Helicopter Aerodynamics Volume II

Ray Prouty's Columns - 1992 - 2004

Ray Prouty
Eagle Eye Solutions, LLC

Table of Contents

Chapter 13
The Truth About Propellers

Compound helicopters, gyroplanes, and tilt-rotor aircraft all use propellers to provide the horizontal force that pure helicopters get from their rotors. While the propeller relieves the rotor from the requirement of providing forward thrust, there are some physical effects that have to be considered.

Size matters

For any aircraft, the more air its lifting or thrusting device can work on, the more effective it will be. This is the reason long-range airplanes and high-performance sailplanes have such long wings and why helicopters have such big rotors.

The same thing applies to propellers and jet engines: the bigger, the better. The effectiveness of a large propeller working with a lot of air is illustrated by the fact that the venerable Navy P-3 and the Air Force C-130 propeller-driven airplanes have not yet been replaced by any version of a jet-propelled airplane. This is because a jet engine—even a high-bypass one—will have to make up for the limited amount of air it has to work with by using more fuel to produce the same thrust. (The propeller also gives the C-130 a short-field advantage by producing more static thrust for take-off and more reverse thrust for landing than could be achieved with a jet engine of the same core size.)

Helicopters and gyroplanes

The helicopter rotor is a quite effective propulsive device in forward flight until it runs into limitations at about 200 knots. It is working with a large amount of air compared to a propeller. An illustration of this can be obtained by comparing the performance of a helicopter and a gyroplane of similar basic design.

For this exercise, imagine converting a Robinson R-44 to a gyroplane by replacing the tail rotor with an eight-foot diameter pusher propeller at the back of the engine compartment and using twin booms to support the tail surfaces. Another change would be to use untwisted main rotor blades in place of the twisted blades used to improve R-44 hover performance.

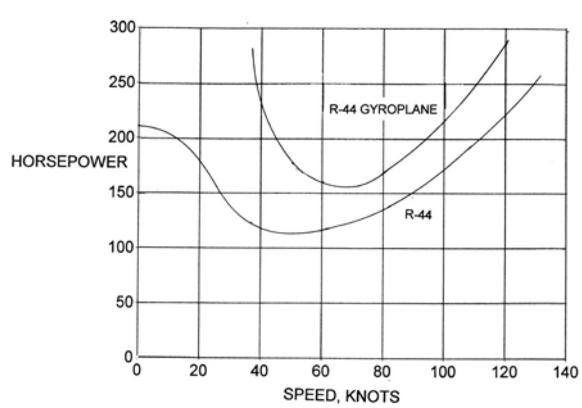

Figure 13-1 Power for hypothetical R-44 Gyroplane

Assuming no change in the gross weight, drag characteristics, blade dimensions, or tip speed and a propeller that operates such that only 10% of the power is overcoming blade skin friction (a very good propeller, indeed), we can generate a speed-power plot for each aircraft as shown in Figure 13-1. It can be seen that the gyroplane version of the R-44 requires more power than the helicopter version. This is because the propeller is working with much less air than the rotor.

It can be argued that if the tip speed of the gyroplane were reduced, the two power curves would be closer together. This is a possibility since the rotor in autorotation is operating with a comfortable margin from retreating blade stall. There is, however, a consideration that has to be kept in mind. The gyro's blade loading coefficient, C_T/σ, would be increased and might reach its limit during flight at altitude or during a maneuver.

Analysis differences

The analysis of propellers in forward flight and rotors in hover begins with the same equations that determine the induced velocity at the prop/rotor disc. It then uses this velocity to calculate the rate of change of momentum in the air to find the induced power.

For the helicopter rotor in hover, the analysis results in the well-known plot of pounds of thrust per horsepower (power loading) versus disc loading. For the propeller, a similar analysis produces a plot of "ideal propulsive efficiency" versus a parameter that we can recognize as the ratio of disc loading to the dynamic pressure of forward flight. The two plots are presented in Figure 13-2 and Figure 13-3.

For the rotor, the high power loading is when the disc loading is low. Here the induced velocity at the disc is low compared to the rotational speed and as a result the lift vector on each blade element is tilted rearward only slightly. Because of this, the induced power is low and one horsepower can produce a high value of thrust (this is why man-powered designs use such large rotors). At the other end, where high disc loadings result in high induced velocities, one horsepower can generate only a limited amount of thrust.

For the propeller, the curve shows similar characteristics. At the left-hand side, the disc loading is either very low or the dynamic pressure is very high. In either case, the induced velocity through the disc is low compared to the forward speed. The result is that the ideal propulsive efficiency approaches unity. On the right-hand side, where the disc loading is high—or the forward speed is low—the ideal efficiency falls off just as power loading for the hovering rotor does.

The minimum propeller power can be determined by multiplying its thrust by the speed in knots and then dividing by the ideal efficiency and by 325 to obtain horsepower.

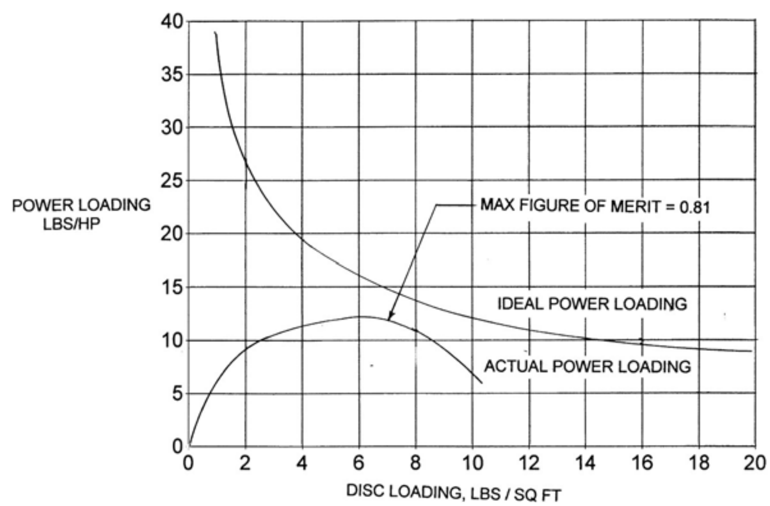

Figure 13-2 Power Loading vs. rotor disc loading

With a little algebraic manipulation, the factor on the horizontal axis of Figure 13-3 can be shown to be the ratio of equivalent flat plate drag area (drag/dynamic pressure) to propeller disc area. Equivalent flat plate area is a useful parameter for the helicopter engineer since it is essentially constant for a given helicopter and accounts for almost all of the drag that the rotor has to overcome.

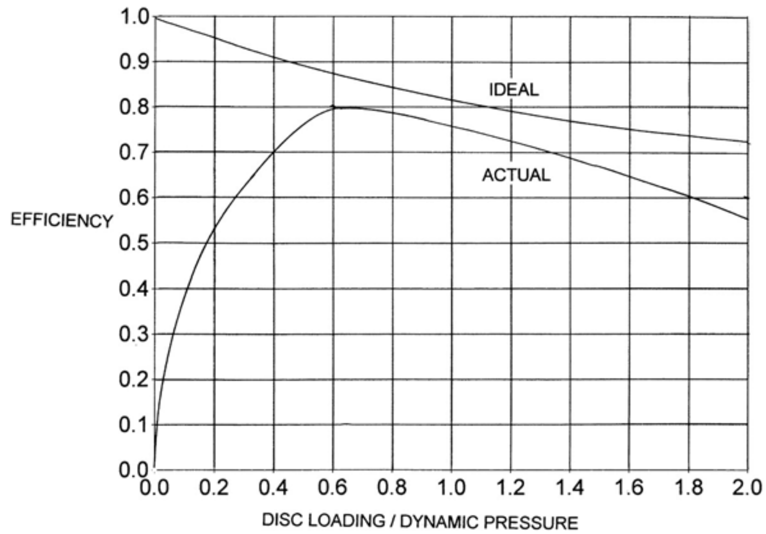

Figure 13-3 Efficiency vs. propeller disc loading

Airplane aerodynamicists don't use it because their total drag is made up both of that of the airframe and of the wing's induced drag. However, at the optimum cruise speed where the lift-to-drag ratio is highest, the concept is useful, since here the induced drag of the wing is equal to the drag of the rest of the airplane. Thus the equivalent flat plate area for determining ideal propeller efficiency of an airplane at cruise can be taken as twice that corresponding to airframe drag. The same relationship does not apply to a gyroplane since the power required to drag the rotor through the air is a function of more than just its induced drag.

On most airplanes and gyroplanes, the ratio of equivalent flat plate area to propeller disc area will be less than one, and for tiltrotors, it will be much less which leads to a high ideal propulsive efficiency. Jet-powered aircraft, on the other hand, suffer from a loss of efficiency because their exhaust nozzle areas are small. This is why modern jet transports are increasing this area by using high-bypass engines

Facts of life

For both the rotor and the propeller, we have so far been concerned with ideal conditions meaning that no blade element profile—or skin friction—drag had to be accounted for. When this is considered for a rotor, we talk about a "Figure of Merit" which decreases the amount of thrust one horsepower can generate since some power is being used to overcome the skin friction of the blades. Figure 13-2 includes a plot of the power loading that corresponds to a typical rotor. The Figure of Merit is the ratio between the actual and ideal values. It is highest where the two curves are closest to each other. For the rotor shown, the maximum Figure of Merit occurs at a disc loading of about 6, but by changing blade area, the designer can move the point to be at his design disc loading.

The highest Figure of Merit will be obtained when every blade element is operating at the angle of attack for its maximum lift-to-drag ratio. The rotor designer has control of this by varying twist, taper, and tip speed as well as by choosing airfoils with good aerodynamic characteristics. In practice, however, a rotor optimized for hover will not have good performance in forward flight, and so some compromises will have to be made.

The same thing applies to a propeller designer. He must be concerned with takeoff, climb, cruise, and high-speed performance at various altitudes. Figure 13-3 includes a line representing the actual efficiency of a typical propeller. This propeller has maximum efficiency at one flight condition but not at others. Even with variable pitch and rpm, one set of geometric parameters; including blade area, twist, and taper will not be the best for all flight conditions.

The airplane designer will select a propeller using non-dimensional charts made for a given geometry from either computer runs or test data in a wind tunnel. For a given advance ratio and thrust coefficient, he can find the corresponding power coefficient, and thus the power required for his application

It should come as no surprise that like the helicopter aerodynamicist, the propeller analyst now uses modern high speed computers not to generate charts, but to predict the performance of a specific propeller with a given set of geometric parameters using sophisticated Computational Fluid Dynamics (CFD) codes.

Aren't we lucky?

When the airplane propeller people, such as Betz and Goldstein, started developing theory for their devices in the early 1900s, they adopted many of the methods developed by Rankine and Froude for marine propellers. These included using diameter and rpm as primary parameters for non-dimensional coefficients. Thus these coefficients include a lot of instances of π. For example, to get a comparable helicopter thrust coefficient, you must multiply the propeller coefficient by 4 and then divide by π^3.

We are fortunate that rotors were used on autogyros before they were used on helicopters. Since the autogyro couldn't hover, let alone go straight up, there was no temptation to use the propeller nomenclature. Analysts such as Glauert, Lock, and Wheatley evidently didn't think of the rotor as a propeller. Fortunately, they chose tip speed and disc area as primary parameters for their non-dimensional coefficients. (Note: Some recent propeller studies use helicopter-type non-dimensional coefficients.)

We define a tip speed ratio as the ratio between the forward speed and the tip speed. This gives a graphic way of thinking of the forward flight condition. A tip speed ratio of 0.3 means that the helicopter is traveling forward at 30% of the tip speed. The propeller people have a similar parameter in their "advance ratio", but it is not so easy to visualize being π times our tip speed ratio.

Using tip speed instead of rpm also gives us a feeling about how close we are getting to compressibility problems since we know that these become significant at about 1000 ft/sec. In forward flight, we can get the speed of the advancing tip by multiplying the tip speed by one plus the tip speed ratio. The propeller people don't have such an easy time.

Another advantage we have is by defining the solidity of our rotors as the ratio of blade area to disc area. If a rotor has a solidity of 0.1, then we know that in the top view, 10% of the disc area is made solid by blade area—something that is easy to visualize.

The propeller engineer works with a similar parameter that he calls the "activity factor". This is a weighted solidity factor accounting for the blade taper. If a rotor with constant-chord blades has a solidity of 10%, the activity factor is 244! (We can take care of tapered blades by calculating a thrust-weighted solidity.)

Since helicopter people are interested in disc loading, it is convenient that when we multiply our thrust coefficient by 1000, we get a good approximation to it. (It would be exact at sea level and with a tip speed of 649 ft/sec.)

Our other useful parameter is the blade loading coefficient, C_T/σ, based on blade area instead of disc area. This tells us how close to stall our rotor is operating. We know that if it comes close to 0.2, the rotor is either stalled or on the verge of it. We also know that designing to operate at half this value assures a good rotor in hover though for good forward flight performance, we would choose a slightly lower value. We can design to these values by choosing tip speed and blade area. The same relationship could be used to select propeller parameters, but I cannot find anything in the propeller literature that gives the propeller designer such a handy rule-of-thumb. Aren't we lucky?

Chapter 14
The Truth About Wings

Should helicopter designers consider adding a wing to their configuration to relieve the rotor of some of its lifting requirement? Maybe so.

Unloading the rotor played no part in the design of attack helicopters, such as the Bell Cobra, the Mil Mi-24 Hind, and the Boeing Apache (Figure 14-1). Their wings were simply convenient places to carry external stores such as rockets, missiles, and fuel tanks.

Figure 14-1 Wings on Attack Helicopters as Stores Carriers

The vertical drag of the wing in hover due to its submersion in the rotor wake was taken as a known penalty for these helicopters reducing the allowable payload by ten to twenty percent.

There is also another possible penalty that might appear at high speed. Here, the partially unloaded rotor, while relieved of some of its lifting requirement, must still act as a propeller and pull the helicopter through the air with the added profile and induced drag of the wing. Compared to the basic helicopter, this requires the rotor to be tilted further forward. The collective pitch must be higher due to the higher inflow through the rotor disc and this, in turn, requires higher cyclic pitch which may result in higher retreating blade angles of attack even though the rotor lift is less.

An anti-wing argument

For a long time, I had used these two penalties to argue against adding a wing to a helicopter. I had said that you only added a wing in conjunction with a propeller or jet engine to make a compound helicopter (or, to be more correct, a “compound airplane”.)

So, when I decided to write this column, I fired up my blade-element computer program for the “example helicopter” from my textbook to generate some numbers to back up my arguments. I was surprised by the results.

What the program does

The program solves the forward flight equations of equilibrium by adjusting the collective pitch to get enough rotor thrust to hold the helicopter up, enough forward tilt of the thrust vector to pull the helicopter through the air, and sufficient blade flapping to balance the pitching and rolling moments about the center of gravity. It also computes all the results of interest, including the engine power.

The helicopter configuration can be specified with or without a wing. The forward speed is increased by five knot increments until no trim solution can be found due to retreating blade stall.

A previous example

One helicopter that was designed with a wing without external store capability was the Russian Mil-6 “Hook” shown in Figure 14-2. It first flew in 1957 and had a gross weight of 94,000 pounds. Descriptions of the Hook say that the wings could be easily removed if used as a flying crane. The wing span is half the rotor diameter, it has an aspect ratio of 7, and the incidence with respect to the rotor shaft is $20°$. I chose these parameters for the investigation of my “winged example helicopter”.

Figure 14-2 Mi-6 “Hook”

There was another winged helicopter, the Boeing Vertol 347, Figure 14-3, an experimental version of the Chinook. The wing was intended to provide an increase in maneuverability and speed, but I can find no reports of the flight characteristics with the wing installed.

Figure 14-3 Boeing 347

A surprising result

For my helicopter at sea level and at its design gross weight of 20,000 pounds the apples-to-apples comparison showed that the addition of the wing reduced the total power required and even raised the maximum speed as limited by rotor capability from 170 to 190 knots. This is not what I had expected. (In both cases, the total engine power was less than the 4000 horsepower that I had given my design.)

Saving face

How about my old argument that the wing would be detrimental? To investigate that, I reduced the gross weight to 15,000 pounds and found the effect I was looking for. At this gross weight, the winged helicopter required more power above 100 knots. Both configurations could get to 190 knots, but at that speed, the winged helicopter was requiring 8% more power.

Since the wing was beneficial below 100 knots, the result sends a message that if the design condition is loiter at low speed to take advantage of minimum power, a wing would be helpful.

Extreme conditions

The investigation was continued with higher gross weights of 25,000 and 30,000 pounds. In both cases, the wing provided a benefit throughout the speed range both in reducing the power required and by increasing the maximum speed that the program could achieve—180 knots compared to 130 at 25,000 pounds and 165 knots compared to 80 at 30,000. (Raising the gross weight to these two values is the equivalent of flying the 20,000 pound helicopter at altitudes of 7,500 and 13,000 ft.)

The program keeps track of the azimuth and radial station of the maximum blade element angle of attack on the rotor disc. Examination of the output shows that at the maximum speed whether with or without a wing, the maximum angle of attack on the retreating side is about $19°$. The calculations were done for a rotor with a NACA 0012 airfoil section. (Similar calculations with the more modern VR-7 airfoil, as used on the Boeing Chinook, give maximum angles as high as $25°$ and correspondingly higher maximum speeds.)

A useful illustration of maximum rotor capability is a plot of blade loading coefficient (C_T/σ) versus tip speed ratio. For the maximum speeds obtained in the study, this is shown by Figure 14-4. At the higher gross weights, the increase in maximum speed made possible by the wing is dramatic. The fact that the fairing of the winged points is lower than that of the basic helicopter is apparently due to the drag of the wing.

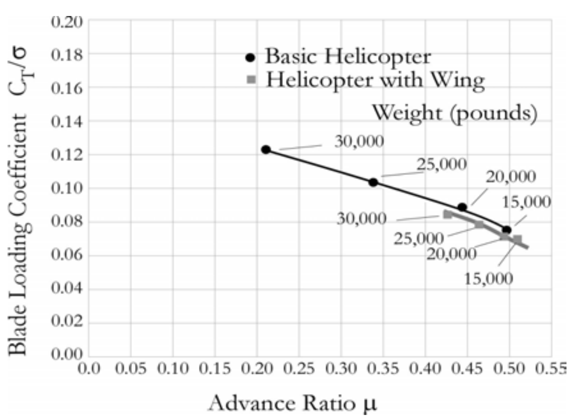

Figure 14-4 Blade loading Coefficient vs. Tip Speed Advance Ratio

More to think about

There are two flying quality effects that should be considered with respect to the use of a wing. One is that if the helicopter has to go into autorotation, the lift on the wing may support so much weight that the rotor has little thrust to work with and therefore cannot autorotate. This was solved on several of the early compound helicopters by using decreased incidence, spoilers, or reverse flaps.

The second consideration is that the wing's center of lift should be located behind the helicopter's center of gravity so that it acts as a stabilizer rather than as a destabilizer.