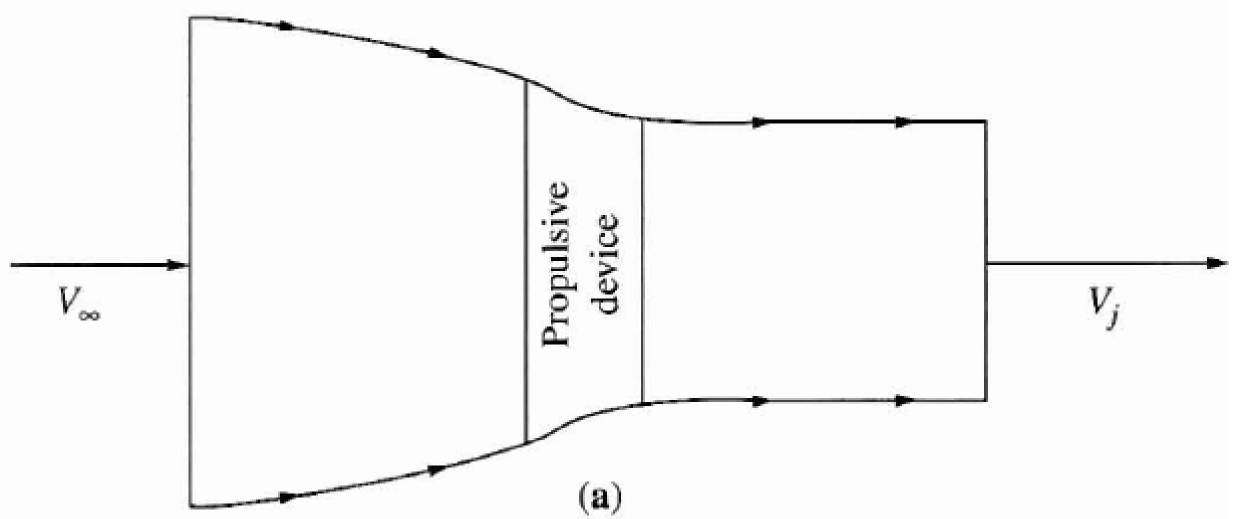
Different types of engines

- 1. Reciprocating engine/propeller
- 2. Turbojet
- 3. Turbofan
- 4. Turboprop

Why do different aircraft propulsion devices exist? For example, many airplanes today are still powered by the classical propeller/reciprocating engine combination, 50 years after the jet revolution. Why?

Each engine represents a compromise between thrust and efficiency

In an elementary fashion, we can state that a propeller/reciprocating engine combination produces comparably low thrust with great efficiency,
a turbojet produces considerably higher thrust with less efficiency, and
a rocket engine produces tremendous thrust with poor efficiency.
There is a tradeoff-more thrust means less efficiency in this scenario.



(a)

Consider stream tube of **air** flowing from left to right through a generic propulsive device; this device may be a propeller, a jet engine, etc. The function of the propulsive device is to produce thrust T, acting toward the left**.** No matter what type of propulsive device is used, the thrust is exerted on the device via the net resultant of the pressure and shear stress distributions acting on the exposed surface areas, internal and/or external, at each point where the air contacts any part of the device.

imagine that you are the air you will accelerate toward the right; if your initial velocity is V, far ahead of the propulsion device, you will have a larger velocity Vj downstream of the device (the ***jet velocity).***

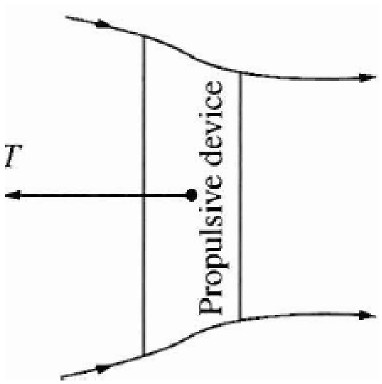
The change in velocity Vj - V, is related to T through Newton's second law, which states that the force on an object is equal to the time rate of change of momentum of that object. Momentum is mass times velocity.

$\dot{m}$ Is the ***mass flow*** (kg/s or slug/s) through the stream tube (we are assuming to have steady flow).

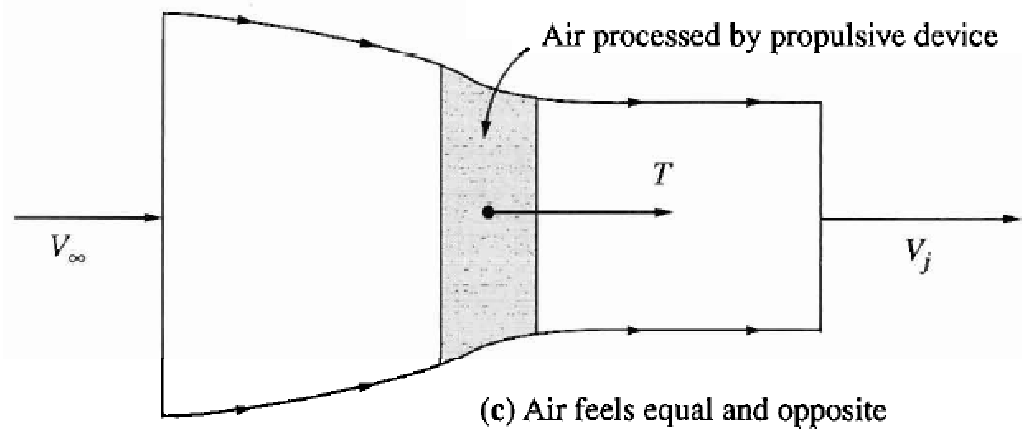
The time rate of change of momentum of the air flowing through the propulsion device is simply the momentum flowing out (mVj) at the right minus the momentum flowing in at the left (mV). From Newton's second law, this time rate of change of momentum is equal to the force T:

$$\boxed{T = \dot{m}(V_j - V_\infty)}$$

from Newton's third (for every action, there is an equal and opposite reaction) the air will exert on the engine an equal and opposite force T, acting towards the left.



(b) Propulsive device produces thrust T acting to the left.



(c) Air feels equal and opposite force T acting to the right.

Efficiency

Consider the equivalent situation where the propulsive device ***moves*** with a velocity V, into stationary air (this is the usual case in practice the propulsive device is mounted on an airplane, and the airplane flies with velocity V, into still air). ***Relative to the device, the*** upstream velocity relative is V and a downstream velocity relative to the device equal to Vj. For us sitting in the laboratory, we do not see velocities V, and Vj we see stationary air in front of the device, we see the device hurtling by us at a velocity V, and we see the air behind the device moving in the opposite direction with a velocity (relative to the laboratory) of V-Vj.

This moving air, which is left behind after the device has passed through the laboratory, has a kinetic energy per unit mass of *(Vj-V)^2.* This kinetic energy is totally wasted; it performs no useful service. It is simply a loss mechanism associated with the generation of trust. It is a source of inefficiency.

when you exert a force on a body moving at some velocity, the *power g*enerated by that force is Power = force x velocity

power available ***Pa*** provided by the propulsive device, is $P_A = TV_\infty$

However, the propulsive device is actually putting out more power because the device is also producing the wasted kinetic energy in the air left behind.

$$\text{Total power generated by propulsive device} = TV_\infty + \frac{1}{2}\dot{m}(V_j - V_\infty)^2$$

The power efficiency can be defined as

$$\eta_p = \frac{\text{useful power available}}{\text{total power generated}}$$

$$\eta_p = \frac{TV_\infty}{TV_\infty + \frac{1}{2}\dot{m}(V_j - V_\infty)^2}$$

$$\eta_p = \frac{TV_\infty}{TV_\infty + \frac{1}{2}\dot{m}(V_j - V_\infty)^2} \quad \Longrightarrow \quad \eta_p = \frac{\dot{m}(V_j - V_\infty)V_\infty}{\dot{m}(V_j - V_\infty)V_\infty + \frac{1}{2}\dot{m}(V_j - V_\infty)^2}$$

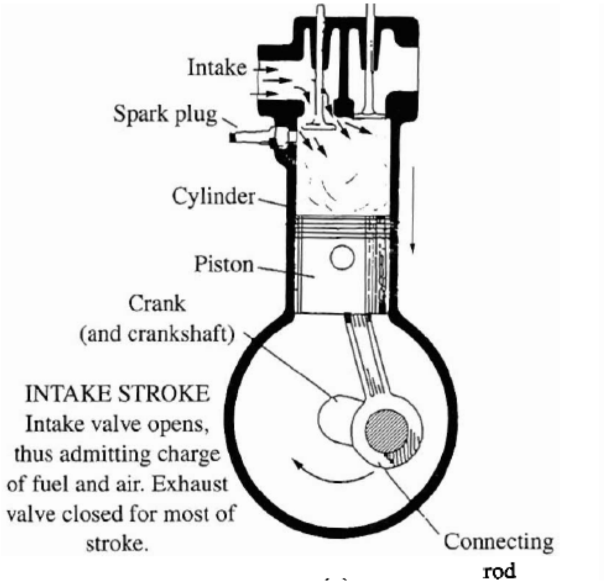
$$\boxed{\eta_p = \frac{2}{1 + V_j/V_\infty}}$$

maximum (100%) propulsive efficiency is obtained when Vj=Vinf. On the other hand, if Vj = Vinf, Thrust=0. Here is the compromise; we can achieve a maximum propulsive efficiency of 100%, but with no thrust. In this compromise, we can find the reasons for the existence of the various propulsion devices. **A** propeller, with its relatively large diameter, processes a large mass of air, but gives the air only a small increase in velocity. A propeller produces thrust by means of a large m with a small Vi - V, and therefore the efficiency is high. However, the thrust of a propeller is limited by the propeller tip speed; if the tip speed is near or greater than the speed of sound, shock waves will form on the propeller. This greatly increases the drag on the propeller, which increases the torque on the reciprocating engine, which reduces the rotational speed (rpm) of the engine, which reduces the power obtained from the engine itself, and which is manifested in a dramatic reduction of thrust. In addition the shock waves reduce the lift coefficient of the affected airfoil sections making up the propeller, which further decreases thrust. The net effect is that, at high speeds, a propeller becomes ineffective as a good thrust-producing device. This is why there are no propeller-driven transonic or supersonic airplanes.

In contrast to a propeller, a gas-turbine jet engine produces its thrust by giving a comparably smaller mass of air a much larger increase in velocity. ***m*** may be smaller than that for a propeller, but *Vj* - V, is much larger. Hence, jet engines can produce enough thrust to propel airplanes to transonic and supersonic flight velocities. However, because *Vj* is much larger than *V,* the propulsive efficiency of a jet engine will be less than that for a propeller.

Because of the tradeoffs discussed above, in modem aeronautics we see low speed airplanes powered by the reciprocating engine propeller combination, because of the increased propulsive efficiency, and we see high-speed airplanes powered by jet engines, because they can produce ample thrust to propel aircraft to transonic and supersonic speeds. We also see the reason for a turbofan engine-a large multi-blade fan driven by a turbojet core-which is designed to generate the thrust of a jet engine but with an efficiency that is more reflective of propellers.

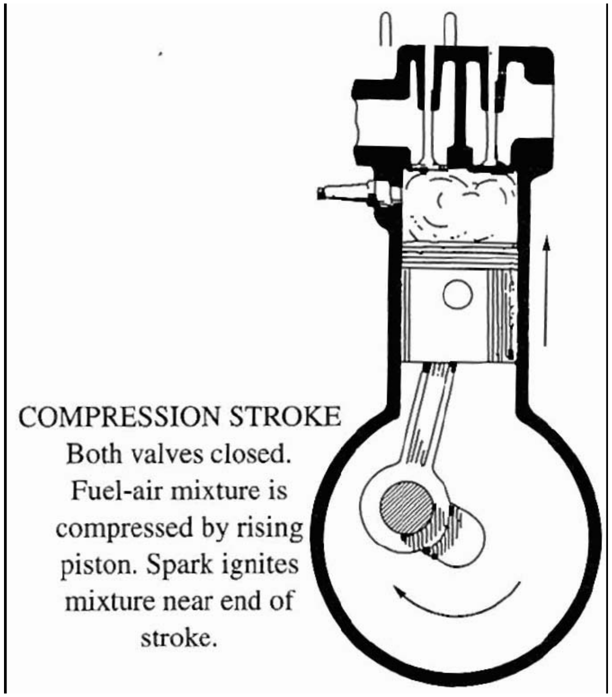
THE RECIPROCATING ENGINE/PROPELLER COMBINATION



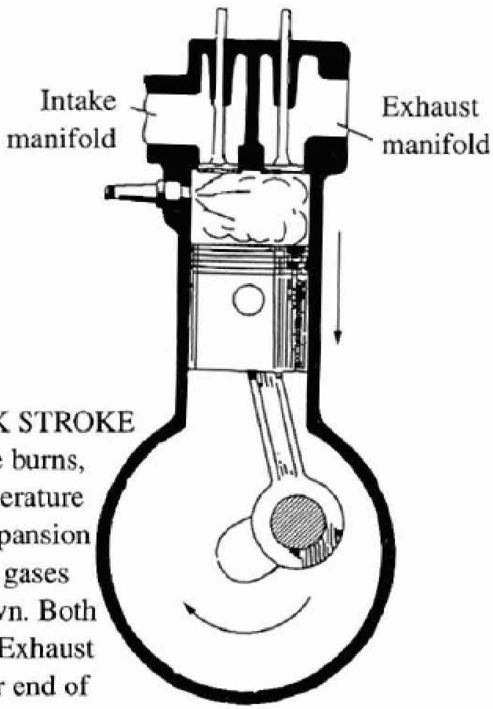
INTAKE STROKE
Intake valve opens, thus admitting charge of fuel and air. Exhaust valve closed for most of stroke.

The translating, up-and-down movement of the piston is converted to rotary motion of the crankshaft via a connecting rod. On the intake stroke the intake valve is open, the piston moves down, and fresh fuel-air mixture is sucked into the cylinder.

During the compression stroke, the valves are closed, the piston moves up, and the gas in the cylinder is compressed to a higher pressure and temperature. Combustion is initiated approximately at the top of the compression stroke; as a first approximation, the combustion is fairly rapid, and is relatively complete before the piston has a chance to move very far. Hence, the combustion is assumed to take place at constant volume.



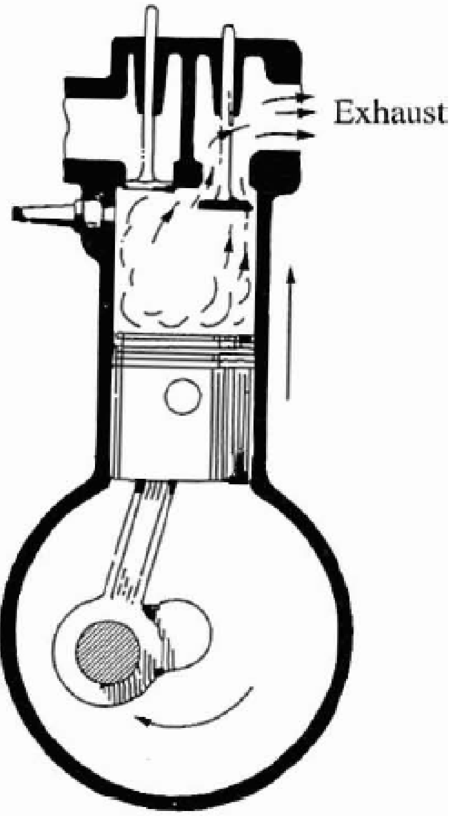
COMPRESSION STROKE
Both valves closed. Fuel-air mixture is compressed by rising piston. Spark ignites mixture near end of stroke.



POWER OR WORK STROKE
Fuel-air mixture burns, increasing temperature and pressure, expansion of combustion gases drives piston down. Both valves closed —Exhaust valve opens near end of stroke.

During combustion, the pressure increases markedly. This high pressure on the face of the piston drives the piston down on the power stroke. <u>This is the main source of power from the engine</u>.

Finally, the exhaust valve opens, and the piston moves up on the exhaust stroke, pushing most of the burned fuel-air mixture out of the cylinder. Then the four-stroke cycle is repeated.



EXHAUST STROKE
Exhaust valve open, exhaust products are displaced from cylinder. Intake valve opens near end of stroke.

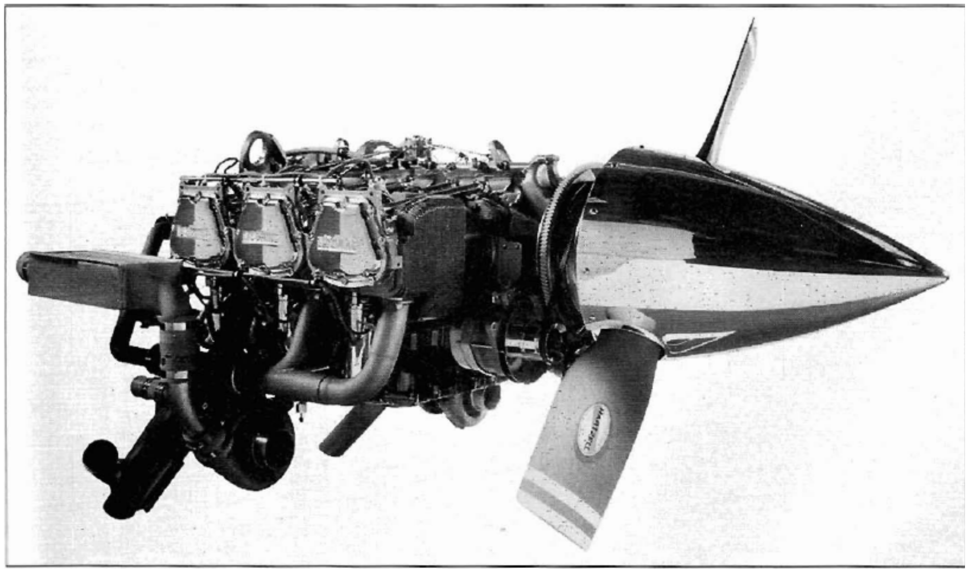
The business end of the reciprocating engine is the rotating crankshaft-this is the means by which the engine's power is transmitted to the outside world-a wheel axle in the case of an automobile, or a propeller in the case of an airplane.

On what characteristics of the engine does this power depend?

- ***Displacement:*** On its travel from the top of a stroke (top dead center) to the bottom of the stroke (bottom dead center), the piston sweeps out a given volume, called the ***displacement*** of the cylinder (d)
- the number of times the piston moves through its four-stroke cycle per unit time will influence the power output. The more power strokes per minute, the greater the power output of the engine (rpm)
- the amount of force applied by the burned gas on the face of the piston after combustion will affect the work performed during each power stroke. Hence, the higher the pressure in the cylinder during the power stroke, the larger will be the power output (Pe).

Therefore the power output is proportional to

$$\boxed{P \propto dp_e \mathrm{RPM}}$$



The specific fuel consumption

The specific fuel consumption is a technical figure of merit for an engine which reflects how efficiently the engine is burning fuel and converting it to power. For an internal combustion reciprocating engine, the specific fuel consumption c is defined as c= weight of fuel burned per unit power per unit time.

$$[c] = \frac{\mathrm{lb}}{(\mathrm{ft}\cdot\mathrm{lb/s})\,(\mathrm{s})}$$

$$[c] = \frac{\mathrm{N}}{\mathrm{W}\cdot\mathrm{s}}$$

$$[\mathrm{SFC}] = \frac{\mathrm{lb}}{\mathrm{hp}\cdot\mathrm{h}}$$

Variations of Power and Specific Fuel Consumption with Velocity and Altitude

Consider the engine mounted on an airplane. As the airplane velocity *V* is changed, the only variable affected is the pressure of the air entering the engine manifold, due to the stagnation of the airflow in the engine inlet. (Sometimes this is called a ***ram*** effect.) In effect, as *V,* increases, this "ram pressure" is increased; it is reflected as an increase in ρ, which in turn increases P. For the high-velocity propeller-driven fighter airplanes of World War II, this effect had some significance. However, today reciprocating engines are used only on low-speed general aviation aircraft, and the ram effect can be ignored. Hence, <u>we assume that P is reasonably constant with *V*</u>*.*

<u>For the same reason, the specific fuel consumption is also assumed to be independent.</u>

As the airplane's altitude changes, the engine power also changes. The air pressure (also air density) decreases with an increase in altitude; in turn this reduces ***ρ*,** which directly reduces P. The variation of P with altitude is usually given as a function of the local air density. We can assume

$$\boxed{\frac{P}{P_0} = \frac{\rho}{\rho_0}}$$

<u>SFC is constant **with** altitude</u>

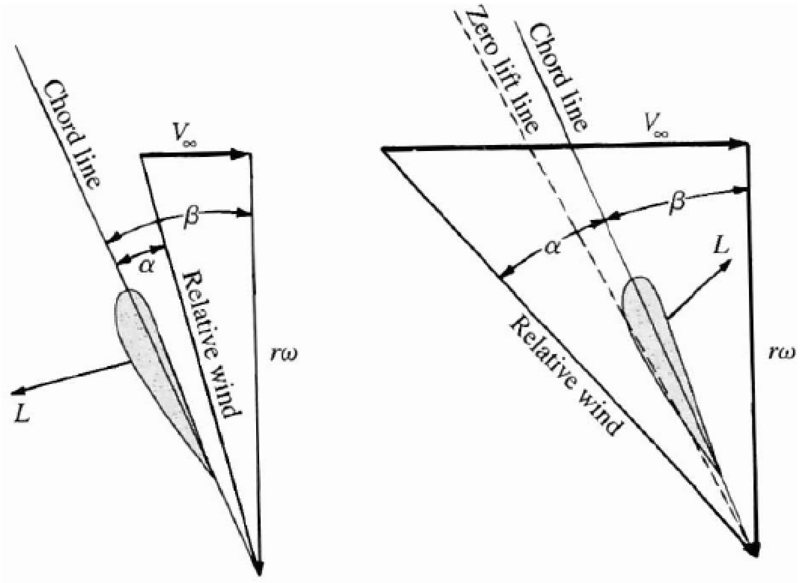
The Propeller

A propeller is essentially a twisted wing oriented vertically to the longitudinal **axis** of the airplane. The forward thrust generated by the propeller is essentially analogous to the aerodynamic lift generated on a wing. Like a wing, it also produces friction drag, form drag, induced drag, and wave drag. This propeller drag is a loss mechanism: the net power output of the engine/propeller combination is always less than the shaft power transmitted to the propeller through the engine shaft. Hence, the power available ***Pa*** from the engine/propeller combination is always less than P.

$$\boxed{P_A = \eta_{\text{pr}} P}$$

The propeller efficiency is a function of the *advance ratio* J, defined as $J = \frac{V_\infty}{ND}$

V∞ is the free-stream velocity,
N is the number of propeller revolutions per second
D is the propeller diameter.



the local relative wind is the vector sum of *V∞,* and the translational motion of the propeller airfoil section due to the propeller rotation, namely, *r ω,* where r is the radial distance of the airfoil section from the propeller hub and ω is the angular velocity of the propeller. The angle between the airfoil chord line and the plane of rotation is the ***pitch angle β.***

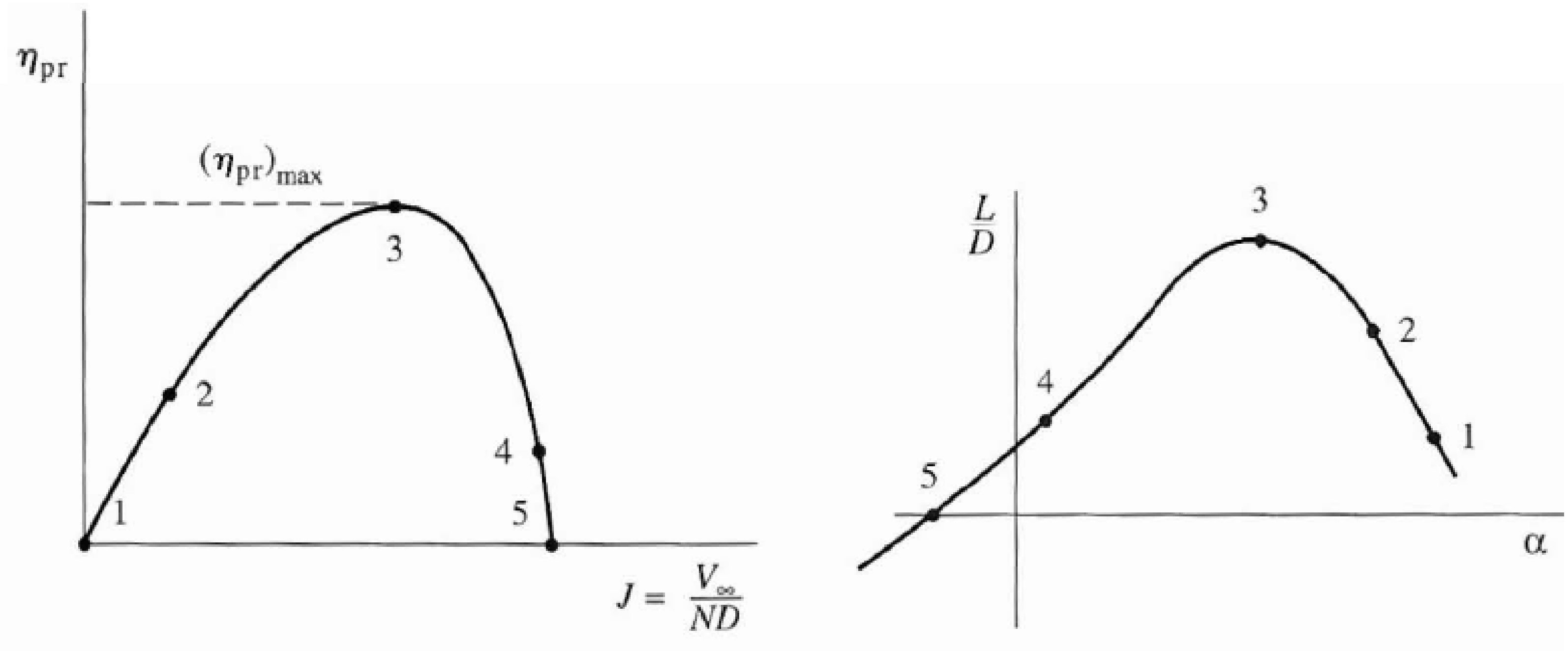
The angle of attack α is the angle between the chord line and the local relative wind. The angle of attack clearly depends on the relative values of ***V∞,*** and ***rω.***

At the propeller tip:

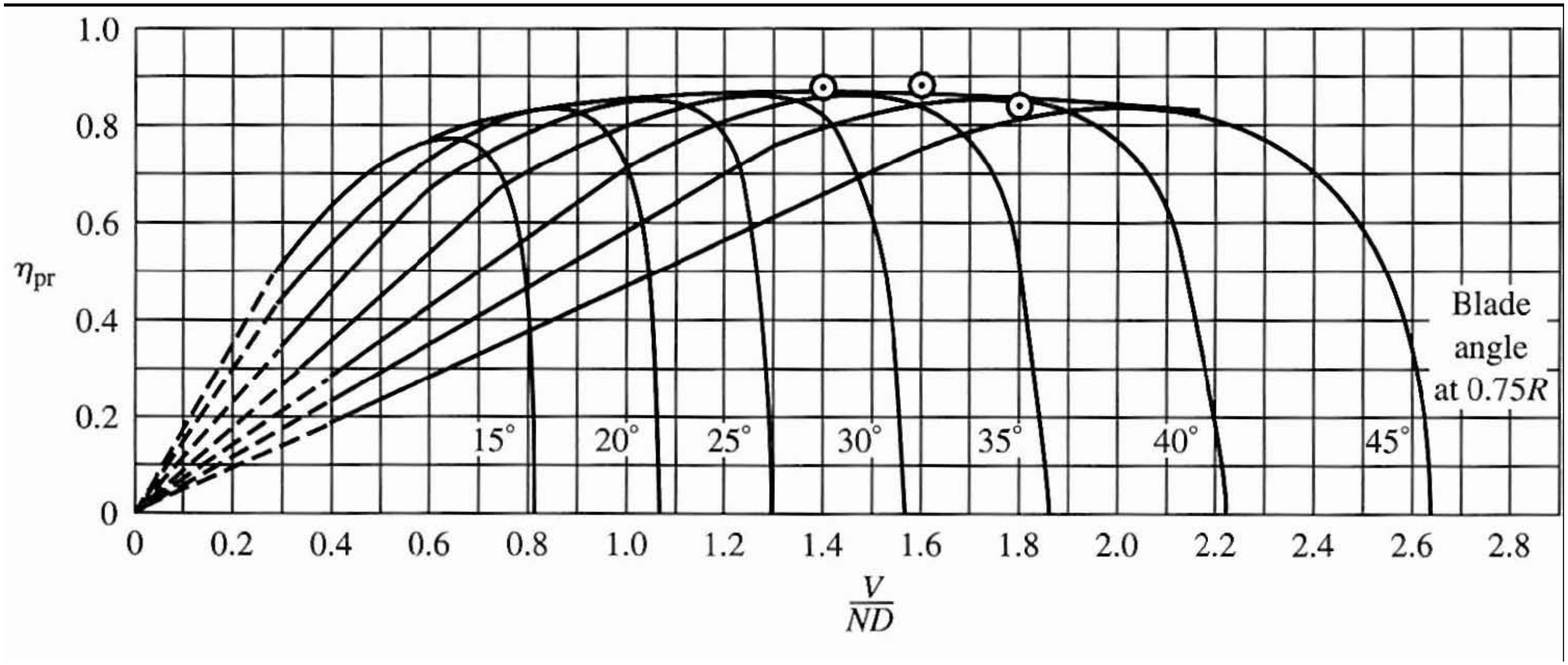
$$(r\omega)_{\text{tip}} = \pi ND$$

$$\left(\frac{V_\infty}{r\omega}\right)_{\text{tip}} = \frac{V_\infty}{(D/2)(2\pi N)} = \frac{V_\infty}{\pi ND} = \frac{J}{\pi}$$

Therefore, the advance ratio J, a dimensionless quantity, plays a strong role in propeller performance and it explains why the efficiency of the propeller is a function of J



Consider an airplane at zero velocity (standing motionless on the ground) with the engines running, producing thrust (this is called the ***static*** thrust). ***Pa=0*** when *Vinf*=0; no power is produced at zero velocity, even though the propulsive mechanism is generating thrust. For *Vinf*= 0, J=***Vinf/(ND)***=0 and the ***efficiency***=0.
For a given N, ***let’s change*** the airplane velocity *Vinf. C*onsequently the angle of attack will change**.** At Vinf=0, the angle of attack is the same as the angle between the propeller airfoil chord line and the plane of rotation: the angle of attack is also the pitch angle. For a pitch angle of, say, **30°,** the angle of attack is also **30°;** for this case the airfoil section most likely would be stalled (point 1). If Vinf is increased, keeping N constant we obtain point 2. L/D is increased, the given airfoil section is now operating with an improved aerodynamic efficiency. Let us continue to increase V, say, to a value such that the angle of attack corresponds to the peak value of L/D; this is shown as point **3. T**he net efficiency of the propeller wiil be maximum, (point **3).** Let us continue to increase V, keeping everything else the same. The angle of attack will continue to decrease, (point 4)**. T**his corresponds to a very low value of L/D, and hence will result in poor propeller efficiency. If **V,** is increased further, the local relative wind will eventually flip over to a direction below the airfoil chord line and the direction of the local lift vector will flip also, acting in the negative thrust direction. When this happens, the propeller efficiency is totally destroyed (point 5)**.**



Seven separate propeller efficiency curves are shown in figure each one for a different propeller pitch angle ***p,*** measured at the station 75% of the blade length from the propeller hub. The efficiency versus J first increases as J is increased, then peaks at a value and finally decreases. For fixed-pitch propellers, which were used exclusively on all airplanes until the early 1930s, the maximum efficiency is achieved at a specific value of J (hence **a** specific value of Vinf). This value of J was considered the design point for the propeller, and it could correspond to the cruise velocity, or velocity for maximum rate of climb, or whatever condition the airplane designer considered most important. However, whenever V, was different from the design speed, **efficiency** decreased precipitously. The off-design performance of a fixed-pitch propeller caused a degradation of the overall airplane performance that became unacceptable to airplane designers in the 1930s. If the pitch of the propeller could be changed by the pilot during flight then high propeller efficiency could be achieved over a wide range of Vinf. Thus, the ***variable-pitch/propeller*** was born; the entire propeller blade is rotated by a mechanical mechanism located in the propeller hub, and the degree of rotation is controlled by the pilot during flight.

However, the variable-pitch propeller per se was not the final answer to propeller design during the era of the mature propeller-driven airplane; the ***constant-speed/propeller*** eventually supplanted the variable-pitch propeller in most high-performance propeller-driven airplanes. The power available from a reciprocating engine/propeller combination depends not only on propeller efficiency**,** but also on the shaft power P coming from the engine. In turn, P is directly proportional to the rotational speed (rpm) of the engine. For a given throttle setting, the rpm of a piston engine depends on the load on the crankshaft. (For example, in your automobile, with the gas pedal depressed a fixed amount, the engine rpm actually slows down when you start climbing a hill, and hence your automobile starts to slow down; the load on the engine while climbing the hill is increased, and hence the engine rprn decreases for a fixed throttle setting.) For an airplane, the load on the shaft of the piston engine comes from the aerodynamic torque created on the propeller; this torque is generated by the component of aerodynamic force exerted on the propeller in the plane of rotation, acting through a moment arm to the shaft. This aerodynamic component is a resistance force, tending to retard the rotation of the propeller. In the case of the variable-pitch propeller, as the pilot changed the pitch angle, the torque changed, which in turn caused a change in the engine rpm away from the optimum value for engine operation. This was partially self-defeating; in the quest to obtain maximum **efficiency** by varying the propeller pitch, the engine power P was frequently degraded by the resulting change in rpm. Thus, the ***constant-speed propeller*** was born. The constant-speed propeller is a variant of the variable-pitch propeller wherein the pitch of the propeller is automatically varied by a governing mechanism so as to maintain a constant rpm for the engine. Although the constant speed propeller is not always operating at maximum efficiency, the product **efficiency-shaft Power** is optimized. Also, the automatic feature of the constant-speed propeller frees the pilot to concentrate on other things-something especially important in combat. The use of variable-pitch and constant-speed propellers greatly enhances the rate of climb for airplanes, compared to that for a fixed-pitch propeller.