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A Study of Propeller Design: Review

Tushar G. Mangale[1], S.H.Chaudhari[2], Dipak Kharat[3]

[1]P.G Student, Department of Mechanical Engineering, [2]P.G Student, Department of Mechanical Engineering, [3]P.G Student, Department of Mechanical Engineering Padm. Dr. V. B. Kolte College of Engineering, Malkapur, Maharastra, India.

ABSTRACT

Propulsion is the science of designing an engine to propel a vehicle forward or up. For aviation, propulsion is generally broken into two categories: air- breathing propulsion for airplanes and rocket propulsion for spacecraft. Both work on the principle of pushing high velocity exhaust gases out the back end (reaction thrust principle), but they differ in one significant detail. An air-breathing engine uses the air stream in which the airplane is flying to augment the propulsive abilities of the engine so it can carry less fuel. A rocket engine travels in space where there is no air, and therefore it must carry all its fuel internally. An air-breathing engine will have both an inlet and an exit, while the rocket will be closed in the front and only have an exit. In general, an air-breathing engine will get more thrust for less fuel than a rocket.
Keywords: Propeller Design, Power, Blade Angle, Pitch.

I. INTRODUCTION

Thrust is the forward facing force generated by the engines of the airplane. The air flows into the engine at roughly the flight speed of the airplane, and it exits the engine flowing much hotter and faster. The thrust is computed using the rate of mass flowing through the engine times the difference between the high velocity of the exhaust gases and the original velocity of the air into the inlet. The exhaust gases flow out the back of the engine, causing a reaction force on the airplane, pushing it forward. This concept is called the reaction thrust principle.

An easy way to demonstrate this principle is to take a balloon and blow it up, filling it with high-pressure air. If the opening of the balloon is pointed to the side and allowed to open, the high-pressure air inside escapes at high velocity to the lower pressure air outside. The airflow is to the side, but the balloon experiences a push, or reaction thrust, in the opposite direction.

Energy, Power and Force

Moving a vehicle, may it be on the ground, on the water, or in the air, requires a force to overcome the friction and inertia forces and to lift the vehicle to a different elevation. A force can be created from any kind of energy, like the energy contained in liquid fuel for an internal combustion engine, the electric energy stored in a battery or like solar energy being transformed by solar cells into electric power. To actually move an object, the force must be must be translated by some sort of engine into power, pushing the vehicle forward. Burning fuel in an open pan does not create a force and having a bottle of compressed air lying around creates a force on the bottles walls, but does not create any power output. Energy may be static (fuel) or dynamic (flywheel), force is static and power is always dynamic. Power equals force times distance per time.

An Engine

The lack of powerful, lightweight engines was one of the reasons for the failures of early attempts to fly. Using natural sources of energy like thermals requires quite sophisticated aircraft, which were of course not available in the beginning. When steam engines became available, they proved to be too heavy for flight, compressed air engines or twisted rubber bands could be used for smaller demonstrations, but were not practical or to heavy for man carrying airplanes. Finally, the piston engine, burning fuel of high-energy content internally, was to become the first successful power plant for aviation. From the early days of the Wright brothers until the 1950s, this type of engine was the main source of aerial propulsion.

The Propeller

Having a power plant available is only one part of aircraft propulsion; we also need means to transform the power output of the engine into something useful. Piston engines usually drive a rotating shaft, which must be connected to a device, which, literally "in turn", creates a force, finally advancing our vehicle.

The idea of placing an "inclined plane" on a rotating shaft is astonishingly old. It was probably first used to pump water and later in windmills. Propellers for the propulsion of vehicles have been developed and successfully used on ships first.

Propellers have also been called *airscrew* in the past, but this term may be misleading, because a propeller does not move like a mechanical screw through a rigid medium. You do not call a wing *knife* or *slicer* because it also does not slice through the air in the direction of its inclined mean line. Each section of a propeller (or of a wing) has a certain *angle of incidence* and is moving through the air at its unique *angle of attack* - both are independent. On the other hand, a mechanical screw or a knife moves through a rigid material exactly in the direction, which is given by its pitch or angle of incidence - a screw with different pitches along its radius, would be stuck, a propeller do not.

Propeller theory

There are a number of blade elements of a propeller, which improve the on-flight conditions of a propeller and the efficiency of the propeller. These elements also determine various aspects like lift force, drag force, thrust, advance ratio and various coefficients of the propeller.

Basic forces on a Propeller

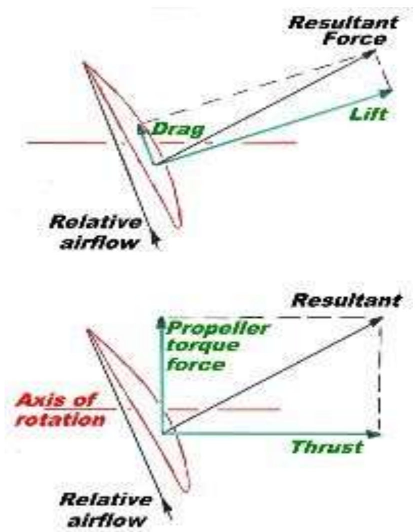


Fig. Basic forces

The diagram at left represents a blade section in flight and rotating around the shaft axis. We represent the aerodynamic force component acting forward and aligned with the aircraft's longitudinal axis as the thrust force, and that component acting parallel to the direction of rotation as the propeller torque force.

In the lower figure the component of the lift acting in the rotational plane has now been added to the drag to produce the 'propeller torque force' vector. The remaining forward acting portion of lift is then the thrust. That is why propeller efficiency is usually no greater than 80– 85%, not all the lift can be used as thrust and the propeller torque force consumes quite a bit of the shaft horsepower.

Blade angle and pitch

The blade angle is the angle the chord line of the aerofoil makes with the propeller's rotational plane and is expressed in degrees. The angle between the aerofoil chord line and the helical flight path (the relative airflow) at the blade station is, of course, the angle of attack and the angle between the helical flight path and the rotational plane is the angle of advance or helix angle. The aoa and helix angle vary with rotational and forward velocity.

Geometric pitch

Is the circumference ($2 \pi r$) of the propeller disc at the blade station multiplied by the tangent of the blade angle. Thus, it is, the distance through which the propeller, and aircraft, would advance during one revolution of the propeller.

Geometrical aspects of a propeller

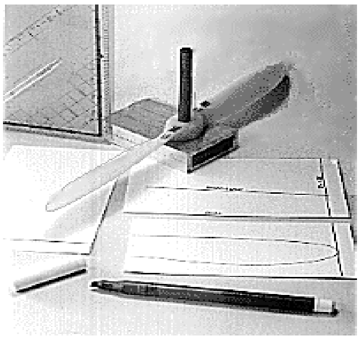
The geometry of a propeller involves the measurement of the characteristics of cross-section variables like the chordal length of the airfoil cross- section, length of propeller, the forward or backward twist etc. there are certain methods of doing so, each being equally efficient.

Measuring the Geometry of Propellers

- Using a Pitch Gauge
- Tracing the Edges
- Slicing the Propeller
- Using Templates

Using a Pitch Gauge

The jig is specially designed for pitch measurements of propellers at different radial sections and the pitch can be read directly from its scales without further calculations. A drawback of the gauge is the fact, that the angle of the lower side of the section is measured, which is not exactly the aerodynamically relevant blade angle. If the relative thickness of all airfoil sections were the same along the radius and if all airfoils would have a flat lower side, then the error would simply be a constant offset from the nominal pitch angles.



Tracing the Edges

A relatively simple way to get the propeller geometry with medium accuracy, is the non destructive *tracing method*. Attach the propeller to a block so that its axis is perpendicular to a flat table. Now prepare some pieces of flexible cardboard, slightly longer than the propeller radius. Then use a water soluble felt tip pen and paint the leading edge of the propeller,quickly place a cardboard sheet vertical on the table and press it against the edge of the propeller, before the felt tip color has dried. Doing the same at the trailing edge leaves you with two traces on the cardboard. Finally, you need a graph of the platform of the prop, which is easily created by holding the third cardboard sheet against the lower side and by tracing the outline of the blade on the board with a pencil.

The calculation procedure is as follows.

- measure the local chord length c from the planform graph,
- measure the distance between cardboard edge and leading edge trace)the height of the leading edge trace above ground) hl,
- measure the height of the trailing edge trace above ground ht,
- calculate the difference $dh = hl - ht$ and,
- calculate the blade angle $ß = sin^{-1}(dh/c)$

Slicing the Propeller

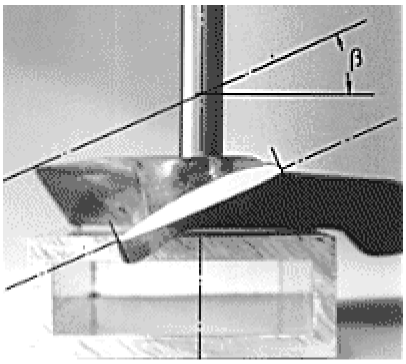


Figure. A photograph of a cut through a threebladed propeller for F3A models (1985)

Unfortunately an almost perfect method to measure the geometry of a propeller is destructive. The method is very simple: beginning at the tip, we cut a sample propeller at the radial station of interest, paint the cut white and take a photograph, including a pin in the axis of the propeller. A paper print or a slide can be used to measure the blade angle ß with respect to the axis as well as the airfoil shape or at least the maximum thickness and the camber.

Using Templates

This method is very similar to the slicing method, but instead of cutting the propeller into pieces, small, flat templates are used, which are attached to the waxed surface of the propeller using quick setting polyester putty. These templates can then be photographed and dealt with as with the slicing method. The templates are made from plywood and should resemble the propeller section closely, leaving a small gap of about 2 millimeters only, which will be closed by the filler. They are made in two parts, so that they can be separated into an upper and a lower segment - the lower part must fit flush to the table to have a reference for the blade angle.

How does a Propeller work?

As Newton stated, *"Actio est reactio"*. For the propulsion problem, this means that a device accelerating air or water in one direction, feels a force in the opposite direction. A propeller accelerates incoming air particles, "throwing" them towards the rear of the airplane, and thus feels a force on itself - this force is called *thrust*. Because the mass of air passing through the stream tube must be constant (conservation of mass), the increased velocity leads to a contraction of the stream tube passing through the propeller disk (neglecting compressibility). Besides the contraction of the stream tube, a propeller also adds a swirl component to its outflow (wake). The amount of swirl depends on the rotational speed of the engine and eats up energy, which is not available for thrust anymore. The swirl angle (about 1°...10°) may cause non symmetrical flow conditions on parts behind the propeller, e.g. at the tail planes.

Design principles of a Propeller

Based on the theory of the optimum propeller (as developed by Betz, Prandtl, Glauert), only a small number of design parameters must be specified. These are the number of blades B, the axial velocity v of the flow (flight speed or boat speed), the diameter D of the propeller, lift and drag distributions of a propeller and the density,ρ, of the medium.

The Number of Blades

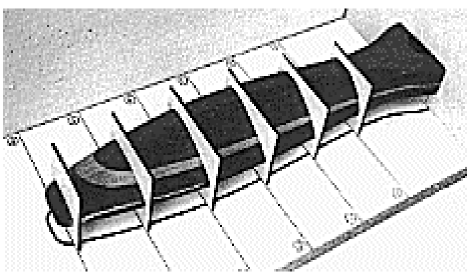
The number of blades has a small effect on the efficiency. Usually a propeller with more blades will perform slightly better, as it distributes its power and thrust more evenly in its wake.

The Velocity

The velocity of the incoming fluid together with the velocity of rotation (r.p.m.) determines the pitch distribution of the propeller. Large pitch propellers may have a good efficiency in their design point, but may run into trouble when the have to operate at axial velocity. In this case, the blades tend to stall.

The Diameter

The propeller diameter has a big impact on performance. Usually a larger propeller will have a higher efficiency, as it catches more incoming fluid and distributes its power and thrust on a larger fluid volume.



Lift and Drag Distributions

The distribution of C_L and C_D along the radius can be examined by performing an analysis for the design point. For maximum performance, the airfoils must operate at maximum L/D. However, if the propeller should also work reasonablygood conditions, it is usually necessary to use a lower angle of attack for the design.

The Fluid Density

The density of the fluid has no influence on the efficiency of a propeller, but strongly affects its size and shape. As the forces and the power are directly proportional to the fluid density, a hydro-propeller will have much smaller dimensions than a propeller working in air. The same is true for high-speed tips of aircraft propellers, where instead of cavitation, but supersonic regions may occur if the pressure gets too low. Therefore, the tip sections of propellers operating at Mach numbers above 0.7 should be designed to operate at small lift coefficients below 0.5 too.

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