Chapter 4

Lecture 15

Engine characteristics – 3

Topics

4.2.10 Procedure for obtaining THP for given h, V, BHP and N

For calculating the performance of the airplane, the thrust horse power (THP) is needed at different values of engine RPM(N), break horse power (BHP), flight speed (V) and flight altitude (h). In this context the following may be noted.

(a) The engine output (BHP) depends on the altitude, the RPM (N) and the manifold air pressure (MAP).

(b) The propeller absorbs the engine power and delivers THP; $THP = \eta_p \times BHP$

(c) The propeller efficiency depends, in general, on BHP, V, N and β.

(d) The three quantities viz. d, V and n can be combined as advance ratio (J = V/nd).

(e) Once η_p is known :

$THP = \eta_p$ x BHP and $T = THP \times 1000 / V$.

The steps required to obtain η_p depend on the type of propeller viz. variable pitch propeller, constant speed propeller and fixed pitch propeller. The steps in the three cases are presented below.

I) Variable pitch propeller

In this type of propeller the pitch of the propeller is changed during the flight so that the maximum value of η_p is obtained in various phases of flight. The steps are as follows.

(a) Obtain the ambient density (ρ) for the chosen altitude. Also obtain engine BHP at chosen V and N.

(b) Obtain $C_P = P/(\rho\, n^3 d^5)$; P is BHP in watts

(c) Obtain J = V/nd

(d) Calculate $C_S = J/C_P^{1/5}$

(e) From the design chart for the chosen propeller (e.g. Fig 4.5c for a two bladed propeller), obtain β which will give maximum efficiency. Obtain corresponding η_p. Consequently,

$$\text{THP} = \eta_p \times \text{BHP and T} = \text{THP} \times 1000 / V \text{ ; note } V \neq 0$$

(f) To get the thrust (T) at V = 0, obtain BHP of the engine at V = 0 at the chosen altitude and RPM. Calculate C_P. From C_P vs J plot (e.g. Fig 4.5b for a two bladed propeller) obtain C_T and β at this value of C_P and J = 0. Having known C_T, the thrust(T) is given by :

$$T = \rho\, n^2 d^4 C_T$$

II) Constant speed propeller

The variable pitch propellers were introduced in 1930's. However, it was noticed that as the pilot changed the pitch of the propeller, the engine torque changed and consequently the engine RPM deviated from its optimum value. This rendered, the performance of the engine-propeller combination, somewhat suboptimal. To overcome this problem, the constant speed propeller was introduced. In this case, a governor mechanism alters the fuel flow rate so that the required THP is obtained even as rpm remains same. The value of β is adjusted to give maximum possible η_p.

The steps to obtain η_p are the same as mentioned in the previous case.

III) Fixed pitch propeller

From Fig 4.5b it is observed that a fixed pitch propeller has a definite value of C_P for a chosen value of advance ratio (J). Consequently, the propeller can absorb only a certain amount of power for a given value of J. Thus when the flight speed changes, the power absorbed by the propeller also changes. However, for the engine-propeller combination to be in equilibrium i.e. run at a constant r.p.m, the power absorbed by the propeller and that produced by the engine must be the same. This would render the problem of determining power output as a trial and error procedure. However, it is observed that the fixed pitch propellers are used in light airplanes which use piston engines. The torque of such an engine remains nearly constant over a wide range of r.p.m's. Using this fact, the torque coefficient (C_Q) and torque speed coefficient (Q_s) are deduced in Ref. 3.7, chapter 16, from the data on C_P & C_T . Further a procedure is suggested therein to obtain η_p at different flight speeds.

Herein, the procedure suggested in the Appendix of Ref 4.1 is presented. It is also illustrated with the help of example 4.5.

It is assumed that the propeller is designed for a certain speed, altitude, rpm and power absorbed.

Let, V_0 = design speed (m/s)

N_0 = design rpm ; $n_0 = N_0 / 60$

BHP_0 = BHP of the engine under design condition (kW)

d = diameter of propeller (m)

J_0 = Advance ratios under design condition = $V_0 / n_0 d$

β_0 = design blade angle; this angle is fixed

η_0 = efficiency of propeller under design condition

The steps, to obtain the THP at different flight speeds, are as follows.

1. Obtain from propeller charts, C_T and C_P corresponding to J_0 and β_0.

   These values are denoted by C_{TO} and C_{PO}.

2. Choose values of J from 0 to a suitable value at regular intervals. Obtain from the relevant propeller charts, the values of C_T and C_P at these values of J's and the constant value of β_0.
3. Calculate J/J_0, C_T/C_P and C_{P0}/C_P from values obtained in step 2.
4. Calculate:

$$T_0 = \eta_0 BHP_0 \times 1000 / V_0 \quad \text{and} \tag{4.22}$$

$$K_0 = T_0 C_{PO}/C_{TO} \tag{4.23}$$

5. The assumption of constant torque (Q_0) gives that N and P are related.

Note: $Q_0 = P_0 / 2\pi n_0$

This yields:

3 (4.24)

$$V = V_0 \times \frac{J}{J_0} \times \frac{N}{N_0} \tag{4.25}$$

and $$T = T_0 \frac{C_{P0}}{C_{T0}} \frac{C_T}{C_P} = K_0 \frac{C_T}{C_P} \tag{4.26}$$

Consequently, THP = TV/1000 and BHP = THP/η_p

The procedure is illustrated with the help of example 4.5.

Example 4.5

Obtain the thrust and the thrust horse power at sea level for V upto 60 m/s for the propeller engine combination of example 4.4

Solution:

From example 4.4 it is noted that the propeller is designed to absorb 97.9 kW at 2500 rpm at V = 59 m/s.The propeller diameter is 1.88 m and $\beta = 20^o$.

Hence, V_0 = 59 m/s, N_0 = 2500, n_0 = 41.67, $\beta_0 = 20^o$

BHP_0 = 97.9 kW, η_0 = 0.83

$$J_0 = \frac{V_0}{n_0 d} = \frac{59}{41.67 \times 1.88} = 0.753$$

From Fig 4.5d, C_{TO} = 0.046

From Fig 4.5b, C_{PO} = 0.041

Hence, C_{TO}/C_{PO} = 0.046/0.041 = 1.122

$$T_0 = \frac{97.9 \times 1000 \times 0.83}{59} = 1377.24 N$$

$$K = T_0 \frac{C_{PO}}{C_{TO}} = 1377.24 \times \frac{0.041}{0.046} = 1227.54$$

The remaining calculations are presented in Table E 4.5

J	J/J_0	C_T *	C_P $	$\frac{C_T}{C_P}$	C_{P0}/C_P	N/N_0 £	V €	T (N) €€	N #	η_p **	THP $$	BHP ££
0	0	0.104	0.066	1.576	0.621	0.788	0	1927	1971	0	0	-
0.1	0.133	0.104	0.065	1.589	0.629	0.793	6.21	1951	1983	0.17	12.15	71.23
0.2	0.266	0.104	0.065	1.606	0.636	0.792	12.49	1971	1993	0.33	24.61	74.60
0.3	0.398	0.102	0.062	1.631	0.657	0.811	19.05	2002	2027	0.49	38.14	77.83
0.4	0.531	0.093	0.060	1.545	0.683	0.827	25.91	1897	2067	0.62	49.15	79.28
0.5	0.664	0.082	0.058	1.420	0.712	0.844	33.05	1743	2109	0.70	57.61	82.29
0.6	0.797	0.070	0.059	1.306	0.765	0.875	41.12	1603	2187	0.77	65.91	85.60
0.7	0.930	0.055	0.046	1.185	0.884	0.900	51.55	1455	2350	0.81	75.00	92.60
0.8	1.062	0.040	0.036	1.099	1.126	1.061	66.50	1349	2653	0.83	89.71	108.1

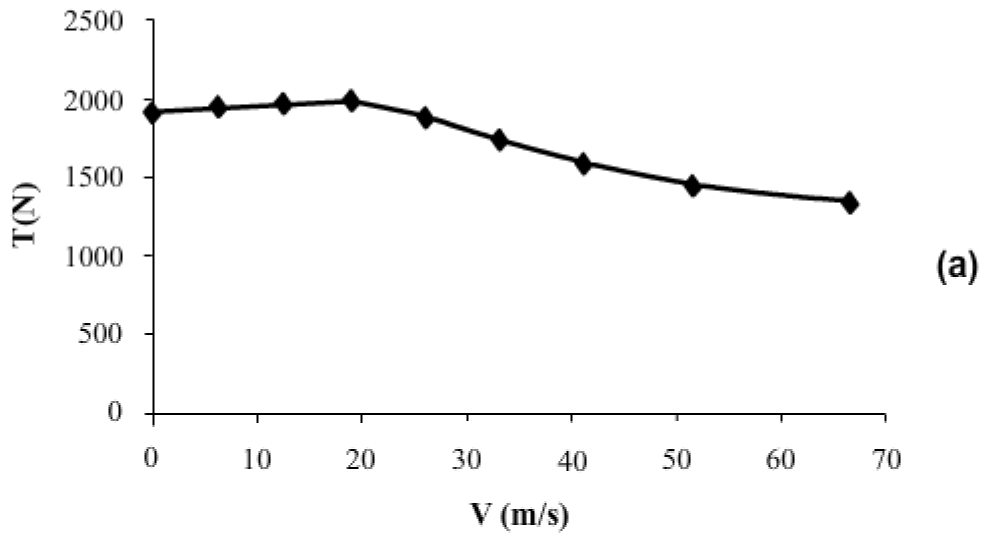
*From Fig 4.5d ; $ From Fig 4.5b; £ From Eq.(4.24); € From Eq (4.25);

€€ From Eq.(4.26); # N = (N/N_0)x N_0 ; ** From Fig 4.5a; $$ THP = TV/1000 ;

££ BHP = THP/η_p

Table E4.5 Thrust and power output of an engine-propeller combination with fixed pitch propeller

The results are shown in Figs E4.5a and b



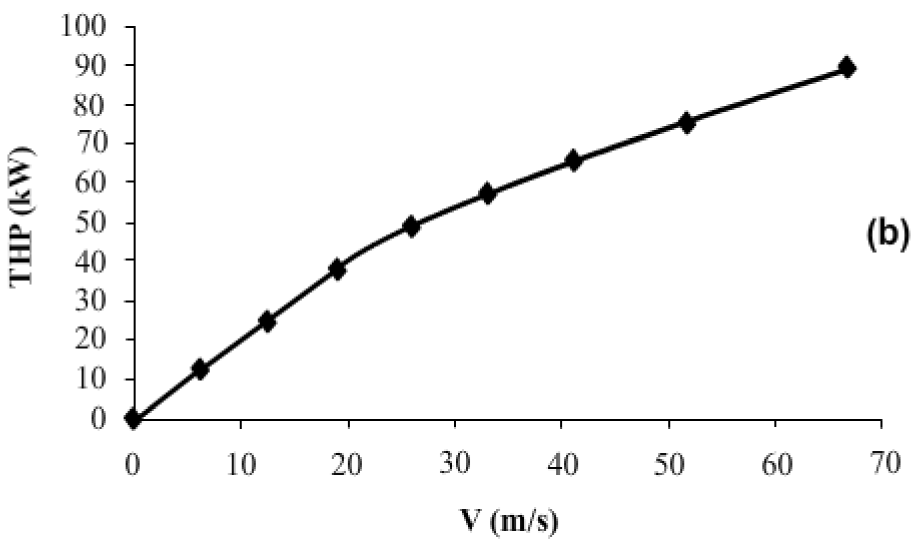


Fig. E 4.5 Variations of thrust (T) and thrust horse power (THP) with velocity(V)
(a) T vs V (b) THP vs V

Answers :

The variations of T and THP with V are given in table below.

V(m/s)	0	6.21	12.49	19.05	25.91	33.05	41.12	51.55	66.50
T (N)	1927	1951	1971	2002	1897	1743	1603	1455	1349
THP(kW)	0	12.15	24.61	38.14	49.15	57.61	65.91	75.00	89.71
BHP(kW)	-	71.23	74.10	77.83	79.28	82.29	85.60	92.60	108.1
N (RPM)	1971	1983	1993	2027	2067	2109	2187	2350	2653

4.2.11 Variations of THP and BSFC with flight velocity and altitude

As mentioned earlier,THP equals $\eta_p \times BHP$. Thus, the variations of THP with V and h depends on variations of η_p and BHP with V and h. In this context, the following may be recalled.

(i)At a given altitude and RPM, the engine output (BHP) is almost constant with flight velocity. (ii) BHP decreases with altitude as given by Eqs (4.1) or (4.1a).

(iii) The propeller efficiency (η_p) depends on BHP, h, V, n and β. For a variable pitch propeller η_p remains nearly constant over a wide range of flight speeds.

Thus for an airplane with variable pitch propeller, the THP vs V curve for a chosen RPM and h remains flat over a wide range of flight speeds. A typical variations of THP with V, at chosen 'RPM(N)' and with 'h' as parameter are shown in Fig 4.6.

From the engine charts the fuel flow rate and BSFC are known at chosen MAP & N. From these values the BSFC at the chosen MAP & N, can be calculated using Eq.(4.1d) . See section 6 of Appendix A for typical calculations.

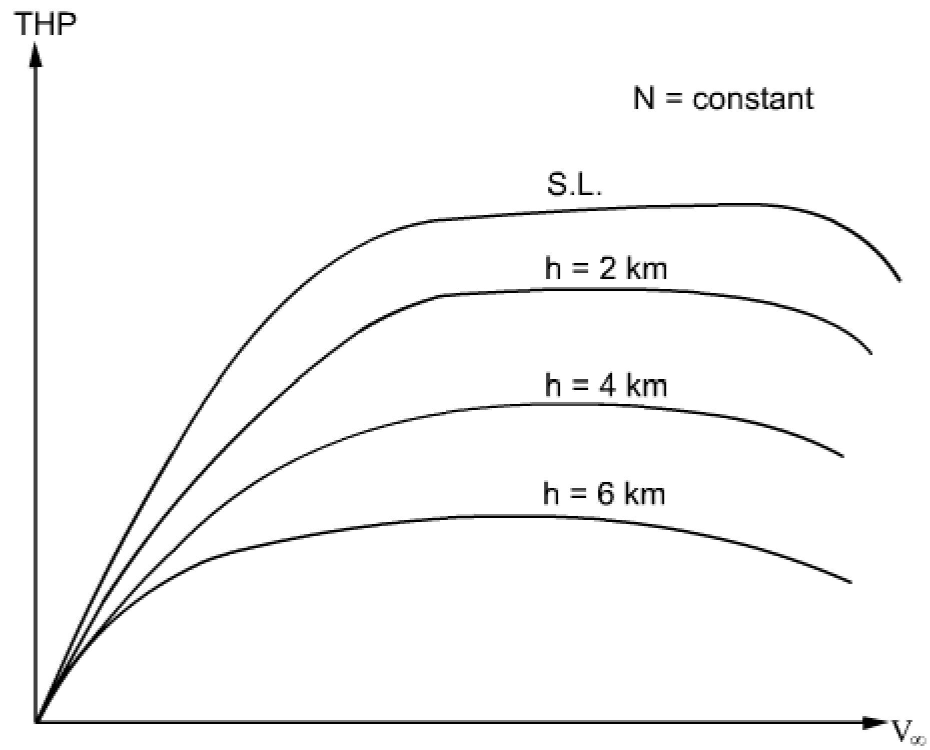


Fig 4.6 Schematic variation of THP with flight speed for an engine-propeller combination with variable pitch propeller

4.2.12 Loss of propeller efficiency at high speeds

As noted earlier, the propeller blade is like a rotating wing with forward motion. The resultant velocity at the propeller tip (V_{Rtip}) would be the highest. It is equal to:

$V_{Rtip} = \{V_{\infty}^{2} + (2\ \pi\ n\ R)^{2}\}^{1/2}$, where R is the radius of the propeller.

When the Mach number corresponding to V_{Rtip} exceeds the critical Mach number for the airfoil used on the propeller, the drag coefficient of the airfoil would increase and the lift coefficient would decrease (see subsection 3.3.3). Consequently, the efficiency of the propeller would decrease. This loss of efficiency can be delayed to higher flight Mach numbers by use of advanced propellers. These propellers have swept blades and are being used on turboprop airplanes up to flight Mach number of 0.7. Figure 4.7a shows one such propeller placed in a wind tunnel and fig 4.7b shows another propeller mounted on ATR 72 airplane.

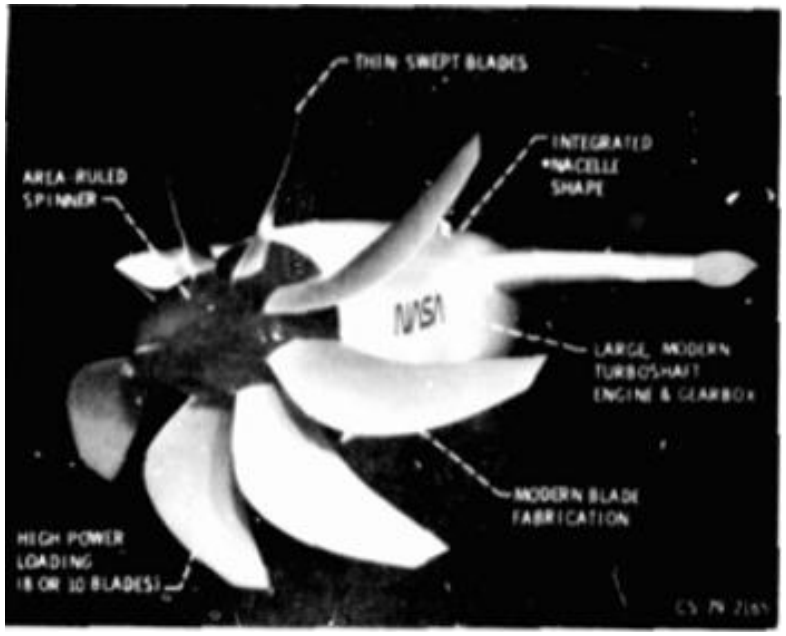


Fig 4.7a Advanced propeller being tested in a Wind tunnel

(Adapted from Ref 4.4)

Fig. 4.7b Advanced propeller mounted on ATR72 airplane

(Source : www.fspilotshop.com)

Fig 4.7 Features of an advanced propeller

4.3 Gas Turbine Engines

A gas turbine engine consists of a diffuser to decelerate the air stream entering the engine, a compressor, a combustion chamber, a turbine and a nozzle (Fig. 4.8a). In some turbojet engines, an afterburner is incorporated between the exit of the turbine and the entry of the nozzle (Fig 4.8b).The hot gases leaving the combustion chamber expand partly in the turbine and partly in the nozzle. The need for three variants of gas turbine engines viz. turboprop, turbofan & turbojet can be explained by considering their propulsive efficiencies.

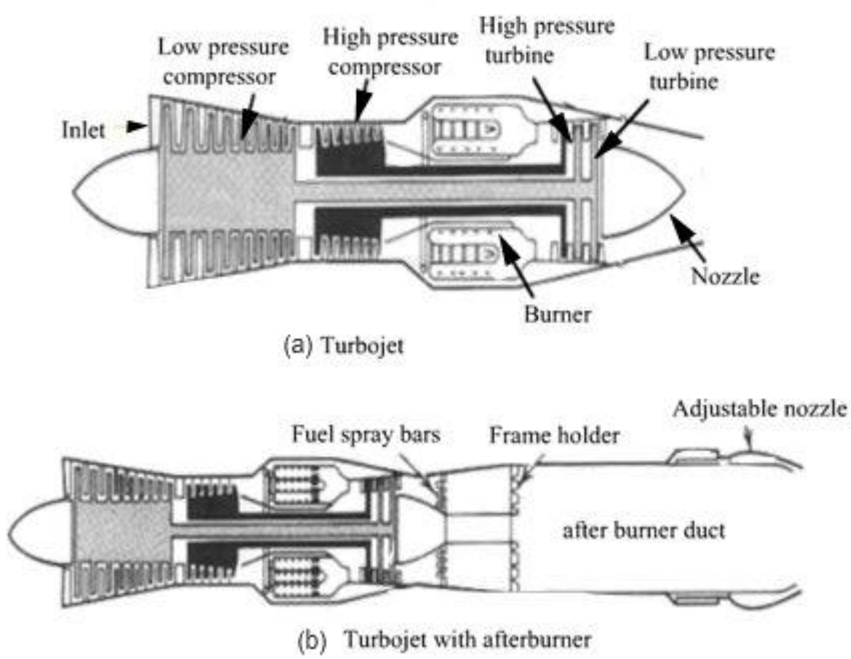


Fig 4.8 Turbojet engine

(Source : http://www.aerospaceweb.org)

4.3.1 Propulsive efficiency

Propulsive efficiency is the ratio of useful work done by the air stream and the energy supplied to it.

In a gas turbine engine, the velocity of the air stream (V_∞) is augmented to V_j,the velocity of the jet stream, thereby imparting kinetic energy at the rate of :

$$(\dot{m}/2)\,[\,V_j^{\,2} - V_\infty^{\,2}] \qquad (4.27)$$

where $\dot{m}$ is the mass flow rate.

The engine develops a thrust T and hence results in a useful work of T V_∞ .

Noting that:

$$T = \dot{m}\ (V_j\ -\ V_\infty), \tag{4.28}$$

the propulsive efficiency ($\eta_{propulsive}$) is:

$$\eta_{propulsive} = \frac{\dot{m}(V_j - V_\infty)(V_\infty)}{\frac{\dot{m}}{2}(V_j^2 - V_\infty^2)} = \frac{2}{1+\frac{V_j}{V_\infty}} \tag{4.29}$$

4.3.2 Why turboprop, turbofan and turbojet engines?

The overall efficiency of a gas turbine engine is the product of items like cycle efficiency, combustion efficiency, mechanical efficiency and propulsive efficiency. The cycle efficiency depends on the engine cycle and in turn on the maximum temperature / pressure in the engine. The combustion efficiency and mechanical efficiency are generally of the order of 95%. Thus propulsive efficiency finally decides the overall efficiency of a gas turbine engine as a propulsive system.

Remark:

The action of a propeller is also similar to that of a jet engine i.e. it also enhances velocity of the free stream from V_∞ to V_j, In this case, V_j is the velocity of the stream far behind the propeller(see subsection 4.2.7). Hence, the propulsive efficiency of a propeller which was called ideal efficiency of propeller, is also given by Eq. (4.29), which is same as given by Eq.(4.13).

The variation of propulsive efficiency with flight speed provides the reason for use of turboprop, turbofan and turbojet engines in airplanes operating at different range of flight speeds.Consider the variation of propulsive efficiency with flight speed. For this purpose, a subsonic jet engine with convergent nozzle is considered. In this case, the Mach number at the exit, would be unity and the temperature of the exhaust gases would be around 600 K. Under these conditions, V_j, the velocity of jet exhaust would be around 500 m/s. Using Eq.(4.29), the values of propulsive efficiency obtained at different flight speeds (V_∞) are given in the Table 4.2.

V_∞ (m/s)	100	125	166.7	250	333.3	400
V_j / V_∞	5	4	3	2	1.5	1.25
η_p %	33.3	40.0	50.0	66.7	80.0	88.9

Table 4.2 Variation of propulsive efficiency with flight speed for V_j = 500 m/s

Remarks:

i) Turboprop engine

It is seen from Table 4.2 that η_p will be low if a pure jet engine is used at low speeds. An analysis of Eqs. (4.28 and 4.29) points out that for having adequate thrust and high propulsive efficiency at low flight speeds, a small increment in velocity should be given to a large mass of air. This is effectively done by a propeller. Thus for airplanes with flight Mach number less than about 0.5, a turbo-prop engine is used (Fig.4.9). In this case, the turbine drives the compressor and also the propeller through a gearbox (Fig 4.9). The gear box is needed because the turbine r.p.m. would be around 15000-20000 whereas, the propeller rotates at about 3000 r.p.m.

For practical reasons, the expansion of the gases coming out of the combustion chamber is not allowed to take place completely in the turbine and a part of the expansion is carried out in the nozzle. Hence, in a turboprop engine, about 80 to 90% of the total output is produced through the propeller and the rest 20 to 10% as output from the jet coming out of the nozzle.

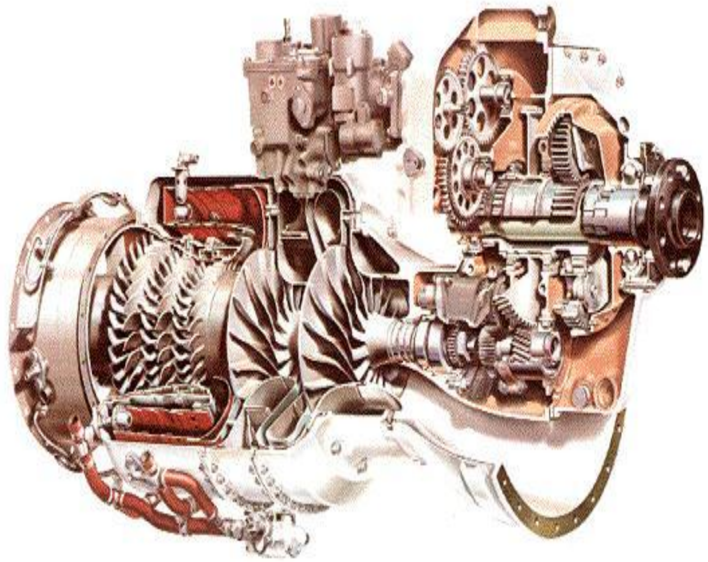


Fig. 4.9 Turboprop engine
(Source: www.aircraftenginedesign.com)

ii) Turbofan engine

As the flight Mach number increases beyond 0.7, the propeller efficiency decreases rapidly due to the formation of shock waves at the tip of the propeller blade. Hence, for airplanes flying near Mach number of unity, a turbo-fan engine is used (Fig.4.10).In this engine a major portion of the power output (about 60%) is obtained as jet thrust and the rest as thrust from the fan. A fan has a smaller diameter as compared to the propeller and it is generally placed inside a duct. A ducted fan has a higher propulsive efficiency than a propeller.

It is observed in Fig. 4.10 that all the air taken in by the fan does not go through the turbine. Incidentally the part of the engine consisting of the compressor, combustion chamber, turbine and nozzle is called 'Gas generator'. The ratio of the mass of the air that passes through the fan to the mass of air that passes through the gas generator is called 'Bypass ratio'.

Early turbofan engines had bypass ratio of 1:1. At present, it is around 6.5:1 and is likely to increase in future.

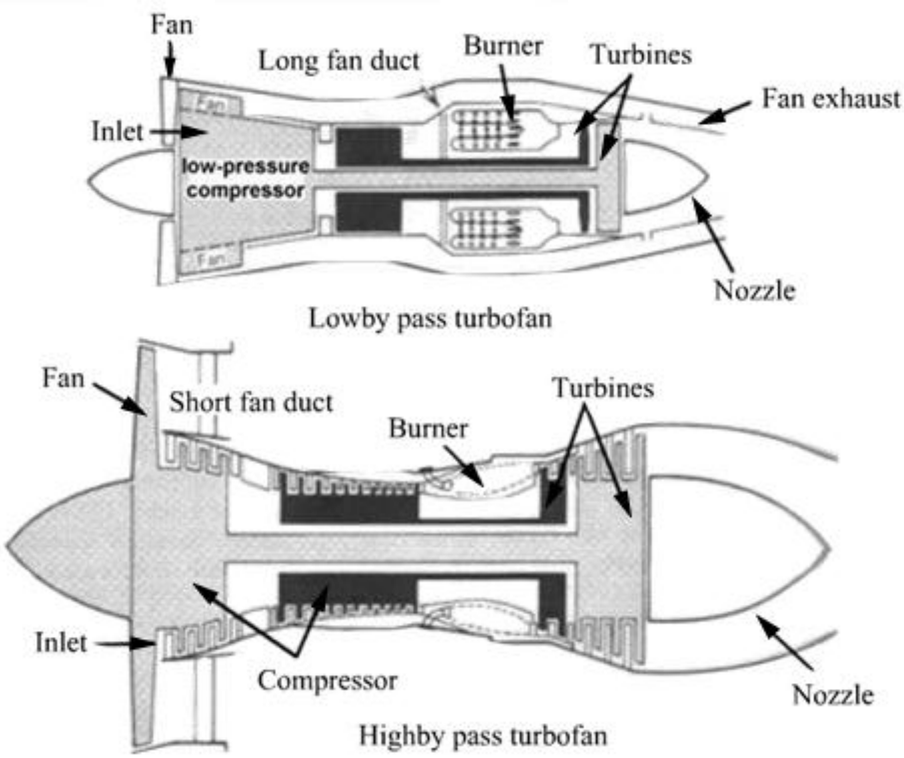


Fig 4.10 Turbofan engine

(Source : http://www.aerospaceweb.org)

iii) Turbojet engine

At supersonic Mach numbers, up to three, a turbo-jet engine is used. In this engine entire power output is through the jet thrust.