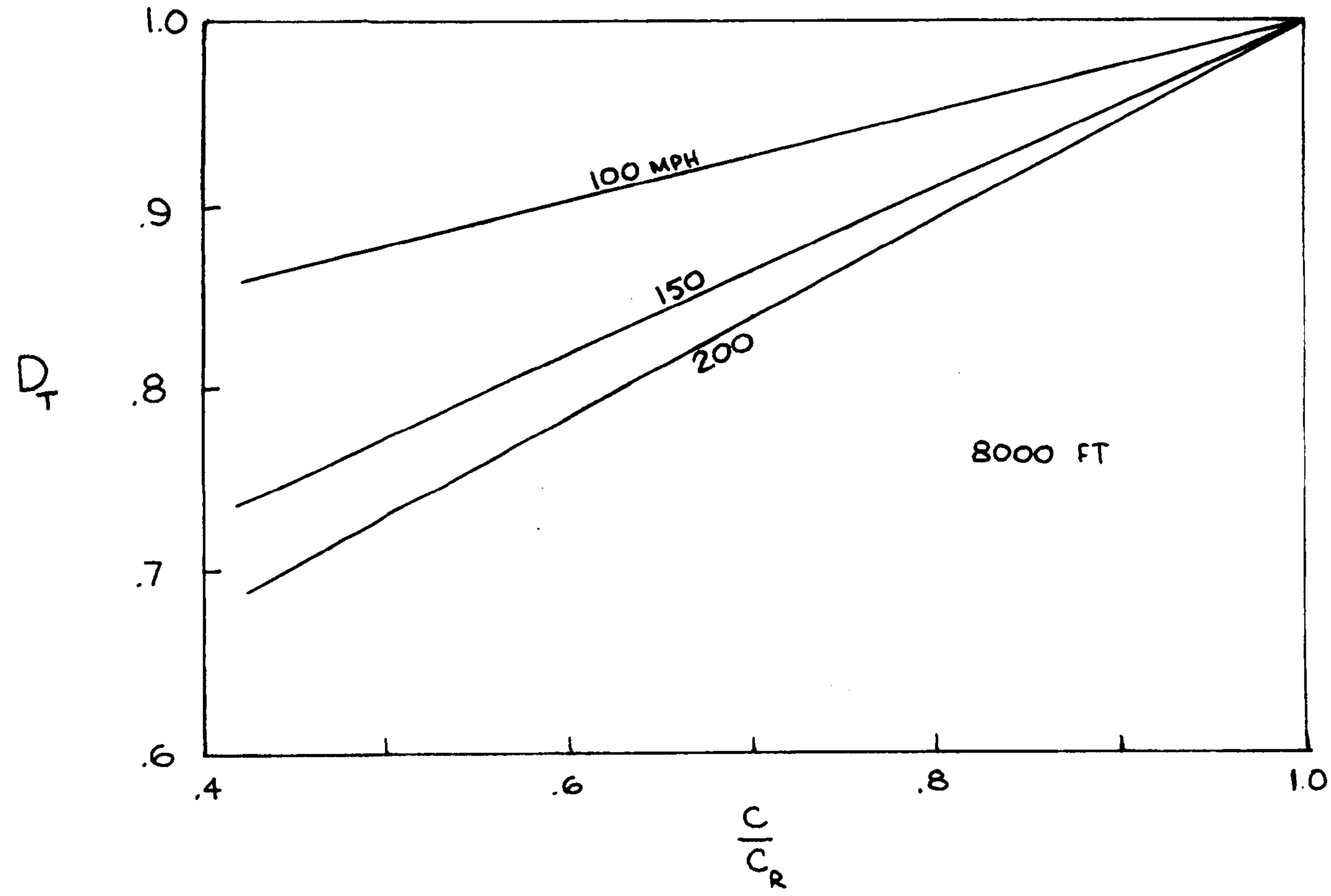

Figure 1. Effect of wing chord reduction on total drag of a typical single-engine light aircraft.

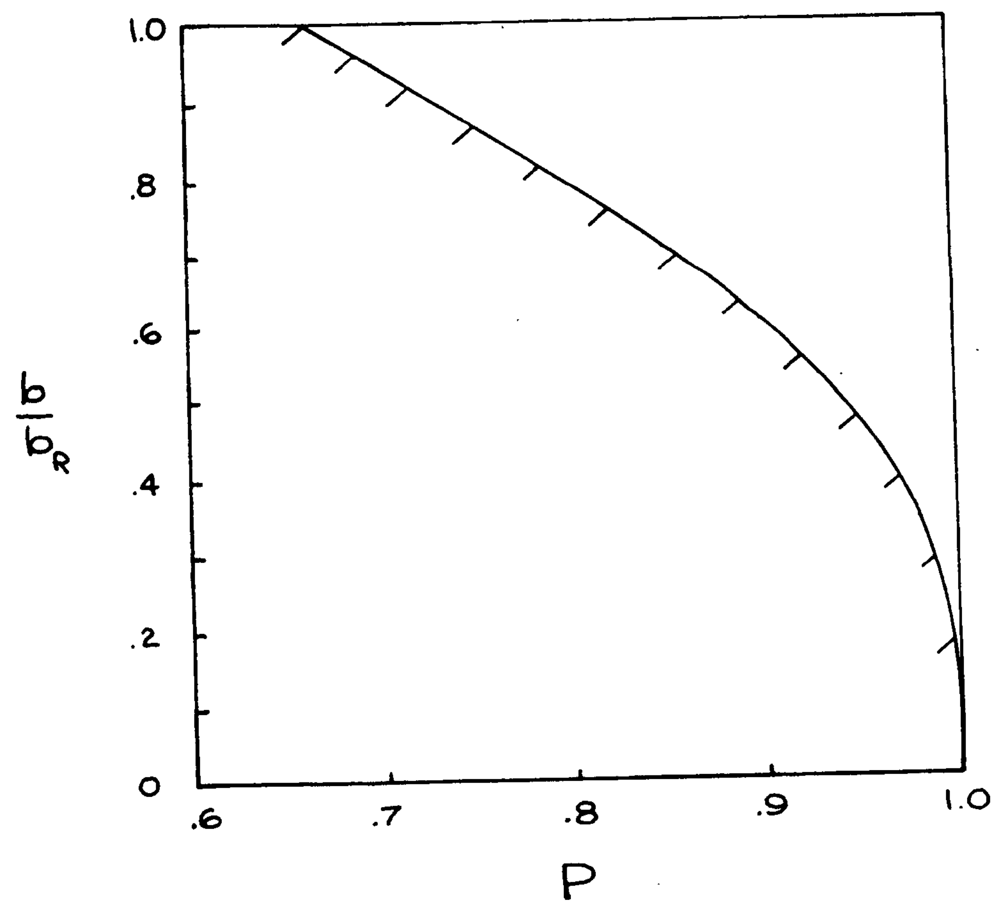

Figure 2. Limit of span reduction to decrease drag as a function of parasite drag ratio.

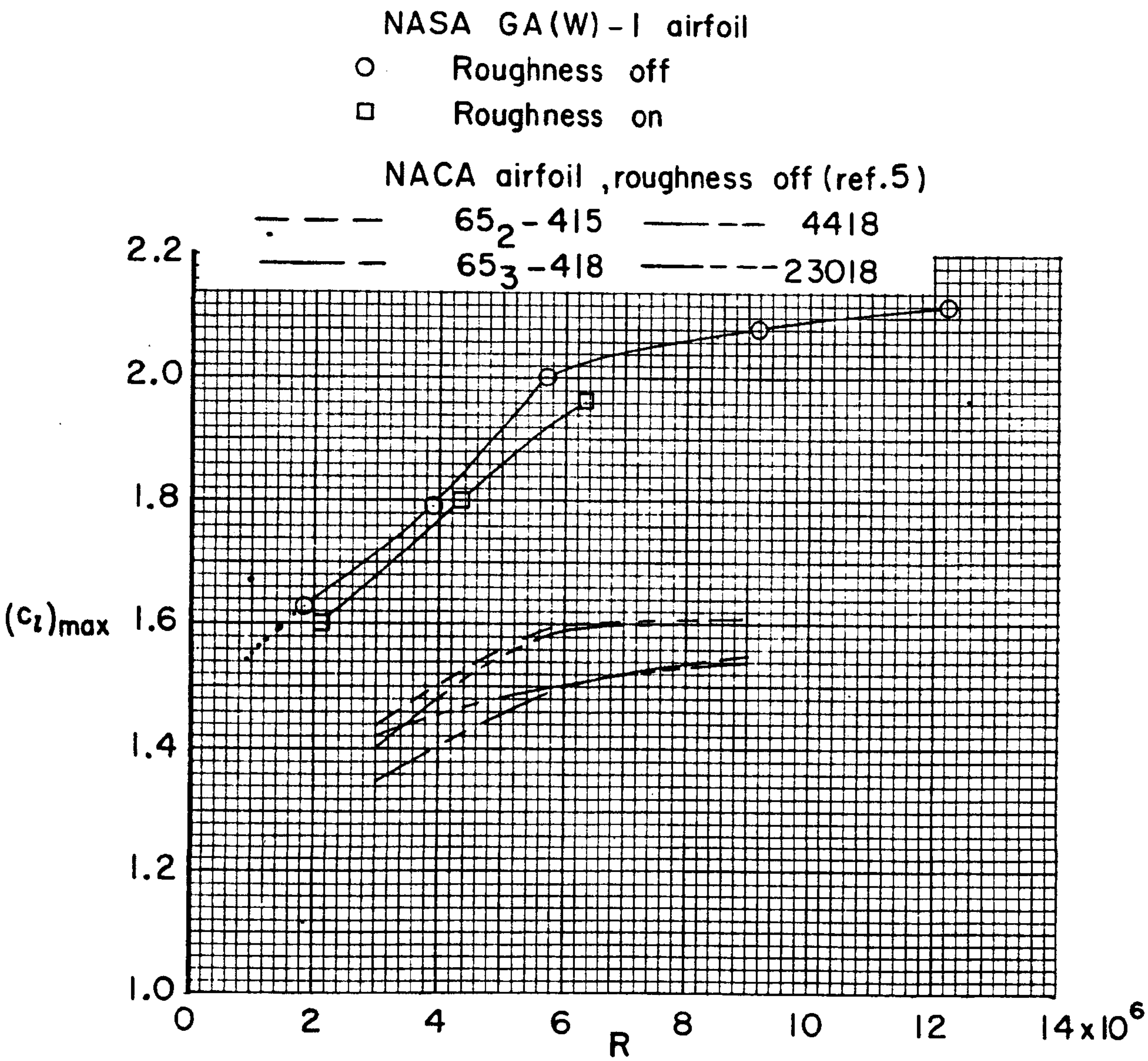

Figure 3. Variation of maximum section lift coefficeint with Reynolds number for various airfoils without flaps. M = 0.15.

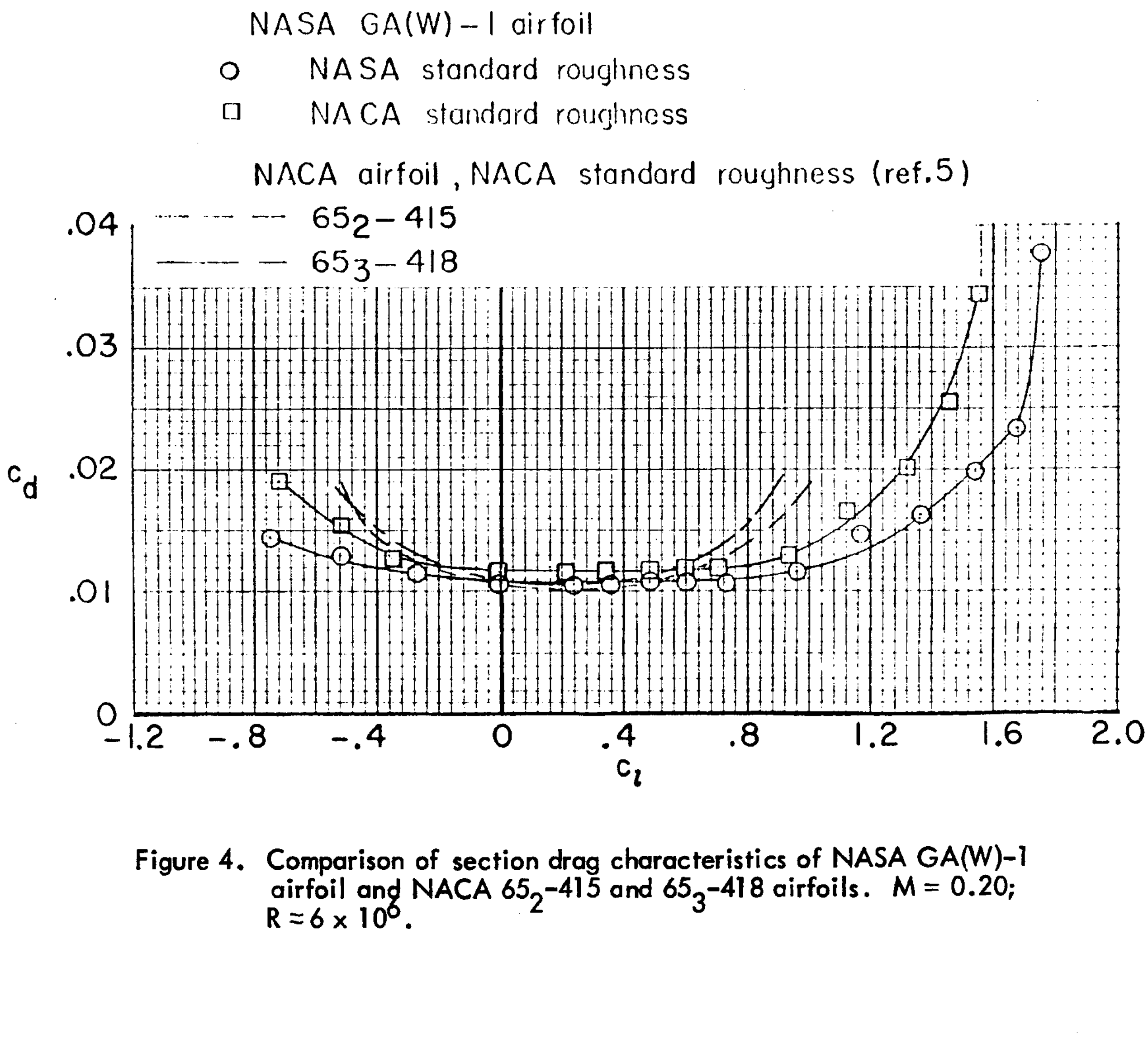

Figure 4. Comparison of section drag characteristics of NASA GA(W)-1 airfoil and NACA 65_2-415 and 65_3-418 airfoils. M = 0.20; R ≈ 6 x 10^6.

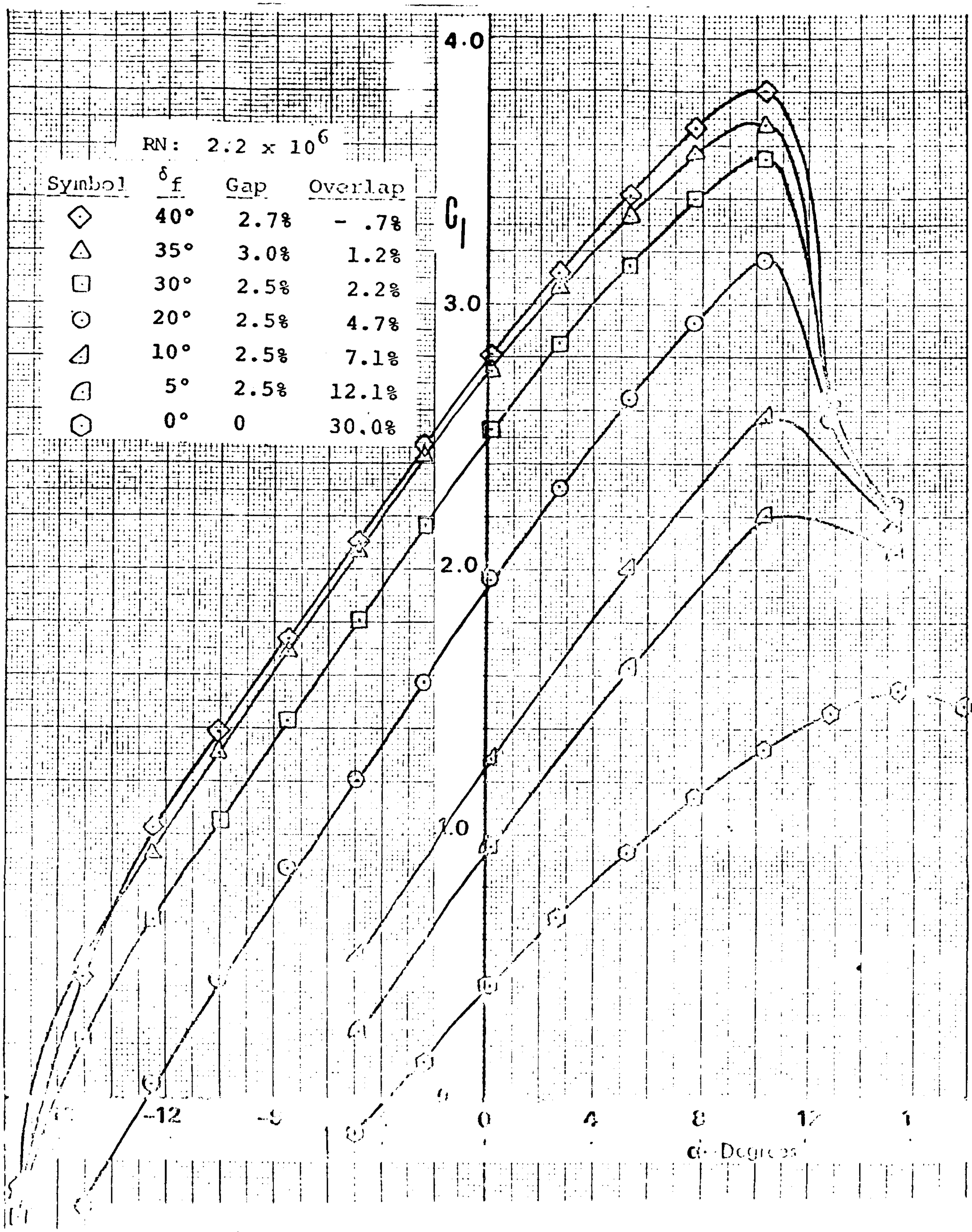

Figure 5. Lift performance of a 30% chord single-slotted Fowler flap on a GA(W)-1 airfoil.