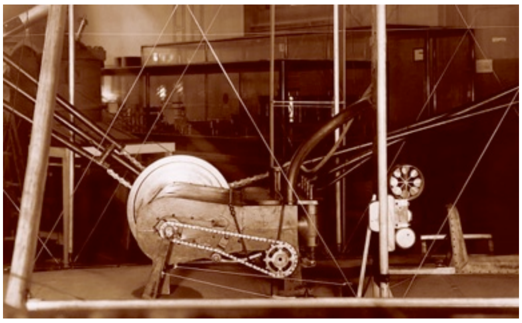
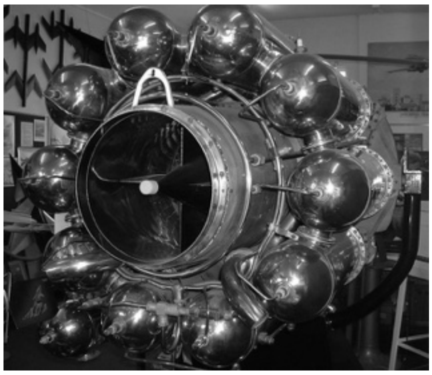
PROPULSION



Aerospace propulsion systems



Torenbeek & Wittenberg Ch 5

Anderson Ch 9

PROPULSION

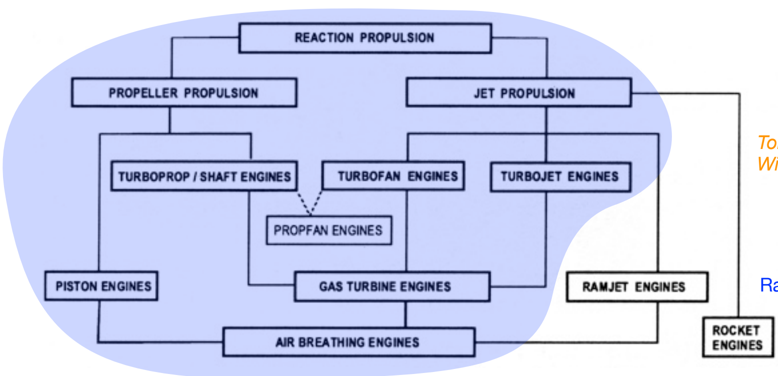
Generation of thrust

All aircraft and rocket engines rely on reaction propulsion: they generate thrust by accelerating a gas flow.

In order to produce thrust the exit gas stream has to travel backward faster than the aircraft travels forward, i.e. relative to the surrounding air it has to acquire velocity in the opposite sense to that of the aircraft.

By transferring momentum to this stream of gas, the propulsion system experiences a thrust that propels the vehicle. Ultimately the thrust is transferred by tractions (principally, pressure) acting on exposed surfaces – propeller blades, compressor blades, ductwork forming part of the propulsion system, and ultimately through mechanical connections (e.g. bolts) to the vehicle itself.

Here will concentrate on the 'air-breathing' + rotating element types in common use.



Torenbeek & Wittenberg

Ramjets have no rotating elements.

Rockets carry fuel oxidiser with them, so are not 'air breathing'.

Propulsion systems are described by their **effectiveness** and **efficiency**, which are different things.

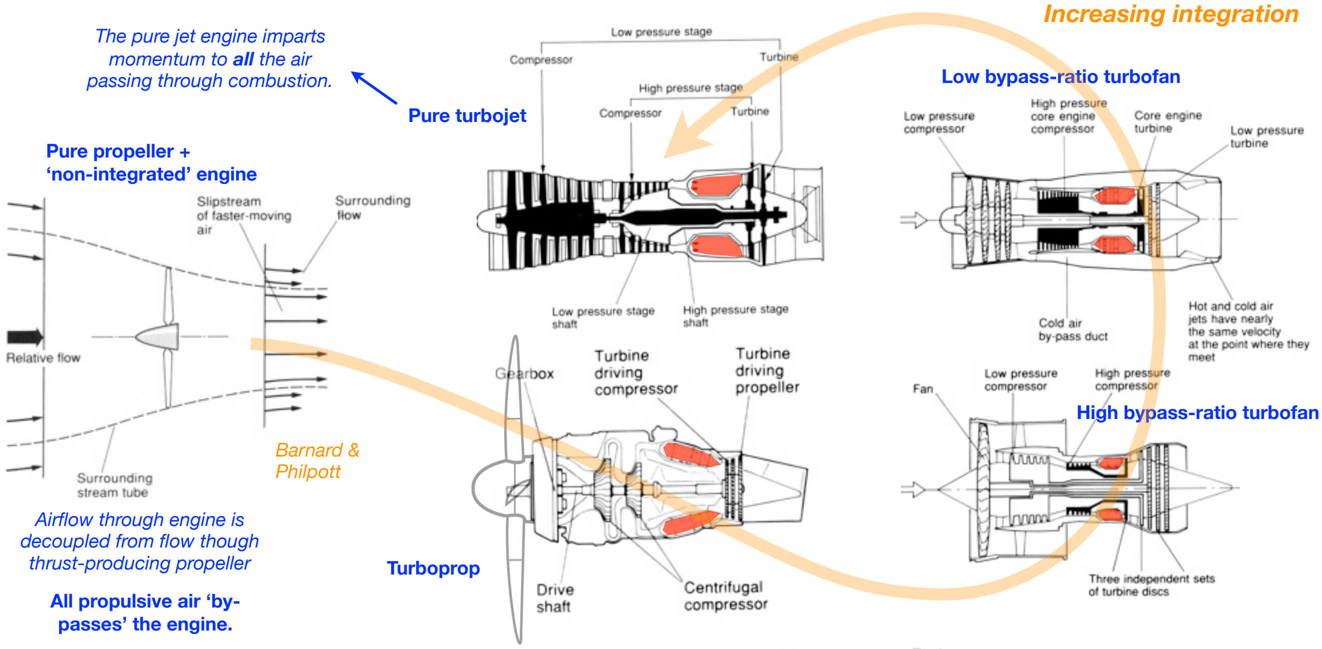
Effectiveness quantifies output (either thrust or power) produced per unit of engine mass.

Efficiency quantifies useful output (either thrust or power) produced per unit of fuel mass (input energy).

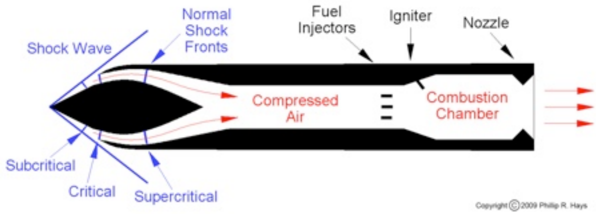
Airbreathing engine types

Rotating-element airbreathing engine types.

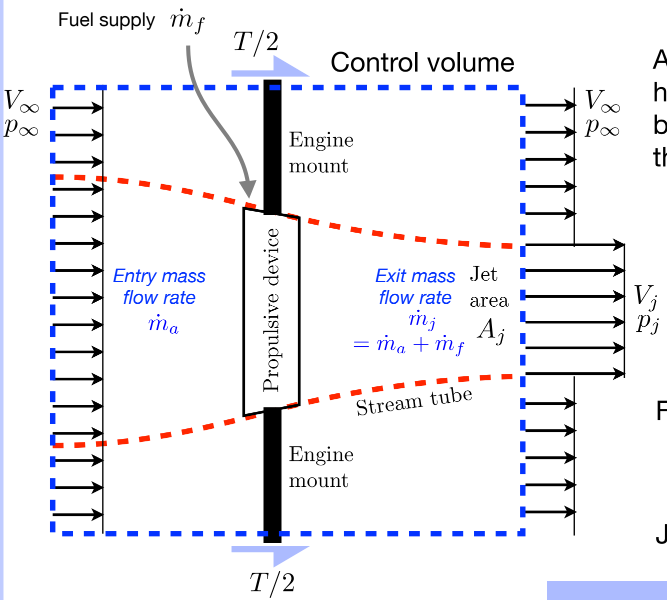
All types rely on burning hydrocarbon fuel in air, leading to heating and expansion of the gas stream.



Ramjets are also air-breathing, have no rotating parts, use shock waves to compress and slow inlet air to subsonic speed before combustion.



Generation of thrust (effect)



Assuming the fuel supply tube is flexible (transmits no horizontal force), and that any flows across horizontal boundaries are vertical, our 1D momentum analysis for the control volume gives

momentum flow out – momentum flow in

$$\Sigma F_{\text{ext}} = T + (p_\infty - p_j)A_j = \dot{m}_j V_j - \dot{m}_a V_\infty$$

$$\Sigma F_{\text{ext}} = T + (p_\infty - p_j)A_j = (\dot{m}_a + \dot{m}_f)V_j - \dot{m}_a V_\infty$$

$$= (1+f)\dot{m}_a V_j - \dot{m}_a V_\infty$$

Fuel:air mass flow ratio $f \approx 0.015 - 0.020$

$$T = \dot{m}_a[(1+f)V_j - V_\infty] + (p_j - p_\infty)A_j$$

Jet pressure differential term $p_j - p_\infty$ typically negligible.

$$T \approx \dot{m}_a(V_j - V_\infty)$$

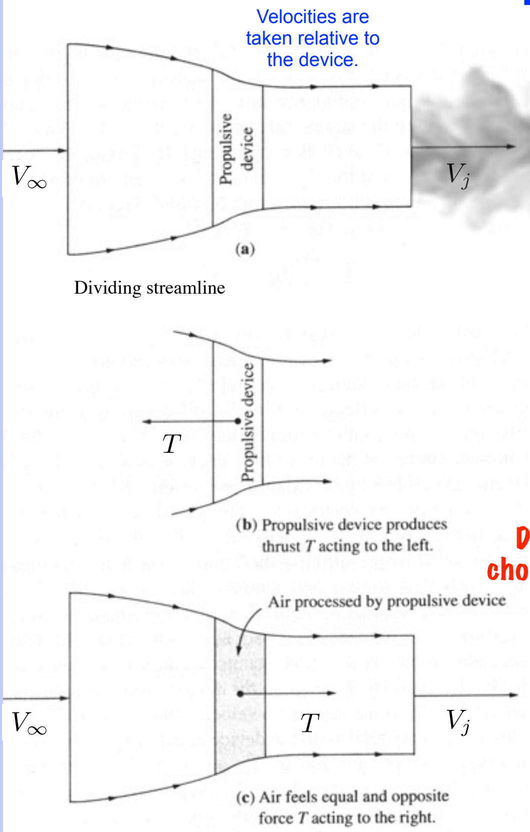
This analysis is enough to capture the main features for propeller and jet propulsion systems.

No thrust is produced unless air passing through the device is accelerated. Hence the faster the aircraft design speed (V_∞), the greater V_j needs to be.

This fact is one determinant of engine type, but we also need to consider propulsive efficiency.

Propulsive efficiency

KE rate of exhaust, dissipated by turbulence



Anderson

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

Useable power $P_A = TV_\infty$

Total power $P_{\text{total}} = P_A + \frac{1}{2}\dot{m}(V_j - V_\infty)^2$

Propulsive efficiency

$$\eta_P = \frac{P_A}{P_{\text{total}}} = \frac{TV_\infty}{TV_\infty + \frac{1}{2}\dot{m}(V_j - V_\infty)^2}$$

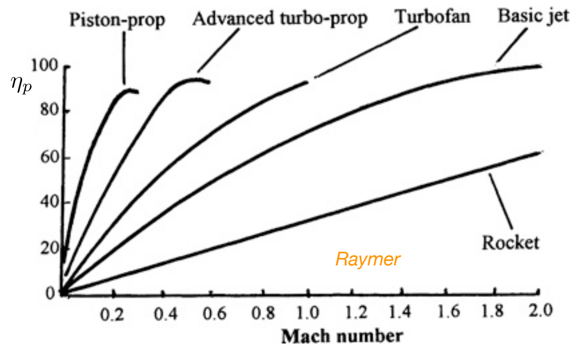
or $$\eta_P = \frac{\dot{m}(V_j - V_\infty)V_\infty}{\dot{m}(V_j - V_\infty)V_\infty + \frac{1}{2}\dot{m}(V_j - V_\infty)^2} = \frac{2}{1 + V_j/V_\infty}$$

Propulsive efficiency could be unity if $V_j = V_\infty$, but then $T = 0$!

To get effect (thrust) we must trade off propulsive efficiency.

For constant propulsive efficiency we should keep V_j/V_∞ constant:

Design principle: for different flight speed regimes (V_∞) we should choose different engines types to keep V_j/V_∞ approximately constant.



Raymer

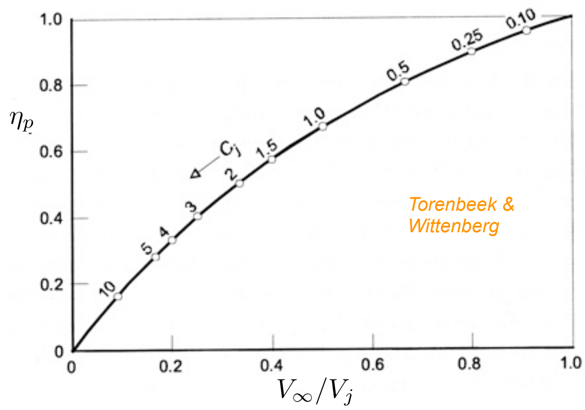
PROPULSION

Powerplant characteristics

Specific thrust (effectiveness) $\frac{T}{\dot{m}_a} = V_j - V_\infty$

Jet velocity coefficient $C_j = \frac{T}{\dot{m}_a V_\infty} = \frac{V_j}{V_\infty} - 1$

From which $\eta_p = \frac{2}{2 + C_j}$

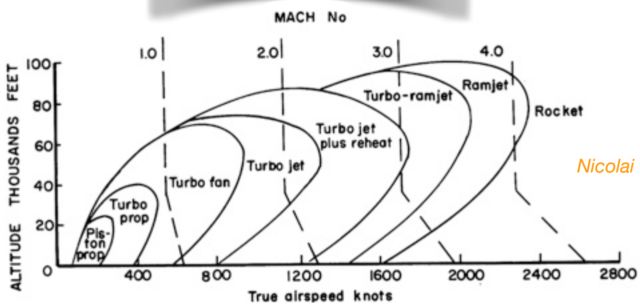


Torenbeek & Wittenberg

Type of propulsion	Altitude km	Flight speed V, m/s (Mach no.)	Jet velocity v_j, m/s	Speed ratio v_j/V	Specific thrust $T/\dot{m}_a$, m/s	Jet coefficient C_j	Propulsive efficiency η_p
propeller	6	150	160 (0.47)	1.07	10	0.067	0.97
subsonic jet engine	9	250 (0.82)	750	3.00	500	2.00	0.50
low BPR turbofan	9	250 (0.82)	582*	2.33	332	1.33	0.60
high BPR turbofan	9	250 (0.82)	418*	1.67	168	0.67	0.75
supersonic jet engine	16	600 (2.03)	1,000	1.67	400	0.67	0.75

* weighted average of primary and secondary airflow

Regimes of applicability.



Nicolai

PROPULSION

The two basic powerplant types

Soon we turn to describing the key characteristics of propulsion systems from the viewpoint of aircraft performance analysis and need to consider

1. The thrust or power produced as a function of aircraft altitude and speed.
2. The mass flow rate of fuel consumed per unit thrust or power.

Engine thrust, or power? Which is more appropriate? We note that by definition the available power delivered by a powerplant, P_A, is simply related to the available thrust, T_A.

$$P_A = V_\infty T_A$$

But we find that having two distinct categories is useful.

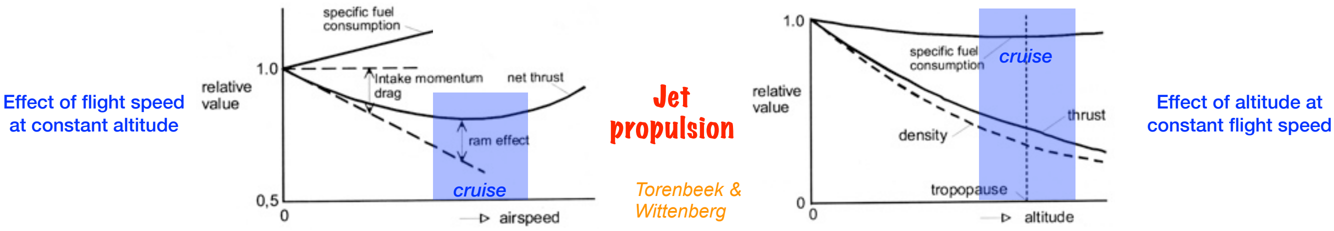
For propeller driven aircraft, the shaft power, while dependent on altitude, is almost independent of aircraft speed, and the total available power (= shaft power × η_p) at cruise is also almost independent of aircraft speed at cruise. So **we work with power-based descriptions for prop aircraft.**

For jet driven aircraft, the available thrust initially falls linearly with airspeed, according to

$$\frac{T}{T_{V_\infty=0}} = \frac{V_j - V_\infty}{V_j} = 1 - \frac{V_\infty}{V_j} < 1$$

However there is a mitigating effect: inlet pressure (hence air density) rises with airspeed ('ram effect').

Overall, at cruise speeds, jet thrust is typically almost independent of airspeed, as is fuel consumption rate.



We work with thrust-based descriptions for jet aircraft.

Powerplant performance modelling

Approximation: jet engines at *cruise* speeds and altitudes provide *thrust* that is independent of airspeed, while piston engine/propeller combinations provide *power* that is independent of airspeed.

The logic for this is that the volume flow rate of air ingested (and fuel burnt) by a piston engine is nearly independent of airspeed, while for a jet engine it is nearly proportional to airspeed.

We will see that for jet engines, it will typically be simplest to deal with thrust characteristics while for piston/prop combinations, it will typically be simpler to deal with power (if the problem allows a choice).

The thrust and power production are also affected by altitude, principally because the amount of oxygen available per unit volume of air falls with altitude (density).

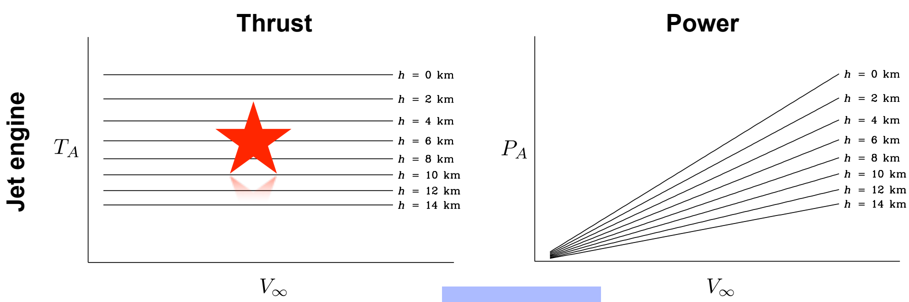
A simple and reasonable approximation for cruise is

$$T_A \approx r\,T_0\left(\frac{\rho}{\rho_0}\right)^s$$

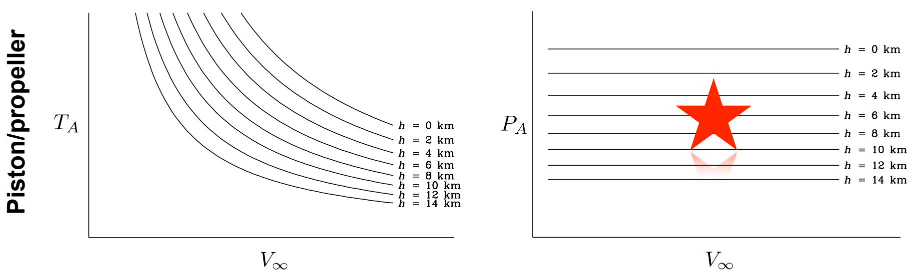
$$P_A \approx r\,P_0\left(\frac{\rho}{\rho_0}\right)^s$$

where 0 denotes sea-level static rated values and

$$r \simeq 0.5, \quad s \simeq 0.7$$



$$P_A = T_A V_\infty$$



Total efficiency and specific fuel consumptions

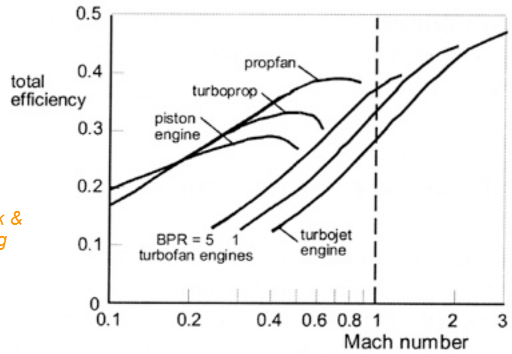
Propulsive efficiency does not include thermal/thermodynamic efficiency, but we can define a **total efficiency** as being the product of propulsive and thermal efficiency.

$$\eta_{\text{tot}} = \eta_{th}\eta_p \qquad \eta_{\text{tot}} = \frac{\text{Available propulsive power}}{\text{Fuel energy supply rate}} = \frac{P_A}{\dot{m}_f H} = \frac{TV_\infty}{\dot{m}_f H}$$

H is the heating value of the fuel, typically *H* ≈ 42 MJ/kg for hydrocarbon fuels.

Fuel	*H* (MJ/kg)
Hydrogen	120
Methane	50
Natural gas	45
Jet fuel/kerosene/petrol/diesel	42
Fat	30
Peanut butter	27
Sugar	15
Lithium-ion battery	0.9

Torenbeek & Wittenberg



Propeller-powered aircraft (<u>where the **power** supplied at the engine shaft, P_s, is approximately independent of aircraft flight speed</u>) have their fuel consumption rates linked to shaft (a.k.a. brake) power:

Brake specific fuel consumption, BSFC, $$c_p = \frac{\dot{m}_f}{P_s}$$ SI units kg/(W s)

Jet-powered aircraft (<u>where the **thrust** supplied by the engine is approximately independent of aircraft flight speed</u>) have their fuel consumption rates linked to the usable thrust delivered:

Thrust specific fuel consumption, TSFC, $$c_t = \frac{\dot{m}_f}{T}$$ SI units kg/(N s)

Thermal, propulsive, total efficiencies

<u>For **propeller powered aircraft**</u>

$$\eta_{\text{tot}} = \eta_{th}\eta_p = \frac{TV_\infty}{\dot{m}_f H} = \frac{P_s}{\dot{m}_f H}\frac{TV_\infty}{P_s} = \frac{P_s}{\dot{m}_f H}\eta_p$$

Recall $c_p = \frac{\dot{m}_f}{P_s}$ so that $\eta_{th} = \frac{1}{c_p H}$

$$\eta_{\text{tot}} = \frac{1}{c_p H}\eta_p$$

The PSFC value, c_p, is almost constant with flight speed but the propulsive efficiency η_p (also called propeller efficiency in this case) may be a strong function of it (and we for now leave it as a variable).

<u>For **jet powered aircraft**</u>, the total jet power

$$P_j = TV_\infty + \tfrac{1}{2}\dot{m}_a(V_j - V_\infty)^2$$
$$= \dot{m}_a(V_j - V_\infty)V_\infty + \tfrac{1}{2}\dot{m}_a(V_j - V_\infty)^2$$
$$= \tfrac{1}{2}\dot{m}_a(V_j^2 - V_\infty^2)$$

and our previous definition of propulsive efficiency

$$\eta_p = \frac{P_A}{P_{\text{total}}} = \frac{TV_\infty}{TV_\infty + \frac{1}{2}\dot{m}_a(V_j - V_\infty)^2} = \frac{P_A}{P_j}$$
$$= \frac{\dot{m}_a(V_j V_\infty - V_\infty^2)}{\frac{1}{2}\dot{m}_a(V_j^2 - V_\infty^2)} = \frac{2}{1 + V_j/V_\infty}$$

Now $\eta_{\text{tot}} = \eta_{th}\eta_p = \frac{P_j}{\dot{m}_f H}\frac{P_A}{P_j}$ and $\eta_{th} = \frac{P_j}{\dot{m}_f H} = \frac{P_j}{c_t H T}$

Finally $$\eta_{\text{tot}} = \frac{P_j}{c_t H T}\frac{TV_\infty}{P_j} = \frac{V_\infty}{c_t H}$$

PROPULSION

Typical specific fuel consumption values

Rather than get into the full complexity of characterising SFC, we will use indicative/typical values.

For power-type (prop) propulsion with brake-specific fuel consumption, BSFC, given the symbol c_p.
SI units are kg/W.s. Note the values below are in mg/W.s (multiply by 10^{-6} to get kg/W.s).

Typical BSFCs, c_p: lbm/bhp/hr {mg/W.s}	Cruise	Loiter
Piston-prop (fixed pitch)	0.4 {.068}	0.5 {.085}
Piston-prop (variable pitch)	0.4 {.068}	0.5 {.085}
Turboprop	0.5 {.085}	0.6 {.101}

Raymer

For thrust-type (jet) propulsion with thrust-specific fuel consumption, TSFC, given the symbol c_t.
SI units are kg/N.s. Note the typical values below are in mg/N.s (multiply by 10^{-6} to get kg/N.s).

Typical TSFCs, c_t: lbm/lbf/hr {mg/N.s}	Cruise	Loiter
Pure turbojet	0.9 {25.5}	0.8 {22.7}
Low-bypass turbofan	0.8 {22.7}	0.7 {19.8}
High-bypass turbofan	0.5 {14.1}	0.4 {11.3}

'Cruise' and 'Loiter' correspond to flying for maximum range (distance travelled) or endurance (time in the air), respectively. Loiter throttle settings (and thrust/power) requirements turn out to be lower than for efficient cruise, but the specific fuel consumptions are a little higher.

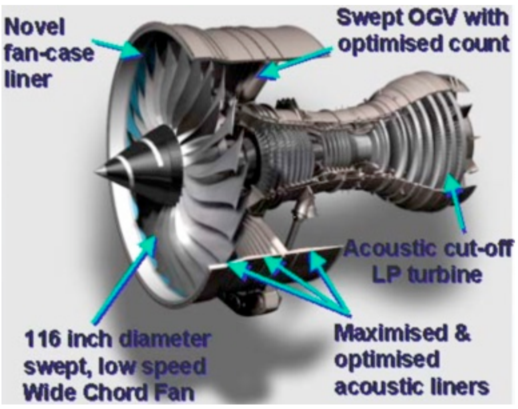
Just as we can convert between T_A and P_A, we can convert also between c_t and c_p.

$$T_A = \frac{P_A}{V_\infty} = \frac{\eta_p P_s}{V_\infty}$$

$$c_t = \frac{\dot{m}_f}{T} \equiv \frac{\dot{m}_f V_\infty}{\eta_\mathrm{p} P_s} = \frac{c_p V_\infty}{\eta_\mathrm{p}}$$

PROPULSION

Powerplant testing



Rolls-Royce Trent 900 turbofan (Airbus A380)

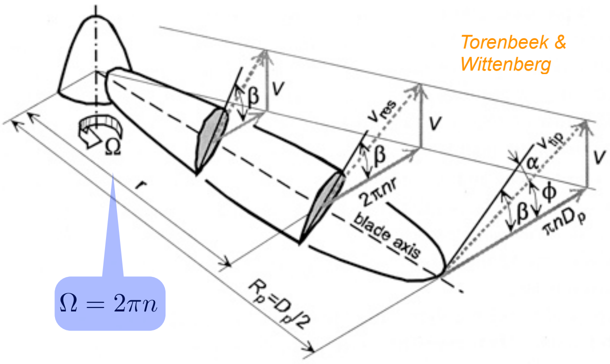
Bypass ratio 8.5

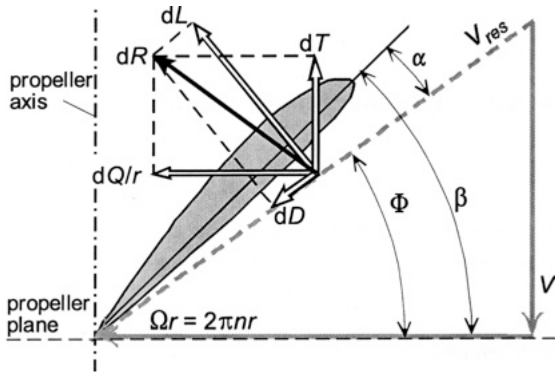
Aircraft engines must meet stringent safety requirements and receive certification testing for strength and performance in adverse conditions.

Examples:

1. Reliable for design altitude and speed range.
2. Start in cold-soaked conditions.
3. Continue to run when water is ingested.
4. Survive bird ingestion event.
5. Contain loss of a fan blade.

Propellers





Propeller blades are like twisted wings: the geometric twist (or pitch) angle β reduces as radius increases so that angle of attack α remains constant along the blade as the peripheral speed Ωr increases.

$$\tan\phi = \frac{V_\infty}{\Omega r} = \frac{V_\infty}{2\pi n r} \qquad \alpha = \beta - \phi$$

Reference pitch angle is typically given at $r = 0.75R_p$ ($\beta_{0.75}$) but also propellers are often described in terms of their diameter and design advance distance per rev, e.g. $D \times P$ = 80cm × 75cm would be a 80cm diameter prop designed for an advance (pitch P) of approx 75cm per rev.

$$P = \pi D \tan(\beta_{r=0.75D/2})$$

(Note that while pitch angle varies with radius, the pitch distance P is a constant.)

At any radial station we can estimate α and if we know the blade chord c and the aerodynamic characteristics of the airfoil section we can find the lift and drag forces per unit length dL *and* dD.

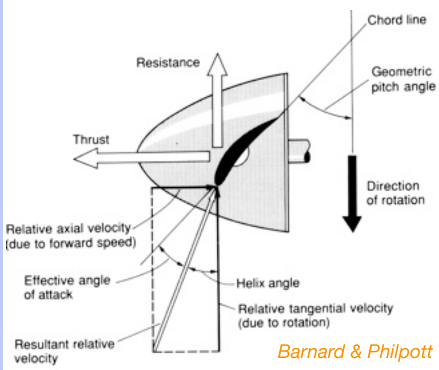
These are then resolved into thrust and peripheral components and from these we can estimate the contribution to thrust (dT) *and* propeller shaft torque (dQ) at each station.

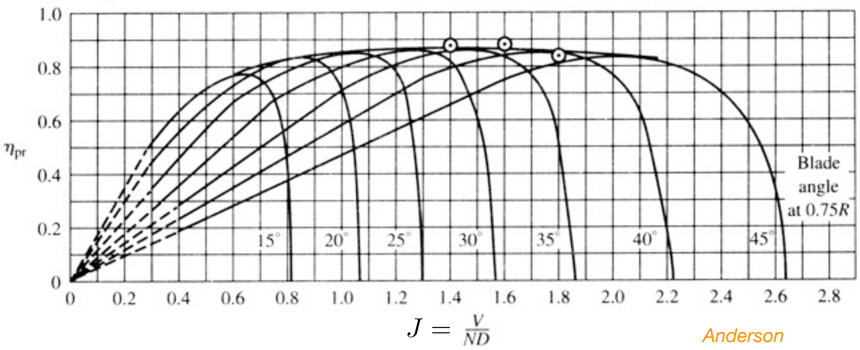
Finally we could integrate along the blade, multiply by number of blades to get total thrust and required driving torque. **This is the basis of blade element theory.**

Propellers

1. Available power P_A depends on propeller efficiency. A propeller is basically a rotating wing and needs to run at the correct angle of attack for maximum efficiency (i.e. maximum L/D). This is characterised by the propeller advance (gear!) ratio J.

$$P_A = \eta_{pr} P_S, \quad \eta_{pr} = f(J), \quad J = \frac{V_\infty}{ND} = \pi\frac{V_\infty}{r_{tip}\,\omega}$$

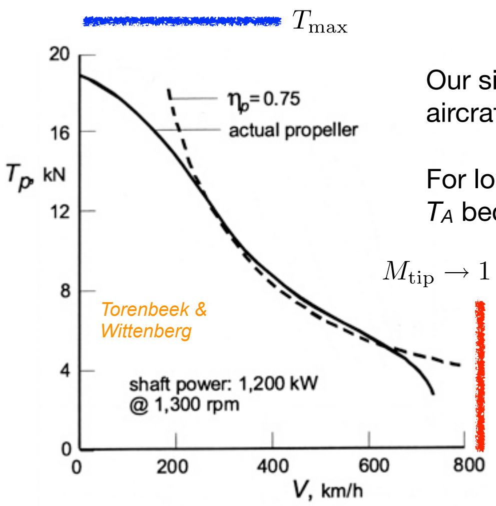


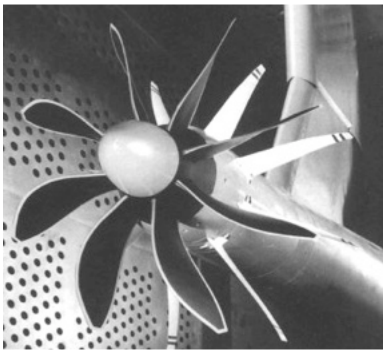


2. Typical maximum values of η_{pr} are in the range 0.8-0.9.
3. For a fixed-pitch propeller, the pitch is chosen to maximise η_{pr} for the most important design task (e.g. cruise speed, rate of climb).
4. If the aircraft cost justifies it, we can use a variable-pitch propeller, or better yet, a constant-speed propeller wherein an automatic governer allows the engine to run at a constant optimal speed (i.e. the governer keeps P_A constant) and the pitch angle is varied automatically with flight speed. This assumption allows considerable simplification in design.

NOTE the difference: for jet engines: $P_A = TV_\infty$ (no separate accounting for η_{pr}).

Propellers





Our simple models for propeller performance are adequate for many aircraft performance problems, but are weak at very low or high speeds.

For low speeds, the simple approximation that $T_A V_\infty \equiv \eta_p P_s$ suggests T_A becomes infinite as $V_\infty \to 0$ if η_p = const. (cannot be correct!).

Other simplified models suggest an upper limit to thrust at $V_\infty = 0$

$$T_{\max} \approx \left(2P_s^2 \rho A_p\right)^{1/3}$$

where $A_p = \pi R_p^2 = \pi D_p^2/4$ is the swept area of the propeller disc.

If the tip speeds approach the speed of sound, shock wave drag will act to limit the available thrust, too (and produce unacceptable noise levels).

$$v_{\text{tip}} = \sqrt{V_\infty^2 + (\pi n D_p)^2} \quad \text{or} \quad M_{\text{tip}} = M_\infty \sqrt{1 + (\pi/J)^2}$$

E.g. $J = 2$ and $M_\infty > 0.54$ gives $M_{\text{tip}} > 1$.

This has limited propeller applications to $M_\infty \lesssim 0.65$

More advanced designs with swept blades and thin sections have been proposed and tested for higher though still subsonic Mach numbers, but so far not much used in practice.