

Aerodynamics of a Helicopter Rotor in Forward Flight

Based on a paper originally written
by Doug Jackson - Spring 2000
(TGG 2006)

INTRODUCTION

EARLY HELICOPTER HISTORY

EARLY CONCEPTS

FIRST SUCCESSES

MODERN HELICOPTER HISTORY

FIRST VERTICAL FLIGHT

NEW DEVELOPMENTS

FIRST TRUE HELICOPTERS

FLAPPING HINGES

NON-ARTICULATED ROTORS

ARTICULATED ROTORS

MAXIMUM FORWARD SPEED

MAXIMUM SPEED

CYCLIC AND FORWARD FLIGHT

TIP PATH PLANE

CYCLIC CONTROL

MOMENTUM THEORY IN FORWARD FLIGHT

BLADE ELEMENT THEORY IN FORWARD FLIGHT

ROTOR WAKE

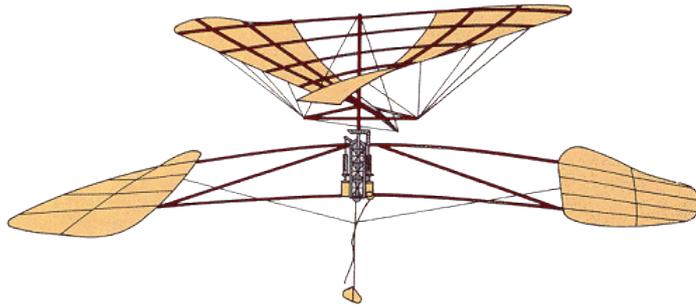
SUMMARY

REFERENCES

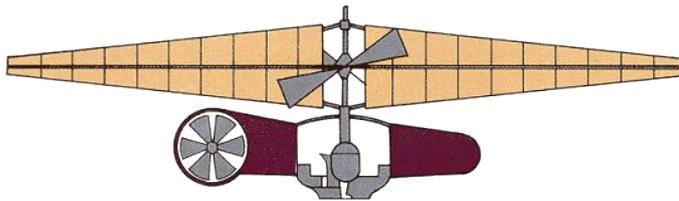
Introduction

Even though the design of the modern helicopter was not perfected until the late 1930s, it is arguably one of the earliest ideas for achieving flight, predating the concept of the glider by perhaps as much as two thousand years. Inspired by the flight of birds, even ancient humans dreamt of soaring at high speeds, stopping on a dime, and hovering in place, much like a hummingbird or dragonfly. Yet no one truly appreciated the complexities needed to make that dream become reality, and it took the collected wisdom and patience of a number of notable aviation pioneers over the course of centuries to bring that technology into existence.

In this paper, we will first explore the history of how the modern helicopter came to be and highlight the great thinkers and designers who made the most significant innovations. Next, we will look at the mechanics of a helicopter rotor in forward flight and introduce the many complex challenges that have to be overcome to make a rotorcraft controllable. We will then discuss the two prevailing analytical theories used by engineers to mathematically describe how a rotor functions before wrapping up with an overview of the wake vortices created by the rotor in flight.



Enrico Forlanini (Italy 1877)



Achenbach (Germany 1874)

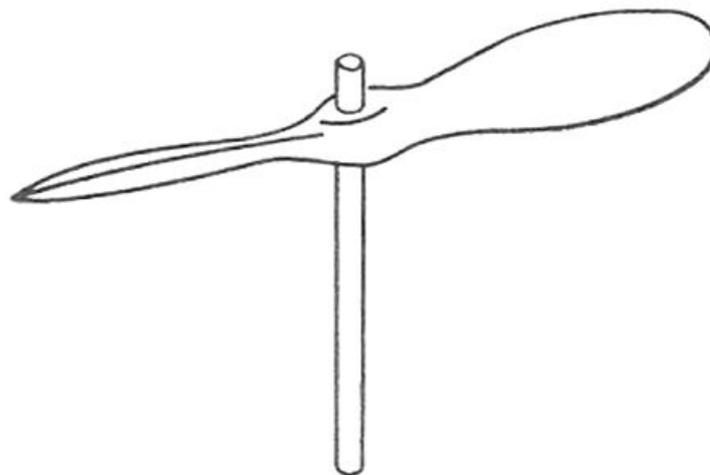


Tiger helicopter (Europe 1991)

Early Helicopter History

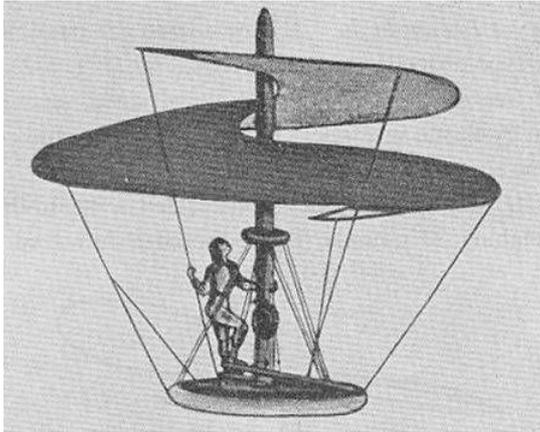
Early Concepts

The helicopter is arguably one of the earliest ideas for achieving flight. Over two thousand years ago, the Chinese constructed what are known as Chinese Tops, illustrated below. These simple toys consisted of a propeller attached to a stick that would be spun rapidly through ones hands to spin the propeller and achieve lift. These toys are still common today.

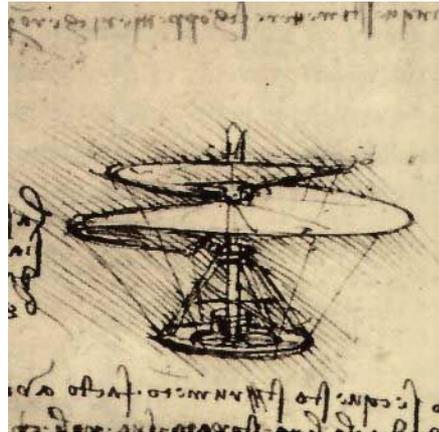


Chinese top [from Gessow and Myers, 1952]

Later, in the 15th Century, famed inventor and artist Leonardo da Vinci designed one of the more aesthetically pleasing concepts for a helicopter, but such a craft was never actually constructed.



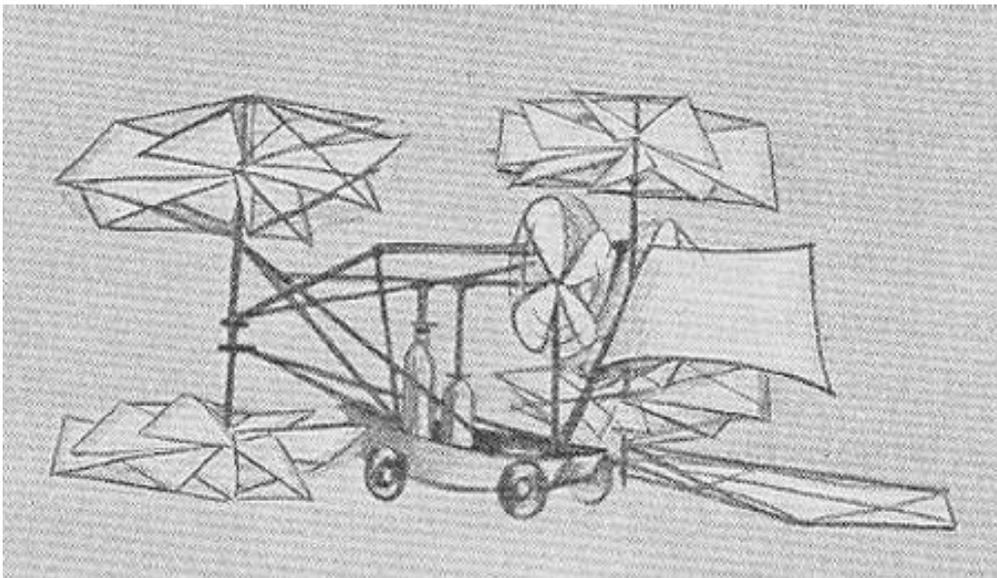
Leonardo da Vinci's "Helicopter", 15th Century
[from Gessow and Myers, 1952]



[original sketch]

First Successes

In England in 1796, Sir George Cayley constructed the first powered models of helicopters that were driven by elastic devices. One of these models, shown below, attained an altitude of ninety feet.



Sir George Cayley's helicopter, 1796 [from Gessow and Myers, 1952]

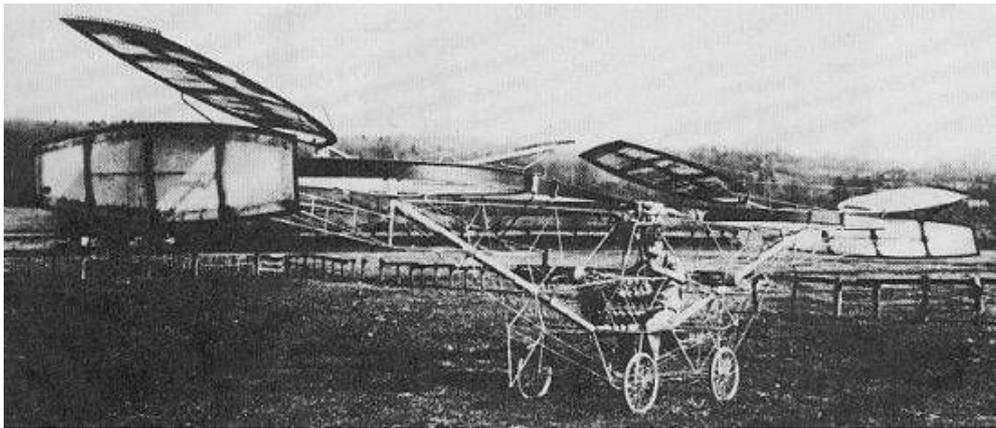
In 1842, almost fifty years after Sir George Cayley, fellow Englishman W. H. Phillips constructed a model helicopter that weighed 20 pounds (9 kg) and was driven by steam. He proposed a full-sized three-propeller machine (one propeller for lift, and two for directional control), but it was never built. In 1878, Enrico Forlanini, an Italian civil engineer, also constructed a steam driven model helicopter that only weighed 7.7 lb (3.5 kg).

In 1880, Thomas Edison was the first American to perform any notable research on helicopters. Edison built a test stand and tested several different propellers using an electric motor. He deduced that in order to create a feasible helicopter, he needed a lightweight engine that could produce a large amount of power.

Modern Helicopter History

First Vertical Flight

The first manned helicopter to rise vertically completely unrestrained was constructed by Paul Cornu, a French mechanic, in 1907. Cornu's helicopter had two propellers that were rotated at 90 rpm by a 24-hp (18 kW) engine.



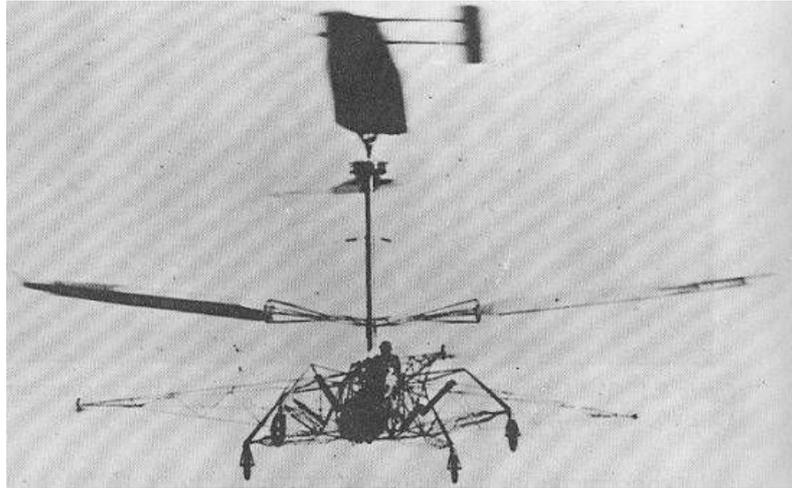
Cornu's helicopter, 1907 [from McCormick, 1995]

As another first, Cornu was most probably the first helicopter experimenter who was concerned with control. To this end, Cornu had installed sets of vanes just below each rotor to deflect the downwash for maneuvering and forward thrust. While Cornu's helicopter was historically significant, its performance and control was rather marginal, and it was never a practical machine.

New Developments

The next influential development in the field of helicopters was brought about by a man who never actually built a helicopter himself. In 1923, Juan de la Cierva successfully flew his C.4 autogiro, an aircraft that has two propellers, a powered one to provide thrust, and an unpowered rotor to provide lift. Cierva's autogiro was noteworthy because it was the first to use an "articulated" rotor that allowed its blades to flap up and down in response to aerodynamic forces on the blades during forward flight. As will be discussed in the next section, the articulated rotor helped to eliminate large blade stresses at the rotor hub. Cierva died in an airliner accident in 1936 at the age of 42, and he never had the opportunity to incorporate an articulated rotor into a helicopter himself.

The first recognized helicopter record was set in October 1930 by Italian Corradino D'Ascanio when he flew his helicopter over a distance of one half mile at an altitude of 59 ft (18 m) for 8 minutes and 45 seconds. D'Ascanio's helicopter had two contrarotating coaxial rotors (two rotors on the same shaft) that were controlled by flaps on booms trailing each blade near its tip.



D'Ascanio's helicopter, 1930 [from McCormick, 1995]

First True Helicopters

Just before and during World War II, Germany made several large, significant steps in helicopter development. The FA-61 helicopter, designed by Heinrich Focke, first flew in June 1936, and was later used in publicity stunts by the Nazis. The FL-282 helicopter, designed by Anton Flettner, became operational with the German Navy, and over 1000 of them were produced. This helicopter utilized twin intermeshing rotors, had a forward speed of 90 mph (145 km/h), and could operate at an altitude of 13,000 ft (3,965 m) with a payload of 800 lb (360 kg).

The first American helicopter was the VS-300, designed by Igor Sikorsky of the Vought-Sikorsky Company. The VS-300 was the first helicopter to use a tail rotor to counteract the torque produced by the main rotor, and it was this innovation that solved the last major hurdle in making helicopters practical flying vehicles. This design is now the most common in today's helicopters.



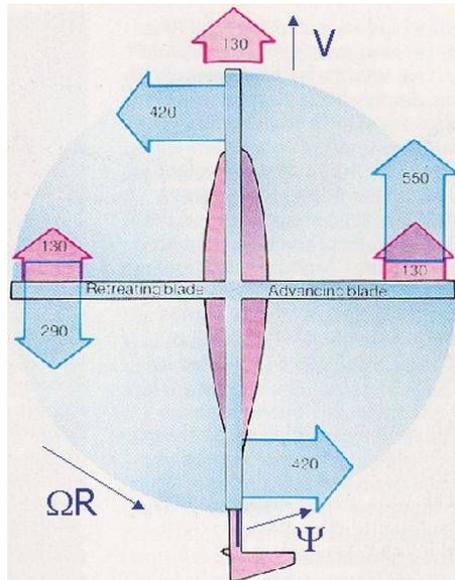
Sikorsky's VS-300, 1939 [from McCormick, 1995]

The VS-300 made its first tethered flight in September 1939 and its first free flight on 13 May 1940.

Flapping Hinges

Non-Articulated Rotors

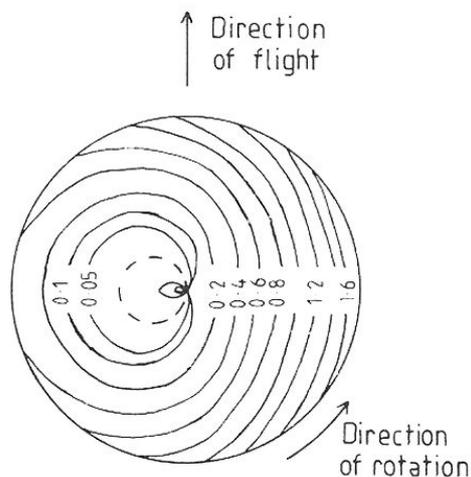
To begin a discussion of a helicopter rotor in forward flight, it is first necessary to consider a non-articulated rotor. A rotor disk viewed from above is depicted below. In this example figure, the helicopter is traveling at a forward velocity V of 130 mph (210 km/h), and the rotor has a rotational speed of Ω and a blade tip velocity of 420 mph (675 km/h). As is the convention in Western countries, the rotor is rotating in a counter-clockwise direction.



Velocities of rotor in forward flight [from Gunston and Spick, 1986]

The advance ratio, denoted as m , is equal to V/WR , and it usually has a value between 0 and 0.5. The azimuth angle of a blade is denoted as Y , where $Y=0^\circ$ at the downstream position. With this definition, advancing blades have $Y=0^\circ$ to 180° , while retreating blades have $Y=180^\circ$ to 360° .

As can be seen in the above figure, the maximum and minimum velocities for the blades occur at $Y=90^\circ$ and $Y=270^\circ$, respectively. If the blades were to rotate at a fixed incidence, then this velocity differential would cause four-fifths of the total lift of the rotor to be created on the advancing side. The calculated pressure contours for a fixed incidence rotor with an advance ratio of $m=0.3$ are shown below.

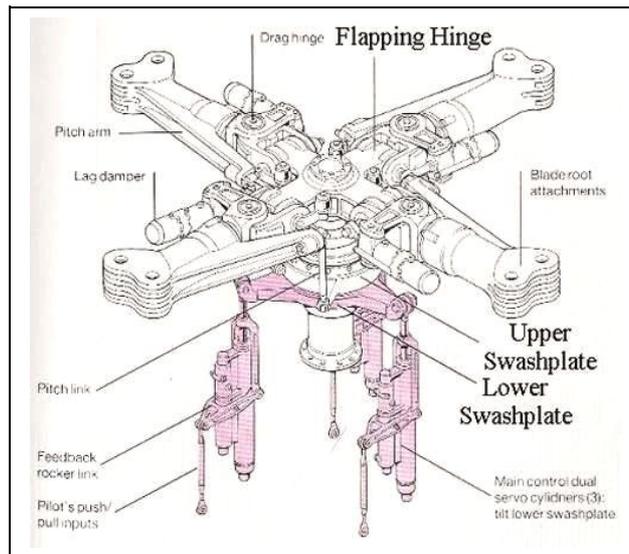


Calculated pressure contours for fixed blade incidence [from Seddon, 1990]

Obviously, this large imbalance of force on the rotor would lead to large oscillatory stresses at the blade roots, along with a large rolling moment. This would make the helicopter very unflyable, both from a dynamics and structural viewpoint.

Articulated Rotors

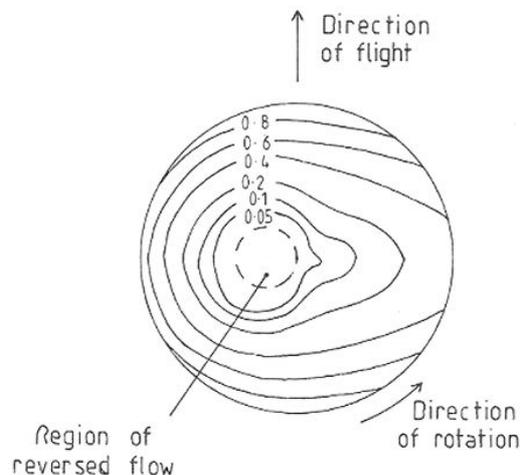
To reduce this large force differential, a cyclical variation of the blade incidence is needed. The most common way of reducing the blade incidence is with flapping hinges, which were first used by Cierva in 1923, as discussed in a previous section on historical developments. When using flapping hinges, the blade is hinged as close as possible to its root, allowing the entire blade to "flap" up and down as it rotates.



An articulated rotor hub [from Gunston and Spick, 1986]

When a blade is on the advancing side, its increased lift causes the blade to flap upwards, which effectively reduces its incidence. The opposite occurs on the retreating side. Due to the presence of the flapping hinges, none of the bending forces or rolling moments is transferred to the helicopter body. Centrifugal force is typically enough to prevent the blades from flapping to a large degree, but many helicopters also employ stops as an added preventative measure.

The use of flapping hinges also creates a better force balance on the rotor, distributing the lift more evenly. Calculated pressure contours for a variable incidence rotor can be seen below.



Calculated pressure contours for variable incidence [from Seddon, 1990]

Maximum Forward Speed

Maximum Speed

The previous section finished the figure that depicts pressure contours calculated on a rotor in forward flight. This diagram also denotes a region of reversed flow on the rotor. As the forward speed of the helicopter increases, a region near the blade roots on the retreating side actually experiences a reversed flow. Combined with the large blade incidence on the retreating side, as forward speed increases, the blades approach a stalled condition. At the same time, regions near the tips on the advancing side experience a very high velocity flow, approaching the point where shock waves form, leading to shock induced flow separation. Due to these limiting factors, the maximum forward speed of a helicopter is limited to about 250 mph (402 km/h).

Drawing a very close comparison to the theory, the world speed record for a helicopter is 249.10 mph (400.80 km/h). This record was set in August 1986, with a Westland Lynx from the United Kingdom flying over a 15 km course, piloted by John Egginton.

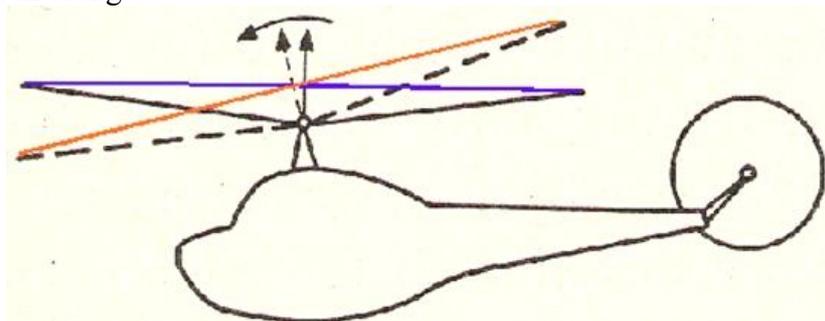


Westland Lynx, world's fastest helicopter

Cyclic and Forward Flight

Tip Path Plane

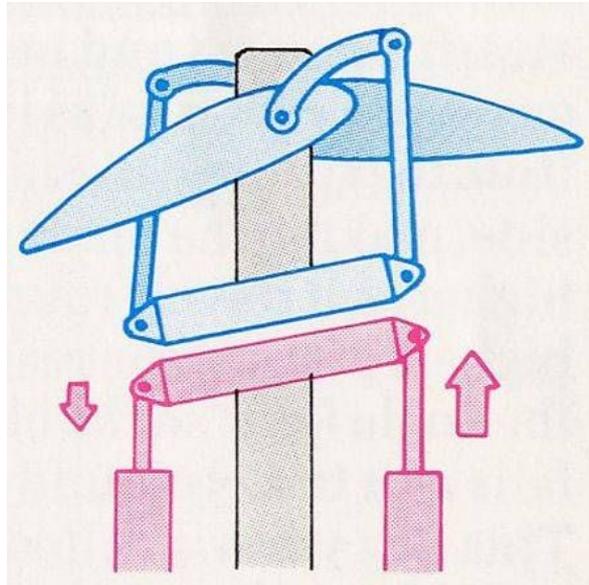
The tip path plane, or TPP, is the plane connecting the rotor blade tips as they rotate. While hovering, the thrust vector of a helicopter is oriented upwards, perpendicular to the tip path plane. In order for the helicopter to travel forward, this thrust vector needs to be rotated slightly in the forward direction. To rotate the thrust vector, it is in turn necessary to rotate the TPP by the same amount, as illustrated below. The hovering TPP is drawn in purple, while the forward TPP is in orange.



*Tip path planes and thrust vectors for hovering and forward flight
[from Gessow and Myers, 1952]*

Cyclic Control

Since tilting the rotor hub or rotor shaft is impractical, an alternative means of rotating the TPP is needed. Most modern helicopters use a system of swashplates. Seen in the following diagram, the swashplate system is composed of upper and lower swashplates.



Cyclic control and swashplates [from Gunston and Spick, 1986]

The red portion of the diagram, including the lower swashplate, remains stationary relative to the helicopter. The upper swashplate (in blue) rotates with the rotor, while remaining parallel to the lower swashplate. By utilizing what is called cyclic control, the swashplates can be angled so as to vary the pitch of the blades depending on their azimuth angle. As the swashplates are tilted in the proper direction, there is an increased lift on the aft portion of the rotor, causing the blades to flap up, which in turn causes the TPP to rotate forwards. As the TPP rotates forwards, the thrust vector does as well, imparting a forward acceleration to the helicopter.

Momentum Theory in Forward Flight

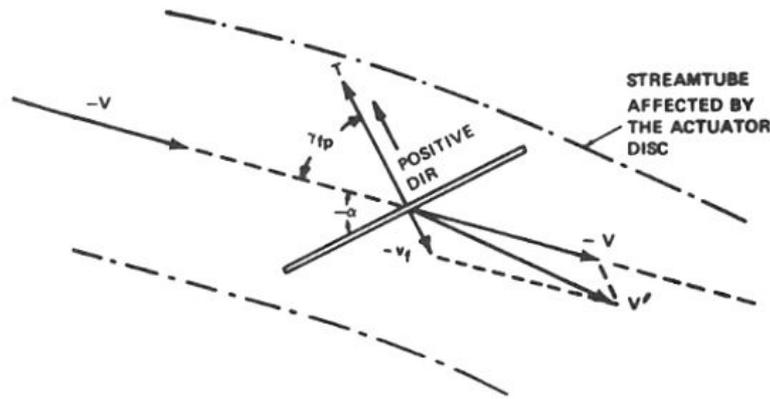
The first analytical theory to consider for a helicopter in forward (nonaxial) flight is the momentum theory. The analysis for vertical (axial) flight is very similar to that of a simple propeller, and will not be discussed here. One notable result of that analysis, however, is the induced velocity of the rotor in hover:

$$V_h^4 = \left(\frac{w}{2\rho} \right)^2$$

where w is the disc loading, given by

$$w \equiv \frac{T}{\pi R^2}$$

In the terms of basic momentum theory, the thrust of a rotor in nonaxial flight is very difficult to derive. In the context of this discussion, a relationship for the thrust that was proposed by Glauert in 1928 will be used. A simple diagram of an actuator disk in nonaxial flow is depicted below.



Actuator disk in nonaxial flow [from Stepniewski, 1979]

The thrust of the actuator disk can be given by:

$$T = 2\pi R^2 \rho V' v_f$$

Far downstream from the disk, the downwash v_f is doubled. Also, the term $\pi R^2 \rho V'$ becomes the mass flow through the stream tube that is defined by the actuator disk. Some validity for these relationships can be inferred by comparing them to the formula for the lift of a wing having $2R$ span with a uniform downwash. The lift of such a wing is expressed by an equation similar to that shown above. After assuming that this equation is valid, determining the thrust requires that the induced velocity in forward flight be determined:

$$v_f = \frac{T}{2\pi R^2 \rho V'}$$

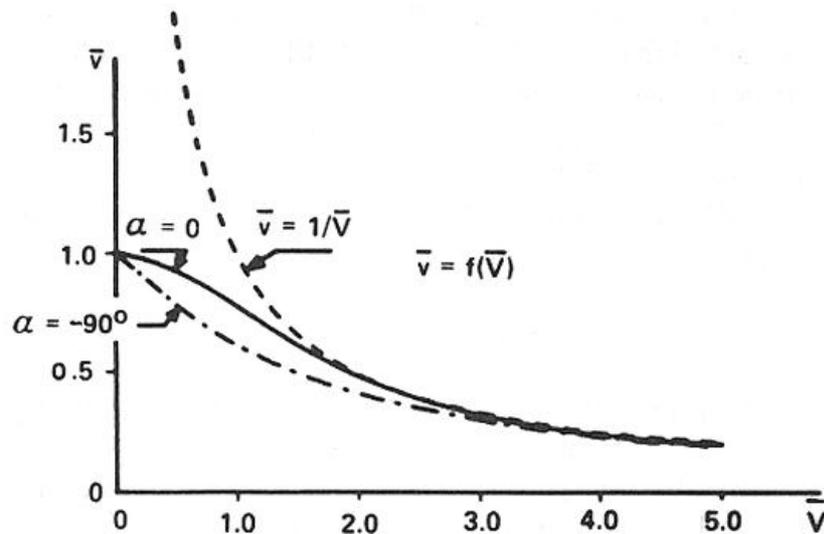
Unfortunately, this equation does not allow a determination of v_f , since V' is also dependent on v_f . In order to solve for the induced velocity, V' must first be expressed in terms of V and v_f :

$$V' = \sqrt{(v_f - V \sin \alpha)^2 + (V \cos \alpha)^2}$$

This value for V' can then be substituted back into the thrust equation, which can then be nondimensionalized by v_h (overbars denote nondimensional values):

$$\bar{v}_f^4 - 2\bar{V}\bar{v}_f^3 \sin \alpha + \bar{V}^2 \bar{v}_f^2 - 1 = 0$$

The above equation can now be solved either graphically or with an iteration scheme. As a check of validity, if this equation is solved for an α of 0° , the solution matches that of the axial case. The other extreme case, where $\alpha = -90^\circ$, represents the other limiting case of helicopter forward flight. The nondimensional induced velocity versus the nondimensional flight velocity for both limiting cases are plotted below.

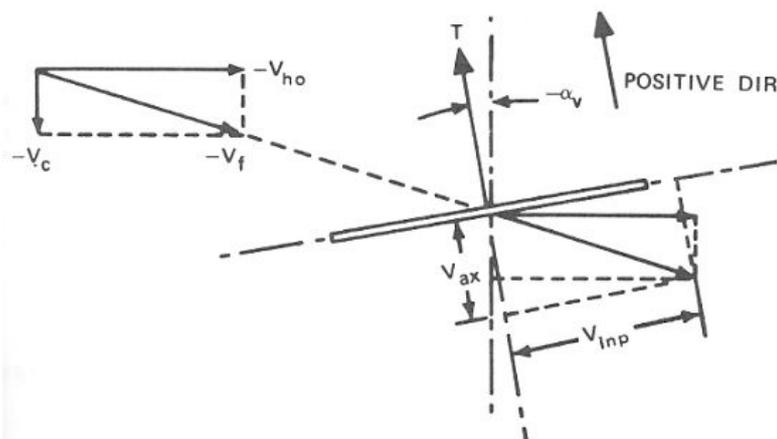


Nondimensional induced velocity versus nondimensional flight velocity [from Stepniewski, 1979]

While most cases of forward flight occur at small α , in which case the $\alpha=0^\circ$ curve would be very representative, all other intermediate cases of flight are within the two curves. It is important to note that beyond a nondimensional flow velocity of about 3, the two curves are almost coincident, and can be approximated by $1/\bar{V}$.

Blade Element Theory in Forward Flight

Blade element theory provides the necessary means to predict the aerodynamic forces and moments acting on a rotor blade in forward flight. Similar to momentum theory, it is necessary to determine the magnitude and direction of the airflow in the immediate vicinity of the blade element under consideration. Once these velocities are known, the calculation of the forces and moments can be performed using two-dimensional airfoil characteristics, taking care not to neglect such aspects as Reynolds and Mach number effects.



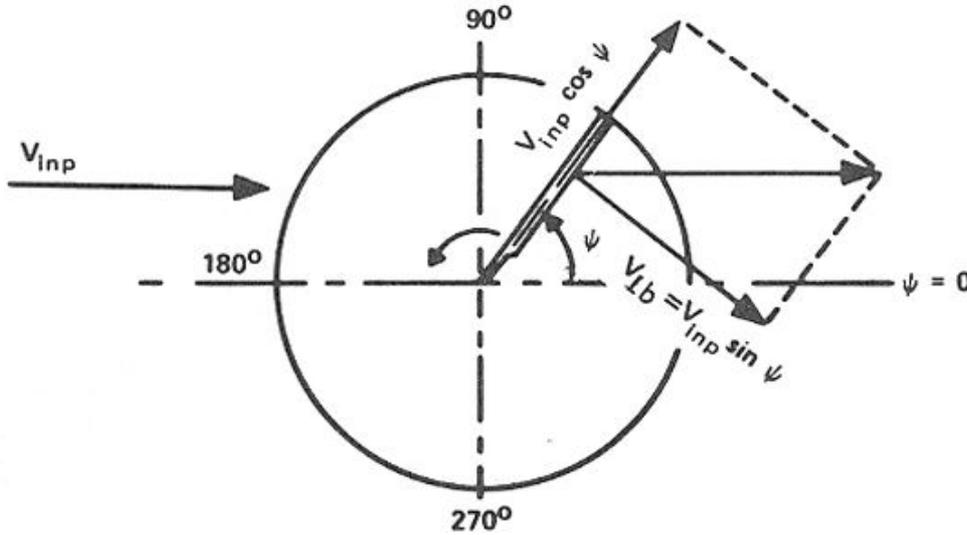
Flow velocity components of a rotor in nonaxial flow [from Stepniewski, 1979]

The flow velocity components of a rotor in nonaxial flow can be resolved into two components, the axial (V_{ax}) and inplane (V_{inp}) components, both shown in the above figure. If a small tilt angle α_v is assumed, then these components can be expressed as follows:

$$V_{ax} = -V_C + V_{h0} \alpha_V$$

$$V_{inp} = -V_{h0} + V_C \alpha_V$$

As a first approximation, only the component of V_{inp} that is perpendicular to the blade axis is important (i.e. $V_{inp} \sin \psi$).

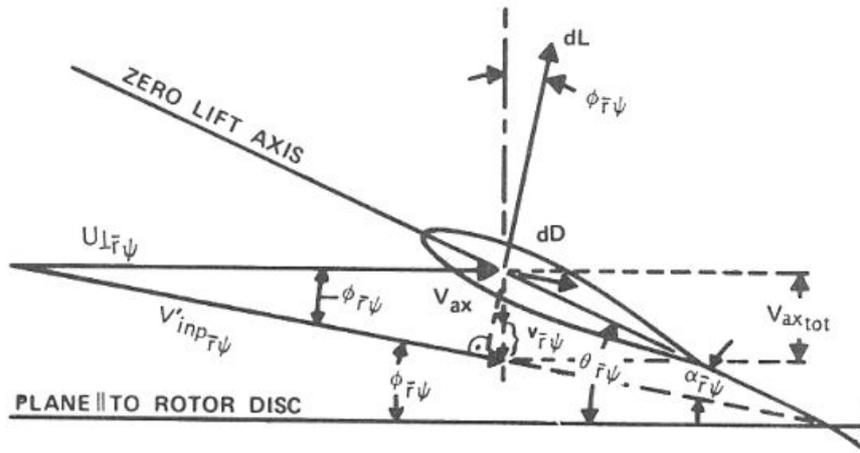


Inplane velocity components [from Stepniewski, 1979]

Also, in the case of forward flight when α_v is small, the inplane velocity V_{inp} may be considered the same as the forward horizontal speed V_{ho} . Taking into account the speed induced by the rotor rotation (ΩR) and the blade azimuth angle, the total component of the inplane velocity perpendicular to the blade axis is (overbars denote nondimensional values):

$$U_{\perp}(\bar{r}, \psi) = V_t \bar{r} + V_{h0} \sin \psi$$

If we assume that the blade tips maintain their position with respect to the TPP, then the flow velocities at a blade element are the same as those shown below.



Flow velocities at a blade element [from Stepniewski, 1979]

The pitch angle of the blade is θ , the angle of attack α , and the total inflow angle is ϕ , which gives the following equation:

$$\tan^{-1} \phi(\bar{r}, \psi) = \frac{V_{ax_{tot}}(\bar{r}, \psi)}{U_{\perp}(\bar{r}, \psi)}$$

where $V_{ax,tot}$ is the sum of V_{ax} and the induced velocity v at the element.

Assuming that the value of $V_{ax,tot}$ is known, it is possible to calculate aerodynamic forces on a blade element. The three significant forces that can be calculated are thrust, dT , total drag, dD , and total torque, dQ .

$$dT(\bar{r},\psi) \approx dL(\bar{r},\psi) = \frac{1}{2} R\rho (V_t\bar{r} + V_{h0} \sin\psi)^2 \alpha(\bar{r},\psi) [\theta(\bar{r},\psi) - \phi(\bar{r},\psi)] c_r - d\bar{r}$$

$$dD(\bar{r},\psi) = dL(\bar{r},\psi) \phi(\bar{r},\psi) + \frac{1}{2} R\rho [(V_t\bar{r} + V_{h0} \sin\psi)^2 c_r - c_d(\bar{r},\psi)] d\bar{r}$$

$$dQ(\bar{r},\psi) = R\bar{r} dD(\bar{r},\psi)$$

For a rotor with rectangular blades, these equations can be integrated as follows:

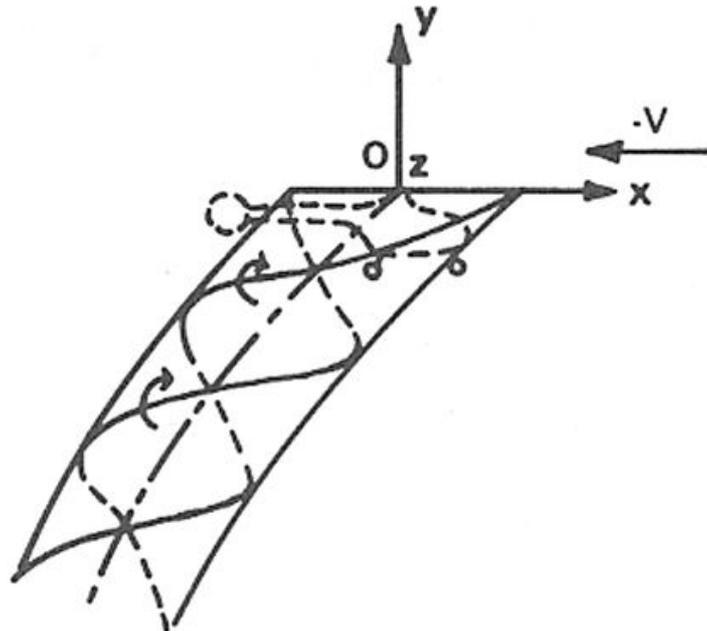
$$T = \frac{1}{4} \sigma R^2 \rho \int_{r_i}^{\bar{r}_e} \int_0^{2\pi} \{(V_t\bar{r} + V_{h0} \sin\psi)^2 \alpha(\bar{r},\psi) [\theta(\bar{r},\psi) - \phi(\bar{r},\psi)]\} d\psi d\bar{r}$$

$$Q = \frac{bR}{2\pi} \int_{r_i}^{\bar{r}_e} \int_0^{2\pi} \phi(\bar{r},\psi) \bar{r} dL(\bar{r},\psi) d\psi d\bar{r} + \frac{1}{4} \sigma R^3 \rho \int_{r_i}^{\bar{r}_e} \int_0^{2\pi} (V_t\bar{r} + V_{h0} \sin\psi)^2 c_d(\bar{r},\psi) \bar{r} d\psi d\bar{r}$$

As with momentum theory, these equations can be integrated either graphically or numerically. Each integration yields the thrust or torque for a selected azimuth angle, which then must be averaged for a complete revolution of the blade. These values must then be multiplied by the number of blades to determine values for the entire rotor.

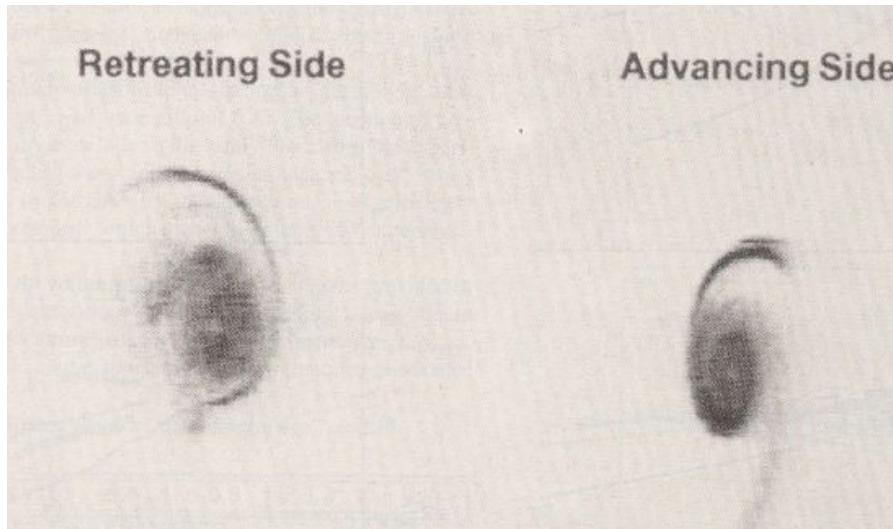
Rotor Wake

A final element of a helicopter rotor that needs to be examined is the wake it creates as it travels with a forward velocity. In the simplest case, where no vorticity is shed along the blade span, vortices would only be shed at the blade tips and roots. Immediately aft of the helicopter, the tip vortices form helical lines on the surface of the stream tube defined by the rotor. The root vortices will coalesce, forming a single vortex along the axis of the stream tube.



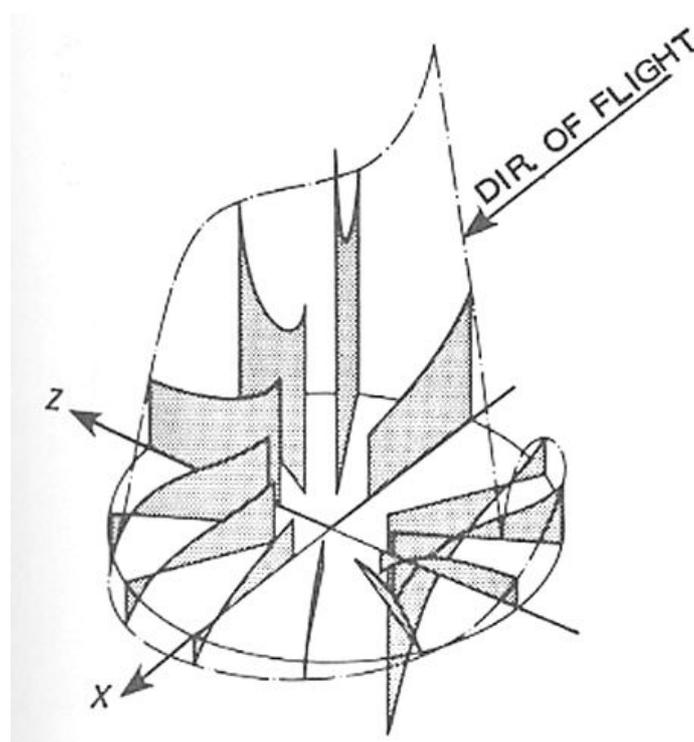
Rotor vortices at low flight speed [from Stepniewski, 1979]

Soon after the vortices leave the rotor, they begin to roll up in a two stage process. First, the individual tip vortices combine into concentrated lines as they are shed from the tips. Then, several rotor radii downstream of the rotor, the overlapping spiral vortices combine to form two trailing vortices very similar to those found trailing fixed wing aircraft.



Trailing vortices viewed from downwind of rotor [from Ghee and Elliot, 1995]

While the trailing vortices depicted above are very similar to those of a fixed wing aircraft, it is important to note the "tighter" vortex on the advancing side of the rotor. These vortices exhibit such a difference because of the variation of the downwash distribution between the advancing and retreating blades. As discussed in the section on flapping hinges, the advancing blades experience a higher velocity and thus a greater downwash at the tip, as demonstrated below.



Downwash distribution on a rotor disk in forward flight [from Stepniewski, 1979]

Summary

Even though the concept of the helicopter is arguably older than that of the airplane, there is still a great amount of research and advancement yet to occur. As the political climate of our world continues to change and military conflicts approach the small-scale urban warfare of recent years, the importance of the helicopter will continue to grow. It is rather ironic that an idea first conceived long before the Common Era will be key to winning military conflicts in the 21st century.



References

1. Bhagwat, Mahendra J., et al. Flow Visualization and Measurements in the Wake of a Rotor with a Subwing Tip, Annual Forum Proceedings-American Helicopter Society, vol. 1, 1999, pp. 951-962.
2. Bramwell, A. R. S. Helicopter Dynamics. New York: Halsted Press, 1976.
3. Gessow, Alfred and Myers, Garry C., Jr. Aerodynamics of the Helicopter. New York: Macmillan Company, 1952.
4. Ghee, Terence A. and Elliot, Joe W. The Wake of a Small-Scale Rotor in Forward Flight Using Flow Visualization, Journal of the American Helicopter Society, vol. 40, no. 3, July 1995, pp. 52-65.
5. Gunston, Bill and Spick, Mike. Modern Fighting Helicopters. New York: Crescent Books, 1986.
6. Johnson, Wayne. Helicopter Theory. Mineola, NY: Dover Publications, 1980.
7. McCormick, Barnes W. Aerodynamics, Aeronautics and Flight Mechanics. New York: John Wiley & Sons, 1995.
8. Newman, Simon. The Foundations of Helicopter Flight. New York: Halsted Press, 1994.
9. Seddon, J. Basic Helicopter Aerodynamics. Reston, VA: American Institute of Aeronautics and Astronautics, 1990.
10. Stepniewski, W. Z. and Keys, C. N. Rotary-Wing Aerodynamics. Mineola, NY: Dover Publications, 1979.
11. _____. World and United States Aviation and Space Records. Arlington, VA: National Aeronautic Association of the USA, 1999.
12. Young, Raymond A. Helicopter Engineering. New York: Ronald Press Company, 1949.