Propeller Performance

7 Apr 09

Lab 10 Lecture Notes, Appendix A

Propellers tested

Tests were performed on a Speed-280 motor driving the following propellers:

APC 5.1 x 4.5
APC 5.5 x 4.5
APC 6.0 x 4.0
APC 7.0 x 4.0 (narrowed)
APC 7.0 x 5.0 (narrowed)

The tests were performed over a range of air velocities and motor power levels, the latter controlled via motor voltage. Measurements consisted of thrust, torque, RPM, current, voltage. This allowed the calculation of all relevant operating parameters and efficiencies.

Figure 1 shows typical thrust performance measurements for four applied voltages, together with predictions from the motor/prop simulation model.

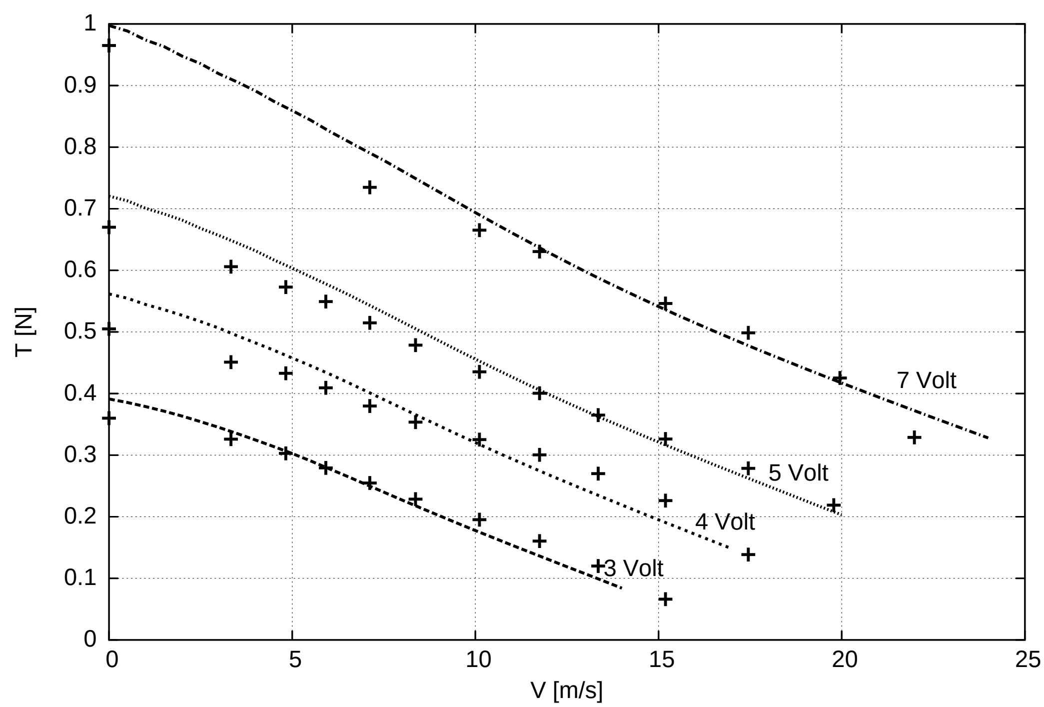


Figure 1: Measured thrust versus velocity (symbols), for APC 5.1x4.5 prop, Speed-280 motor. Lines are motor/prop numerical model predictions.

The intent here is to validate the numerical model, which is used to generate all the subsequent performance curves.

Maximum-Power Thrust

Figure 2 shows the thrust of the propellers for the maximum available battery rest voltage of 7.4 Volts (the actual battery voltage is reduced somewhat by battery's internal resistance).

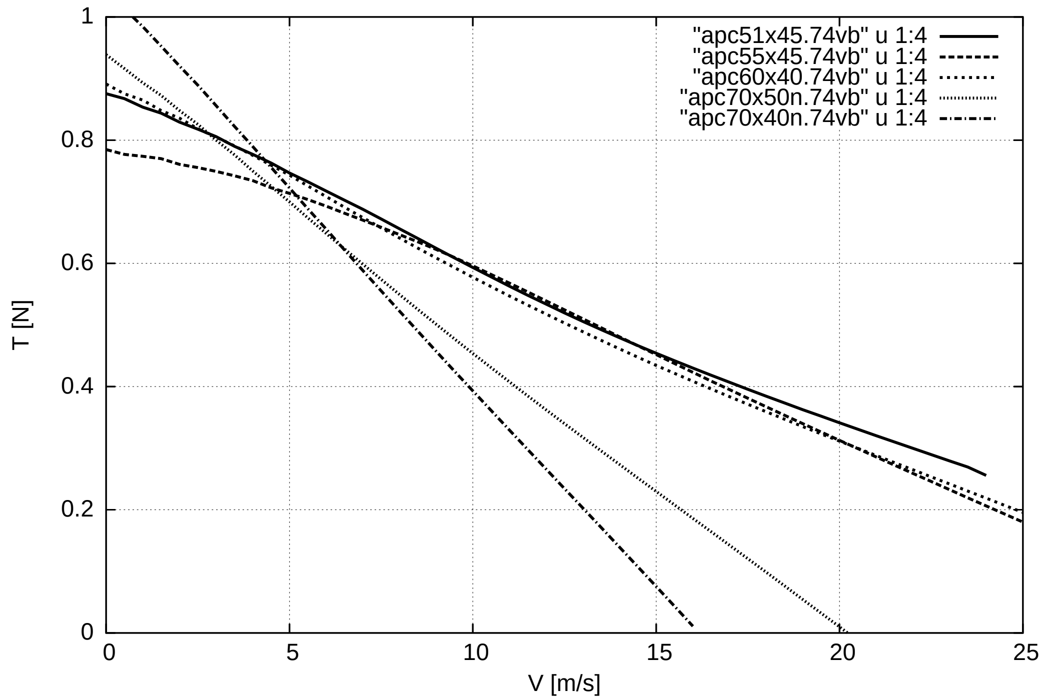


Figure 2: Maximum thrust versus velocity, for 7.4 Volt, 0.30 Ohm battery.

Performance Modeling

For optimization purposes, it is necessary to obtain simple expressions for the above prop/motor performance curves. For the three best props in Figure 2, the maximum thrust is closely approximated by the simple linear curve-fit function

$$T_{\max}(V) \simeq T_0 + T_1 V \tag{1}$$

$$T_0 = 0.86\,\mathrm{N} \tag{2}$$

$$T_1 = -0.027\,\mathrm{N/(m/s)} \tag{3}$$

Six airfoils suitable for a multipurpose light electric aircraft are shown overlaid in Figure 3. The thickness/chord ratios vary from $\tau = 0.07$ to $\tau = 0.12$. Computed drag polars are shown in

	UE12	UE11	UE10	UE09	UE08	UE07
area =	0.07503	0.06896	0.06298	0.05663	0.05028	0.04395
thick. =	0.12000	0.11006	0.10018	0.09005	0.08000	0.07007
camber =	0.02801	0.02701	0.02600	0.02772	0.02953	0.03141
r_{LE} =	0.01424	0.01188	0.01019	0.01001	0.00968	0.00938
$\Delta\theta_{TE}$ =	6.85°	6.07°	5.28°	5.03°	4.78°	4.54°

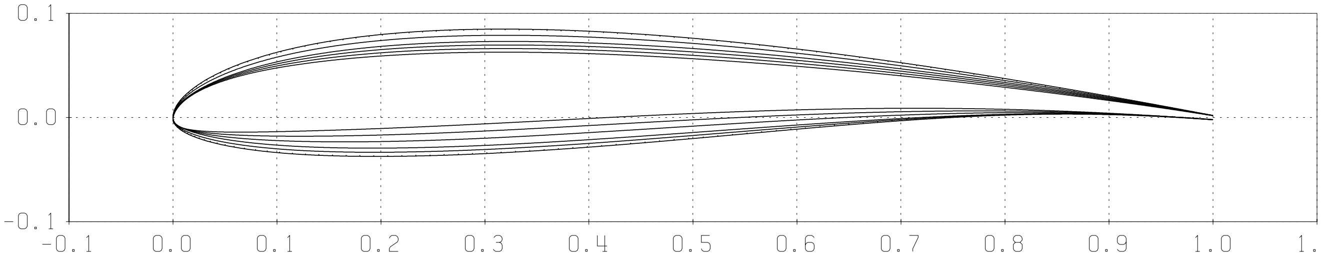


Figure 3: Six airfoils suitable for light electric aircraft.

separate plots. The drag coefficient is in effect a function of the three variables (c_ℓ, Re, τ). For optimization calculations, it is desirable to approximate this function, preferably with explicit formulas. A suitable approximation is

$$c_d(c_\ell, Re, \tau) \simeq \left[c_{d_0} + c_{d_2}(c_\ell - c_{\ell_0})^2\right]\left(1 + k_\tau \tau^3\right)\left(\frac{Re}{Re_{\mathrm{ref}}}\right)^a \tag{4}$$

where the constants are set to match the computed polars over narrow parameter ranges of interest.

The following constants give a reasonable approximation for $c_{d_{\mathrm{slow}}}$ in the "slow" range,
$0.8 \le c_\ell \le 1.0$, $40000 \le Re \le 60000$.

$$c_{d_0} = 0.020 \tag{5}$$
$$c_{d_2} = 0.05 \tag{6}$$
$$c_{\ell_0} = 0.8 \tag{7}$$
$$k_\tau = 350 \tag{8}$$
$$Re_{\mathrm{ref}} = 50000 \tag{9}$$
$$a = -0.8 \tag{10}$$

The following constants give a reasonable approximation for $c_{d_{\mathrm{fast}}}$ in the "fast" range,
$0.1 \le c_\ell \le 0.3$, $80000 \le Re \le 120000$.

$$c_{d_0} = 0.0115 \tag{11}$$
$$c_{d_2} = 0.0 \tag{12}$$
$$c_{\ell_0} = 0.2 \tag{13}$$
$$k_\tau = 350 \tag{14}$$
$$Re_{\mathrm{ref}} = 100000 \tag{15}$$
$$a = -0.5 \tag{16}$$

Plain Vanilla Fuselage Drag Measurements
7 Apr 09

Lab 10 Lecture Notes, Appendix C

Plane Vanilla Drag Test Results

Test article: Plane Vanilla fuselage + tail. No wing. No prop.

Test rig: Force balance in 1×1 wind tunnel.

Drag results:

q_∞ (Pa)	D (N)
5.47	0.0211
11.06	0.0411
20.79	0.0877
31.46	0.1243

This data gives an implied CDA_0 estimate which can be used for your performance model.

Improved CDA_0 Model

It may be advantageous to break up CDA_0 into separate fuselage+tail contributions.

$$CDA_0 \;=\; CDA_{\rm t} \;+\; CDA_{\rm f}$$

XFOIL calculations for Plane Vanilla's 3/32" balsa tail "airfoils" suggest that the tail contributes about a quarter to the measured fuselage+tail drag.

$$\begin{aligned} CDA_{\rm f} &\simeq \tfrac{3}{4} CDA_0 \\ CDA_{\rm t} &\simeq \tfrac{1}{4} CDA_0 \end{aligned}$$

This breakdown is useful when we note that $CDA_{\rm t}$, which is dominated by friction drag, is roughly proportional to the tail areas (and hence to the wing area).

$$CDA_{\rm t} \;\sim\; S_{\rm t} \;\sim\; S$$

In contrast, $CDA_{\rm f}$ is dominated by the frontal area of the motor, landing gear, and wing mount, which will be roughly constant.

$$CDA_{\rm f} \;\sim\; \text{constant}$$

These assumptions allow the creation of a $CDA_0(S)$ function which is much more realistic than simply assuming CDA_0 to be constant.

Wing Taper and Twist Consideration
7 Apr 09
Lab 10 Lecture Notes, Appendix D

Tapering a wing gives significant aerodynamic and structural advantages, but it can also cause problems if overdone. Consider three $AR = 10$ wings of the same span and area, but different taper ratios $\lambda = c_{\rm tip}/c_{\rm root}$. When operated at some overall lift coefficient C_L, these wings have the $L'(y)$ and $c_\ell(y)$ distributions shown in Figure 4.

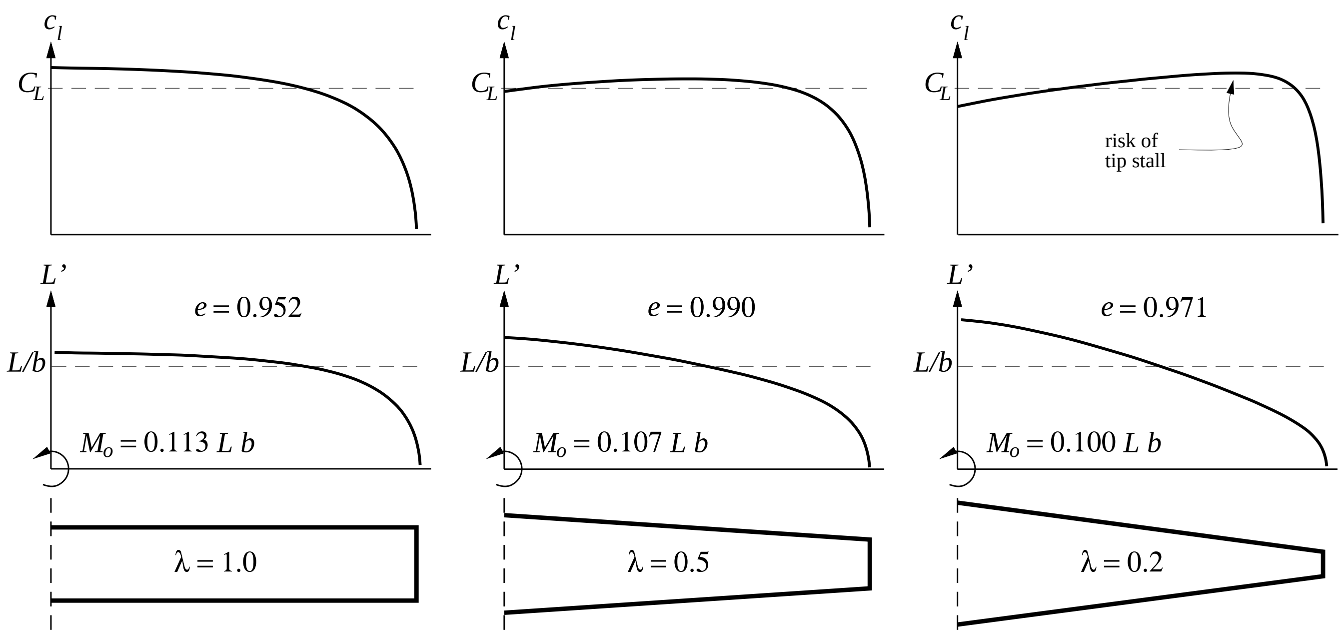


Figure 4: Load distributions, root bending moment, and span efficiency for three taper ratios. All three cases have $AR = 10$, and no wing twist.

More taper (smaller λ) gives the following advantages:
+1) Smaller tip deflection ratio δ/b, due to its larger root chord giving a greater local stiffness, and also due a slightly smaller root bending moment.
+2) A larger span and aspect ratio for a given maximum δ/b, giving a potentially lower induced drag.

More taper also has a number of drawbacks:
-1) It causes the local c_ℓ to have a maximum near the tip, giving the possibility of *tip stall* during flight. When one wingtip stalls before the rest of the wing, the loss of lift at at that tip can give a sudden unexpected roll of the aircraft. This is potentially dangerous when it happens near the ground. In contrast, stall on the untapered wing occurs first at the center, which will not cause a roll control upset.
-2) It gives small chord Reynolds numbers near the tips. This will reduce the maximum c_ℓ that the tips can achieve, and aggravate the tip stall problem even more.

In addition to taper, another wing design consideration is washout. Adding washout (smaller incidence, or $\alpha_{\rm aero}$, towards the tip) gives the following advantages:
+1) It mitigates tip stall problems.
+2) Like taper, it can further unload the tips, allowing a slightly larger span for a given δ/b.

And washout also has drawbacks:
-1) It reduces the local $c_\ell(y)$ towards the tips, so that the entire wing cannot operate close to a

constant best c_ℓ all across the span, which increases average c_d/c_ℓ for the wing.
-2) It can cause problems when the wing is operated at speed where the overall α is decreased. The local $\alpha + \alpha_{\rm aero}(y)$ at the tips can then become negative, giving a negative local $c_\ell(y)$ and large local $c_d(y)$.

Picking a suitable wing taper / washout combination clearly involves tradeoffs. The main tradeoffs are between structural merit, adequate resistance to tip stall, and acceptable high-speed performance.

Online Wing Planform and Twist Analysis

There is a simple but useful online program written by Prof. Ilan Kroo of Stanford, for trying out different planform and twist combinations.

Go to `http://adg.stanford.edu/aa241/AircraftDesign.html`
Click on "6.7 *Wing Analysis Program*".
Try the following parameters:

Aspect Ratio:	10
Sweep:	0
Taper:	0.3
LE Extension:	0
TE Extension:	0
Extension Span:	0.6
Root Incidence:	0
Break Incidence:	0
Tip Incidence:	0

Click on "Compute"
Click on plot (with or without Shift key held) to change overall airplane α to reach design C_L.

The red line shows the $\Gamma(y)$ distribution, which determines the span efficiency e. The blue line plot shows the local $c_\ell(y)$, which can be used to indicate how close to stall each spanwise location is. With the above parameters, the $c_\ell(y)$ shows a peak near the tip, so this wing will be susceptible to tip stall. Two possible fixes are:
1) Increase the **Taper** ratio, e.g. to 0.5 or more
2) Add washout, by setting **Root Incidence** = +2 and **Tip Incidence** = -2, for example.

Both fixes will reduce c_ℓ near the tip and thus alleviate the risk of tip stall. Fix 2) will in addition give smaller structural tip deflections (or a greater span for the same tip deflection), but the smaller tip chords may cause the tip airfoils have high profile drag c_d due to small tip Reynolds numbers. Also, a wing with washout will have possibly negative c_ℓ's near the tip when at high speed or small C_L (you can check this), which may be bad for profile drag. Some design judgement will therefore be required.

You can also use a nonlinear twist by setting the **Break Incidence**, which is at the **Extension Span** (semispan fraction) location. Similarly, a multi-panel taper can be specified via the **LE Exension** and **TE Extension** parameters. Either option will require cutting each wing-half in two separate panels, which may be desirable in any case to make the hot-wire cutting easier.

For reference, the **Incidence** quantities in the program correspond to our $\alpha_{\rm aero}$ angle defined in lecture F8. This is the net effective aerodynamic incidence, including $\alpha_{L=0}$ from airfoil camber.

Foam Properties

7 Apr 09

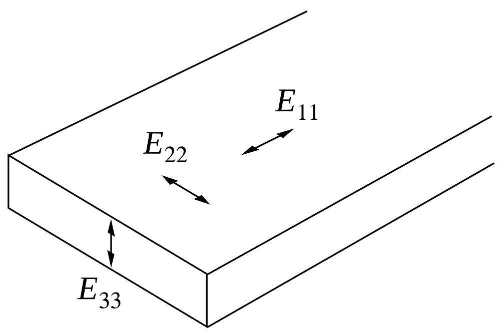
Lab 10 Lecture Notes, Appendix E

Two types of foam can be used for constructing the wings: *Dow Blue* and *HiLoad-60*. Both foams have the same light blue color, and are supplied in 8 ft × 2 ft × 2 in boards. The foams can be easily distinguished by feel. The Dow Blue foam feels relatively soft to the touch on the printed sides, and can be easily dented with a finger. In contrast, the HiLoad-60 feels much harder on its shiny printed sides – almost like wood.

The foams are orthotropic, with significantly different moduli E_{11}, E_{22}, E_{33}, along the three principal directions. The figure shows the definition of the 1,2,3 directions on the foam board. Direction 1 is along the longest (8 ft) dimension, and direction 3 is along the shortest (2 in) dimension.

The material properties are given in the table. The moduli have been measured by 3-point bending tests.

The hard feel of the HiLoad-60 printed sides is clearly due to its relatively large E_{33} value.



Foam	ρ_{foam} kg/m^3	E_{11} MPa	E_{22} MPa	E_{33} MPa
Dow Blue	25.5	12.0	10.0	20.0
HiLoad-60	33.0	11.0	19.0	47.0