Helicopter Aerodynamics

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Ray Prouty's Rotor and Wing columns 1979 - 1992

Eagle Eye Solutions

10 Downwash Patterns

If we could see air, we would all be a lot smarter. This is especially true for the helicopter engineer who has to wonder about the mysterious things that happen to his aircraft whether it be in the fields of performance, flying qualities, loads, vibration, or noise. Some of these mysterious happenings can be traced to the rotor wake and to the presence in it of tip vortices.

They come and they go

Vortices are formed at the blade tips as the air tries to go from a high-pressure region to a low-pressure region (bottom to top). This sets the air to spinning, leaving long whirlpools where each blade tip has passed. Airplane wing tips do the same thing.

Wing-tip vortices trailing behind an airplane tend to retain their energy and their relative position for several minutes. Their primary mutual interference on each other slowly forces them downward, corresponding to the wake's induced velocity.

Smaller vortices or even vortex sheets are also generated wherever or whenever lift changes, but they are never as influential as those generated at the wing's tip or the rotor blade's tip. Since theoretically a vortex cannot have an end, each blade-tip vortex must be accompanied by a corresponding blade-root vortex. These have a less-direct—but still significant—effect than tip vortices.

Rotors are different

Tip vortices from rotor blades are not as long lasting as those behind wings. But because they "loiter in the neighborhood," they have more effect. In hover, they generate the induced velocity and go down with it, but stay close enough together to interact and entwine in knots.

This happens even during model tests in a quiet room where under the best of conditions only three or four healthy vortices can be traced down into the wake. As they mutually destroy each other, they induce local fluctuations in the entire wake, even at the rotor disc itself.

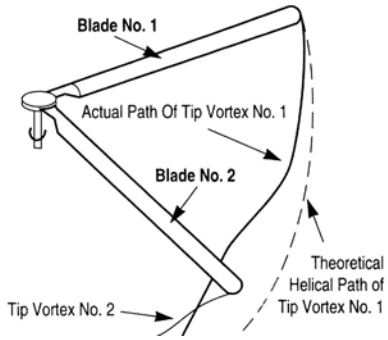


Figure 10-1 Blade-Tip Vortex Interference Effect In Hover

Additionally in many cases, the vortex shed by one blade stays near the rotor's plane until the next blade comes along (Figure 10-1). When this happens, that blade's aerodynamics will be affected.

Specifically, the local angle of attack will change depending on the strength and proximity of the vortex. Since both positive and negative changes are possible, a portion of the blade may find itself either being stalled or producing less than normal lift, thus changing its aerodynamic characteristics from what would be expected.

Observations indicate that this is a fluctuating phenomenon that seems to affect only a part of the rotor at any one time, probably as a function of the unevenness in the induced flow field at the rotor disc. As evidence of this, rotor tests made on whirl towers produce time histories of thrust and torque that vary in a random manner.

A nearly ideal test

One of the most carefully controlled whirl-tower tests that I know of was done with a six-foot-diameter rotor at the NASA Ames Research Center. Ray Piziali and Fort Felkner reported on that test.

As part of a study of rotor-wake recirculation effect, the rotor was tested on an outside whirl tower nearly 30 feet above the ground. It was installed upside-down so that its wake went up instead of down to minimize the recirculation due to the ground. Testing was done at night during periods of dead calm.

Even with all of these precautions, time histories of thrust and torque varied randomly (Figure 10-2). The variation in these two parameters was almost 1% from their mean over a time period of almost a minute, and it is not clear that, even with this long time slice, the maximum variations were captured.

Because of the randomness in thrust and torque, the Figure of Merit, which represents hover efficiency, varied almost 1.5%. This magnitude is often used to distinguish between a good rotor and a bad one, and so depending on the instant the performance was recorded, this rotor could have been either.

Is it any wonder that hover performance measured under less-ideal circumstances on a whirl tower produces "scatter of the datter," as illustrated for the Boeing YUH-61A rotor in Figure 10-3?

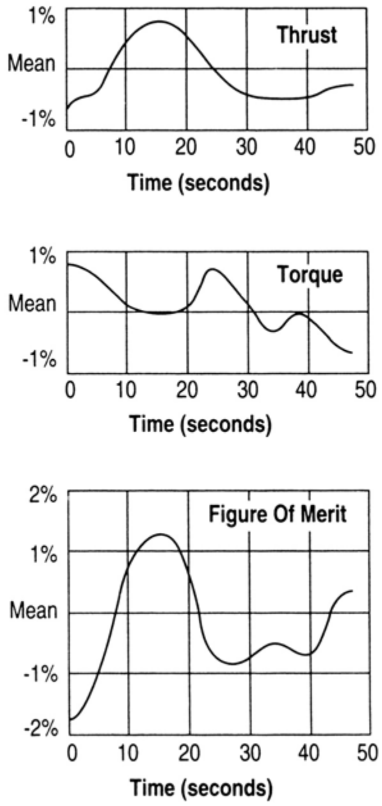


Figure 10-2 Results Of Whirl Tower Hover Test

Calculating hover performance

Besides the difficulty in accurately measuring rotor performance, the not-so-well-understood positioning of the tip vortices and their effect on the induced flow field at the rotor disc also make it difficult to accurately predict hover performance. Even if the flow were rock-steady, its distribution would depend heavily on the actual location of the first several tip-vortex spirals down in the wake.

Trying to calculate these positions has been the subject of much research in the past 20 years. One approach is to use flow-visualization techniques with model and full scale rotors to measure the radial contraction and vertical position of the vortices as a function of thrust, twist, and number of blades.

Then this knowledge is generalized into a method for generating a "prescribed wake." This can be used to analytically produce the induced flow field for performance calculations using the equation known as the Biot-Savart Law.

A more-sophisticated method is that of the "free wake," in which the effect of each vortex in forcing all the others into the final pattern is accounted for theoretically without need of previous knowledge about vortex spacing.

Despite all of the effort in this work since 1960, it has not noticeably increased the accuracy of hover calculations for conventional rotors over those calculations made with the old-fashioned empirical methods developed at the beginning of the helicopter era. This is shown by the correlation of both simple and sophisticated calculating methods with Boeing whirl-tower data of a CH-47B rotor (Figure 10-4).

The main argument for the sophisticated methods is that they do a better job with heavily loaded rotors, such as tail rotors, tiltrotors, and unconventional rotors that have sudden changes in twist, taper, or sweep.

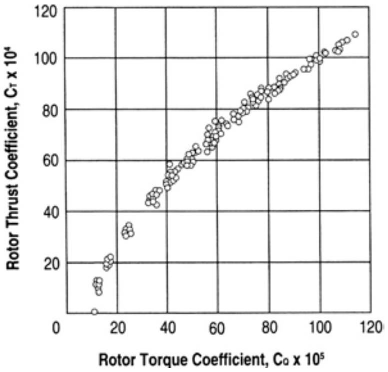


Figure 10-3 Typical Whirl Tower Data Scatter For Boeing YUH-61ARotor

Forward flight, the difference

In hover, the mutual destruction of the tip vortices under the rotor disc is important in that it produces a gusty inflow. That is not the case in forward flight. Here the rotor quickly moves away from the vortices it has produced so that their tangling behind in the "far wake" has little effect on the induced flow at the rotor.

However, the fact that a blade passes close to healthy tip vortices that were just laid down is important. It means that the blade sees local changes of angle of attack regularly, instead of randomly as in hover.

In forward flight, the blade tip traces out a figure called a "cycloid" as the result of both translation and rotation. Figure 10-5 shows the track of the vortices laid down in still air and not distorted by their mutual interference—an effect we will get to later.

The number of possible close encounters of a blade with a tip vortex from another blade, or even one deposited by itself on a previous revolution, depends on the number of blades and the ratio of forward speed to tip speed or the "tip-speed ratio".

With data from a specially instrumented helicopter, the influence of vortex proximity can be seen in the measured lift distribution. Figure 8-6 shows this for a station 85% of the radius out toward the tip for one

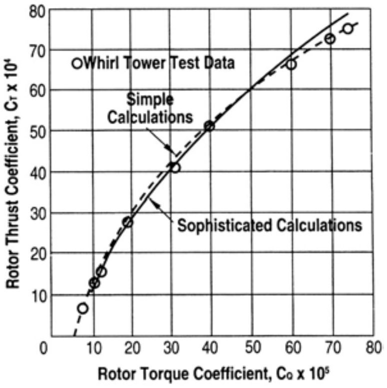
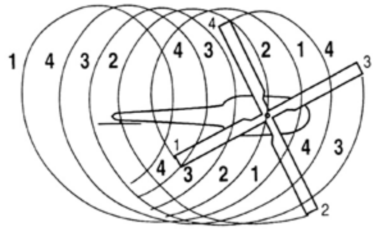


Figure 10-4 Correlation Of Calculating Methods With Whirl Tower Test Data

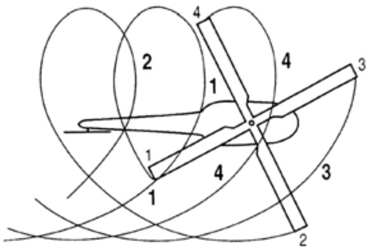
blade of a four-bladed Sikorsky H-34 (S-58) rotor at a tip-speed ratio of 0.2 (about 77 knots).

Also shown is the lift, calculated using a simple method that ignores the presence of discrete tip vortices. It may be seen that for this case, there are important variations on both the advancing and retreating sides. This would be expected looking at the density of the vortices in these regions (Figure 10-5a). In particular, on the advancing side there is a distinct down-up characteristic. Figure 10-7 shows the relative positions of the blade and the vortex that explains this.

Despite this wide variation in blade loading, the average is the same. Most rotor aerodynamicists will accept that the simple method is satisfactory for computing overall rotor performance, even though it does not do a good job on the local distribution of airloads.



a. Tip Speed Ratio = 0.2–Moderate Speed



b. Tip Speed Ratio = 0.4–High Speed

Figure 10-5 Vortex Trails In Forward Flight

Changes at high speed

At higher speeds, the helicopter tends to outrun the vortices laid down on the retreating side as illustrated by the vortex pattern for the tip-speed ratio of 0.4 in Figure 10-5b. Thus the effect on the retreating side diminishes, but not so much on the advancing side where the density is still high.

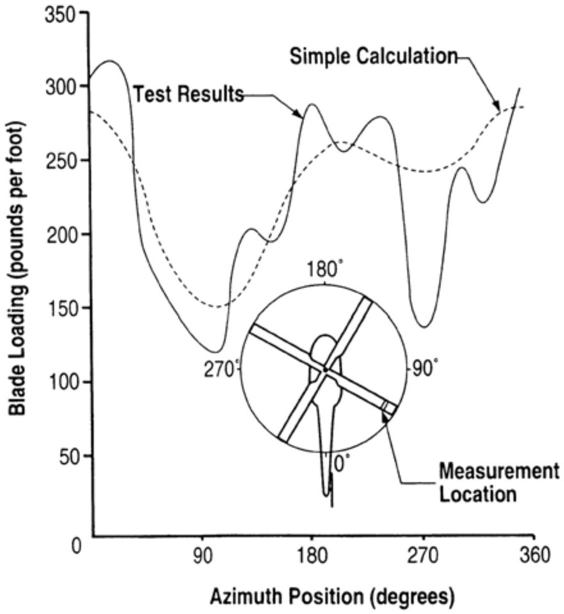


Figure 10-6 Test And Calculated Blade Loading

In addition, another strange thing has been seen from high-speed data. On the advancing side near the tip, instead of the pulse being down-up, it is up-down. This is explained by the fact that in high speed flight, rotors carry a download on their advancing tips and leave a tip vortex that rotates opposite to the normal one.

The influence of a vortex on a blade is most pronounced where they lie nearly parallel to each other. Here the entire blade is influenced at once, instead of being subjected to the relatively local influence when it and the vortex are more perpendicular to each other.

Whether they are parallel or perpendicular can be seen by replotting Figure 10-5 in a different format. This involves looking at the pattern as it would be seen by an observer standing on the hub and sighting along blade No. 1. Figure 10-8 shows the location on the blade that would be directly above each of the tip vortices generated by blades of a four-bladed rotor.

It may be seen that at about a 60° azimuth angle, which is on the advancing side in the right-rear quadrant, there is a tendency for the blade's outer portion to line up parallel with a series of vortices. Here the interference is significant because a large part of the blade is affected rather than just a local segment.

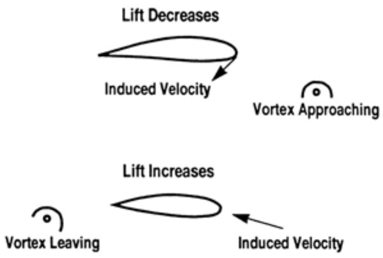
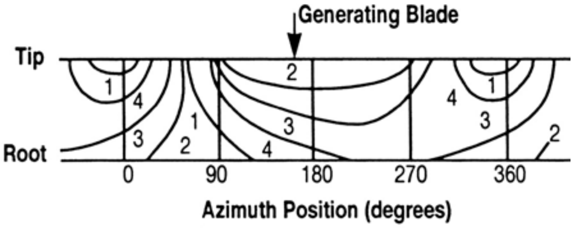


Figure 10-7 Source Of Down-Up Pulse

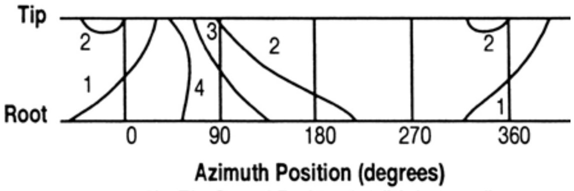
Wake distortions

Calculations that attempt to account for the effect of the nearby tip vortices must also account for their actual position at the time the blade passes. This is done with a "free-wake" analysis that uses vortex theory in the form of the Biot-Savart Law to calculate the wake's distortion as influenced by all of the vortices in it.

A comparison of non-distorted and distorted wakes at a fairly low forward speed is given in Figure 8-9. Doing the free-wake analysis by computer takes too long to be used routinely in the blade-load calculation, so various schemes to specify a "prescribed wake" have been developed using the results of a few free-wake computations as guides.



8a: Tip-Speed Ratio = 0.2 (moderate speed)



8b: Tip-Speed Ratio = 0.4 (high speed)

Figure 10-8 Location Of Vortices For Blade No. 1

Even with the most sophisticated of these procedures, those working in the field are not satisfied with their ability to match test data. But perhaps it is not too critical. The argument for developing advanced methods for calculating blade loadings is that if these were known very accurately, the designers could use the knowledge to either design lighter blades or blades with longer fatigue lives.

In real life, however, it is not the loads in straight and level flight that cause most of the fatigue damage, but loads during maneuvers when the rotor is being used to pitch or roll the helicopter or to make it go up or down. These loads would be relatively easy to estimate if you had a good crystal ball to predict the pilot's control actions. Since we hear of few in-flight blade failures, I conclude that the designers are doing OK even if they do not exactly know what the vortex-caused loadings are.

Blade slap and rocky road

In most forward-flight conditions, the blades do not actually strike the vortices. But when they do, this produces very large and rapid changes in pressure just like you do in slapping a table with your hand instead of pressing on it.

This is one source of the type of impulse noise commonly called "blade slap" or, as noise experts call it, "blade-vortex interaction" (BVI). It is most often heard when rolling into a turn or during low-power descents, which give the blades the chance to pass through the vortices in the wake.

Even if a helicopter has a smooth ride in other flight conditions, it will probably be rough in at least one: the landing flare. This is because at some point, the blades will actually strike tip vortices left, by previous blade passages. Figure 10-10 shows how the relative positions of the rotor and its wake change during the landing maneuver. Descending at low power, the air is approaching the rotor from below and carrying the wake up and above the tip-path plane.

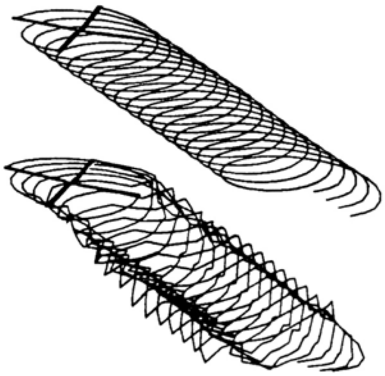


Figure 10-9 Undistorted And Free-Wake Distorted Vortex Patterns At Low Speed