Helicopter Aerodynamics Volume III

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CHAPTER 14 Evolution of a Compound Helicopter

With the recent demonstration of high speeds by the Sikorsky X2 and the Eurocopter X3, there is an anticipation that the next generation of rotary-wing aircraft will be faster than the ones we know today.

FIGURE 1.

To illustrate some of the challenges involved, I have thought about how to make the conventional example helicopter of my textbook into a compound helicopter, raising the top speed from 185 to 285 knots at an altitude of 5000 feet at the engine's 30-minute rating.

Making Changes

This would be done by adding a wing and a pusher propeller to make a configuration like the Lockheed Cheyenne of the 1960's. (Making an advanced configuration from an existing design is the modern way. No new helicopter design has reached the production stage for many years.) I am going to retain the main and tail rotors of my conventional helicopter. Since the new one will undoubtedly have some low-speed mission segments, I will even keep the blade twist that helps hover performance.

FIGURE 2. **Lockheed Cheyenne**

When fully loaded, my conventional helicopter has a gross weight of 20,000 pounds and carries 30 passengers at a cruise speed of 172 knots. As a high-speed compound helicopter at this same gross weight it would also carry passengers, 'but not so many. This is because of the increase in empty weight due to the addition of the wing, propeller, landing gear retraction mechanisms, bigger engines, and stronger drive systems. Another requirement that would add weight is stronger windshields and side windows to be able to survive with more than twice the dynamic pressure. The increased fuel to do a same mission at the higher cruise speed of 270 knots would also reduce the payload.

Even with a decrease in the number of passengers, the fuselage would have about the same shape and basic drag, but drag would be reduced by retracting the landing gear and using a thin door-hinge main rotor hub as on the Cheyenne. The change to the landing gear should give a reduction of 6.5 square feet of equivalent flat plate area and the hub redesign an additional 2.5 square feet resulting in reducing the equivalent flat plate area from 19.3 square feet to 10.3.

The Wing and Propeller

My criterion for the wing is that it should be able to support the full gross weight at 160 knots at sea level at a lift coefficient of 1.0. This requires 117 square feet. With an aspect ratio of 10, the wing span is 34 feet, just over half the rotor diameter of 60 feet. Of course, the purpose of the wing is to relieve the lift requirement on the rotor while the propeller relieves it of the requirement to provide a forward propulsive force. Each of these reduces the possibility of retreating blade stall.

A propeller with a diameter of 10 feet should be adequate. It will be assumed for this study that for all speeds, its efficiency is 80%.

Changing Rotor Thrust

At high tip speed ratios, the rotor is subject to retreating blade stall so it has to be unloaded. I propose to do this by reducing its collective pitch. For this early in the project, I have selected a reduction, starting at 100 knots, of a tenth of a degree per knot until the average pitch of the blade element at the 75% radius position is zero. In this condition, any change in rotor thrust is developed by a positive tip path plane angle of attack like an autogyro. At maximum speed, the rotor is calculated to be carrying about 20% of the gross weight with reasonable efficiency since it operates with a large amount of air.

Changing Tip Speed

Another goal is to avoid compressibility effects on the advancing blade tip. This is done by limiting the Mach Number at the tip to 0.85 by reducing the tip speed from 650 feet per second to 470 starting at about 180 knots. At 285 knots the tip speed ratio would be 1.02.

There would be a challenge in reducing the rotor RPM by 30%. We must find out from the Dynamic Engineers where the blade natural frequencies are to avoid dwelling on resonance points as we reduce rotor speed. Should the reduction be done with the engine governors as on the Osprey or with a gear shift as on the Bell X-3? Should the propeller be driven from the main rotor transmission or from a separate gear box with a variable gear ratio? These decisions are to be made later.

The Bottom Line

The calculations show that at 285 knots at 5000 ft, this aircraft needs engine power of 4000 horsepower which despite the reduction in flat plate area, is higher than the 3400 needed in the conventional 185 knot helicopter. The power of these bigger engines would probably be just enough to compensate for the aerodynamic download of the wing in hover.

These are ’first day’ decisions just to get started. They would certainly be modified as the project develops.

CHAPTER 15 *Sizing the Osprey*

One of the first parameters needed when starting out on new helicopter design is the disc loading. On conventional helicopters the procedure is fairly straight-foreward. The requirements would be known: including the payload, the mission, the maximum speed and the hover performance. Based on a knowledge of existing helicopters, the payload and mission can be used to estimate the gross weight and drag characteristics. The next step is to estimate how much power is needed to meet the high speed requirement. With the engine(s) that does this, what is the smallest rotor diameter that satisfies the hover performance? With the estimated gross weight, this sets the first estimate for disc loading to give a minimum-sized 'balanced' design that just barely meets both the high speed and hover requirements.

For the balanced Black Hawk and Apache configurations with maximum speeds of about 150 knots, the disc loading is about nine pounds per square foot, but for the CH-53E, with three big engines to make 170 knots, hover is no problem and so the resulting disc loading is higher, at 14.

A New Requirement

It would seem that the same procedure could have been used on the V-22 Osprey, but it wasn't. A special requirement for this aircraft was that it had to be compatible with the small carriers that it would be operating from. A critical 'flight' condition was taxiing the length of the flight deck without running into the island or falling overboard. Shipboard compatibility tests with conventional helicopters were made and safety considerations resulted in the requirement that the rotor tips had to be at least fifteen feet from the island and the outboard wheel could be no closer than five feet from the outer edge of the deck.

FIGURE 1.

For the smallest carrier that the Marines were considering as an Osprey operating base, this established a maximum rotor 'span' of 85 feet. The fuselage width is established by the payload and the distance between the rotor tips is determined by the clearance from the fuselage in airplane flight. Thus the rotor diameters were limited to 38 feet. At a gross weight of 46,000 pounds, the resulting disc loading is 20 pounds per square foot.

This is enough to generate hurricane-like velocities in the rotor wake with resulting problems when operating close to any ground softer than concrete.

Lesson Learned

This is just an example of how special requirements other than performance can influence the design. The Bell HSL anti-submarine tandem-rotor helicopter, unlike other tandems, had its two rotors at the same height so that it could be stowed in the limited ceiling height of the carrier's on-board hanger. The result was high noise coming from blade-vortex interference even in normal hover and forward flight conditions.

CHAPTER 16

Canted Tail Rotors

How It All Began

The first canted tail rotor appeared on the Sikorsky Black Hawk as a result of having to meet an Army requirement. When writing the specifications for the Utility Tactical Transport System (UTTAS) competition, a requirement was included that one of these helicopters must fit into an Air Force C-130 cargo airplane and two should fit into a C-141. The preliminary design process for the Black Hawk had been completed. The diameters of the main and tail rotors had been chosen to give the performance required. That set the tail boom length and the length of the nose had been designed to put the center of gravity close to the rotor shaft. As a last check, two small cardboard planforms of the design were placed on the floor plan of the C-141's cargo compartment, and they did not fit!

Back to the Drawing Board

The solution was to shorten the nose. This put the center of gravity well behind the main rotor mast. For airplanes, a center of gravity behind the center of lift can be a serious problem by leading to an aircraft that is longitudinally unstable. The situation is different for helicopters because of the way that rotor flapping is used to trim out the pitching moments about the center of gravity. An aft C.G. does not cause instability. (For a discussion of this, see my column in the March 1997 issue of Rotor and Wing, or Chapter 48 of my book, Helicopter Aerodynamics, Volumn II.)

So the aft C.G. on the Black Hawk is not a stability issue, but it is bad in that the nose-down flapping to balance moments about the center of gravity produces high fatigue loads in the rotor hub. The Sikorsky solution was to cant the tail rotor by twenty degrees so that its upward force would produce a nose-down moment about the center of gravity opposite to the nose-up moment from the main rotor thrust. This reduced the flapping required for trim.

FIGURE 1. The Sikorsky Black Hawk

Which Side?

American aerodynamicists would like to see the tail rotor mounted on the left side of the fin. In this ’pusher’ arrangement, it is sucking air past the fin instead of blowing on it as it would be if it were mounted on the right side of the fin as a ’tractor.’ As a tractor, the opposing fin force makes the tail rotor work harder to do the anti-torque job than as a pusher and the additional power required is significant. Despite this, Sikorsky chose to use the tractor position to assure more clearance with the tail boom if something went wrong.

Couplings

Another result of this design choice is a coupling that makes the helicopter pitch as a result of moving the rudder pedals. A push on the left pedal to start a left turn will increase tail rotor thrust, and its upward component will pitch the helicopter nose-down. Another coupling is due to the main rotor being ahead of the center of gravity. An increase in collective pitch will produce a nose-up pitching moment. These couplings are reduced by using a rather complicated and heavy mixing box in the control system.

Yet another coupling due to the canted tail rotor is produced by sideslip. In an inadvertent slideslip to the right, the tail rotor thrust will be reduced along with its vertical component. This will result in a nose-up pitching moment about the center of gravity. Sikorsky chose not to correct this with the rotor, but to use the stabilator instead. An accelerometer in its computer senses lateral acceleration and changes the incidence--positive in the case of an inadvertent right sideslip.

I once heard a Sikorsky engineer giving a paper on the Black Hawk control system and these complications that were introduced by the canted tail rotor. He concluded his verbal presentation by saying, ’We’ll never do that again.’ The response to that opinion these days is ’Well, all modern helicopters will be fly-by-wire.’

Sikorsky later used the canted tail rotor on the CH-53E which was also tail-heavy. A difference was that it had a canted fin so that the tail rotor could be mounted on the left side with plenty of clearance.

FIGURE 2. The Sikorsky CH-53E

The Comanche also had a canted ducted fan, but the motivation for this aircraft was to decrease its radar signature.

FIGURE 3. **The Comanche**

Other benefits

The shortening of the nose on the Black Hawk saved a little structural weight and reduced the aerodynamic download in hover.

There is yet another significant effect on hover performance. This is the result of trigonometry functions. The thrust on the canted tail rotor must be higher than without cant by 1/cosine of the cant angle. For twenty degrees, this factor is 1.06. This accounts for a modest increase in required tail rotor power to do the anti-torque job. On the other hand, the vertical component of thrust is proportional to the sine of the cant angle, or 34%. This is the amount of tail rotor thrust that can be used to relieve the thrust and power requirements of the main rotor.

I have calculated the hover performance of my example helicopter at its design gross weight of 20,000 pounds at sea level with and without a 20 degree cant angle. With the cant, the main rotor power required is 59 horsepower less than without cant, but the tail rotor power is 8 horsepower more. Since the power loading is 9 pounds per horsepower, I could have increased the payload of my design by about 450 pounds (two passengers) by using tail rotor cant.

Yes, but...

When I used my forward flight program on my example helicopter, I got another result. The power required was higher with the 20 degrees of tail rotor cant than without it. This is just another example of the designer’s dilemma: ’Whatever helps hover, hurts forward flight.’

Whereas in hover the tail rotor lift was beneficial by helping the main rotor hold the aircraft up, in forward flight, its effect on trimming the pitching moments about the center of gravity was not beneficial. This is because the lift of the tail rotor made a nose-down pitching moment which must be balanced by nose-up rotor flapping. But the attitude of the rotor with respect to the horizon is essentially the same, so the fuselage will fly more nose-down and thus have higher drag than without cant.

For my helicopter at 150 knots, the power difference is 540 horsepower. For a three hour mission, this requires an additional 750 pounds of fuel. Oh-oh! there goes my gain in payload.

A possible help for this situation is to carry more download on the horizontal stabilizer.

A New Trend ?

There are three other designs now using tail rotor cant. The Army is studying Future Multi-Role Helicopters. This design uses a canted tail rotor to take advantage of the increase in hover performance.

FIGURE 4. An Army Study for a Future Vertical Lift Helicopter

The other two are Bell's Model 525, and Eurocopter's EC 175.

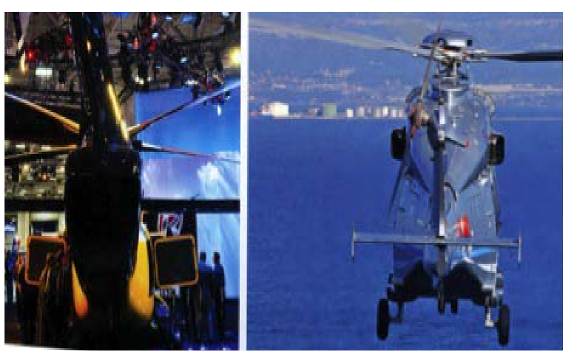

FIGURE 5. The Bell 525 The EC 175