Flight Determination of Partial Span Flap Parasite Drag With Flap Deflection

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Nomenclature

b = wing span.
c = airfoil or wing chord.
C_ℓ = Two dimensional section lift coefficient
C_{D_o} = Drag coefficient
e = Oswald efficiency factor.
f = aircraft equivalent parasite drag area.
S = wing reference area.
THP_{req} = thrust horsepower required.
$THP_{\text{req std}}$ = thrust horsepower required at standard weight and altitude.
V = true airspeed.
V_{std} = standard airspeed.
W = weight of the aircraft.
W_{std} = aircraft standard weight.
δ_f = flap deflection angle.
ρ_{SL} = density at sea level.
σ = ratio of the density at altitude to that at sea level, ρ/ρ_{SL}.

Introduction

Various lift enhancing devices are used to increase the operational speed range of aircraft, particularly at the low end near stall. Lower stall speeds decrease the landing distance. Fundamentally, there are only three techniques available for increasing the lift on an airfoil – camberline change, boundary layer control and area increase. Deflecting a trailing edge flap, drooping the leading edge of an airfoil or adding an external downward deflected leading edge slat are examples of devices that change the camber of the airfoil. Fixed leading edge slots, extensible leading edge slats and single or multiply slotted trailing edge flaps, as well as direct boundary layer blowing or suction, are examples of lift-enhancing devices that utilize boundary layer control. Fowler and multiple slotted trailing edge flaps and extensible leading edge slats are devices that depend on increasing area to enhance lift. Obviously, individual devices may use multiple methods for lift enhancement. Modern wing design typically incorporates both leading edge and trailing edge devices at the expense of additional mechanical complexity.

Typically, light general aviation aircraft of less than 6000 lbs depend on trailing edge flaps for lift enhancement. Full deflection of trailing edge flaps is used to increase the

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approach and landing descent angles. Fully or partially deflected flaps may be used as speed brakes. Because small flap deflections result in proportionally greater increases in lift than in drag, partial flap extension may be used to decrease the takeoff distance. Partial flap extension may also be used to decrease the maneuvering turn radius. For multiengine aircraft, partial flap extension lift and drag characteristics are important for single engine climb performance. Typically, only partial span flaps are used because the trailing edge is also used for lateral control devices.

A literature review revealed several early NACA technical reports, wartime reports and technical notes reporting wind tunnel experiments on NACA 230 mean line airfoils with slotted flaps, as well as a number of experiments on finite wings with full or partial span slotted flaps. The works of Wenzinger and Harris (Ref. 1) and House (Ref. 2) are representative of these efforts and particularly germaine to the present study.

The experiments by Wenzinger and Harris compare and evaluate the characteristics of an NACA 23012 airfoil with $0.2c$ split and plain flaps, along with $0.2667c$ external airfoil, Fowler and various single slotted flaps. They found that an optimum single slotted flap provided a superior maximum lift coefficient compared to split, plain and external airfoil flaps. However, the slot had to be carefully shaped and positioned to achieve optimal results. A Fowler flap provided a slightly higher maximum lift coefficient than the optimal single slotted flap but at the expense of additional complexity.

House investigated the effects of center and tip located partial span flaps on finite wings of aspect ratio six. He concluded that center span flaps had higher values of maximum lift coefficient and that the values of $C_{L_{\max}}$ did not significantly change with an increase in flap span beyond $0.40b$.

The Aircraft

The flight tests were conducted in an E33A Beech Bonanza. The aircraft had approximately 600 hours on a recently installed Teledyne Continental Motors IO-520BB 285 BHP factory remanufactured six cylinder fuel injected engine. The aircraft has a fuel computer capable of measuring and displaying fuel flow and fuel remaining. The aircraft empty weight is 2142 lbs , including the weight of six gallons of unusable fuel and ten quarts of oil. The aircraft is equipped with a recently overhauled McCauley 3-blade propeller (3A32C76 hub with 82NB-2 blades) with a nominal diameter of 80". The aircraft is fitted with a Century II autopilot and panel mounted IFR (Instrument Flight Rules) certified GPS avionics along with an S-TEC PSS60 altitude hold. This particular aircraft has the speed sweep windshield to reduce drag. Improved engine baffling for better engine cooling and reduced cooling drag has also been fitted. In addition, the Beechcraft "birdwing" antenna as well as the 10 ft belly ADF sense antenna have been removed to further reduce drag. The aircraft is shown in Rogers (Ref. 3).

The Wing

The aircraft wing span is 33.6 ft including wing tips (see Figure 1). The straight tapered wing has a taper ratio of 0.5. The quarter chord of the wing is unswept. The theoretical airfoil at the centerline of the aircraft is an NACA 23016.5 with a chord of 84". The airfoil at the wing tip is an NACA 23012. The modified leading edge extension (LEX) at the aircraft centerline extends forward of the quarter chord by 37.6", to yield a theoretical centerline chord of 100.6". The leading edge of the LEX extends in a straight line from the leading edge of the theoretical centerline airfoil to intersect the leading edge of the straight tapered wing at station 47 to form a crank in the wing. There is a triangular spin strip at the crank of the wing. There is also a small 7.875" long triangular spin strip on the wing centered at wing station 70.4375. The wing has 3° of washout, varying linearly from the theoretical root section to the tip. The wing dihedral is 6°. The reference wing area is 181 ft^2, which yields a reference aspect ratio of 6.2.

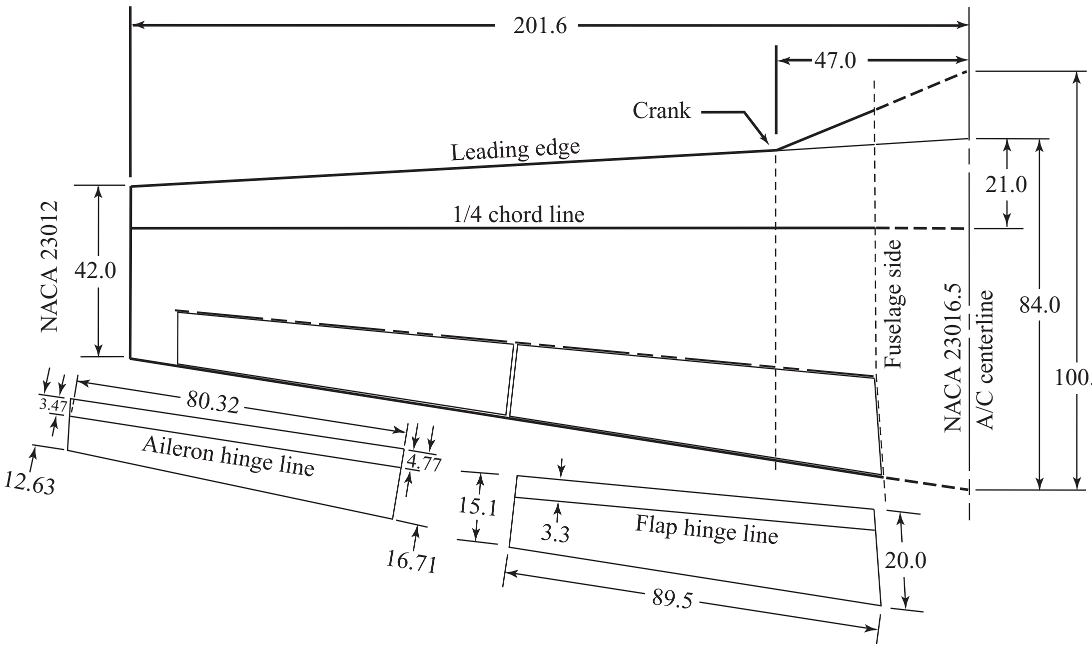

Figure 1. Wing schematic.

The Flap

The single slotted flap extends from the fuselage sidewall outboard along the wing to station 109.3 (inches from the aircraft centerline), as shown in Figure 1. The flap chord at the inboard end is 20.0" and at the outboard end 15.1". The individual flap span measured at the flap quarter chord is 87.2". The planform area of an individual flap is 10.6 ft^2. The slot is well formed. At full flap deflection the trailing edge moves aft 2" from the stowed position. Flap deflection was measured at station 29 approximately 5" outboard of the fuselage at the undeflected flap trailing edge. Both a manual jig and protractor and a digital inclinometer were used to measure the deflection. Maximum deflection was measured as 32° at this location.

The Flight Tests

The flight tests were conducted at a pressure altitude of 6000 ft . A box pattern was flown in order to acquire data for the horseshoe heading technique used to determine the true airspeed from the GPS ground speed (Ref. 4). Constant brake horsepower settings from 38% to 75% were used to set the airspeed for each data run and to remain below the maximum flap extension speed. The aircraft tachometer was calibrated against a stroboscopic tachometer and thereafter used to measure propeller RPM. The aircraft instrument was used to measure engine manifold pressure in order to determine power available. Mixture was set to correspond to best power (Ref. 5), i.e., approximately 100° rich of peak exhaust gas temperature. During the flight tests, aircraft weight varied from 3179 lbs to 2669 lbs for the various flights. Outside air temperature (OAT) varied from 32 to 52° F for the various data runs. Typically the OAT remained nearly constant for each data run. Manifold pressure varied from approximately 18.2" Hg to 23.2" Hg in 0.5 to 1" Hg increments, while propeller speed varied from approximately 1850 to 2500 RPM in approximately 100 RPM increments. The clean configuration tests, i.e., gear and flaps retracted, were conducted with cowl flaps and all cabin vents closed. The gear down tests were conducted with cowl flaps open. Typically five or six data points were obtained for each flap setting during a single flight.

Data Acquisition and Reduction

The true airspeed was determined using the horseshoe heading technique as detailed by Rogers (Ref. 4) and the references therein. This technique has been shown to be as accurate, within less than ±1 kt, as a traditional trailing cone or Kiel tube (Ref. 6). Basically the flight test consists of flying three legs with headings ninety degrees apart while recording the GPS ground speed. Using these GPS ground speeds and headings and solving three algebraic equations in three unknowns yields the true airspeed, wind direction and wind speed.

Aircraft weight was determined by subtracting the fuel used from the aircraft gross weight before engine start. Atmospheric density was determined from measured outside air temperature and the pressure altitude. Engine brake horsepower was determined from the manufacture's engine charts (Ref. 5) for best power mixture using measured manifold pressure and engine RPM. The propeller efficiency was calculated from polynomial curves determined from the manufacture's propeller map (Ref. 7). The results were reduced to a standard gross weight of 3300 lbs at sea level using true airspeed and the technique described in Appendix A of Rogers (Ref. 3). The results of these flight tests are shown in Figures 2–4.

The Results

Recalling the classical thrust power required equation for an aircraft with a parabolic drag polar equipped with a reciprocating engine driving a propeller

$$THP_{\text{req}} = \underbrace{\frac{\sigma\rho_{\text{SL}}}{2} f V^3}_{\text{parasite}} + \underbrace{\frac{2}{\sigma\rho_{\text{SL}}} \frac{1}{\pi e} \left(\frac{W}{b}\right)^2 \frac{1}{V}}_{\text{effective induced}} \tag{1}$$

Multiplying by the true airspeed, V, yields

$$THP_{\text{req}} V = \frac{\sigma\rho_{\text{SL}}}{2} f V^4 + \frac{2}{\sigma\rho_{\text{SL}}} \frac{1}{\pi e} \left(\frac{W}{b}\right)^2 = A + BV^4 \tag{2}$$

which is a linear relation in V^4 with

$$A = \frac{2}{\sigma\rho_{\text{SL}}} \frac{1}{\pi e} \left(\frac{W}{b}\right)^2 \quad \text{and} \quad B = \frac{\sigma\rho_{\text{SL}}}{2} f \tag{3}$$

Hence, the aircraft equivalent parasite drag area† is given by the slope of the straight line. Specifically

$$f = \frac{2}{\sigma \rho_{\mathrm{SL}}} B \tag{4}$$

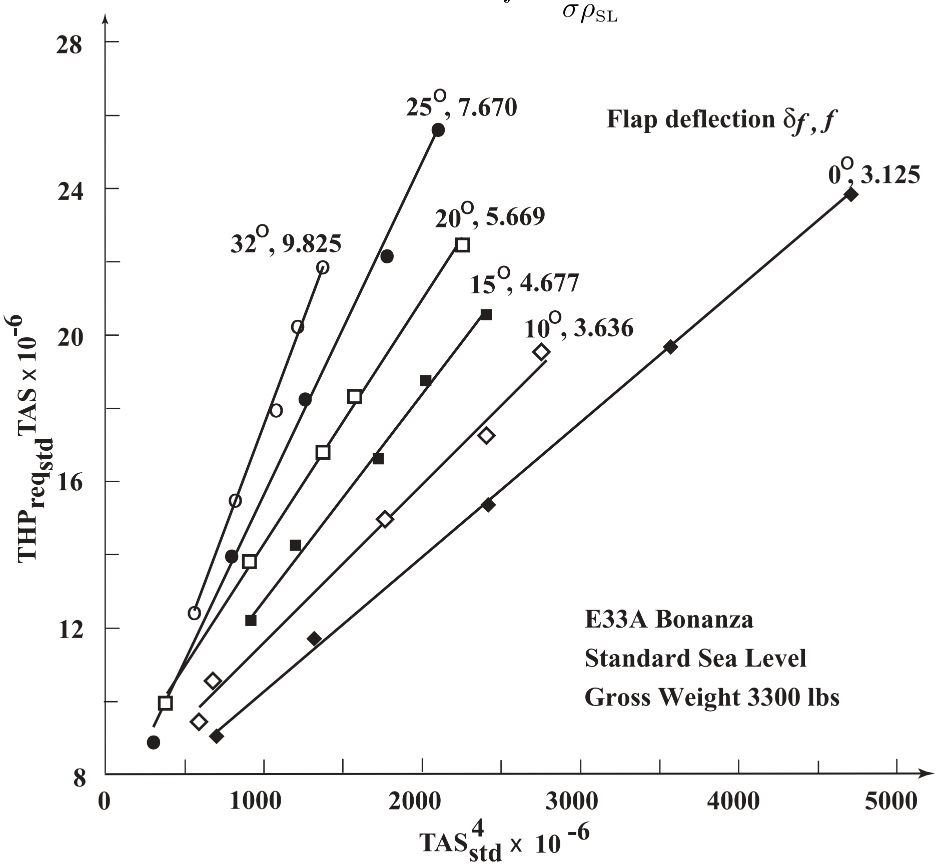

Figure 2. Equivalent parasite drag area for various flap deflections.

Figure 2 shows the data plotted as $THP_{\mathrm{req\,std}}V$ against V^4 as suggested by Eq.(2). A linear least squares fit is also shown for each flap deflection. Clearly, the expected linear relation results. The increased slope for the aircraft with increasing flap deflection indicates increased parasite drag as expected. Table 1 shows the values for the slope, B, the R^2 value and the value f obtained using Eq.(4). The results in Table 1 show that, as expected, increasing flap deflection increases the equivalent parasite drag area These are significant changes.

The equivalent parasite drag area plotted against flap deflection is shown in Figure 3. The parabolic least squares fit to the data, also shown in Figure 3, clearly indicates that the equivalent parasite drag area varies parabolically with flap deflection.

† The aircraft equivalent parasite drag area as used here is simply the classical parabolic drag polar constant term, i.e. the zero lift drag coefficient multiplied by the aircraft reference wing area.

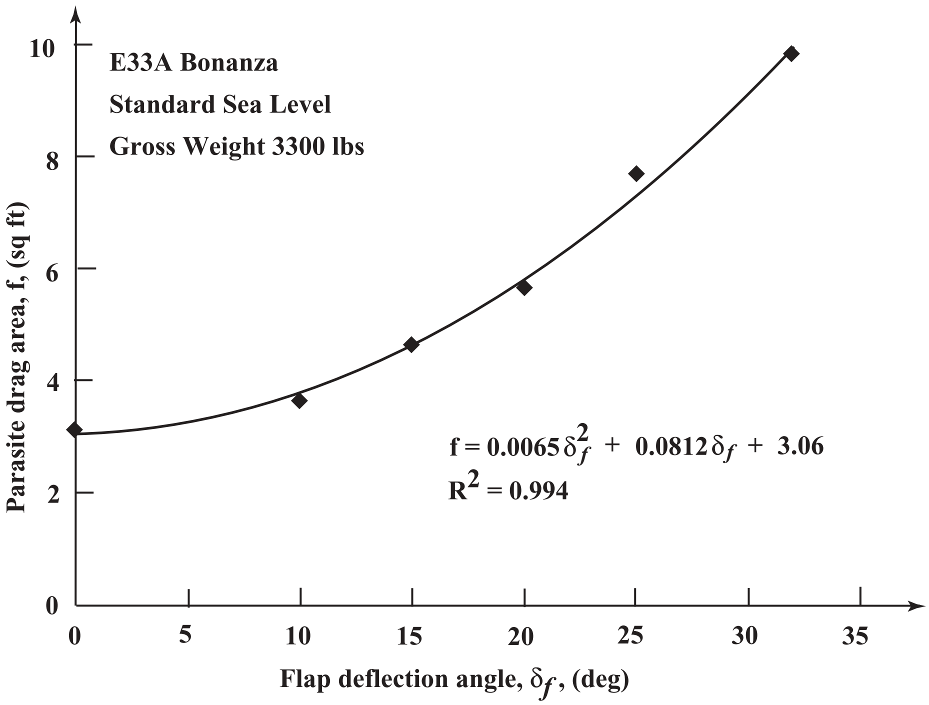

Figure 3. Equivalent parasite drag area as a function of flap deflection angle, δ_f.

Table 1. Results for f, clean

δ_f°	$B \times 10^3$	R^2	$f(\text{ft}^2)$	$\Delta f(\text{ft}^2)$
0	3.714	0.995	3.125	0.000
10	4.321	0.991	3.636	0.511
15	5.556	0.992	4.677	1.552
20	6.737	0.998	5.669	2.544
25	9.116	0.997	7.670	4.545
32	11.676	0.996	9.825	6.700

The parabolic variation of the equivalent parasite drag area with flap deflection suggests a linear variation with the square of the flap deflection. Figure 4 shows the equivalent parasite drag area for the flight test data plotted against the square of the flap deflection in radians, along with a linear least square fit to the data of Table 1.

McCormick (Ref. 8 Table 4.2) gives the skin friction coefficient for a Model V-35 V-tail Bonanza as 0.0049. Eckalbar (Ref. 9) gives the wetted surface area based on an estimate by Stinson (Ref. 10) as 620 ft^2 for the V-35 and estimates that the wetted surface area of the conventional tailed Model E33A as 640 ft^2. Using McCormick's value for the skin friction coefficient and Eckalbar's estimate for the wetted surface area yields an equivalent parasite drag area of 3.14 ft^2 , which agrees quite well with the current flight test result for $\delta_f = 0$.

A literature search revealed no similar flight test data for partial span partially deflected flaps. However, Wenziger and Harris (Ref. 1) present wind tunnel airfoil data for an NACA 23012 airfoil equipped with a 0.2566 chord slotted flap, although they do not plot the data versus δ_f^2. Extracting the data from Wenzinger and Harris (Ref. 1, Figure 15) for C_{d_0} at $C_l = 0$ for flap deflections from zero to forty degrees and performing a linear least square fit, again yields a linear relation in the square of the flap deflection as shown in the inset in Figure 4. Data from Wenzinger and Harris for split, plain and Fowler flaps also yield a linear relation in the square of the flap deflection for similar flap deflection angles, although the slopes are, not surprisingly, different. This result suggests that two or three level flight performance tests with partially extended flaps will yield adequate data for estimating performance for modest flap deflections.

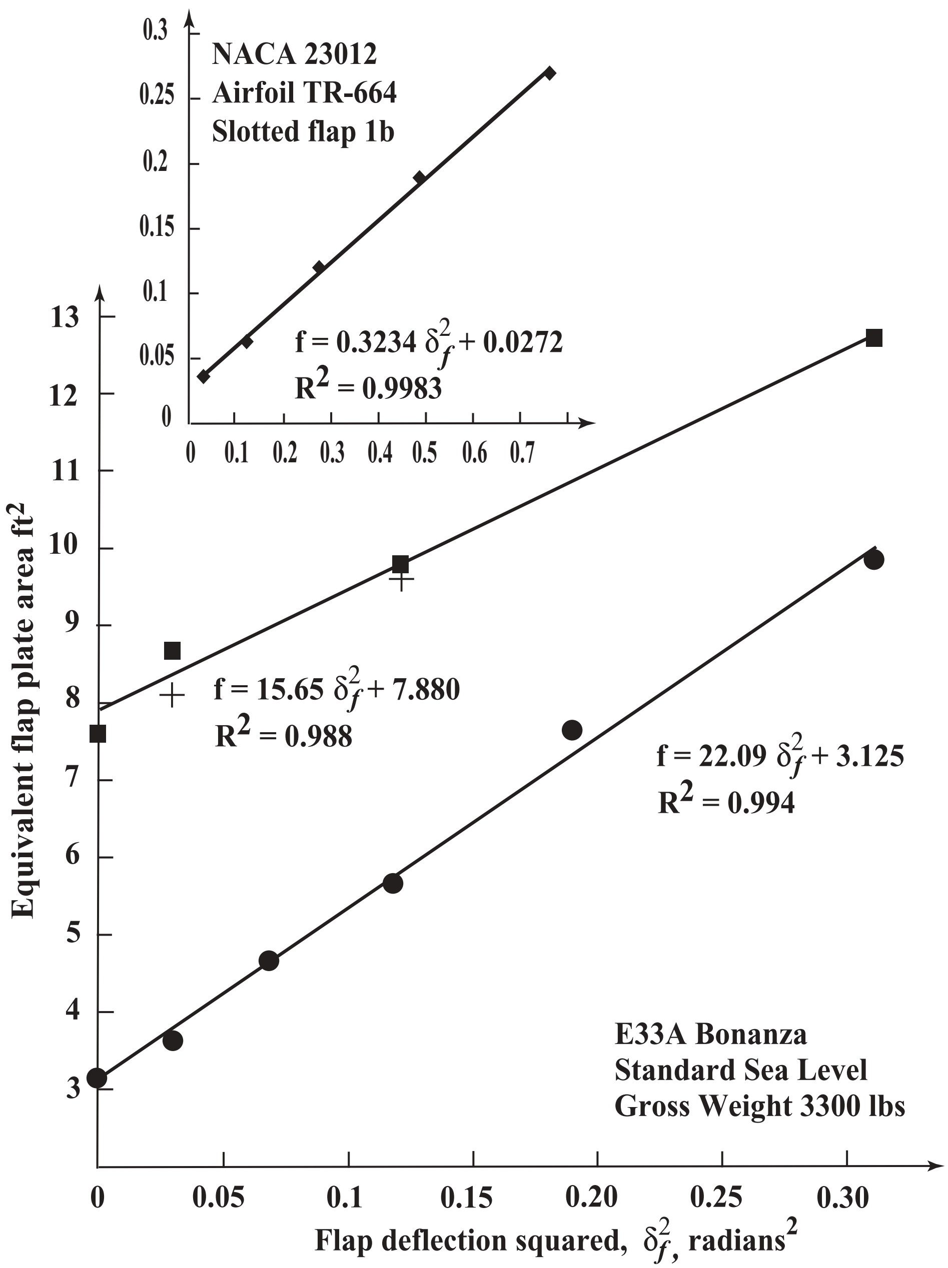

Figure 4. Equivalent parasite drag area as a function of the square of the flap deflection angle, δ_f^2.

Table 2. Results for f
gear down cowl flaps open

δ_f°	$B \times 10^3$	R^2	$f(\text{ft}^2)$	$\Delta f(\text{ft}^2)$
0	8.808	0.9897	7.593	4.286
10	10.276	0.9711	8.646	5.521
20	11.681	0.9995	9.829	6.522
32	15.114	0.9932	12.717	9.592

In order to test the suggestion above, four additional flight tests were conducted in the power approach configuration, i.e., gear down and cowl flaps open with various flap deflections. The results are shown in Table 2 and in Figure 4. The first flight test was conducted with gear down and a flap deflection of zero. The second flight test was conducted with gear down and a flap deflection of 32°. From these two results the equivalent parasite drag area for gear down and flap deflections of 10° and 20° were estimated as shown by the +s in Figure 4. Flight tests where then conducted in the power approach configuration with flap deflections of 10° and 20°. The results are shown by the squares in Figure 4. The flight test results are in good agreement with the estimates.

Conclusions

Level flight performance tests were conducted on a typical light general aviation single engine retractable aircraft to determine the equivalent parasite drag area of partially deflected partial span flaps. The equivalent parasite drag area in the gear up configuration increased by a factor of 1.16 for 10° and by a factor of 1.81 for 20° flap deflection angle. At a maximum deflection of 32° the aircraft equivalent parasite drag area increased by a factor of 3.14 compared to the aircraft value when the flaps were undeflected. Both a parabolic variation of the equivalent parasite drag area with flap deflection angle and a linear relation with the flap deflection angle squared were found. Additional flight tests in the gear down configuration confirmed the linear variation with flap deflection angle squared. Classical NACA wind tunnel data for an NACA 23012 airfoil equipped with a similar single slotted flap also resulted in both a parabolic variation of the equivalent parasite drag area with flap deflection angle and a linear relation with flap deflection angle squared. The results are expected to be similar for similar aircraft.

References

1. Wenzinger, C.J. and Harris, T.A., "Wind-tunnel Investigation of an N.A.C.A. 23012 Airfoil with various arrangements of Slotted Flaps", NACA Report 664, 1939.
2. House, Rufus O., "The Effects of Partial-span Slotted Flaps on the Aerodynamic Characteristics of Rectangular and Tapered N.A.C.A. 23012 Wing." NACA TN-719, 1939.
3. Rogers, David F., "Comparative Flight Tests With and Without Tip Tanks", *AIAA J. of Aircraft*, Vol. 44, No. 5, September–October 2007, pp. 1740–1744.
4. Rogers, David F., "An Engineering Flight Test Course Emphasizing Flight Mechanics Concepts", *AIAA J. of Aircraft*, Vol. 39, No. 1, January–February 2002, pp. 79–83.
5. Teledyne Continental Motors, Aircraft Products Division, *IO-520 Series, Operator's Manual*, Form No. X30041, September, 1980.

6. Lewis, G., "A Flight Test Technique Using GPS for Position Error Correction Testing," *Cockpit, Quarterly of the Society of Experimental Test Pilots*, Jan/Feb/March 1997, pp. 20–24.
7. McCauley Accessory Division, The Cessna Aircraft Company, 3535 McCauley Drive, Vandalia, OH 45377.
8. McCormick, B., *Aerodynamics, Aeronautics and Flight Mechanics*, John Wiley & Sons, New York, 1979.
9. Eckalbar, J., *Flying the Beech Bonanza*, McCormick-Armstrong Co., Wichita, KS, 1986.
10. Stinton, D., *The Design of the Airplane, 2/e*, AIAA, 2001.

