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Comparative Flight Tests with and Without Tip Tanks

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Comparative level flight performance tests were conducted on a typical light general aviation single engine retractable aircraft with and without tip tanks. True airspeed was determined using the global positioning system based horseshoe heading technique. The addition of tip tanks resulted in an increase in the equivalent parasite drag area of one-third as well as an increase in the Oswald efficiency factor. As expected, tip tanks increase the horsepower required at high speeds and decrease the horsepower required at low speeds for the same aircraft speed. At the crossover point of 157 kt true airspeed and 62% brake horsepower the effect of tip tanks is neutral. The crossover point closely corresponds with typical cruise operating conditions and altitudes as well as Carson cruise conditions for this aircraft. The results are expected to be typical for similar aircraft. A flight test data reduction and analysis technique based on true airspeed rather than calibrated airspeed is detailed.

Nomenclature

b	=	wing span
$\mathrm{BHP}_{\mathrm{avl}}$	=	brake horsepower available
C_D	=	aircraft drag coefficient
C_L	=	aircraft lift coefficient
e	=	Oswald efficiency factor
f	=	equivalent flat plate area
S	=	wing reference area
$\mathrm{THP}_{\mathrm{req}}$	=	thrust horsepower required
$\mathrm{THP}_{\mathrm{req}_{\mathrm{std}}}$	=	thrust horsepower required at standard weight and altitude
V	=	true airspeed
V_{cruise}	=	cruise airspeed
V_{knee}	=	airspeed at the knee in the altitude vs true airspeed curve
$V_{L/D_{\max}}$	=	airspeed at maximum lift to drag ratio
V_{stall}	=	stall speed
V_{std}	=	standard airspeed
W	=	weight of the aircraft
W_{std}	=	aircraft standard weight
η_p	=	propeller efficiency
ρ	=	density
ρ_{SL}	=	density at sea level
η_p	=	propeller efficiency
σ	=	density altitude ratio, ρ/ρ_{SL}

Introduction

FOR light general aviation aircraft, defined as less than 6000 lb gross weight, fuel is typically carried in the wings. As a result, space, and hence capacity, is a significant limiting factor. Consequently, tip tanks are an attractive alternative, either as part of the initial design or as an aftermarket addition. Furthermore, because the weight of the fuel carried in the tip tank acts opposite to the wing lift, aftermarket tip tanks frequently carry a modest gross weight increase that partially compensates for the additional fuel weight when the tanks are filled. The aircraft gross weight may also be increased even when fuel is not carried in the tip tanks because of the increase in wing effective aspect ratio.

For single engine aircraft, tip tanks typically add 15 to 20 gal of fuel per side, although larger tanks do exist (up to 100 gal). For retractable aircraft, this translates into an additional two to three hours of flight, an increase in range of about 350 to 450 nm. Tip tanks for twin engine aircraft are typically larger, for example, 30 to 50 gal per side with a similar range increase.

Tip tanks decrease the induced drag of the aircraft by acting as end plates [1,2] thus increasing the effective aspect ratio of the wing. Hardley and Haines [3], in wind tunnel tests on a swept wing with tip tanks at Mach numbers and Reynolds numbers typical of light general aviation aircraft, found that the lift curve slope of the wing was increased by approximately 6–8% when tip tanks were fitted. Salter and Jones [4] and Tinling and Kolk [5,6] report similar effects. This effect is frequently considered as an increase in effective aspect ratio and/or Oswald efficiency factor. Hardley and Haines also observed a slight increase in maximum lift coefficient.

Tinling and Kolk [6], in wind tunnel tests on a 35 deg semispan swept wing with a single tip tank, found an increase in parasite drag of approximately 15% compared with the wing without tip tanks. Höerner [2] points out that in addition to the increase in parasite drag caused by the increased tip tank frontal area and skin friction on the tank, a parasite component results from interference drag caused by the juncture between the wing and the tank. Hardley and Haines [3] report a large suction peak ($C_p = -0.7$) at the wing-tank junction that supports this conclusion.

Question

From the above discussion it is anticipated that fitting tip tanks increases the parasite drag of the aircraft, resulting in a decrease in the speed at any given power setting. However, the decrease in induced drag of the aircraft, which results from the end plate effect, increases the speed. An interesting question is how do these two effects interact? Is the net result a decrease in drag and thus an increase in speed, or is the net result an increase in drag and a decrease in speed for any given power setting?

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

$$\mathrm{THP}_{\mathrm{req}} = \eta_p\left[\underbrace{\frac{\sigma\rho_{\mathrm{SL}}}{2}fV^3}_{\text{parasite}} + \underbrace{\frac{2}{\sigma\rho_{\mathrm{SL}}}\frac{1}{\pi e}\left(\frac{W}{b}\right)^2\frac{1}{V}}_{\text{effective induced}}\right] \tag{1}$$

we can anticipate the results. Specifically, note that the first term in the equation, the parasite power required, involves the equivalent parasite drag area f, and is proportional to the cube of the true airspeed V. Because f increases, adding tip tanks is expected to decrease the true airspeed at high cruise airspeeds and power settings.

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However the second term, the effective induced power required, involves the Oswald efficiency factor e. The Oswald efficiency factor is increased by the effect of the tip tanks, and the induced drag is decreased. Hence the effective induced power required is reduced. Because the effective induced power required is inversely proportional to the velocity, it is most important at low true airspeeds that correspond to high wing lift coefficients and high induced drag. Notice that this term is also inversely proportional to the wing span b. If the tip tanks increase the effective wing span, then the effective induced power required is reduced.

If the increase in parasite power required occurs at high true airspeed while the decrease in effective induced power required occurs at low true airspeed, then it is reasonable to expect that at some true airspeed the effects are equal and cancel each other. Typically, an aircraft designer, as well as an aircraft operator, wants that true airspeed to be at the design cruise true airspeed or close to it.

Fig. 1 1969 E33A Beech Bonanza CE-280.

Aircraft

The flight tests were conducted in two 1969 E33A Beech Bonanzas that differed by ten manufacturers serial numbers, CE-270 and CE-280. Consequently the airframes, except for the tip tanks, were identical [7]. Each aircraft had approximately 100 h on recently installed Teledyne Continental Motors IO-520BB 285 BHP factory remanufactured six cylinder fuel injected engines. Both aircraft had fuel computers capable of measuring and displaying fuel flow and fuel remaining. The aircraft were equipped with recently overhauled McCauley 3-blade propellers (3A32C76 hub with 82NB-2 blades) with a nominal diameter of 80 in. Both aircraft have essentially the same empty weight at 2151 and 2142 lb, including the weight of 6 gal of unusable fuel and 10 qt of oil. The wing span is 33 ft 4.5 in. without tips tanks and 33 ft 6.5 in. with the tip tanks fitted. The reference wing area is 181 ft^2, which yields a reference aspect ratio of 6.2. Both aircraft were fitted with Century autopilots and panel mounted IFR (instrument flight rules) certified global positioning system (GPS) avionics. One aircraft (CE-270) was equipped with nominal 15 gal aftermarket Beryl D'Shannon tip tanks. The length of the tip tanks was $75\frac{1}{2}$ in. and the maximum diameter 12 in. for a fineness ratio of 6.3. CE-280, the aircraft without tip tanks, is shown in Fig. 1. CE-280 is equipped with modified Höerner tips as shown in Fig. 2. The tip tanks fitted to CE-270 are shown in Fig. 3.

Fig. 2 Höerner style wing tip fitted to CE-280.

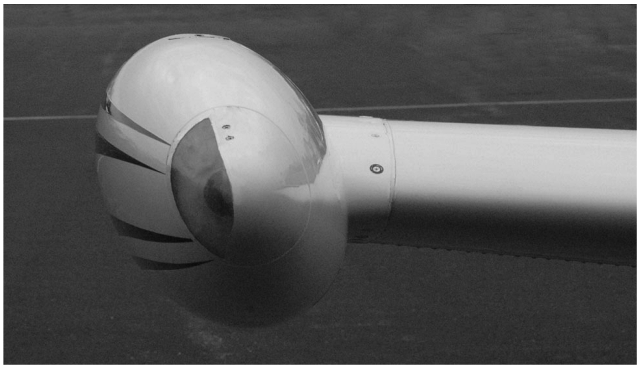

Fig. 3 Tip tank fitted to CE-270.

Flight Tests

The flight tests were conducted at a pressure altitude of 6000 ft. A box pattern was flown to acquire data for the horseshoe heading technique [8] used to determine the true airspeed from GPS ground speed. Constant brake horsepower settings from 42.5 to 75% were used to set the airspeed for each data run. A stroboscopic tachometer was used to measure propeller rpm, and the aircraft instrument was used to measure engine manifold pressure to determine power available. Mixture was set to correspond to best power [9], that is, approximately 100° rich of peak exhaust gas temperature. Takeoff weight was 2988 lb for the aircraft fitted with tip tanks and 3151 lb for the aircraft without tip tanks. During the flight tests, weight varied from 2960 to 2899 lb for the aircraft fitted with tip tanks and from 3125 to 3035 lb for the aircraft without tip tanks. Outside air temperature (OAT) varied from 59 to 62°F during the data runs for the aircraft fitted with tip tanks, with most data runs occurring with an OAT of 62°F. For the aircraft without tip tanks the OAT was constant at 33°F. Manifold pressure varied from approximately 19 to 23 in. in 1 in. Hg increments. Propeller speed varied from approximately 2000 to 2500 rpm in approximately 100 rpm increments. Six data runs occurred in a single flight for each aircraft.

Data Reduction

The true airspeed was determined using the horseshoe heading technique as detailed in Rogers [8] 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 [10]. Basically the flight test consists of flying three legs with headings 90 deg 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 [9] for best power mixture using measured manifold pressure and engine rpm, that is, approximately 100° rich of peak exhaust gas temperature. The propeller efficiency was calculated from polynomial curves determined from the manufacture's propeller map. The results were reduced to a standard aircraft gross weight of 3300 lb at sea level using the technique described in the Appendix. The results of these flight tests are shown in Figs. 4 and 5.

Results

Figure 4 shows the data plotted as $THP_{req_{std}} V$ against V^4 as suggested by Eq. (A1). A linear least squares fit is also shown.

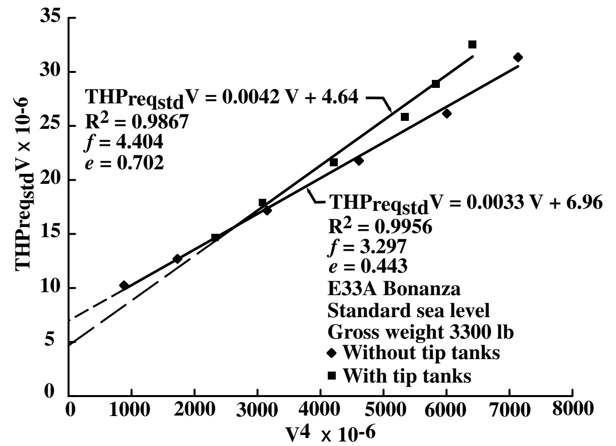

Fig. 4 Comparison of equivalent flat plate area f and Oswald efficiency factor e with and without tip tanks.

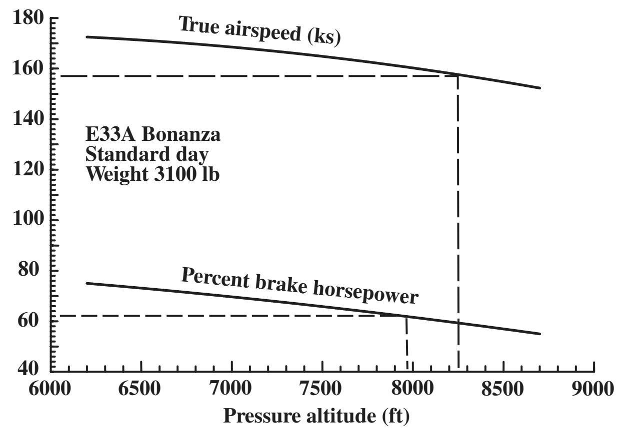

Fig. 6 True airspeed and percent brake horsepower for the flight test aircraft without tip tanks.

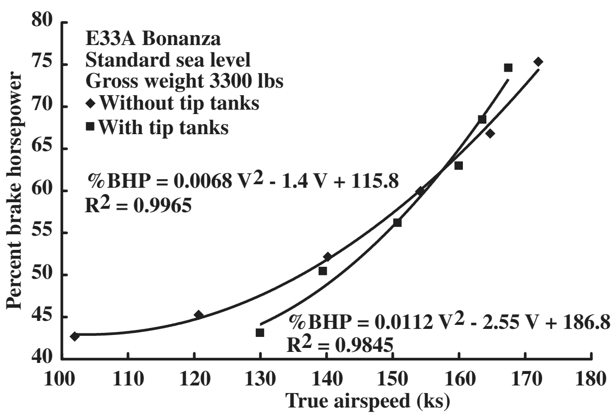

Fig. 5 Illustration of the crossover point at 157 kt TAS and 62% BHP.

Clearly the expected linear relation, with and without tip tanks, results. The increased slope for the aircraft with tip tanks indicates increased parasite drag compared with the aircraft without tip tanks, as expected. The smaller ordinate intercept value as indicated by the dashed lines and constant term in the linear least squares fit equations for the aircraft without tip tanks compared with the aircraft with tip tanks results in an increased Oswald efficiency value. Again, this result is expected because of the end plate effect of the tip tanks. Table 1 shows the values for e and f obtained using Eq. (A3) from the Appendix. The results in Table 1 show that adding the tip tanks increases the equivalent parasite drag area f by one-third. This result compares favorably with the 15% increase found by Tinling and Kolk on a semispan swept wing equipped with a single tip tank. The tip tanks increase the Oswald efficiency factor e by 58.5%. These are significant changes. However, because the flight test data were all acquired on the "front" side of the power curve, the results for the Oswald efficiency factors are considered less reliable than those for the equivalent parasite drag area.

Figure 5 shows the data plotted as percent brake horsepower (BHP) vs true airspeed V, along with parabolic least squares curve fits. Percent BHP is chosen because it is the parameter normally available to the aircraft operator. Brake horsepower is obtained by multiplying by 285. Again, for a given true airspeed, at *high* speeds *more* horsepower is required for the aircraft fitted *with tip tanks*. At

Table 1 Results for e and f

Aircraft	f	e
CE-280 without tips tanks	3.297	0.443
CE-270 with tips tanks	4.404	0.702

low speeds *more* horsepower is required for the aircraft *without tip tanks*. The crossover (intersection) point is at approximately 157 knots true airspeed (KTAS) and approximately 62% brake horsepower (177 BHP). At the crossover point the effect of the tip tanks on aircraft level flight performance is neutral.

For an aircraft equipped with a normally aspirated reciprocating engine driving a propeller, at a fixed percentage of available brake horsepower (BHP_{avl}) the airspeed increases linearly with increasing altitude until the fixed percentage of BHP_{avl} can no longer be maintained. That altitude is referred to as the knee in the KTAS vs altitude curve. Above the knee the engine is typically operated at full throttle and fixed rpm. Under these conditions KTAS decreases with increasing altitude. Figure 6 shows the knee true air speed (TAS) and percent BHP cross plotted from [11] for the subject aircraft without tip tanks. From Fig. 6, at the crossover BHP (62%) and TAS (157 KTAS), the aircraft equipped with tip tanks can operate at the same speed as the aircraft without tip tanks without penalty between approximately 8000 and 8250 ft pressure altitude. This is a typical cruise altitude but a slightly slower airspeed for the subject aircraft. Hence, the fitted tip tanks result in little or no change in the aircraft performance for typical cruise conditions. Cruising slightly faster results in a small performance penalty and cruising slightly slower results in a small performance gain.

Classically, maximum range occurs at the speed for $V_{L/D_{\max}}$. However, this speed is typically quite slow. Consequently aircraft are generally flown at speeds in excess of $V_{L/D_{\max}}$. Carson [12] asked the question "What is the unit cost in increased fuel consumption for each unit increase in speed?" His results show that the best rate of return for increased fuel consumption as a result of increased cruise speed is

$$V_{\text{cruise}} = (3)^{1/4} V_{L/D_{\max}} = 1.32 V_{L/D_{\max}} \tag{2}$$

whereas the increase in fuel consumption is $2/\sqrt{3} = 1.16$, that is, a 32% increase in cruise TAS for just a 16% increase in fuel consumption. The increase in cruise TAS results in a 52% increase in power required and a 24% decrease in the flight time. Assuming that time has value, from this one can conclude that the value of a 24% decrease in flight time is worth the cost of an additional 16% for fuel. V_{cruise} has become known as the Carson cruise, for example, CAFE (Comparative Aircraft Flight Efficiency Foundation) calculates the Carson cruise speed when evaluating an aircraft.

By comparing the Carson cruise TAS, V_{cruise}, and the knee velocity V_{knee}, for the subject aircraft as a function of percent BHP using the two curves in the lower plot of Fig. 7, we see that the two curves cross at approximately 58.6% BHP, yielding a TAS of approximately 157 kt. For 58.6% BHP, the knee in the altitude vs TAS curve occurs at a pressure altitude of approximately 8300 ft, as shown by the upper plot in Fig. 7. These conditions are very close to the crossover point where the tip tanks have a neutral effect on aircraft performance. For

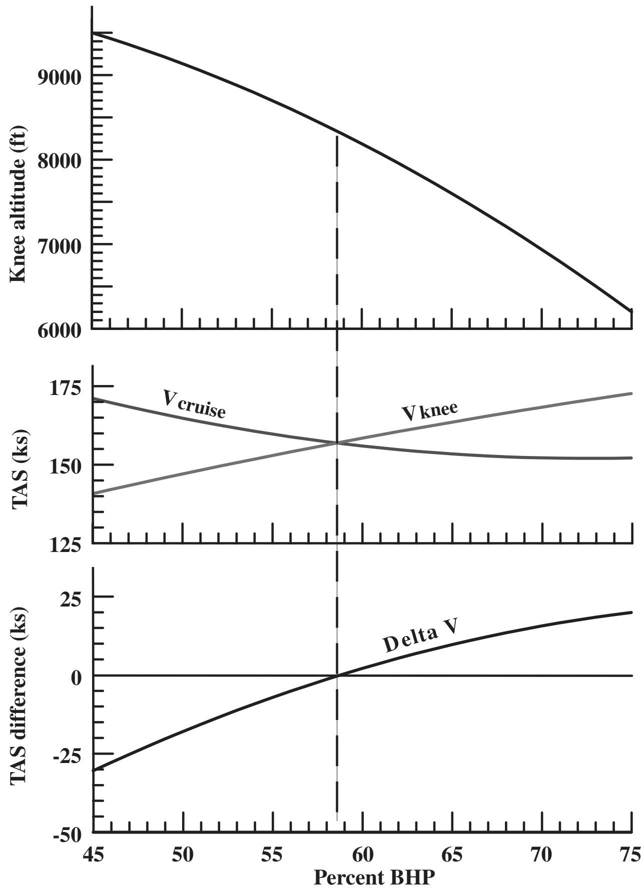

Fig. 7 Carson cruise conditions for the aircraft without tip tanks.

this power setting the approximate fuel flow is 12.5 gph [11]. Hence, two 15 gal tip tanks yield an approximate 375 nm increase in range under no wind conditions.

Conclusions

Comparative level flight performance tests were conducted on a typical light general aviation single engine retractable aircraft with and without tip tanks. The addition of tip tanks resulted in an increase in equivalent parasite drag area of one-third as well as an increase in the Oswald efficiency factor. As expected, tip tanks increase the horsepower required at high speeds and decrease the horsepower at low speeds. At the crossover point of 157 KTAS and 62% BHP, the effect of tip tanks is neutral. The crossover point closely corresponds with typical cruise operating conditions and altitudes as well as Carson cruise conditions for this aircraft. The results are expected to be typical for similar aircraft.

Appendix: Data Reduction Method

Reduction to Standard Conditions Using True Airspeed

With the advent of GPS and the horseshoe heading technique for directly determining true airspeed, an alternate technique for reducing test results to standard conditions and determining the equivalent flat plate area f and the Oswald, or airplane efficiency factor e, using true airspeed rather than calibrated airspeed is of interest.

Recalling Eq. (1) and multiplying by the true airspeed, V yields

$$\mathrm{THP}_{\mathrm{req}}V = \frac{\sigma\rho_{\mathrm{SL}}}{2} f V^4 + \frac{2}{\sigma\rho_{\mathrm{SL}}}\frac{1}{\pi e}\left(\frac{W}{b}\right)^2 = A + BV^4 \tag{A1}$$

which is a linear relation in V^4 with

$$A = \frac{2}{\sigma\rho_{\mathrm{SL}}}\frac{1}{\pi e}\left(\frac{W}{b}\right)^2 \quad \text{and} \quad B = \frac{\sigma\rho_{\mathrm{SL}}}{2} f \tag{A2}$$

Hence e, the Oswald efficiency factor, is given by the intercept of a straight line on a $\mathrm{THP}_{\mathrm{req}}V$ versus V^4 plot and f, the equivalent flat plate area, is given by the slope of the straight line. Specifically

$$e = \frac{2}{\sigma\rho_{\mathrm{SL}}}\frac{1}{\pi A}\left(\frac{W}{b}\right)^2 \quad \text{and} \quad f = \frac{2}{\sigma\rho_{\mathrm{SL}}} B \tag{A3}$$

Reduction to Standard Sea Level and Weight Conditions

For any given standard weight W_{std} at sea level on a standard day the true airspeed V_{std} is given by

$$V_{\mathrm{std}} = \sqrt{\frac{2}{\rho_{\mathrm{SL}}}\frac{W_{\mathrm{std}}}{S}\frac{1}{C_L}} \tag{A4}$$

where S is the wing planform area.

Similarly, the thrust horsepower required at standard weight at sea level on a standard day, $\mathrm{THP}_{\mathrm{req}_{\mathrm{std}}}$, is given by

$$\mathrm{THP}_{\mathrm{req}_{\mathrm{std}}} = \sqrt{\frac{2}{\rho_{\mathrm{SL}}}\frac{W_{\mathrm{std}}^3}{S}\frac{C_D^2}{C_L^3}} \tag{A5}$$

At any other conditions the true airspeed V and the thrust horsepower required $\mathrm{THP}_{\mathrm{req}}$ are given by

$$V = \sqrt{\frac{2}{\rho}\frac{W}{S}\frac{1}{C_L}} \tag{A6}$$

and

$$\mathrm{THP}_{\mathrm{req}} = \sqrt{\frac{2}{\rho}\frac{W^3}{S}\frac{C_D^2}{C_L^3}} \tag{A7}$$

At the same lift coefficient C_L

$$\frac{V_{\mathrm{std}}}{V} = \sqrt{\frac{\rho}{\rho_{\mathrm{SL}}}\frac{W_{\mathrm{std}}}{W}} \tag{A8}$$

and

$$\frac{\mathrm{THP}_{\mathrm{req}_{\mathrm{std}}}}{\mathrm{THP}_{\mathrm{req}}} = \sqrt{\frac{\rho}{\rho_{\mathrm{SL}}}\frac{W_{\mathrm{std}}^3}{W^3}} \tag{A9}$$

Hence, test conditions can be reduced to standard weight at sea level on a standard day using

$$V_{\mathrm{std}} = V\sqrt{\sigma}\sqrt{\frac{W_{\mathrm{std}}}{W}} \tag{A10}$$

and

$$\mathrm{THP}_{\mathrm{req}_{\mathrm{std}}} = \mathrm{THP}_{\mathrm{req}}\sqrt{\sigma}\left(\frac{W_{\mathrm{std}}}{W}\right)^{3/2} \tag{A11}$$

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