Aerobasics – An Introduction to Aeronautics

9. Airplane Propulsion

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An airplane needs a propulsive device to overcome drag. A piston engine driven propeller was the first solution to this problem and was developed rapidly during the early days of aeronautics. The jet engine was invented during the Second World War and quickly replaced the piston engine which is now used only on very small aircraft. Variants of the jet engine were later developed to improve the performance and economy. Currently the turbofan or bypass jet engine is the dominant type of engine in use. The turboprop is a variant which is suitable for lower flight speeds. In this article we describe the general principles of operation of the different propulsive devices and indicate the range of flight conditions. All engines are noisy during operation. Noise is annoying and affects a large number of people on the ground near airports. Considering this, a small section on engine noise is included at the end.

1. Propulsive Efficiency

An airplane needs a suitable propulsive device (engine) to produce thrust for overcoming drag in level flight. The thrust is also required during take-off and in accelerated flight to overcome the force of inertia. It is possible to generate thrust on any flight vehicle by the force of reaction from a gas jet issuing from a propulsive device carried on board. A rocket motor is one such device which generates a gas jet by expanding in a nozzle, hot gas obtained by burning a fuel and an oxidizer in a combustion chamber. However, a rocket

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motor consumes the fuel and oxidizer at such rapid rates that it is impractical to carry enough fuel and oxidizer on board an airplane for any useful mission. A better solution is to generate thrust by imparting additional momentum to atmospheric air which is freely available around the airplane. A source of mechanical energy is required to add momentum to this air which can be drawn into the propulsive device. A device which generates this energy by burning a fuel using oxygen in atmospheric air, the internal combustion engine, is an effective solution. However, other methods of mechanical energy production using fuel cells or electrical storage batteries are feasible and have been attempted recently. We analyze below the effectiveness of airplane propulsion using devices of this kind.

The propulsive device on an airplane produces thrust by imparting additional momentum to the air entering it as illustrated schematically in *Figure* 1. Relative to the airplane, the propulsive device draws air which is at the flight speed V far ahead of the device. After the unit imparts mechanical energy to this air stream, the air exits the device and attains a final slipstream speed V_s far downstream where the pressure returns to the ambient condition. The thrust T produced by the unit is the difference of momentum flux between the outgoing and incoming air streams as:

$$T = m\,(V_s - V). \tag{1}$$

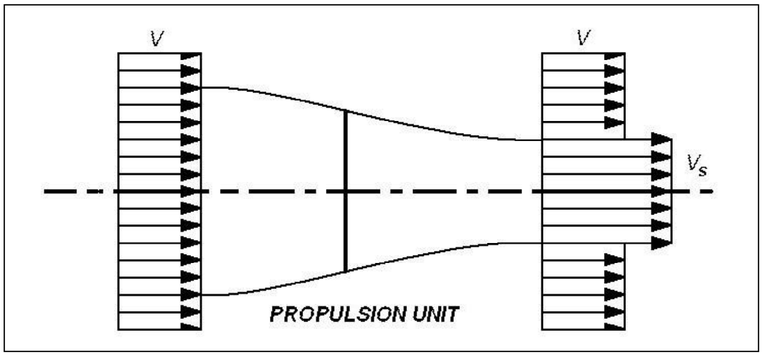


Figure 1. Principle of air-breathing propulsion. The propulsion unit draws air at the flight speed from the atmosphere and imparts additional mechanical energy to it and discharges it to create a slip stream of higher speed than the flight speed. The difference in momentum flux between the outgoing and the incoming streams constitutes the thrust of the device.

For efficient propulsions, the slipstream speed should be only somewhat larger than flight speed.

Here m is the mass flux (mass flow per unit time) through the unit. The mechanical power expended by the propulsive device to increase the air velocity from V to V_{s} is the difference in kinetic energy flux and given by

$$P_{\mathrm{IN}} \;=\; m\,\frac{1}{2}(V_{\mathrm{s}}^2 - V^2). \qquad (2)$$

The propulsive power of the unit is the product of thrust and forward speed and is:

$$P_{\mathrm{OUT}} \;=\; m\,(V_{\mathrm{s}} - V)\,V. \qquad (3)$$

Thus one may define a propulsive efficiency η_{p} as the ratio of P_{OUT} to P_{IN} as

$$\eta_{\mathrm{p}} = 2\,\frac{(V_{\mathrm{s}} - V)\,V}{(V_{\mathrm{s}}^2 - V^2)} \;=\; \frac{2}{(1 + \frac{V_{\mathrm{s}}}{V})}. \qquad (4)$$

The variation of propulsive efficiency with (V_{s}/V) is shown in *Figure* 2. Obviously, a value for η_{p} close to unity is desirable. For this to happen, (V_{s}/V) should be near unity. Under this condition, equation (1) shows that the thrust produced per unit mass flow is small. Thus a large mass flux is required to produce the desired thrust. But this results in a large size and weight for the propulsion device and is undesirable. Thus a compromise has to be made between small size and high propulsive efficiency. If one were to accept a propulsive

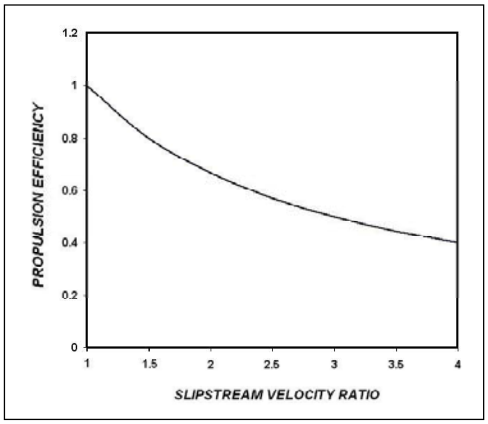


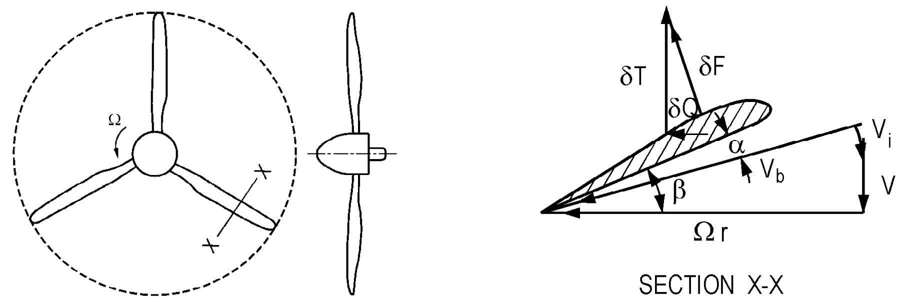
Figure 2. Variation of propulsive efficiency with slipstream velocity ratio. The propulsive efficiency rapidly falls off with increase in slipstream velocity ratio. For efficient propulsion, it is necessary to keep this ratio small.

efficiency of 67% in the cruise condition for an airplane, the corresponding slipstream speed for the propulsion unit is 2 times the flight speed and represents an acceptable maximum value for it.

2. The Airplane Propeller

A common type of propulsion device particularly suitable for low flight speeds is the propeller. The propeller, schematically shown in *Figure* 3a consists of a number of radial blades fixed to a shaft turned at a rotational speed Ω by connecting it to a source of mechanical power (typically an internal combustion engine). Each blade has the shape of a twisted wing with a suitable airfoil cross-section and may be thought of as a rotating wing. The flow around any blade cross-section is the combined result of the forward velocity of the propeller as a whole due to the motion of the airplane and the rotational motion of the blade about the shaft. In addition, there is an induced flow at the location of the propeller due to the action of the propeller itself. *Figure* 3b shows the vector diagram of flow velocities at a typical blade cross-section. Relative to the blade section, the velocity V_b is the resultant of the flight velocity V, the blade velocity due to rotation, Ωr, and the induced velocity V_i due to the action of the propeller itself. V_i is nearly perpendicular to V_b. The calculation of V_i is complex. One may calculate it approximately by using the principles of conservation of linear and angular momenta applied

Figure 3. The propeller. The blades of a propeller are of airfoil section. As the propeller rotates in the airstream produced due to the combined effect of the forward motion of the airplane and its own rotation, the blade sections experience a lift, a component of which is in the forward flight direction. The integrated thrust from all the blade elements constitutes the thrust of the propeller.



(a) The geometry of the propeller ***(b) The flow relative to a blade element***

to the whole propeller. This will not be indicated here. The resulting flow produces an incidence α for the blade element under consideration ,as in *Figure* 3b. In this figure, β represents the setting of the blade. Blade-setting angle is the angle made by the blade chord with the rotation plane of the propeller. The blade incidence is the difference between the blade setting and the flow angle as in the figure. Thus it depends on the flight speed as well as the blade setting. The resulting flow at the blade incidence α induces an aerodynamic force $\delta\mathbf{F}$ (the resultant of lift and drag for the blade element under consideration) at any blade section in the direction nearly perpendicular to the local flow direction. The axial component of this force, $\delta\mathbf{T}$ acts in the flight direction and contributes to the thrust. The combined (integrated) contribution from all the blade elements thus constitutes the thrust of the propeller.

The aerodynamic force on each blade element also has a component $\delta\mathbf{Q}$ in the tangential direction and contributes to the resisting torque on the shaft. The torque Q can be obtained by integrating the elemental contributions of all the blade elements. Shaft power from the engine is required to overcome this torque and constitutes the power input to the propeller.

Using theoretical methods on the lines indicated above, one may calculate the thrust produced T, and the torque required Q, at any rotation speed Ω and at any flight speed V. The results of such an analysis are generally presented in the form of relations among certain dimensionless variables as indicated below.

3. Propeller Performance

The thrust produced by a propeller at any flight speed depends on the geometry of the propeller and its rotation speed. The geometry of the propeller is defined by the number and shape of the blades. As shown in *Figure* 3, each blade at every radius consists of an airfoil shape whose chord is set at a suitable angle β with respect to the plane of rotation. β is large at the root and decreases towards the tip. The performance of the propeller is very sensitive to this blade setting. Blade setting is related to the geometric pitch of the propeller, P, at any radius r as:

$$P = 2\pi r \tan\beta. \qquad (5)$$

More often, the pitch of the propeller is expressed as a fraction of propeller diameter D as

$$P/D = (2\pi r/D)\tan\beta. \qquad (6)$$

As the pitch of the propeller generally varies somewhat over the radius of a blade, the value at 0.75 times the tip radius is taken to be characteristic of the whole propeller. Typical values of P/D are in the range of 0.4 to 1.5. A propeller with a small P/D is said to be a fine-pitch propeller and is better suited for low flight speeds as at take-off. A coarse-pitch propeller with a larger value of P/D is better suited for cruise. A propeller of any particular pitch is efficient over a narrow range of flight speeds and a careful choice of propeller pitch is required in any specific application. Fixed-pitch propellers, often used on small aircraft, are chosen for best cruise. Performance penalties in take-off and climb are accepted.

A fixed-pitch propeller is not efficient at all flight speeds. A variable-pitch propeller solves this problem but is more complex.

Propellers are often constructed such that the pitch of a propeller can be adjusted in flight. This is done by rotating any blade about a radial axis, using a suitable mechanism in the hub. This rotation changes β at all radial sections by a constant amount. Such propellers are called variable-pitch propellers and are commonly used on large airplanes. Variable-pitch propellers are adjusted in flight to run at constant speed and have good performance over the entire range of flight speeds of an airplane. They can be ‘feathered’ in flight (stopped in a low drag position with the blade chords nearly along the flight direction). This feature is useful in the case of an engine failure as a rotating propeller without shaft power input causes a large drag. A variable-pitch propeller can also be set for reverse pitch, for use as a brake to reduce the stopping distance after landing.

The performance of a propeller is generally presented in terms of dimensionless variables, the thrust coefficient C_{T} and the power coefficient C_{P}, as functions of the advance ratio J which represents the dimensionless flight speed, as:

$$C_{\mathrm{T}} = T/\rho n^2 D^4, \tag{7}$$

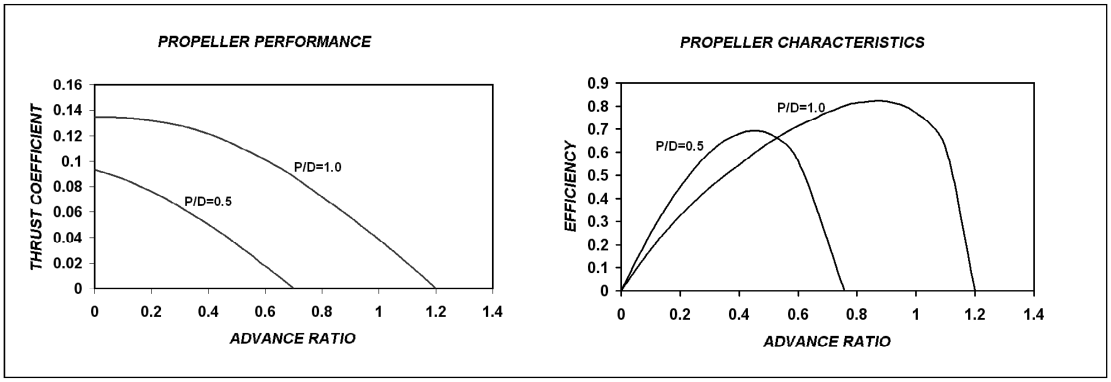
$$C_{\mathrm{P}} = P/\rho n^3 D^5, \tag{8}$$

$$J = V/nD. \tag{9}$$

T and P in the above equations are respectively the thrust and power absorbed by the propeller and n represents the propeller rotation speed (revolutions per second). It is easily seen that the propulsive efficiency is related to the above variables as:

$$\eta_p = \frac{C_{\mathrm{T}} J}{C_{\mathrm{P}}}. \tag{10}$$

Figures 4 and 5 show the performance characteristics of a class of two-bladed propellers for two different values of pitch–diameter ratios, namely 0.5 and 1.0. These characteristics are useful in selecting a propeller of this



Figures 4 (left) and 5 (right). Propeller performance. The performance of a propeller strongly depends on its pitch. A fine-pitch propeller in which the blades make a relatively small angle with the plane of rotation is suited for low flight speeds in relation to the tip speed of the propeller. A coarse-pitch propeller is suited for relatively higher speeds.

class for any specific application when the power plant characteristics are known.

Propeller blade-tip speed should be below the speed of sound. This limits propeller operation to a flight speed below M = 0.5.

Figure 5 shows the variation of η_{p} with J for the above class of propellers (which are geometrically similar but of any size). This clearly indicates that if a propeller is chosen for best efficiency at a particular J, the efficiency is lower at lower speeds (smaller J). Thus a fixed-pitch propeller chosen for best cruise efficiency loses some of its efficiency at lower speeds (during take-off and climb). The fall can be reduced to an extent by selecting a lower pitch (smaller P/D). But such a propeller will severely restrict the maximum flight speed and will not be acceptable. Variable-pitch propellers which can vary their pitch in flight use this feature to advantage and achieve the best efficiency possible over the entire range of flight speeds of any airplane.

Propellers are ideally suited for flight at all speeds up to about a mach number of 0.5. The motion of a propeller blade is due to a combination of forward motion of airplane and the rotational motion of the propeller about its axis. Thus the tip of the propeller travels through air at a speed substantially higher than the flight speed. The local blade speed approaches the speed of sound at an aircraft speed of around $\mathrm{M} = 0.5$. Further increase of flight speed will bring in compressibility effects and the associated loss of performance. These effects can be delayed to an extent by using for the propeller, thin blades of wide chord operating at small lift coefficients. For higher flight speeds a ducted fan is better suited and this will be considered later.

4. Energy for Propulsion

Energy required for operating the propulsive device has to come from a store of energy onboard the airplane. Energy is conveniently stored for this purpose in the form of a fuel. On demand, the fuel can be combined with oxygen which can be obtained from the atmospheric air to release the chemical energy. This can be converted into mechanical energy by using an internal combustion engine or a fuel cell. The weight of fuel carried adds to airplane wieght. Any reduction in fuel weight thus permits an equal addition to useful load which adds to the economy of the flight operation. Thus the energy density of the fuel is important – larger the better. *Table* 1 lists the energy storage possibilities onboard and their energy densities. The table clearly shows that hydrogen is by far the best energy storage medium for powering an airplane. However due to difficulties in handling this fuel (large volume as a gas or low temperature as a liquid), it has not yet been of practical use though the feasibility of using liquid hydrogen on an airplane has been demonstrated. Hydrocarbon fuels (diesel or petrol) are the next best and are extensively used due to their easy availability and handling properties. Electrical storage batteries are far inferior to fuels in energy density. The best electrical storage battery available, the Lithium ion battery, has an energy density lower than that of hydrocarbon fuels by a factor of over 20. Even though the use of batteries for propulsion has been demonstrated on very small and model airplanes, they are not likely to be of use for powering large airplanes. However, they have been used for storing solar energy collected using photoelectric panels onboard unmanned airplanes.

Table 1. Energy available from storage media.

Storage medium (weight of air for combustion not included)	**Energy density (MJ/kg)**	**Conversion efficiency**	**Net mechanical energy available (kWhr/kg)**
Hydrogen	142	25–40%	9.9–15.8
Hydrocarbon fuels	46	25–40%	3.2–5.1
Lithium ion battery	0.54–0.72	95%	0.14–0.19
Lead-acid battery	0.09–0.11	70%	0.017–0.02

5. Aircraft Reciprocating Engine

Reciprocating internal combustion engines based on the Otto cycle (i.e., petrol engines) were the earliest prime movers for powering aircraft propellers and they dominated the field till the invention of the jet engine during the Second World War. Currently they are used only on small general aviation aircraft.

A reciprocating internal combustion engine, generally referred to as a piston engine, generates power by expanding, using a reciprocating piston, the hot high pressure gas produced by burning a fuel inside a cylinder containing compressed air. The fuel is generally petrol which is very volatile and is easily vaporized and mixed with air before compression, or diesel which is less volatile and is injected as fine droplets into the hot air at the end of compression. In either case, the expansion of the burnt gas produces mechanical power available at the main shaft of the engine. Due to the different types of combustion involved, the petrol engine operates at a lower peak pressure and is thus lighter but thermally somewhat less efficient. However recent advances in engine design have made the diesel engine more attractive and they are coming into use.

Any reciprocating engine draws a certain volume of air per cycle of operation. The power produced by the engine is dependent on the mass of this air and thus depends on air density. As the density of air changes with altitude, the power produced by an engine directly breathing atmospheric air falls off with altitude in step with density. This can be prevented over a range of altitudes by using a supercharger. A supercharger compresses atmospheric air and delivers it to the engine. Up to an altitude (around 2–3 km), the power of supercharged engine is approximately constant and falls off with further increase in altitude. A common type of supercharger uses engine exhaust gas to power a turbine

Currently piston engines for aircraft use are below 500 HP. They are used only on small civil aircraft. Large piston engines of over 3000 HP of Second World War vintage are museum exhibits.

which drives a centrifugal compressor. The delivery pressure from the compressor is regulated by using a diverter valve which allows a part of the exhaust gas to bypass the turbine at low altitudes.

The piston engine is about as efficient in converting energy of the fuel into mechanical power as a turbo-shaft engine to be considered later. But it is mechanically more complex (and thus has lower reliability and life by a factor of around 10) and is relatively heavy, weighing about five times more than a turbo-shaft engine of the same power in the larger sizes. However, it is very much lower in cost. The high cost of the turbo-shaft engine is due to the use of expensive high temperature materials in its construction. The high temperatures arise due to continuous combustion in these power plants. These high temperature materials are not required in the reciprocating engine due to the periodic nature of combustion in these engines.

The Wankel engine, which is a rotary form of the reciprocating internal combustion engine considered above, has some advantage in terms of weight over the piston engine but till now has only found limited application on some unmanned airplanes.

6. The Jet Engine

The invention of the jet engine near the end of the Second World War was a major step in aircraft propulsion. A pure jet engine (also called the turbojet engine) produces a propulsive stream of air directly by expanding a hot compressed gas in a nozzle. The gas is generated by using a compressor to compress atmospheric air by a ratio which could be up to about 20. A fuel is burnt in this air and the gas is partially expanded in a turbine to produce mechanical power required to drive the compressor. The exhaust from the turbine which is still at a high pressure is expanded in a nozzle to produce

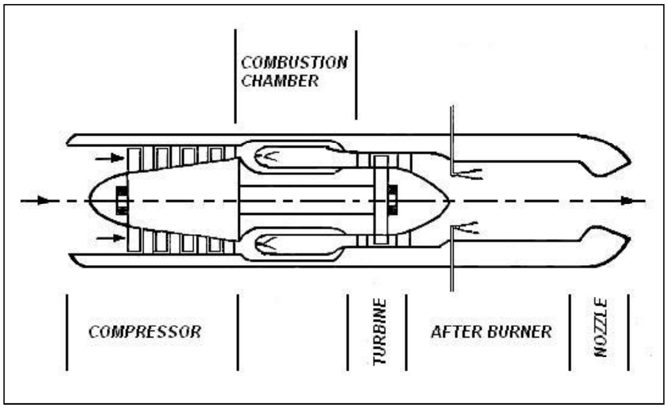


Figure 6. The turbojet engine with reheat. The engine takes in atmospheric air and passes it through a compressor with a pressure ratio of about 20. Fuel is added to this air in the combustion chamber to raise the temperature to about 1500 °K. This hot, high pressure gas is partially expanded in the turbine to produce shaft work required to run the compressor. The gas after leaving the turbine is expanded in a nozzle to generate the propelling jet. Additional fuel may be added after the turbine but before the nozzle to raise the gas temperature further. This increases the jet thrust but at a high price in terms of fuel consumption.

the propulsive jet. The engine is schematically shown in *Figure* 6.

In implementing the jet engine principle as indicated above, one comes across some limitations which affect engine performance. The first is the limitation to the quantity of fuel which can be burnt in the combustion chamber. If enough fuel is added to completely consume all the oxygen available, the resulting gas temperature (about 2300 °K) is beyond the admissible temperature of materials used in engine construction (about 1500 °K). Thus, the fuel flow to the engine is to be restricted. This limits the thrust of the engine. The second limitation arises due to the slipstream speed achieved which could be up to 1000 m/s. Thus the propulsion efficiency of a jet engine is very low at subsonic flight speeds of below 250 m/s. This will be clear from equation (4) which indicates a propulsive efficiency of about 40% under these conditions. Variations of the simple jet engine principle have been devised for overcoming these limitations.

Considering the first limitation of the simple jet engine, it will be seen that restricting the fuel flow to keep the maximum temperature low at the end of combustion implies that all the oxygen available in the air is not consumed. It is possible to burn extra fuel in the air stream after the turbine but before the nozzle in a chamber called the ‘afterburner’. This is schematically shown in *Figure* 6. Such afterburning or reheating increases the static thrust (thrust at zero flight speed) by up to about 50% and more at supersonic flight speeds. But this also increases the specific fuel consumption (fuel consumed per unit thrust) by as much as 100% and is not acceptable for continuous use during flight. Combat aircraft use reheating only when necessary (during supersonic flight and for rapid acceleration).

Considering the second limitation, propulsive efficiency can be increased by modifying the engine in one of two ways. The modified engines go by the names of turboprop and turbofan/bypass jet engines.

The turboprop engine extracts the energy from the hot high pressure gas emerging from the turbine using an additional turbine (thus converting the jet engine into a shaft power machine called the turbo-shaft engine) which then drives a propeller through a suitable gear box. Such engines are suitable for low subsonic speeds. The jet thrust plays only a minor role in this application.

In a turbofan or bypass jet engine, the air drawn into the engine is divided into two streams as in *Figure* 7. The first stream, after some compression (by a ratio in the range of about 1.5–2.5) often using a single stage fan, is expanded in a nozzle to provide a propulsive

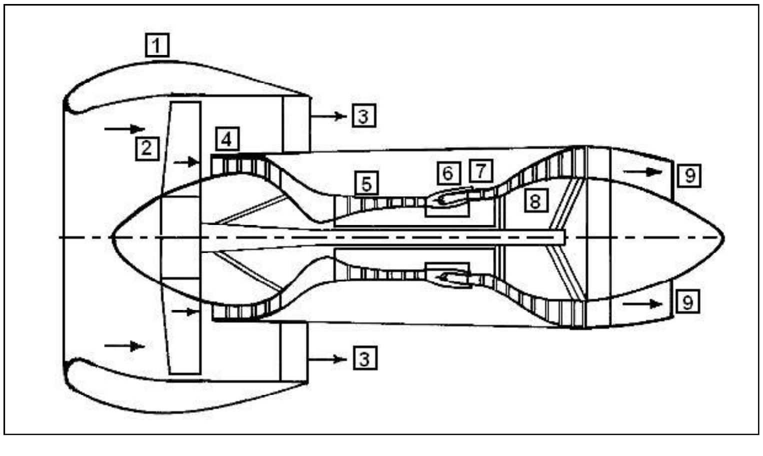


Figure 7. The turbofan engine. This engine draws atmospheric air into the ducted fan 1. The fan 2 in the duct compresses it by a small pressure ratio of 1.2 to 1.5. A large part of this air is expanded and discharged at 3 to produce the main propelling jet. The balance passes through the low pressure (LP) compressor 4 and the high pressure (HP) compressor 5. Fuel is added in the combustion chamber 6 to generate the hot high pressure gas. This gas is expanded in the HP turbine 7 which drives the HP compressor and the LP turbine 8 which drives the LP compressor and the fan. The gas emerging from the LP turbine is expanded to produce the second propelling stream of gas. 4 to 9 thus constitute the core engine which drives the fan 2.

jet of relatively lower velocity than a pure jet engine. The second stream is passed through a simple jet engine (called the core engine) consisting of a compressor, combustion chamber, turbine and a nozzle in series to produce power to compress the first gas stream and also produces a propulsive jet. The ratio of the mass flow bypassing the core to the flow in the core engine (called the bypass ratio) can be varied to suit the application. The bypass ratio varies from about five for use on subsonic aircraft to about half for use on supersonic combat aircraft. It will be seen that such an engine handles a larger mass flow of air than the simple jet engine and produces two propelling jets of approximately the same but lower speed. This increases the propulsive efficiency of the modified engine. Thus, these engines are more fuel efficient than the turbojet engine.

Current engines for civil and military use are mostly bypass types but with bypass ratios optimally chosen to suit the different applications.

At high flight speeds, the air entering the engine is compressed to a significant extent due to 'ram effect'. Thus, it is possible to dispense with the compressor and turbine and use only a combustion chamber followed by a nozzle to produce a propelling jet. Such a device is named the 'ramjet'. The ramjet engine generates little thrust at low speeds and is only suitable for supersonic flight. Ramjet engines are not suitable for use on airplanes. Some missiles use such engines in combination with rocket boosters.

7. Jet Engine Performance

The performance of an airplane depends on the thrust produced by its engine(s). In this context, the variation of thrust of an engine over a range of flight speeds and altitudes is of interest. A full thermodynamic study of the engine is required for getting this information, but some broad conclusions are possible without such a detailed study.

The variation of thrust with altitude is primarily due to the reduction in air density as the thrust keeps in step with it. There is a smaller effect due to the variation of air temperature at altitudes less than 11 km. Increase of air temperature results in a decrease in possible temperature rise in the combustion chamber to keep within the maximum temperature limitation of the turbine. This results in a loss of thrust which is particularly important during take-off on a hot day when the need for thrust is greatest.

Choice of engine type depends strongly on flight speed. Each engine type is best suited for a range of flight speeds.

Flight speed affects the engine thrust in two ways. Increase in flight speed increases the momentum of the incoming air and this subtracts from jet thrust. This represents a loss which is felt as a small reduction in thrust. There is also the effect of speed on temperature and pressure of the inlet air due to ram compression. Increase of pressure at inlet results in an increase of jet thrust due to increased mass flow into the engine. This is dominant at moderate airspeeds of $0.5 \leq M \leq 2.0$. Thus there is an increase of thrust with Mach number in this range. However, at the higher end of this range, the loss of thrust due to increase of air temperature (which demands a reduction in fuel flow to stay within engine temperature limits) becomes significant and there is decrease of thrust with further increase of M.

From the discussions above, it is clear that the choice of an engine type for an airplane depends on its range of flight speeds and altitudes and is shown in *Table* 2.

Table 2.

Engine type	**Maximum flight Mach number**	**Maximum altitude (m)**
Piston engine with propeller	0.5	8,000
Turboprop	0.7	2,000
Turbofan/bypass jet	0.8–1.5	20,000
Turbojet	2.2	25,000
Turbojet with reheat	3.0	30,000
Ramjet	4.0	30,000

8. Engine Noise

Airplane engines are a major source of noise which is nothing but unwanted sound. Sound consists of fluctuations of air pressure which propagate in all directions with the speed of sound. A simple sound consists of sinusoidal variations of pressure characterized by its amplitude δP and frequency n (measured in cycles per second or Hertz, Hz). Human ear is sensitive to sound over a frequency range of about 20–20,000 Hz. But the sensitivity to sound is not uniform, the maximum sensitivity being at about 1000 Hz. The ear is also sensitive to the amplitude of sound δP over a large range of about ten million to one. The weakest audible sound corresponds to a root mean square (RMS) value of pressure fluctuations, P_0, of about 20 micro Pascals (μPa). The sound pressure level (SPL) which is an indication of the energy density of pressure fluctuations is measured on a logarithmic decibel scale (dB) defined by (11) as:

$$\mathrm{SPL(dB)} = 20\ \log_{10}(\frac{P}{P_0}). \qquad (11)$$

Here P is the RMS value of the fluctuating pressure and P_0 is the reference value corresponding to the weakest audible sound. Audible sounds cover a very large range from 0 dB to about 140 dB which is seven orders of magnitude. *Table* 3 gives an indication of sound pressure levels (ambient noise) in typical situations. Beyond this range, ear pain and hearing damage may occur. SPL approximately indicates the level of annoyance due to noise. However, as the sensitivity of the human ear varies over the audible spectrum, the level of annoyance is better represented by the perceived noise level in decibels (PNL) which is obtained as the average energy density suitably weighted over the audible spectrum. It may be noted here that the pressure fluctuation even at 140 dB (which is about 200 Pa) is barely 0.2 % of the ambient pressure at sea level.

Table 3. Perceived noise levels in typical situations.

Situation	dB
Jet engine at 3m	140
Rock concert	120
Noisy factory	90
Busy traffic	70
Residential area at night	40
Rustling of leaves	20

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Engine noise from an airplane is very intense and is particularly unpleasant to the people in the region of the flight path of airplanes during take-off. A major source of noise is the propelling jet of any jet engine. The PNL of a jet emerging with a speed V_{jet} in the range of 300 to 750 m/s from a nozzle of area A and of density ρ at a distance of 60 m from it is typically obtained from [1] as:

$$\text{PNL}_{\text{jet}}(\text{dB}) = 20\log\rho + 6\log A + 88\log V_{\text{jet}} - 100. \quad (12)$$

The large coefficient associated with V_{jet} in the above equation implies that the sound pressure increases as a large power (about 4.4) of jet speed. It is for this reason that turbofan engines with smaller jet speeds are far quieter than turbojet engines.

A second major source of noise is the rotating fan/compressor in the front part of any engine. At a distance of 60 m from it, the noise due to a fan handling a mass flow m running at a tip speed V_{tip} is obtained from [1] as:

$$\text{PNL}_{\text{fan}}(\text{dB}) = 47.5\,\log\text{V}_{\text{tip}} + 7.5\log m - 9.5. \quad (13)$$

The noise levels indicated by (12) and (13) have strong directional dependence. The noise level is generally maximum at an angle of 40–60° from the axis of the jet or fan. The above factors have to be taken into account in planning the take-off and landing paths of airplanes in the neighborhood of populated areas.

Suggested Reading

[1] P Zwanchuk, V Labendik and V Mukhin, Board monitoring airplane noise levels based on engine's thermo-gas dynamic parameters, *Ultragarsas Journal*, published by the Ultrasound Institute, Kaunas, Lithuania, Vol. 61, No.4, 2006.

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