MODEL AIRPLANE PROPELLERS

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SYNOPSIS
This document describes the general characteristics of model airplane propellers and their application. It is divided into six sections.

Section 1. Physical Properties
Describes the general physical properties of propellers including why they are shaped the way they are. It describes the basic geometry used in defining and analyzing their performance.

Section 2. Performance Properties
Describes the blade element force relationships, the concept of propeller wind, and how it relates to angle of attack that produces thrust.

Section 3. Normalized Performance Relationships
Contains formulas and graphs defining the three performance coefficients used in determining the thrust, engine power and efficiency of a typical model propeller. Contains an example of how to use the information.

Section 4. Matching Propellers to Engines
Describes basic engine power & torque characteristics. Provides tables and graphs relating engine CID and BHP to suggested ranges of propeller sizes. Provides an example set of calculations showing how to use the tables, graphs and formulas to estimate the performance of a selected propeller and engine.

Section 5. Static Thrust
Describes some experimental static thrust test results and their application. Describes the reasons for propeller unloading in flight and the consequences of choosing a propeller that is either too small or too large for the engine.

Section 6. Attitude Effects, Noise and Safety Tips
Describes the effects on airplane attitude of torque-induced roll, P-factor, gyroscopic precession and slipstream swirling. Has a brief description of propeller noise and its sources. Provides a list of safety tips.

Author's Commentary

References

Model Propellers - Part 1, Physical Properties

Model aircraft propellers are simple looking devices having no adjustable or moving parts. All of the manufacturers produce propellers similar in shape and design. They do vary in minor ways one from another. Given this similarity there must be some underlying reason for it. The purpose of this article is to discuss the 'why' of this similarity and the consequences that flow from it.

Figure 1-1is a picture of a typical model airplane propeller. It is long relative to its width, tapering in thickness from the center hub to the outer tip. The width also varies, flaring slightly outwards from the hub, then tapering to the tip. The blades are also twisted along their length.

Figure 1-1. Typical Model Airplane Propeller

In order to understand this shape it is useful to know what the purpose of a propeller is and how it accomplishes that purpose. The primary purpose is to convert engine power to axial thrust via torque transfer (rotational force) to the propeller. Thrust occurs as the rotating propeller captures air, a fluid, and expels it out the back. The more air it expels per unit of time, the more power converted and the greater the thrust. In order to push the air it must be able to capture or grab the air. If the blades were flat (no twist) and oriented perpendicular to the direction of flight they would not capture any air. The flat blades could be tilted so they 'bite' into the air. This works after a fashion but is very inefficient. So the blades are twisted to improve the efficiency. **Figure 1-2** illustrates what happens to a blade when it is twisted and moves forward for one revolution along the Z-axis.

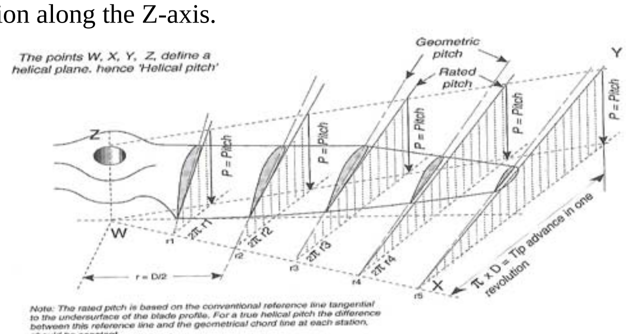


Figure 1-2. Blade Twist or Pitch Illustration

The objective is to make each piece of the blade along its length advance axially the same distance in one revolution. That way each section produces the maximum amount of thrust at the same time. The pitch is defined as the distance traveled forward in one revolution if there were no slippage; i.e. assuming movement through a solid. Note that the angle of the blade relative to the X-Y plane increases from the tip inward toward the hub. This angle is called the blade angle and is measured on the blades lower surface. The geometric pitch is measured to the airfoil chord line.

The propeller acts like a twisted wing with air pressing on its lower surface and pulling via lower pressure on its upper surface. The blade cross-section thus has an airfoil shape to maximize lift and minimize drag. The blade moves slowest in distance around the shaft near the hub and fastest at the tip. Thick airfoil shapes generally perform best at low speeds while thin airfoils perform best at high speeds. The designers then taper the thickness and the width to maximize the lift and drag at each location along the blade. Increasing the width would increase lift but would also increase drag. Designers have determined that the optimum length to width ratio as defined by the aspect ratio is about 7:1. Hence most model propellers have approximately this aspect ratio and hence the same overall appearance.

Another reason for the thickness and width tapering is mechanical. The greatest stresses occur near the hub so thickness there provides the strength needed. Decreasing the thickness and width with radius also reduces the overall weight and reduces the angular momentum, a desirable property for combating the gyroscopic effects of spinning masses.

While two blades are the most common, three or more blades are sometimes used. Since three blades have more lifting area than two blades of the same size, the blade length can be reduced somewhat while maintaining the same forward speed, rpm and engine shaft power. The blade tips move a little slower so they produce less noise and provide greater ground clearance.

Propellers need to be balanced in rotation and aligned symmetrically along the thrust axis. If one blade is heavier than the other vibration may occur that can damage the engine and the airplane. Inexpensive prop balances are available that can be used to check for imbalance. The author's experience with standard propellers is that most are out of balance when new.

If the hub hole is off-center or canted unequal forces will occur on the drive shaft that can damage the engine. Standing behind the plane and looking through the propeller, if the tips appear to produce two overlapping circles the hole is off-center. Standing to the side if the tips form a broad pattern instead of a point-like pattern the hole is canted. In both cases don't use the prop.

Propellers are defined in terms of their diameter and pitch. Diameter is the diameter of the circle swept by the blade tips, measured either in inches or millimeters. In the case of two-bladed propellers it is the tip to tip length. For three-bladed propellers it is twice the length of a blade.

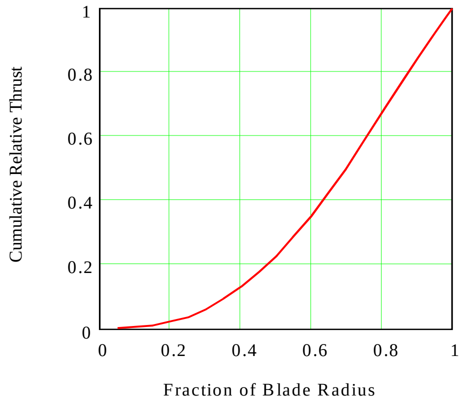


Figure 1-3 Cumulative Thrust versus Relative Blade Radius

Some propeller designs vary the pitch somewhat over the radius in an effort to improve the performance during some operational regime. By convention the pitch is defined in either inches or millimeters at 75% of the blade radius. The 75% radius is a fair choice since about half of the thrust of a propeller occurs on each side of this value. In fact, about 80% of the thrust is generated by the outer 50% of a blade, **Figure 1-3**. Since virtually no thrust is generated around the hub**,** the hub area can be designed for strength. Spinners do not appreciably affect the thrust but do reduce drag of the engine area.

Propellers are marked with their nominal diameters and pitches. The pitch values should be viewed with some skepticism. Pitch measurements (ref 4) made about 1996 on nearly 200 propellers from four major manufacturers resulted in about 30% of them being off by at least a half-inch, in a few cases by more than an inch.

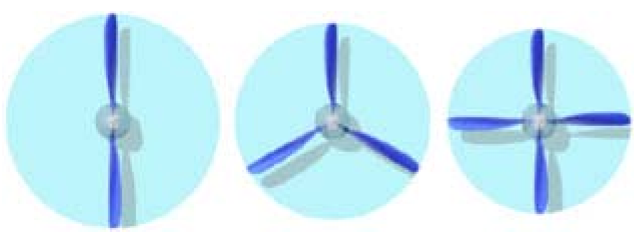
Although most model propellers have two blades, there are versions with three or more blades. The diameters of these propellers can be reduced relative to two-bladed versions while maintaining the same pitch and engine power. An approximate relationship as a function of the number of blades is as follows:

DN = $D2\left(\frac{2}{Bn}\right)^{\frac{1}{4}}$

DN is the diameter of a propeller of N blades
D2 is the diameter of a two-bladed prop.
Bn is the number of blades of the N-bladed prop.

For three blades D3 = 0.904*D2

For four blades D4 = 0.840*D2



This figure shows the resulting relative size for 2, 3 and 4 - bladed propellers having approximately the same performance

These relations are valid only for propellers of the same family having similar blade shapes. You can use the same diameter for different blade numbers if you change the width of the blades. Also the aerodynamic influence of additional blades reduces the power consumption by a small amount, which means, that the replacement 3 blade prop will consume slightly less power than calculated above. On the other hand it will operate at lower Reynolds numbers so that some additional losses can be expected. The formula shown above should get you close to a working solution, though.

Model Propellers - Part 2, Performance Properties

While a propeller is a physically simple device, its performance characteristics are complex. There are four performance parameters, namely, Thrust (T), Thrust Power (Pt), Torque (Q) and Shaft Power (Ps). Considered alone performance is a function of diameter (D), pitch (p), rpm, forward velocity (V) and airfoil shape and dimensions characterized by lift (Cl) and drag (Cd) coefficients. Propeller performance theory was developed in the first half of the 20th century, reaching its zenith during WWII.

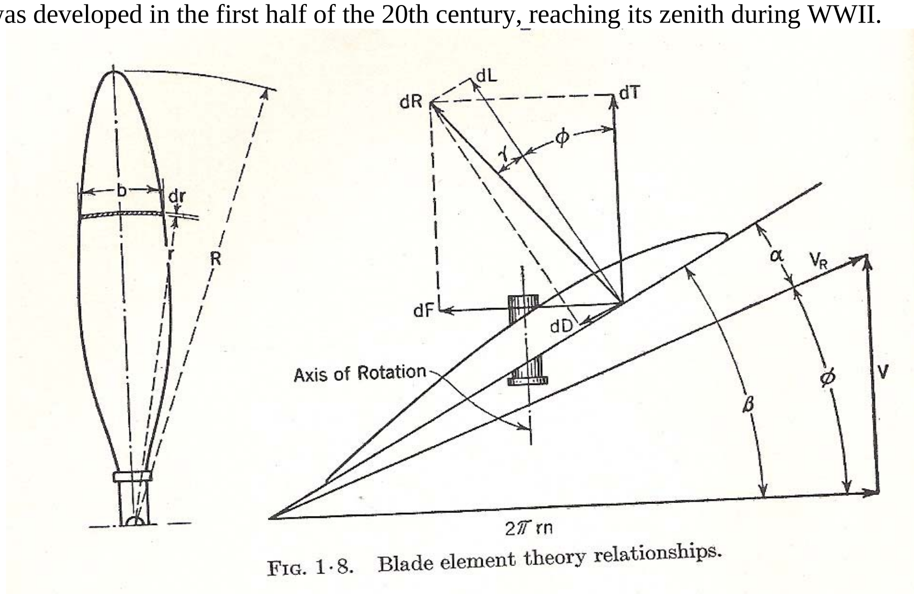


Figure 2-1. Blade Element Force Relationships

The amount of thrust generated by a propeller is minimum at the hub and maximum near the tip. The reason for this variation is due to the way the effective wind velocity varies along the blade. Refer to Figure 2-1. On the right is an arrow labeled V parallel to the axis of rotation whose value (length) is proportional to the forward wind speed. Across the bottom is an arrow labeled 2 π r n (which will be labeled Vr in what follows), which is the wind speed caused by the rotation of the propeller. Note that its value is proportional to the radius r. The two wind vectors combine to form the resultant vector VR (which will be labeled Vp in what follows) which is the source of the pressure on the blade at r providing the lift, dL and the drag, dD. The angle of attack on the airfoil, α , is equal to the difference between the blade angle β and the angle ϕ formed by the wind vectors V and Vr. While V is constant, Vr varies with r so that Vp and ϕ vary with r as well. **Figures 2-2** illustrates how V and Vr vary along the propeller.

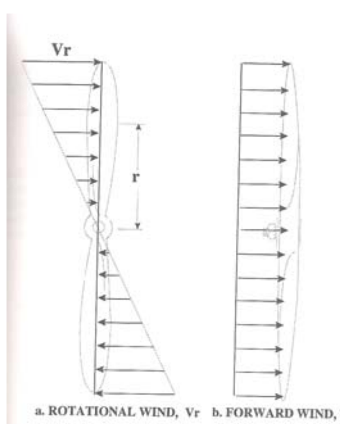


Figure 2-2 Rotational and Forward Wind Vectors Along the Propeller

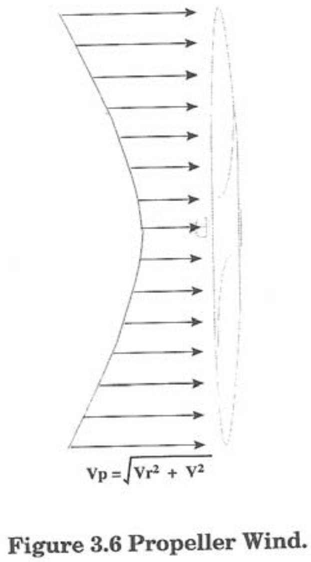


Figure 2-3. Composite Propeller Wind

Figure 2-3 illustrates the magnitude of resultant wind Vp along the propeller length. Therefore the pressure is least around the hub and greatest at the tips. Hence the thrust increases with increasing blade radius position.

Another property of propellers can be derived by examination of **Figure 2-1**. The angle α in the figure is the angle of attack, similar to that of a wing. As it decreases the lift (in this case the thrust) decreases, eventually becoming zero. Assume for the moment that the rpm remains constant so $2\pi rn$ (the horizontal wind component) remains constant. An increase in the forward velocity V decreases α thereby decreasing the thrust. The thrust becomes zero when V = $\frac{np}{1056}$ mph where n is rpm and p is pitch in inches. Thus to achieve maximum speed increase rpm or pitch.

At low forward speeds the attack angle may become so large along part of the blade that stalling will occur. The larger the pitch, the more of the blade will become stalled. The blade will still produce thrust but at less than optimum efficiency.

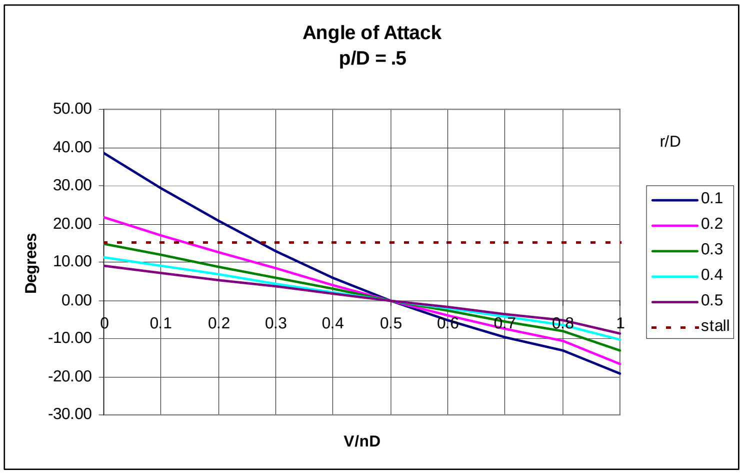


Figure 2-4 Blade Angle of Attack, p/D = .5

In **Figure 2-4** the angle of attack is illustrated for a pitch/diameter ratio of 0.5 with r/D, the radius along the blade divided by the diameter, as a parameter. The ratio V/nD is a measure of the horizontal wind angle. The blade will stall at an angle of attack of around 15 degrees (horizontal dashed line). For this case most of the blade is not stalled, even to small values of V/nD. As the value of V/nD increases beyond 0.5, the attack angle becomes negative, meaning that the propeller is being pushed rather than pulling.

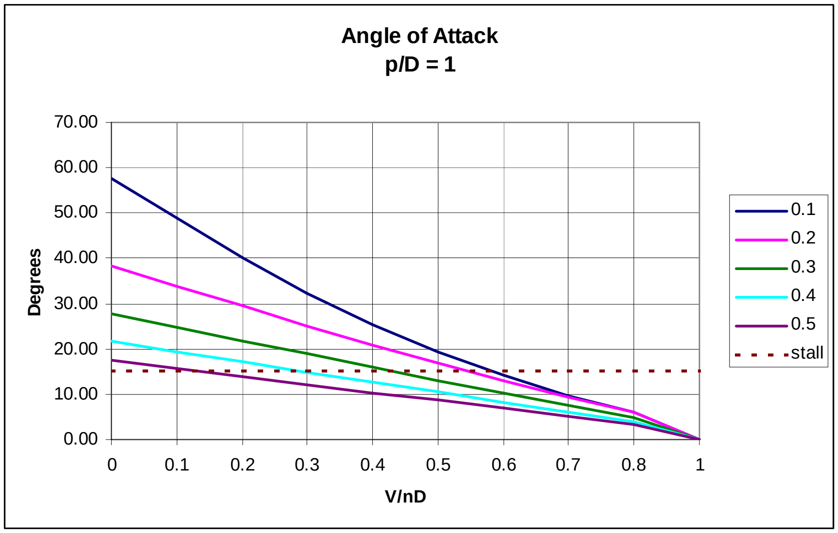


Figure 2-5 Blade Angle of Attack, p/D = 1

Figure 2-5 illustrates what happens for a high-pitch propeller. In this case most of the blade is stalled at low V/nD that typically occurs at high rpm and low forward velocity such as take-off. A plane equipped with such a propeller is likely to be initially sluggish on takeoff but can fly faster than the lower pitch blade.

Model Propellers -Part 3, Normalized Performance Relationships

There is no simple relationship between all of the propeller parameters. Some normalized relationships will be described, without proof, as a way of introduction to some of the complexities. There are three such normalized relationships. They are the thrust coefficient, Ct, the power coefficient, Cp, and the efficiency coefficient, η, all defined in terms of a variable called the advance ratio, J.

Equation 3-1 defines the advance ratio J.

Eq. 3-1 $$J = \frac{V}{nD}$$

where V is the axial or forward velocity of the propeller,
n is the revolution rate
D is the diameter.
A consistent set of units such as ft/sec, rev/sec and ft are required. J is dimensionless. J is an indirect measure of the angle ϕ at the blade tip.

The thrust is given by Equation 3-2

Eq. 3-2 $$T = Ct \times \rho \times n^2 \times D^4 \text{ lbf}$$

ρ is air density equal to 0.002378 slugs/ft^3.
n is the revolution rate in rps
D is the diameter in feet
Ct is the thrust coefficient. It is a function of pitch, diameter, rpm, forward velocity, and blade shape.

Figure 3-1 plots the thrust coefficient as a function of J and p/D, the ratio of pitch to diameter, for a typical model propeller profile

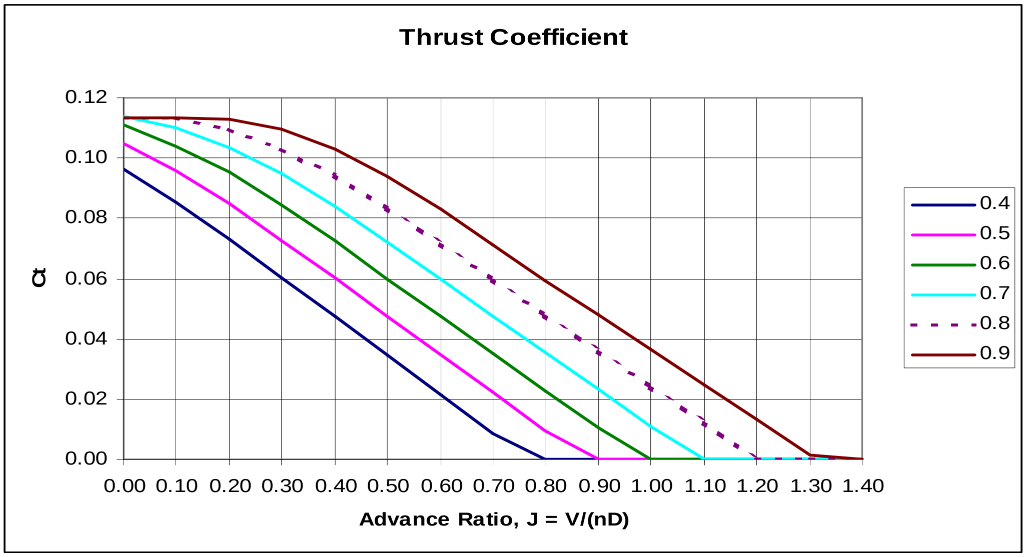


Figure3-1. Thrust Coefficient Graph

All of the curves have the same shape and Ct range of about 0.0 to about .095. Maximum thrust is achieved at the lowest advance ratio, decreasing essentially linearly to 0 as J increases. The values are not reliable in the region at the top where the curves decrease to the left. In this region a portion of the blades become stalled. The greater the pitch ratio the larger the range of J affected by stalling. All of these curves go to zero as J increases, meaning that the thrust also goes to zero. The underlying reason is that that the angle of attack, α , becomes zero so the blade does not provide lift or thrust.

Using this chart and the equations for J and Ct the thrust can be estimated for a given set of conditions. For example:

V = 88 ft/sec (60 mph)
n = 200 rev/sec (12,000 rpm)
D=1 ft (12 in)
p/D = .7

Then J = V/(nD) = 88/(200x1) = 0.44

From the chart, Ct = .056

Then T= $Ct \times \rho \times n^2 \times D^4$ = .056x.002378x $200^2 x1^4$ = 5.3 lbf

Engine (Shaft) Power

The engine power required to produce the thrust is Given by Equation 3-3.

Equation 3-3 Ps = $Cp \times \rho \times n^3 \times D^5 / 550$ hp

The power coefficient, Cp, is a function of J and the pitch to diameter ratio p/D. **Figure 3-2** is a graph of the power coefficient as a function of J and p/D for a typical sport propeller. In this case the power increases as the fifth power of diameter and the cubic power of the revolution rate. Again, the graphs are

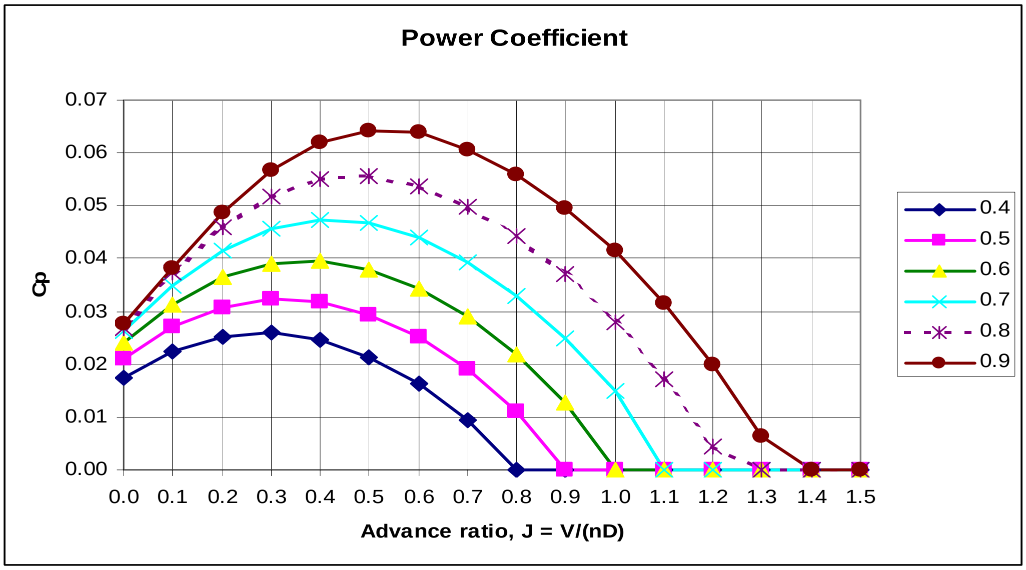


Figure3-2. Power Coefficient versus Advance Ratio, p/D a Parameter

not reliable for small values of J as the calculations do not adequately model stalled operation.

Continuing the example used for the thrust for J = .44, p/D = .7, and from Figure 2-5
Cp = .034

Ps = .034x.002378x $200^3 x1^5$ /550 = 1.17 hp

Power Efficiency

Of interest is the power efficiency defined as the ratio of thrust power to engine power. The higher this ratio the more efficient the propeller. Equation 3-4 defines the power efficiency coefficient. Note that thrust power is defined as the product of the thrust, T, and the forward Velocity, V. This is the conventional definition in which useful work is done only when there is actual motion.

Equation 3-4 $Eff = \dfrac{Ct \times J}{Cp}$

Figure 3-3 plots the power efficiency coefficient as a function of advance ratio, J, and pitch ratio, p/D for a typical sport propeller.

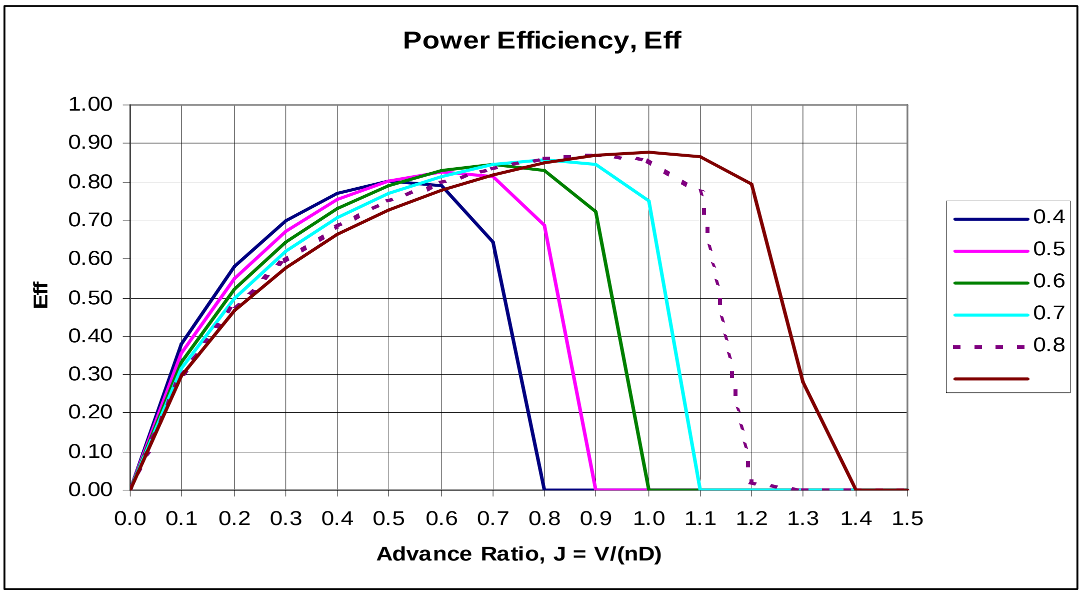


Figure 3-3. Efficiency Coefficient

The efficiency is zero at J=0 when the propeller is not advancing. The peak efficiency is a function of the pitch to diameter ratio, being the least for the lowest ratio and the greatest for the highest ratio. In our example for J= 0.44 and p/D = 0.7 the efficiency is about 0.73 or 73%. Over most of the in-flight operating values for J the efficiency is about 50% or greater.

These graphs were generated using the simple blade element theory. The theory does not take into a number of factors such as tip vortices and inter-blade interaction. As a result it overestimates efficiency, underestimates engine power and underestimates thrust by an estimated 5 to 10%. The graphs do provide a means for comparison between propellers but the process is tedious if done by hand.

Model Propellers - Part 4, Matching Propellers to Engines

The description in Part 3 provides a means for examining the performance of a propeller in isolation but is of little use without taking into account the additional limitations when attached to an engine. Glow-fueled engines (the only ones included here) have maximum power and rpm limits that in turn restrict to some degree the propeller dimensions and performance for a given airplane. **Figure 4-1** is a graph illustrating how power and torque vary with rpm for typical 2 and 4-stroke engines having the same maximum power.

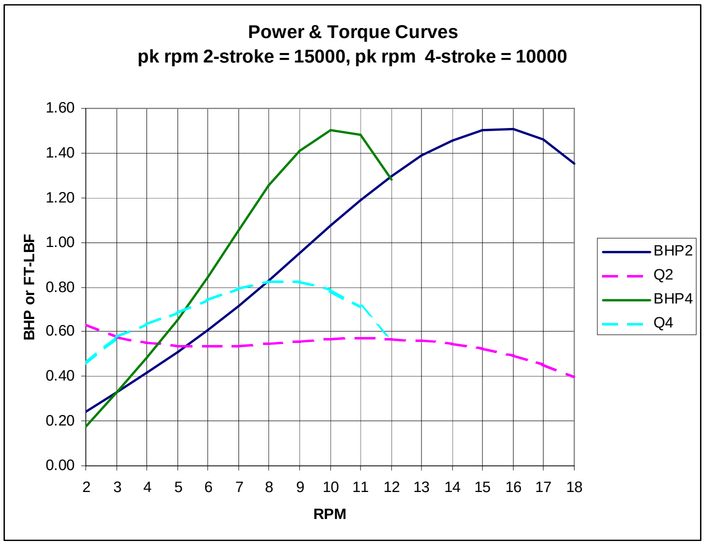


Figure 4-1 Typical Engine Power & Torque Curves

Brake horsepower is the maximum power that an engine can produce at a given rpm without stalling. Hence it is a not-to-exceed limit. Practically the maximum usable power is somewhat less than this value.

Power and torque are related according to Equation 4-1.

Eq. 4-1. $$P = \frac{2\pi n Q}{33000} \text{ hp}$$

Q is in ft-lbf
n in rev/min

Knowing the power automatically defines the torque or visa - versa. In fact, power is determined by measuring torque and calculating the power.

The peak torque of the 4-stroke engine is greater than that of the 2-stroke engine so the 4-stroke can generate more twisting force and therefore support a larger diameter propeller.

An issue for determining what size propeller to use with a given engine is determining what the BHP is given only the cubic inch displacement (CID). **Figure 4-2** provides an estimate of this relationship derived from available engine data sheets. The curves are a best linear fit to the data available. There was some small variation around these curves, probably caused by slightly different implementations.

There is a linear relationship between CID and BHP since power is related to the amount of fuel burned which in turn primarily the CID determines. For the same CID the 4-stroke engines have approximately half the BHP. Conversely for the same BHP the 4-stroke requires twice the CID of the 2-stroke (follow the arrows).

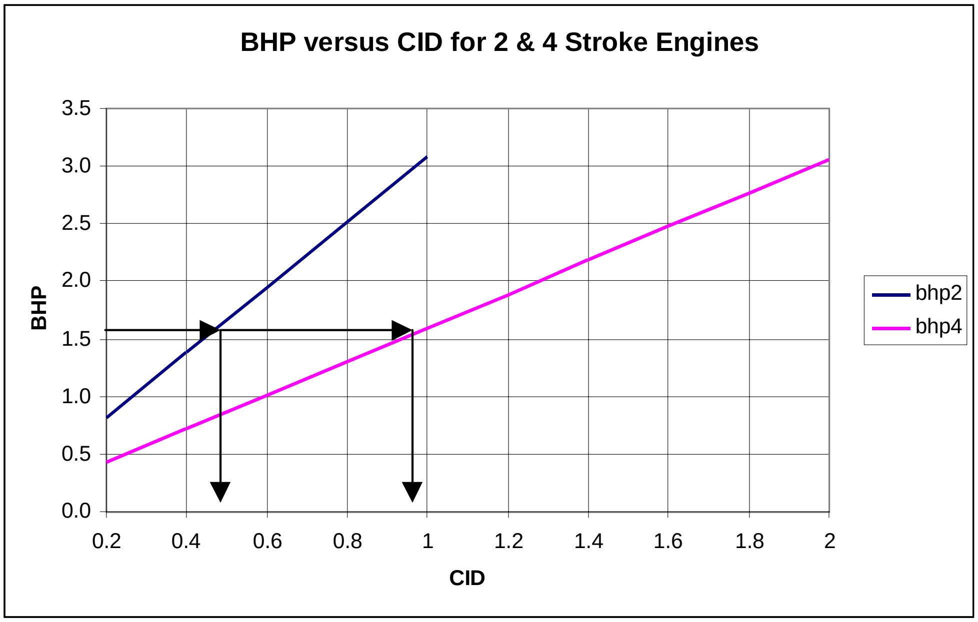


Figure 4-2. Relationship between BHP and CID for 2 & 4-stroke engines

Because there are so many variables in relating propeller dimensions to performance for a given engine and because the theory is complex, the author has been unable to find a satisfactory way of analytically selecting propellers without a computer program. An alternative is to use engine manufacturer's propeller recommendations.

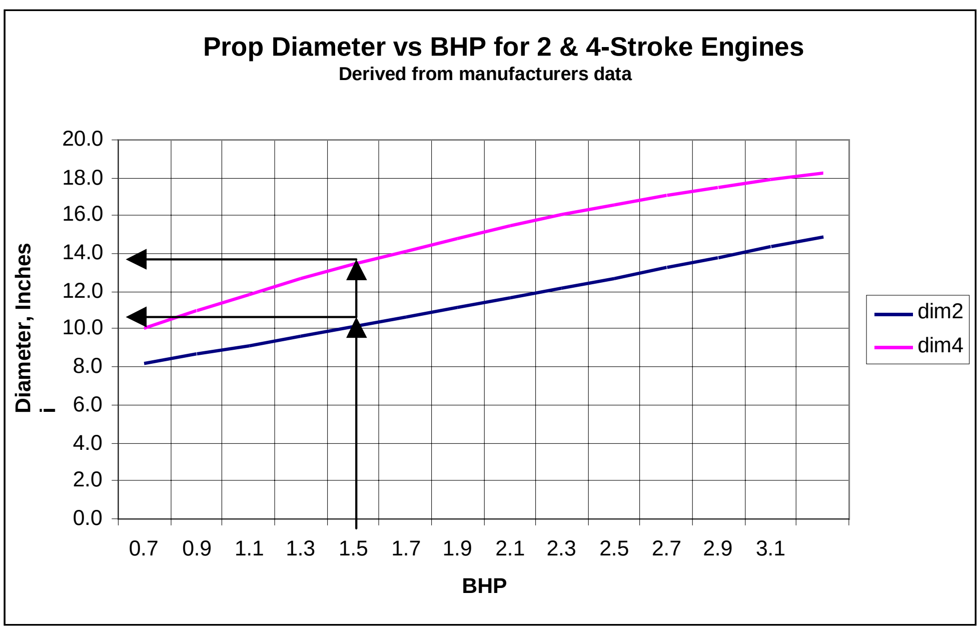


Figure 4-3. Nominal Recommended Propeller Diameter for a Given BHP Requirement

Figure 4-3 plots recommended starting propeller diameters as a function of BHP for 2 & 4 stroke engines. The recommended propellers were found listed against CID and then using **Figure 4-2, Figure 4-3** was derived. The arrows indicate the recommended starting propeller diameters for a BHP of 1.5 HP; 10 inches for the 2-stroke and 14 inches for the 4-stroke. The pitch to diameter ratio for these propellers varies somewhat in the range from about 0.45 to 0.6. An interesting observation about the data available is that for the same CID the recommended diameters are nearly the same, the 4-stroke being typically 1-inch greater. **Tables 4-1 and 4-2** list the propeller data from which **Figure 4-3** was derived. These charts were copied from reference 5.

Table 4-1. Prop Chart for Two-Stroke Glow Engines

Alternate Propellers	Starting Prop	Engine Size
5.25x4, 5.5x4, 6x3.5, 6x4, 7x3	6x3	.049
7x3,7x4.5,7x5	7x4	.09
8x5,8x6,9x4	8x4	.15
8x5,8x6,9x5	9x4	.19 - .25
9x7,9.5x6,10x5	9x6	.20 - .30
9x7,10x5,11x4	10x6	.35 - .36
9x8, 11x5	10x6	.40
10x6,11x5,11x6,12x4	10x7	.45
10x8,11x7,12x4,12x5	11x6	.50
11x7.5, 11x7.75, 11x8,12x6	11x7	.60 - .61
11x8,12x8,13x6,14x4	12x6	.70
12x8,14x4,14x5	13x6	.78 - .80
13x8,15x6,16x5	14x6	.90 - .91
15x8,18x5	16x6	1.08
16x10,18x5,18x6	16x8	1.20
18x8,20x6	18x6	1.50
18x10,20x6,20x8,22x6	18x8	1.80
18x10,20x6,20x10,22x6	20x8	2.00

Table 4-2. Prop Chart for Four-Stroke Glow Engines

Alternate Propellers	Starting Prop	Engine Size
9x5,10x5	9x6	.20 - .21
10x6,10x7,11x4,11x5.11x7,11x7.5,12x4,12x5	11x6	.40
10x6,10x7,10x8,11x7,11x7.5,12x4,12x5,12x6	11x6	.45 - .48
11x7.5,11x7.75,11x8,12x8,13x5,13x6,14x5,14x6	12x6	.60 - .65
12x8,13x8,14x4,14x6	13x6	.80
13x6,14x8,15x6,16x6	14x6	.90
14x8,15x6,15x8,16x8,17x6,18x5,18x6	16x6	1.20
15x6,15x8,16x8,18x6,18x8,20x6	18x6	1.60
18x12,20x8,20x10	18x10	2.40
18x10,18x12,20x10	20x8	2.70
18x12,20x10	20x10	3.00

Example Thrust and Engine Power Calculations

The preceding information can be used to estimate the thrust and engine power required as a function of forward velocity for a specific example.

Assumptions
4-stroke engine, .91 CID, peaks atrpm = 10000.
From **Figure 4-1** BHP = 1.5 hp.
From **Table 4-2** the start propeller size is 14x6.

The defining equations are as follows:

T= $Ct \times \rho \times n^2 \times D^4$ lbf

Ps = $Cp \times \rho \times n^3 \times D^5 / 550$ hp

J = $\dfrac{V}{nD}$

In these equations n is in revs/second, D is in feet, V is in feet/second
Then:
n = 11000/60 = 183 rps
D = 14/12 = 1.17 ft
nD = 183 x 1.17 = 254
Vftps = Vmph x 1.467

And:
T/Ct = (.002378)x(183)^2 x(1.17)^4 = 147.5

Ps/Cp = (.002378)x(183)^3 x(1.17)^5/550 = 58.1

Process:
1. For each Vfps calculate J
2. For each J find Ct from **Figure 3-1** and p/D = 6/14 = .43 (interpolate)
3. Calculate T = Ct x 147.5
4. For each J find Cp from **Figure 3-2** and p/D = .43 (interpolate)
5. Calculate Ps = Cp x 58.1

Table 4-3. Example Calculation of thrust and engine power as a function of velocity

Vmph	Vftps	J=Vftps/254	Ct	T=147.5*Ct	Cp	Ps=58.1*Cp
20	29.3	0.14	0.06	8.9	0.019	1.1
30	44.0	0.21	0.052	7.7	0.019	1.1
40	58.7	0.27	0.045	6.7	0.018	1.0
50	73.3	0.34	0.034	5.0	0.017	1.0
60	88.0	0.41	0.026	3.8	0.016	0.9

This process can be repeated for other propeller dimensions. **Figure 4-4** plots the thrust results for propellers of dimensions 14 x 6, 14 x7 and 15 x6. **Figure 4-5** plots the shaft power results for the same combinations.

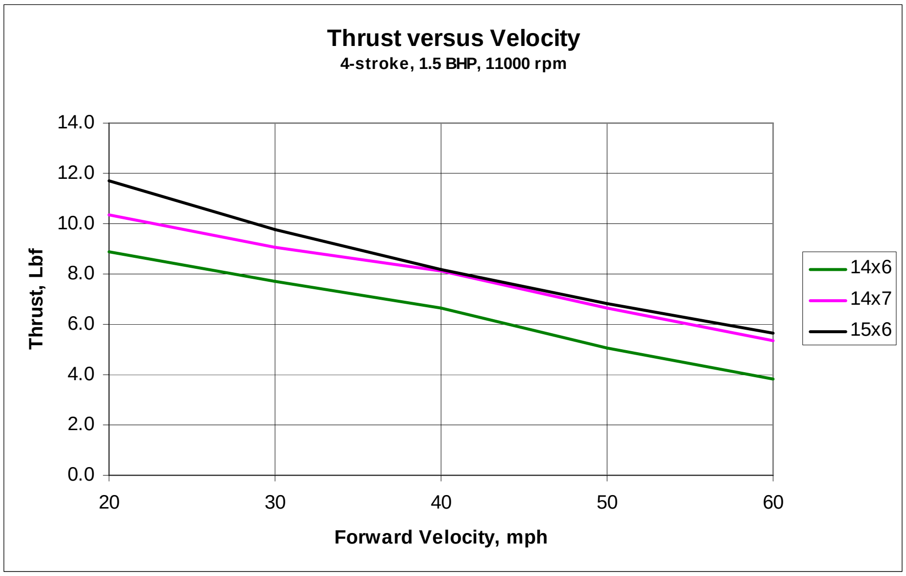


Figure 4-4. Example Thrust versus Velocity Graph

Using the 14 x 6 propeller as a reference, increasing the pitch by one inch from 6 to 7while keeping the diameter at 14 inches increases the thrust by approximately 25%. Increasing the diameter from 14 inches to 15 inches while keeping the pitch at 6 inches increases the thrust by about 25% at the higher speeds but increases it by more than 30 % at the lowest speed. More will be said about this phenomenon in a discussion on static thrust.

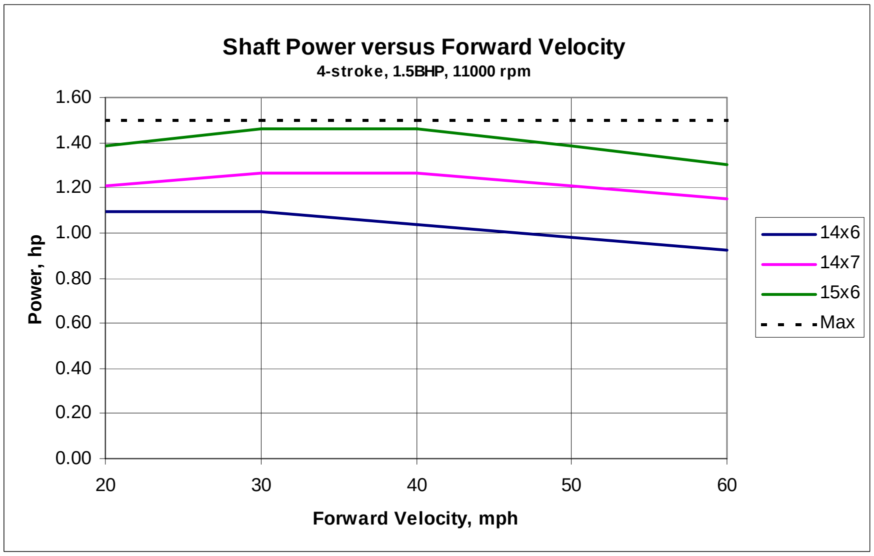


Figure 4-5. Example Engine Power versus Forward Velocity

The shaft power does not vary much with velocity. Increasing the pitch from 6 inches to 7 inches (a 17% increase in pitch) increases the power demand by about 20%. Increasing the diameter from 14 to 15 inches (an increases of 7%) increases the power by about 30 %. The power requirement of slightly less than 1.5 hp is probably not achievable with this engine. If such a propeller were placed on this engine the rpm would decrease making the power and thrust decrease until equilibrium was achieved.

Model Propellers - Part 5, Static Thrust

Static thrust is the thrust generated when the forward wind velocity, V, is zero. The equations and coefficient graphs given in Part 3 of this document are generally not reliable under static conditions. Donald W. Brooks has published a document (ref 4) that describes extensive experiments and measurements he made on about 200 different model propellers under static conditions. His results are applicable to many static conditions. Among his findings are the following items.

For a given propeller the thrust changes as the square of the rpm.

$$T2 = T1\left(\frac{N2}{N1}\right)^2$$

For constant rpm and a given propeller series (same manufacturer, same design) in which the pitch remains constant the thrust changes as the fourth power of the diameters.

$$T2 = T1\left(\frac{D2}{D1}\right)^4$$

These two findings mean that if the thrust of a particular propeller operating at a specific rpm is known (by measurement), then the thrust can be estimated when rpm is changed or diameter is changed.

The conclusions on pitch changes are not as clear. **Figure 5-1** is a scatter diagram of the measured thrust coefficient, Ct, as a function of pitch/diameter ratio for Zinger wooden props.

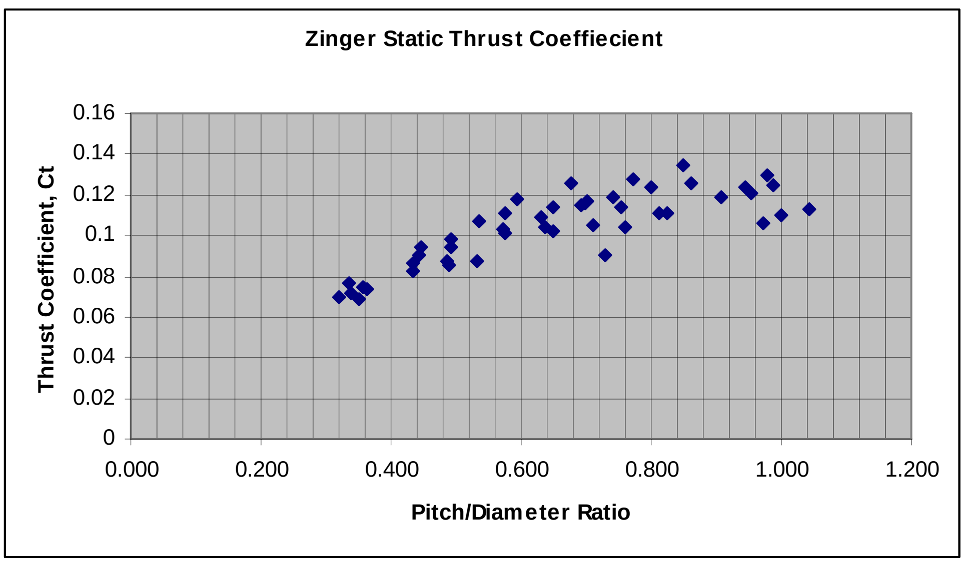


Figure 5-1 Zinger Static Thrust Coefficient vs p/D Ratio

The thrust coefficient increases more or less linearly for p/D ratios less than about 0.6. For greater ratios the values are more scattered and show a generally flat trend as the p/D ratio increases. The lower ratio propellers are operating with relatively little stalling while the higher ratios are show major stall characteristics. **Figure 5-2** is a similar plot for APC Scimitar molded propellers.

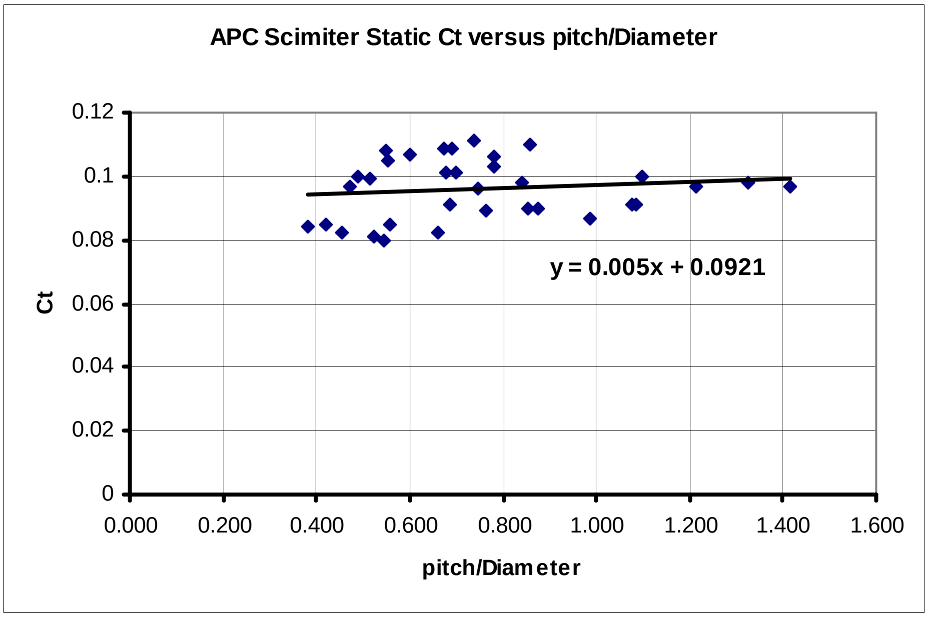


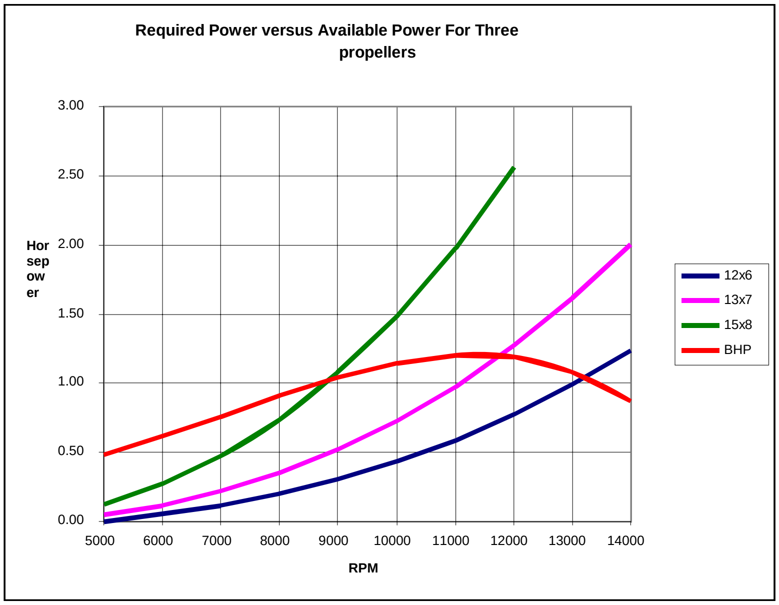
Figure 5-2 APC Scimitar Static Thrust Coefficients

These propellers have a different characteristic with the static thrust coefficient showing a fairly flat trend with p/D but with considerable scatter. The data seems to indicate that these props were designed to have this characteristic.

The conclusion is that there is no satisfactory way to predict the effects of pitch on thrust without making measurements. Brooks describes how to make these measurements. Measuring thrust is easy. Attach a scale to the tail of the airplane and anchor the scale to something solid. Fire up the engine and make the measurement. Measure the rpm at the same time and compute the Ct from the formula in Part 3 of this document.

Propeller Unloading

A well-known phenomenon is that of propeller unloading in which the rpm increases in flight compared to that achieved under static conditions. The reason is that under static conditions the load may be greater than the engine can support so it slows down to reduce the load until equilibrium is attained. As the forward wind velocity increases the load decreases as the thrust decreases and the overall efficiency increases. The engine then can speed up until it reaches equilibrium again. If the load is too small the engine can over-rev, potentially resulting in damage or early wear out. **Figure 5-3** shows what happens if the propeller is either to large or too small for the engine. If the propeller is too small (12 x 6) the engine over revs. If the propeller is too big (15 x 8) the engine slows down or "lugs". The 13 x 7 propeller is well matched as it uses the maximum available power of the engine.



V = 40 mph

Figure 5-3 An Illustration of Using a Too large or Too Small a Propeller on Engine Performance

Model Propellers - Part 6, Attitude Effects and Noise

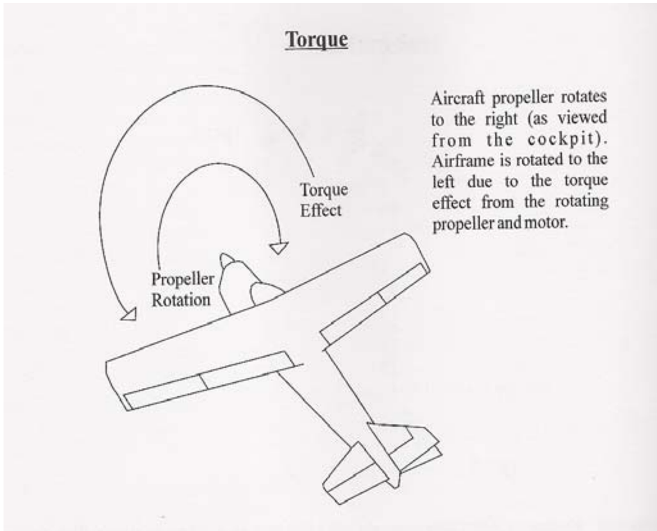


Figure 6-1 Torque Induced Roll

Figure 6-1 illustrates the torque-induced roll caused by the rotation of the propeller. Because the mass of the plane is considerably greater than that of the propeller and because the wings resist the rolling motion, this effect is minor in most modes of flight. (Figures 6-1... 6-4 taken from reference 3).

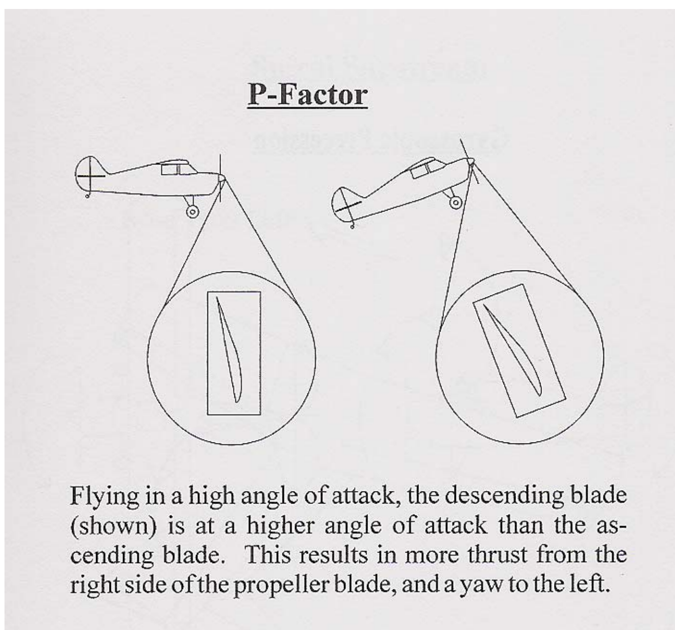


Figure 6-2 P-Factor

Figure 6-2 illustrates P-factor, a cause of yaw when the model changes attitude in pitch or flies at angle to the forward wind as in a climb. When pitched up, the P-factor causes a leftward yaw. When pitched down, it causes a rightward yaw. The effect is proportional to forward wind speed and angle, becoming more pronounced as speed increases.

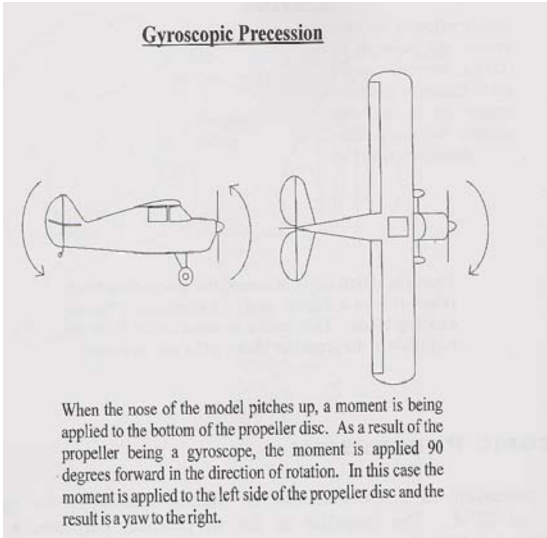


Figure 6-3 Gyroscopic Precession.

When the nose of the model pitches up, a moment is being applied to the bottom of the propeller disc. As a result of the propeller being a gyroscope, the moment is applied 90 degrees forward in the direction of rotation. The moment is applied to the left side of the propeller disc resulting in a yaw to the right (**Figure 6-3**). If the pitch is downward, the yaw is to the left. The effect is most noticeable at low speeds when the dynamic forces of air moving across the countering control surfaces is minimum.

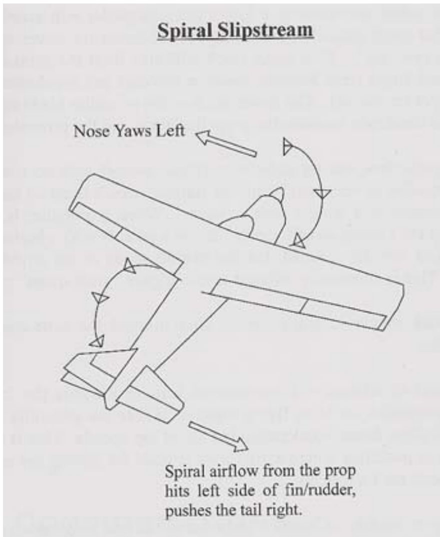


Figure 6-4 Slipstream Effects

Figure 6-4 illustrates how the spiraling airflow from the propeller strikes the left side of the rudder with greater force than on the right side. The effect is to cause a leftward yaw. As the forward speed increases, the spiral tends to straighten out resulting in lesser yawing.

Table 6-1 summarizes the effects of P-factor, gyroscopic precession and slipstream on yaw.

Table 6-1 Propeller-Induced Yaw Summary

Pitch Direction	P-Factor	Gyroscopic Precession	Slipstream
Up	Left	Right	Left
Down	Right	Left	Left

While these effects are present in all modes of operation, they are most noticeable on take-off. Consider the takeoff effects of nose wheel and tail wheel models.

Tricycle Gear Takeoff Yaw

During the initial roll there is no gyroscopic or P-factor yawing (The rotation axis is lined up with the forward wind).

The slipstream tends to cause a left yaw, corrected by right rudder and the nose wheel-to- ground contact.

On rotation, the nose pitches up.

Precession causes a right yaw.

The slipstream causes a left yaw as nose wheel not engaged and rudder not sufficient.

P-factor causes a minor left yaw, as forward speed typically is low.

The direction of yaw is most likely to the left.

Tail Wheel Takeoff Yaw

During the initial roll the tail wheel is on the ground, the nose pitched up.

The slipstream causes left yaw, corrected by rudder and tail wheel.

P-factor produces minor left yaw as the forward speed is typically low.

No precession as there is no tipping of the rotation axis.

As the nose pitches down & the tail wheel comes up, precession causes left yaw.

The slipstream continues to cause left yaw, no longer held back by the tail wheel.

P-factor produces minor right yaw, as forward speed tends to be low.

The result is left yaw.

On rotation the nose pitches up.

Precession introduces right yaw.

The slipstream continues left yaw.

P-factor causes left yaw as the speed increases.

The direction of yaw is most likely to the left.

Propeller Noise

There are three types of noise generated by a propeller. The pulsing of the air as the blades rotate generates periodic noise. The pulse rate is equal to the rotation rate per second multiplied by the number of blades. For example, consider a two-bladed prop turning at 12,000 rpm (200rps). Then:

Pulse rate = 200 x 2 = 400 pulses per second.

The turbulence of the air passing over the blades also generates a random noise component whose magnitude increases with increased rpm.

Transonic noise is created when airflow over the top surface at or near the tips approaches or exceeds the speed of sound. This flow occurs typically when the tip speed is on the order of 0.55 to 0.7 times the speed of sound since the curved upper surface of the blade causes the sir to speed up relative to the bottom surface. **Figure 6-5** plots the approximate propeller diameter boundary for transonic noise generation as a function of rpm (ref 7).

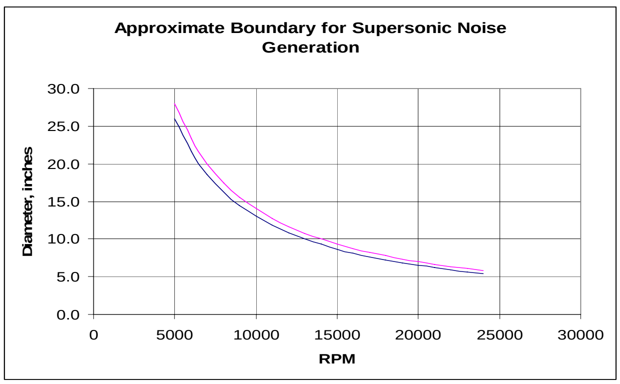


Figure 6-5 Transonic Noise Graph

Safety Tips

Following are some safety-items that, although they seem elementary, still are worth repeating regarding propellers and their use.

- Install the prop with the curved side of the blade facing forward and tighten the prop nut or bolt with the proper size wrench.
- Recheck the tightness of the nut or bolt often, especially on wood props, which tend to compress and loosen more often.
- When starting the engine, keep spectators at least 20 feet clear of the model and out of the path of the propeller.
- Keep hands away from the prop as much as possible. Use a chicken stick or and electric starter.
- Keep face and body out of prop arc as engine is started and run.
- Make all adjustments from behind the prop except on pusher prop installations.
- Never throw anything into the prop to stop the engine. Use a kill switch or pinch off the engine's fuel supply.
- Discard any prop with nicks, scratches, splits, cracks or any other sign of damage. Never attempt to repair, alter or bend a prop.
- Don't run an engine in areas of loose gravel or sand for the prop can throw such material into your face and eyes. It's not a bad idea to wear eye protection.
- Keep loose clothing, shirtsleeves, and other such items away from the prop and avoid carrying objects that can fall into the prop such as pens, screwdrivers, etc.
- Be sure to keep the glow driver wire out of the prop path.
- If a spinner is used, be certain that it's edges are not in contact with the propeller blades.

Author's Commentary

The subject of propellers has been something of a mystery, at least as how to choose one for a particular application. When modeling friends are asked how they choose, the answers generally are vague, such as use the manufacturer's recommendations, or try different props until you find one you like. Articles on the subject, which tend to be short and vague also, are of little help. Prop manufacturer's sites aren't much helping either. I wanted something more tangible, preferably something that could be computer modeled so that it would be possible to at least get some idea how a particular propeller would perform prior to using it.

In the winter of 2008 I began a search for answers and methodology. The best theoretical source found was from 1930! (Reference 1). So I began building a computer model using that text. The initial model, the one I still use, provided satisfactory results for a typical propeller in isolation but lacked any connection to engine performance. The next step was to try to find typical model glow engine power & torque versus rpm graphs with no luck. The substitute was to scale two-cycle snow mobile engine data to the desired range. While there is some error in this approach, fueled engines have similar transfer curves across all types. Then the model was expanded to match engine and propellers. That program was used to generate the figures and graphs in this document.

Needless to say there are a lot of assumptions built into the model so the results should be viewed with some caution. The model is especially useful in comparing propellers as the assumptions tend to be neutralized. The original model is written in Mathcad, a natural language math program. It is not user friendly nor is it well annotated, so don't ask for a copy. There is a somewhat simpler program written in Excel which is available upon request. It can be used to compute thrust, torque, required engine power and available engine power as a function of diameter, pitch, rpm, velocity and peak engine power.

Other information contained in the document was extracted from various sources, most of which are listed in the references.

When our flying club was seeking newsletter articles from members, I thought it would be possible to write a series of short one or two page articles in a series about propellers. However, as the writing progressed, it became apparent that brevity would not do justice to the subject. As a consequence this document has been extended to make it more complete.

If you or anyone you know has information to improve or supplement this document please contact me.

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wbgarner08@verizon.net

References

1. Weick, Fred E., "Aircraft Propeller Design", McGraw Hill, 1930. Out-of-print.
Provides a step by step development of three propeller theories, all related. The best source found. Written for engineers.

2. Simons, Martin, "Model Aircraft Dynamics", 4th Edition, 1999, Special Interest Model Books, UK.
Contains a chapter on airplane props and one on helicopter blades. Not much math is included.

3. Stoops, Scott, "The Pilots Guide to Mastering Radio Controlled Flight", 2nd Edition, 2005. RC Pilot Guide, Mead, Colorado.
Has a chapter on the effects of propellers on airplane attitude.

4. Brooks, Donald W., "Proptalk", 1997, ARPI, Idaho Falls, Idaho
This book describes static operation derived from experiments on about 200 propellers.

5. www.modelflight.com
This site is the source for the prop chart tables in this document. Not much else here.

6. www.mh-aerotools.de
The best web source found for descriptions of how propellers work with some practical application information. Also contains a downloadable Java program for designing propellers that is recommended only for those who really want to delve deeply into propeller design.

7. Pappas, Dean, "If It Flies ... Model Aircraft Noise Abatement", Model Aviation, October 1997, pp 94-96.
This article is the primary source for the information on noise. It provides more detailed information on the subject.

8. Chevalier, Howard, "Model Airplane Propeller Selection and Performance For the Modeler", 1997, Challenge Engineering. Out-of-print.
This book provides an introduction to propeller theory and operation with lots of drawings & graphs. Has a step by step procedure for selecting propellers using graphs and formulas that is tedious. Original book had a PC diskette containing a program to do the calculations.