Helicopter Physics

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Lift Happens

Lift is a mechanical aerodynamic force produced by the motion of an aircraft through the air, it generally opposes gravity as a means to fly. Lift is generated mainly by the wings due to their shape. An Airfoil is a cross-section of a wing, it is a streamlined shape that is capable of generating significantly more lift than drag. Drag is the air resistance acting as a force opposing the motion of the aircraft.

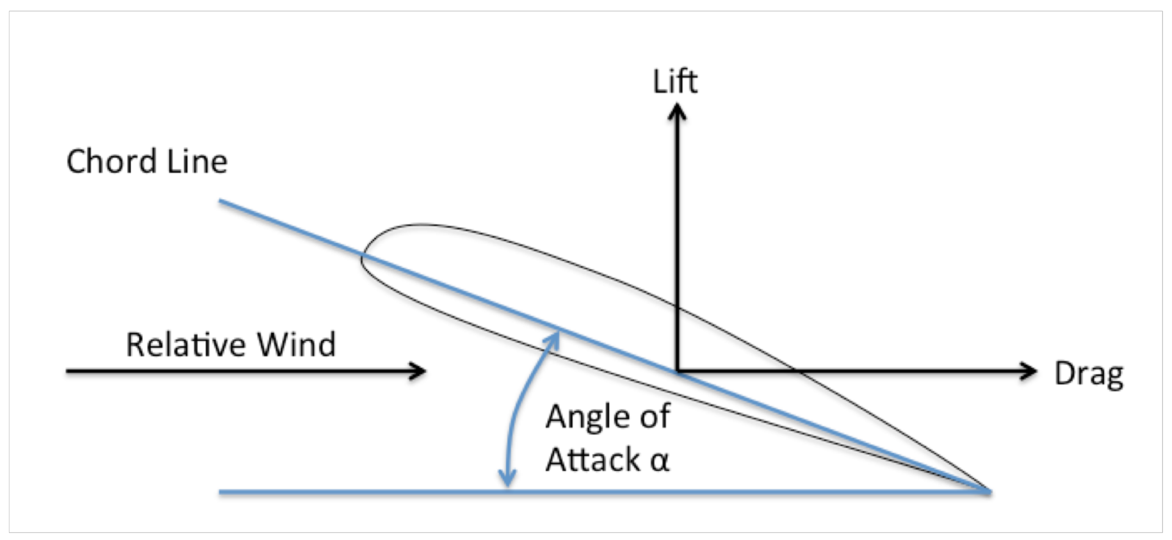


Diagram of Lift and Drag acting on an Airfoil
Here the angle of attack represents the angle between the inclination of the wing and the incoming wind (a relative representation of horizontal aircraft movement, think of a wind tunnel)
Image Source: AviationChief.com

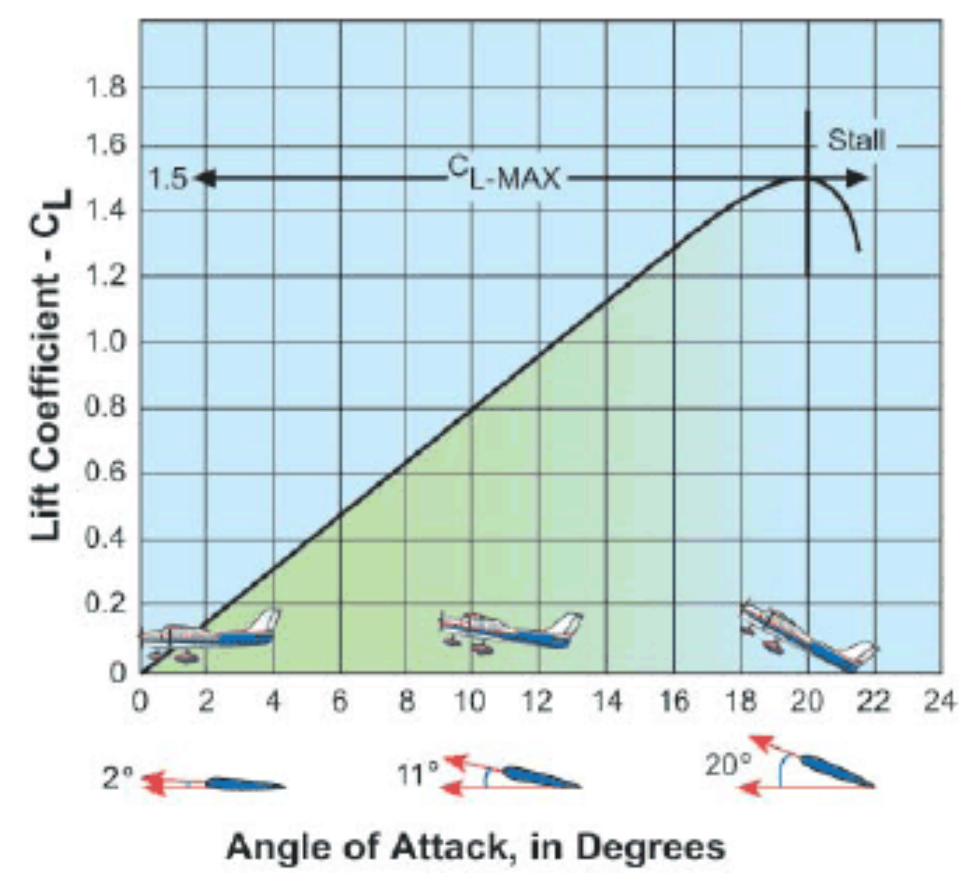
Helicopter Wing Dynamics

Helicopters derive their name from their unique way of flying. Unlike other aircraft helicopters rotate their wings. Most aircraft generate lift through their fixed wing design, however this limits their movement. Helicopters take advantage of their unique rotating wings (blades) and through a combination of rotors (blade sets) generate lift in a way that gives them more maneuverability, e.g. hovering.

A helicopter during hover. This helicopter design utilizes a main rotor and a tail rotor.
Image Source: Pinterest.com

Lift Formula

Lift is calculated using the following formula: $L = \frac{1}{2}\rho v^2 C_L S$
Where ρ is the air density, v is the velocity, C_L is the lift coefficient and S is the surface area of the wing. Even though most of these components are relatively easy to measure, the lift coefficient is highly dependable on the shape of the airfoil. Therefore it is usually calculated through the angle of attack of a specific airfoil as portrayed in charts much like the following:



Example of a Lift Coefficient vs Angle of Attack chart.
The higher the angle of attack the more lift that is generated, until a cutoff point.
Image Source: flightlearnings.com

Lift in Rotating Wings

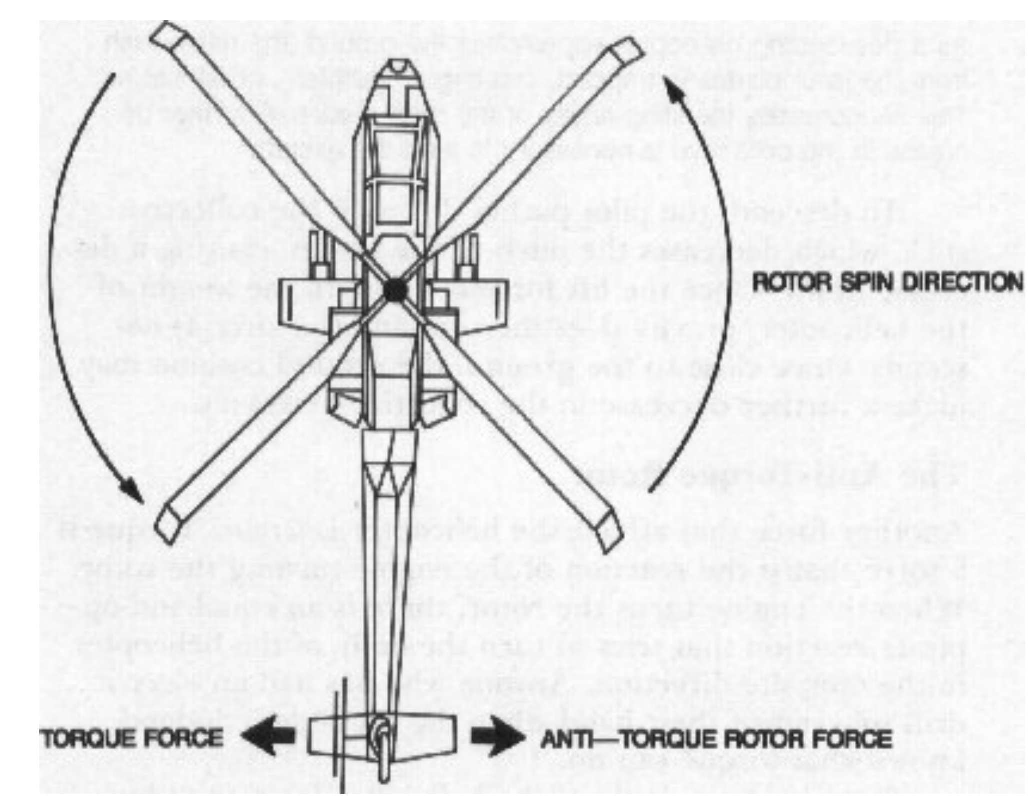
By looking at the Lift formula its easy to notice that there is a problem when using it with helicopters. Helicopter wings rotate, therefore parts of each blade move faster than other parts relative to their distance from the center of rotation. This is dealt with by expressing the velocity (v) in terms of angular velocity (ω) and the radius (r). The next step is to simply do an integration in order to calculate the Lift through each little segment of the blade along its length, as follows: $L = \frac{1}{2}\rho\omega^2 C_L y \int_{r_1}^{r_2} r^2 dr$
Where y represents the width of the blade and dr represents the change in radius throughout the length of the blade such that $y\int_{r_1}^{r_2} dr = S$. Note that this calculates the lift for only one blade.

Drag

The movement of the blades through the air generates drag, which can be calculated for helicopters with the formula $D = \frac{1}{2}C_D y\rho\omega^2 \int_{r_1}^{r_2} r^2 dr$. C_D is the Drag Coefficient which depends on the cross sectional area of the wing as it moves against the air. Note that this formula is for one blade only.

Torque

Torque is a measure of how much a force acting on an object causes that object to rotate. As the blades of a helicopter rotate against the air, the air pushes back on the blades following Newtons 3rd Law of Motion: "To every action there is an equal and opposite reaction". This reaction force is translated into the fuselage of the helicopter via torque, and can be measured for individual blades as follows: $\tau = rD = \frac{1}{2}C_D y\rho\omega^2 \int_{r_1}^{r_2} r^3 dr$, where D is the Drag Force. As a result the fuselage tends to rotate in the opposite direction of its main rotor spin. This is compensated by generating a force to counter it, which is usually done with a secondary rotor. If done with a tail rotor design then the compensation to the Torque is done via Lift in a horizontal direction and can be measured as follows: $\tau r = L_T$, where L_T represents the Anti-Torque Lift and r is the distance that separates the axes of rotation of both the main and tail rotors.



Visual representation of torque compensation via a tail rotor in a helicopter.
Image Source: FlightSimBooks.com

Acknowledgments

- H. H. Hurt, Jr. "Aerodynamics for Naval Aviators", 1965
- S. Tulio, "Mathematical Model and Simulation for a Helicopter with Tail Rotor"
- https://www.military.com/equipment/uh-60a-l-black-hawk

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