Propeller Efficiency
Cruise Climb

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Introduction

Recall from previous articles[†] that propeller efficiency is characterized by two nondimensional parameters, the advance ratio, J, and the power coefficient, C_p, given by

$$J = \frac{V}{ND} \quad \text{and} \quad C_p = \frac{\text{BHP}}{\rho N^3 D^5}$$

where V is the true airspeed, N is the propeller RPM, D is the diameter of the propeller, ρ (rho) is the local density and BHP is, of course the brake horsepower.

From that discussion we developed A Simplified Rule of Thumb (ASROT)[‡] that allowed estimation of the appropriate RPM for a given cruise true airspeed (KTAS) and using the cruise performance graph in the pilot operating handbook (POH) 'calibrated' the result for the McCauley C76 propeller to yield an ASROT ratio of 14.5 i.e.,

$$\frac{RPM}{KTAS} = 14.5$$

In the second article we illustrated that propeller efficiency during takeoff is significantly lower than during typical cruise flight.

Once the takeoff maneuver is complete and the aircraft cleaned up, a cruise climb to altitude is initiated. Let's take a look at the propeller efficiency during that phase of flight.

Cruise Climb

Although climbing at full throttle and 2700 RPM at 95 KIAS (knots indicated airspeed) provides a least time or near least time to climb to altitude, many of us climb at reduced

[†] "Propeller Efficiency—Rule of Thumb" and "Propeller Efficiency—Takeoff"

[‡] Pronounced AS ROT

power, i.e. a cruise climb, for comfort, noise reduction and efficiency. A typical cruise climb is at full throttle or 25" Hg manifold pressure and 2500 RPM at 110 KIAS. Let's look at propeller efficiency for a bare three blade McCauley C76 propeller during a 25/2500 cruise climb at 110 KIAS in an E33A on a standard day from sea level to 14,000 ft. The IO-520BB engine altitude performance curves provide the available brake horsepower.† For a constant indicated climb speed of 110 KIAS and 25/2500 or FT/2500, the true airspeed continues to increase with altitude all the way to 14,000 ft. Of course, above the knee in the altitude vs airspeed curve, the rate of climb decreases as does the available horsepower. The results are shown by the black curve in Figure 1 and in detail in Table 1. The results for level cruise and for takeoff from previous articles are also shown for comparison.

Because both the RPM, N, and the propeller diameter, D, are fixed, the advance ratio, J, increases directly with the true airspeed. Similarly, the power coefficient, C_p, varies as the ratio of the BHP to the density, ρ. Because, above the knee in the altitude vs airspeed curve, the horsepower decreases slightly faster than the density, the power coefficient decreases. Fourteen thousand feet is an exception; there it increases slightly.

The results in Figure 1 and Table 1 show that propeller efficiency increases by approximately 4.7% during the climb, principally as a result of the increase in true airspeed.

Turbonormalize Cruise Climb at 110 KIAS

For comparison, consider a turbonormalized climb at full throttle and 2500 RPM. Full throttle and 30" Hg manifold pressure yields 275 BHP. Again, the advance ratio increases as the true airspeed increases. Here, the power coefficient increases continuously because the density decreases continuously during the cruise climb. The green line in Figure 1 shows the

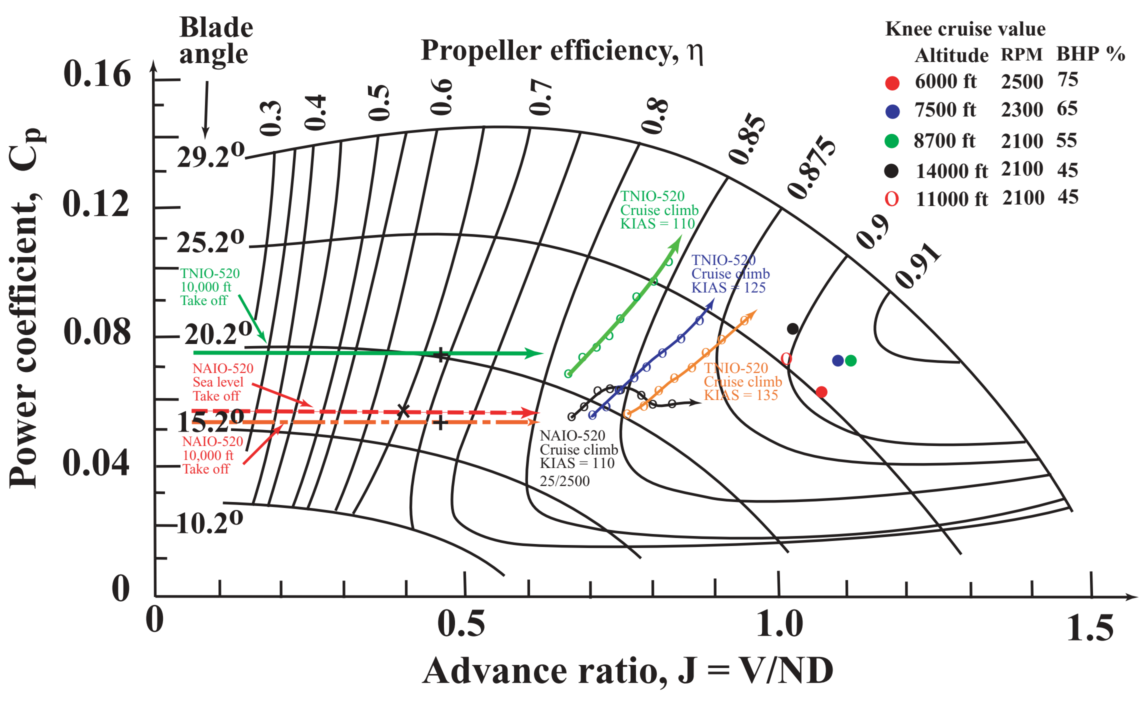

Figure 1. McCauley C76 propeller map.

† Teledyne Continental Motors, Aircraft Products Division, "IO-520 Series, Operator's Manual", Form No. X30041, September, 1980.

results. Detailed results are given in Table 2. Compared to the normally aspirated climb, shown by the black line in Figure 1, the bare propeller efficiency, except at sea level, is slightly lower throughout the climb (1–2%). Basically, this is because the power coefficient is larger in the turbonormalized climb than in the normally aspirated climb—on the order of 1–4%. Obviously, with the additional available power the rate of climb is higher.

Table 1 Cruise Climb Efficiencies — IO-520BB @ 25/2500 or FT/2500

Altitude ft	Density ratio σ	KTAS	$J = \frac{V}{ND}$	BHP	C_p	Efficiency η	%BHP
0	1	110.0	0.669	220	0.0534	0.815	77.2
2000	0.9428	113.3	0.689	224	0.0577	0.830	78.6
4000	0.8881	116.7	0.710	228	0.0623	0.835	80.0
6000	0.8359	120.3	0.732	214	0.0621	0.845	75.0
8000	0.786	124.2	0.755	200	0.0618	0.855	70.2*
10000	0.7385	128.0	0.779	186	0.0612	0.857	65.3*
12000	0.6948	132.0	0.803	170	0.0594	0.860	59.6*
14000	0.65106	136.3	0.829	160	0.0597	0.862	56.1*

E33A, IO-520BB, Weight = 3100 lbs, standard day
*FT above 6000 ft

Table 2 Cruise Climb Efficiencies at 110 KIAS— TNIO-520BB @ FT/2500

Altitude ft	Density ratio σ	KTAS	$J = \frac{V}{ND}$	BHP	C_p	Efficiency η	%BHP
0	1.0000	110.0	0.669	275	0.0668	0.818	96.5
2000	0.9428	113.3	0.689	275	0.0708	0.823	96.5
4000	0.8881	116.7	0.710	275	0.0752	0.825	96.5
6000	0.8359	120.3	0.732	275	0.0799	0.828	96.5
8000	0.7860	124.1	0.755	275	0.0849	0.834	96.5
10000	0.7385	128.0	0.779	275	0.0904	0.839	96.5
12000	0.6948	132.0	0.803	275	0.0961	0.843	96.5
14000	0.6511	136.3	0.829	275	0.1026	0.845	96.5

E33A, TNIO-520BB, Weight = 3100 lbs, standard day

Turbonormalize Cruise Climb at 125 KIAS

Because of the additional available power with turbonormalization, a faster cruise climb might be more advantageous. Let's look at the results for a cruise climb at full throttle, 2700 RPM and 125 KIAS. The additional available horsepower increases the power coefficient, but the higher RPM decreases it. The advance ratio also increases because of the increased true airspeed at all altitudes. The results are shown in Table 3 and as the blue line in Figure 1. As Table 3 and Figure 1 show, the net result is a decrease in the power coefficient (1–2%). However, the propeller efficiency increases—on the order of 1–2.5% compared to the turbonormalized cruise climb at 110 KIAS. Compared to the normally aspirated cruise climb at 110 KIAS the propeller efficiency increases on the order of 0–2%. These results suggest that cruise climbing faster in a turbonormalized aircraft increases the propeller efficiency. This is not unanticipated. Thus, let's look at climbing at 135 KIAS.

Table 3 Cruise Climb Efficiencies @ 125 KIAS — IO-520BB @ FT/2700

Altitude ft	Density ratio σ	KTAS	$J = \frac{V}{ND}$	BHP	C_p	Efficiency η	%BHP
0	1.0000	125.0	0.704	285	0.0549	0.830	100.0
2000	0.9428	128.7	0.725	285	0.0583	0.840	100.0
4000	0.8881	132.6	0.747	285	0.0619	0.850	100.0
6000	0.8359	136.7	0.770	285	0.0657	0.852	100.0
8000	0.7860	141.0	0.794	285	0.0699	0.855	100.0
10000	0.7385	145.5	0.819	285	0.0744	0.860	100.0
12000	0.6948	150.0	0.845	285	0.0791	0.863	100.0
14000	0.6511	154.9	0.873	285	0.0844	0.867	100.0

E33A, TNIO-520BB, Weight = 3100 lbs, standard day

Turbonormalize Cruise Climb at 135 KIAS

Here, we consider a cruise climb in an E33A with turbonormalized TNIO-520BB at full throttle and 2700 RPM at 135 KIAS. Because of the increase in true airspeed during the climb compared to either the 110 KIAS or 125 KIAS, the advance ratio increases. However, the power coefficient remains the same as when climbing at 125 KIAS, full throttle and 2700 RPM. The effect is to move the resulting curve to the right, as shown by the orange line in Figure 1, and hence to higher propeller efficiencies at all altitudes during the climb. Notice that now the bare propeller efficiency is getting close to that seen in typical level cruise flight. The detailed results are given in Table 4.

Table 4 Cruise Climb Efficiencies @ 135 KIAS — IO-520BB @ FT/2700

Altitude ft	Density ratio σ	KTAS	$J = \frac{V}{ND}$	BHP	C_p	Efficiency η	%BHP
0	1.0000	135.0	0.761	285	0.0549	0.852	
2000	0.9428	139.0	0.783	285	0.0583	0.855	
4000	0.8881	143.3	0.807	285	0.0619	0.860	
6000	0.8359	147.7	0.832	285	0.0657	0.864	
8000	0.7860	152.3	0.858	285	0.0699	0.868	
10000	0.7385	157.1	0.885	285	0.0744	0.873	
12000	0.6948	162.0	0.912	285	0.0791	0.876	
14000	0.6511	167.3	0.943	285	0.0844	0.883	

E33A, TNIO-520BB, Weight = 3100 lbs, standard day

Conclusions

In a cruise climb at 110 KIAS in a normally aspirated aircraft, the propeller efficiency varies from approximately 81% to 86% and increases with altitude. In a cruise climb in a turbonormalized aircraft, propeller efficiency also increases with increasing altitude and in addition also increases with increasing indicated climb airspeed.