AE 452 Aeronautical Engineering Design II

Installed Engine Performance

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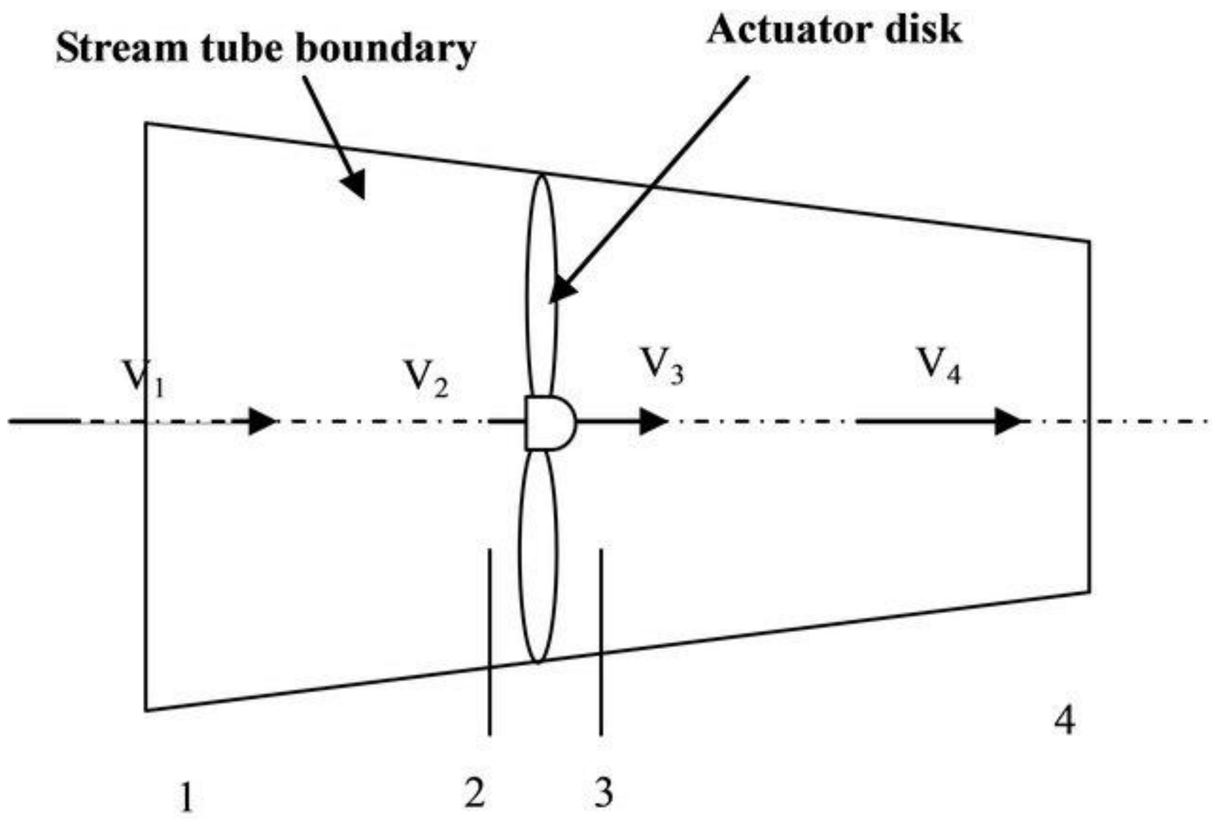
Propulsion



Propulsion

- $F = ma = \dot{m}\Delta V = \rho V_o S(V - V_o)$; thrust,
- $P_t = FV_o = \rho V_o S(V - V_o)V_o$; thrust power
- $P_{t,spent} = \frac{\partial E}{\partial t} = \frac{1}{2}\dot{m}V^2 - \frac{1}{2}\dot{m}V_o^2 = \frac{1}{2}\dot{m}(V^2 - V_o^2)$.
- $\eta_{pr} = \frac{P_t}{P_{t,spent}} = \frac{2}{V/V_o+1}$; propulsive efficiency.
- $\frac{V}{V_o} \approx 3.0$ for turbojets, ≈ 1.5 for propellers.

Jet-engine thrust

- Turbojet cycle parameters: overall pressure ratio, turbine inlet temperature, bypass ratio, flight condition.

  $$\frac{T}{T_{SL}} = \frac{\rho}{\rho_{SL}} \text{ up to 40 000 ft.}$$

- As $V_o \nearrow, T \nearrow$ due to $\dot{m} \nearrow$ but $V - V_o \searrow$ as $V_o \nearrow$.
- For subsonic flight, the gases at the exhaust are at a choked condition ($M = 1$).

  $\Rightarrow V = a_\infty$, almost independent of flight speed.

  $\Rightarrow$ thrust is almost constant with velocity upto transonic speeds.

Jet-engine thrust

- $T = T(OPR)$ and $\eta_{pr} = \eta_{pr}(OPR)$;

  OPR: overall pressure ratio $= \frac{pressure\ @\ engine\ exhaust}{pressure\ @\ engine\ inlet}$

  $OPR \approx 15 - 30{:}\,1$ for current engines.

  TIT: turbine inlet temperature $\approx 1100 - 1400^o C$, increased 180^o/decade since 1950s.
- BPR: bypass ratio. As $BPR \nearrow, \eta_{pr} \nearrow$.
- High bypass ratio turbofan; $M < 0.9$,
- Low bypass ratio turbofan; $0.9 < M < 2.2$,
- Pure turbojet; $M > 2.2$.

Turbojet installed thrust

- Uninstalled thrust is obtained from engine manufacturer, preliminary cycle analysis or a fudge factor approach.
- Every 10 years: 25% less SFC, 30% less weight,
  30% less length,
- Installed thrust = uninstalled thrust – installation effects
  – drag contribution assigned to the propulsive system

Installed thrust

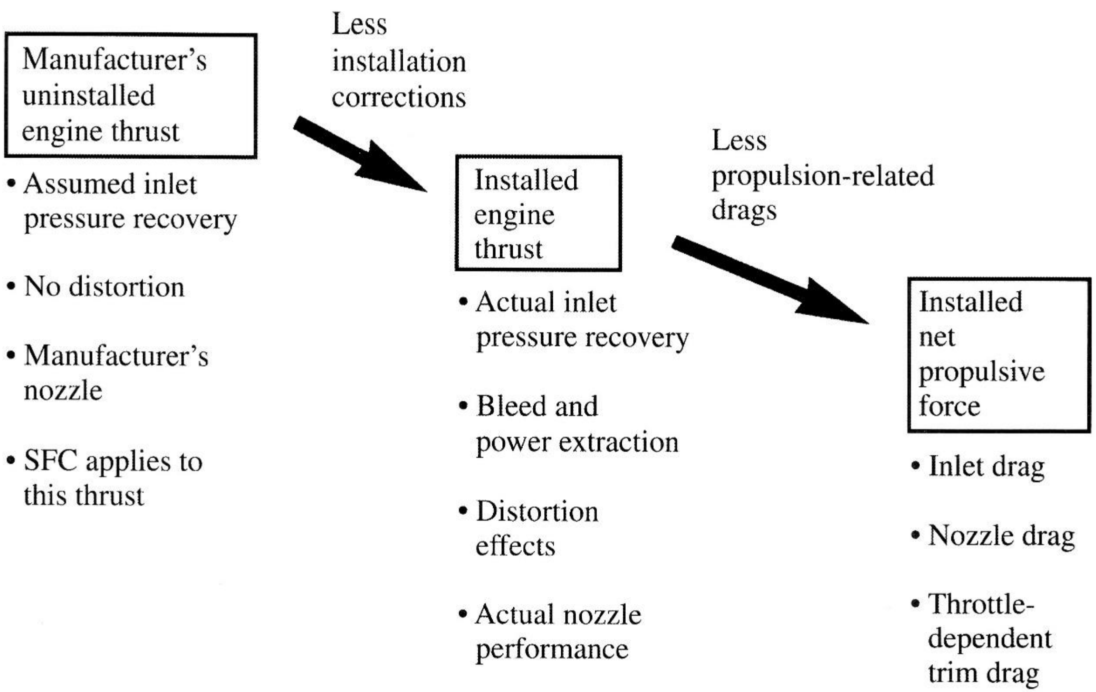


Fig. 13.5 Installed thrust methodology.

Installed engine thrust corrections

Inlet pressure recovery:

$$\frac{P_1}{P_o} = \frac{total\ pressure\ at\ the\ engine\ front\ face}{total\ pressure\ in\ the\ freestream}$$

$\frac{P_1}{P_o} \approx 1.0$ at subsonic speeds,

$\frac{P_1}{P_o} = 1 - 0.075(M-1)^{1.35}$ at supersonic speeds

Installed engine thrust corrections

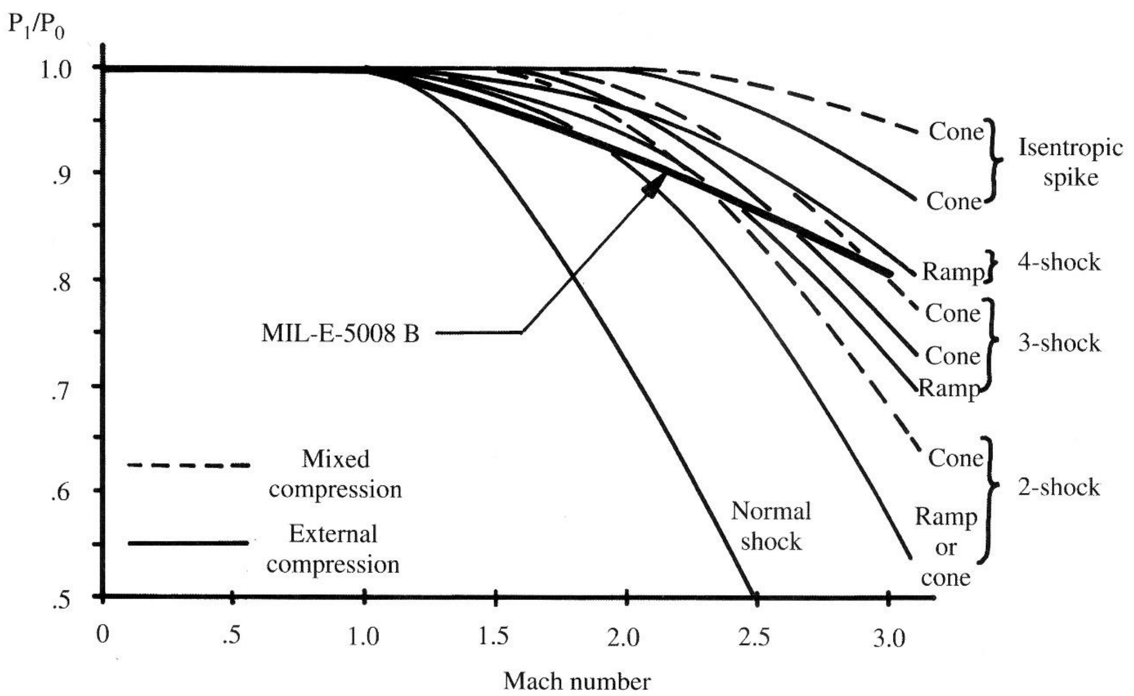


Fig. 13.6 Reference and available inlet pressure recovery.

Installed engine thrust corrections

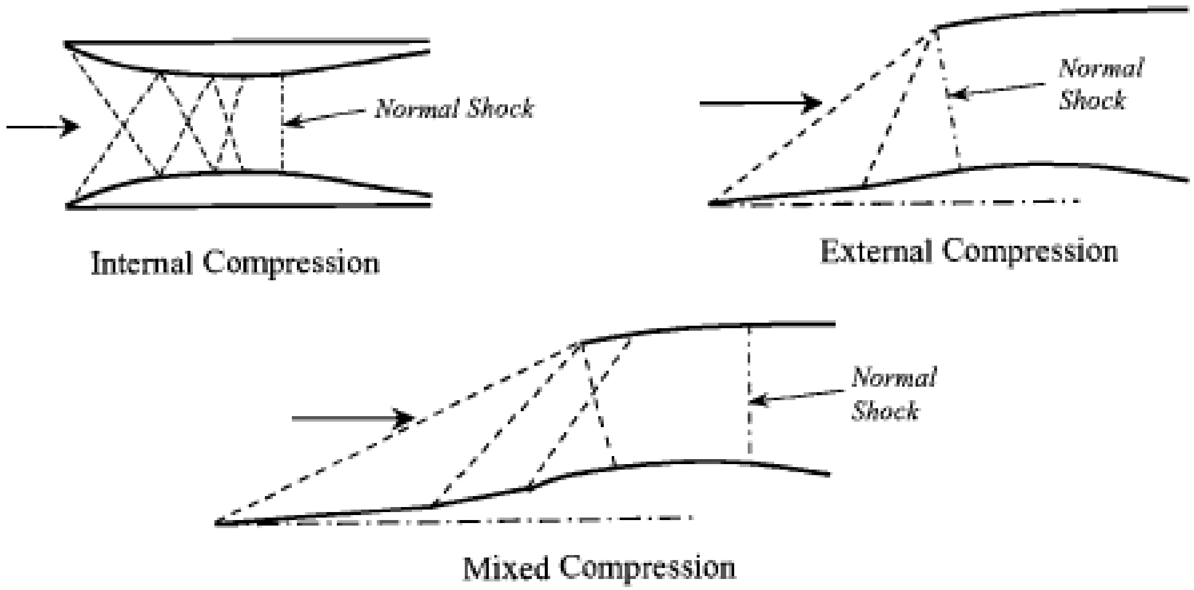


Fig. 6.3 Types of supersonic inlets.

Installed engine thrust corrections

- Pressure recovery loss due to flow in the inlet must also be accounted for:

  F: internal pressure recovery factor,

  $F = 0.96$, straight duct,

  $F = 0.94$, S-shaped duct,

  $F = 0.98$, short duct of podded nacelle

Installed engine thrust corrections

- % thrust loss = $C_{ram}\left[\left(\frac{P_1}{P_o}\right)_{ref} - \left(\frac{P_1}{P_o}\right)_{actual}\right] * 100.$

  C_{ram}: ram recovery correction factor,

  $C_{ram} \approx 1.35$ for subsonic flight,

  $C_{ram} \approx 1.35 - 0.15(M - 1)$ for supersonic flight.

Installed engine thrust corrections

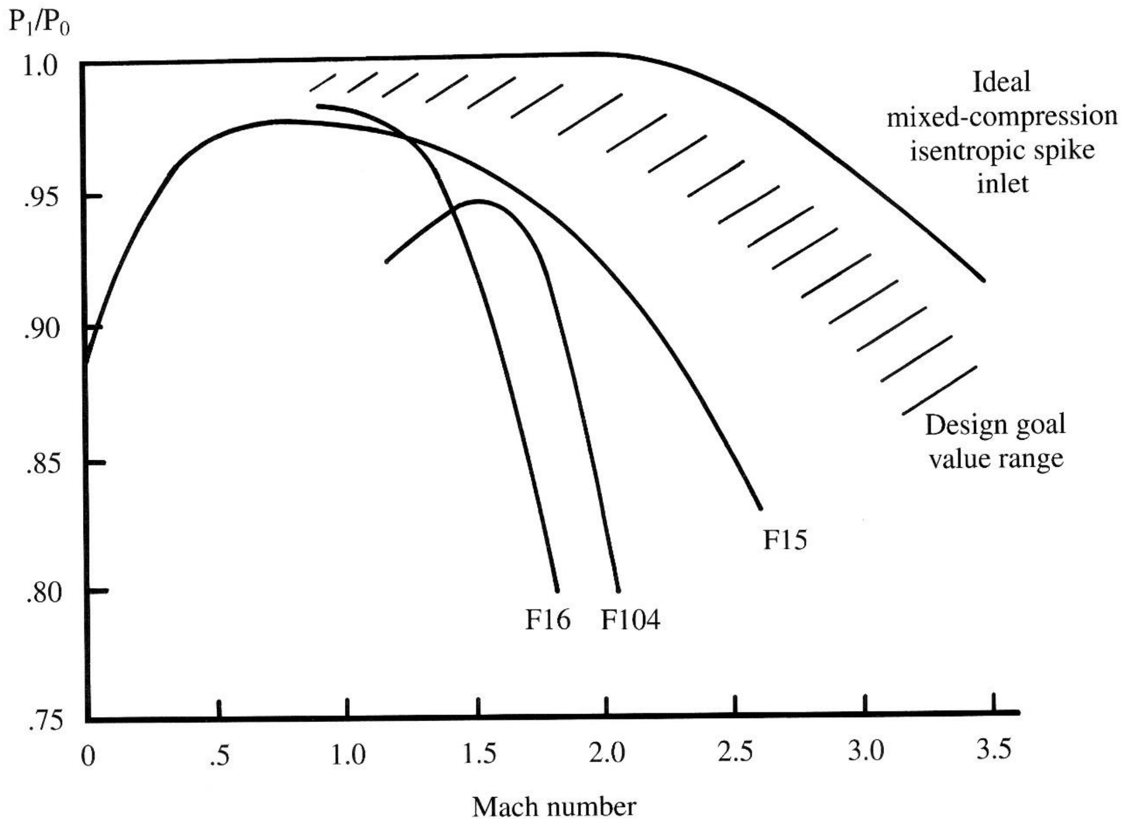


Fig. 13.7 Actual inlet pressure recoveries.

Installed engine thrust corrections

Bleed air:

- This is the high pressure air that is bled from the engine for cabin heating, anti-icing, etc.

$$\%\ thrust\ loss = C_{bleed}\left(\frac{bleed\ mass\ flow}{engine\ mass\ flow}\right) * 100$$

$$C_{bleed} \approx 2.0, \frac{bleed\ mass\ flow}{engine\ mass\ flow} \approx 1 - 5\%$$

Installed net propulsive force corrections

Engine produces three forms of drag that must be subtracted from the engine thrust:

- Spillage or additive drag,
- Inlet boundary-layer bleed drag,
- Nozzle drag.

Installed net propulsive force corrections

- Most of the engine related drag is produced by the inlet due to the mismatch between the amount of air required by the engine and the amount of air the inlet can supply at a given flight condition.
- When the inlet is providing exactly the amount of air that the engine demands, the inlet drag is negligible (mass flow ratio=1).
- The inlet is sized according to the worst-case scenario when the engine demands a lot of air, this sets the **capture area.**
- When the mass flow ratio < 1, the excess air must either be spilled before the air enters the inlet or bypassed around the engine via a duct.

Installed net propulsive force corrections

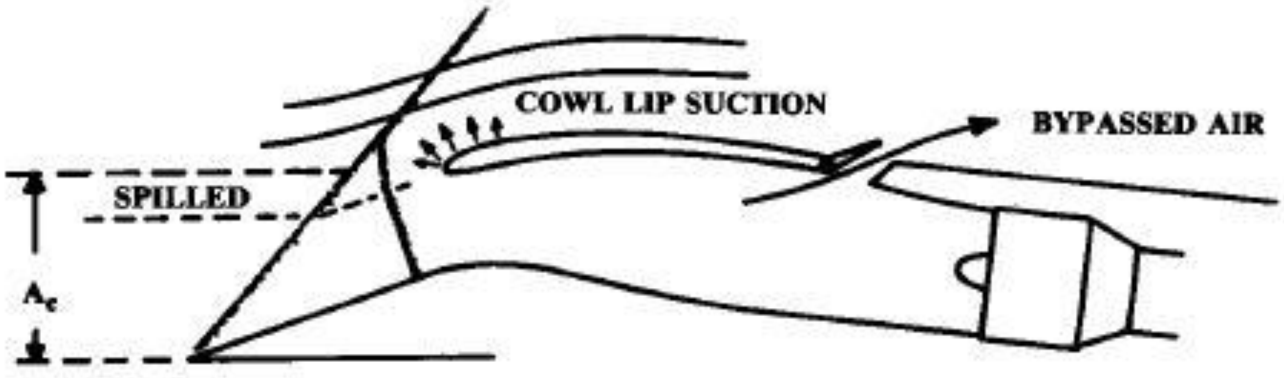


Fig. 13.5 Additive drag, cowl lip suction, and bypass subcritical operation.

Installed net propulsive force corrections

- The spilled air will be turned back toward the freestream direction by the inlet cowl lip producing a **suction zone** on the cowl.
- This has a component in the thrust direction reducing spillage drag by 30-40%.
- With well-rounded cowl lips, the spillage drag may be completely eliminated for a subsonic jet.

Installed net propulsive force corrections

- Allowing the excess air to enter the inlet and bypassed overboard or into an ejector nozzle will further reduce the additive drag.
- Another contributor to inlet drag is the momentum loss related to the **inlet boundary layer bleed**.
- Air is bled through holes or slots on the inlet ramps within the inlet to prevent shock-wave induced separation and to prevent boundary-layer growth.

Installed net propulsive force corrections

- For preliminary analysis, the following figure may be used for supersonic airplanes at either maximum dry or afterburning power setting at maximum mass-flow ratio.

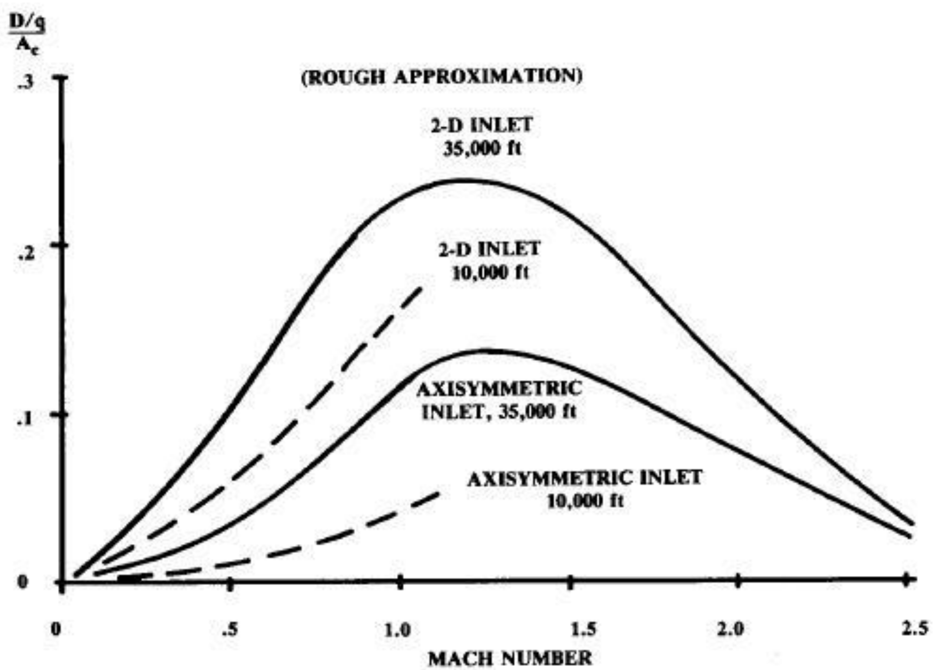


Fig. 13.6 Inlet drag trends.

Installed net propulsive force corrections

- For estimating **nozzle drag**, the following table may be used:

Table 13.1 Nozzle incremental drag[10]

Nozzle type	Subsonic $\Delta C_{D_{Fuselage}}$*
Convergent	.036–.042
Convergent iris	.001–.020
Ejector	.025–.035
Variable ejector	.010–.020
Translating plug	.015–.020
2-D nozzle	.005–.015

*Referenced to fuselage maximum cross-section area.

Installed net propulsive force corrections

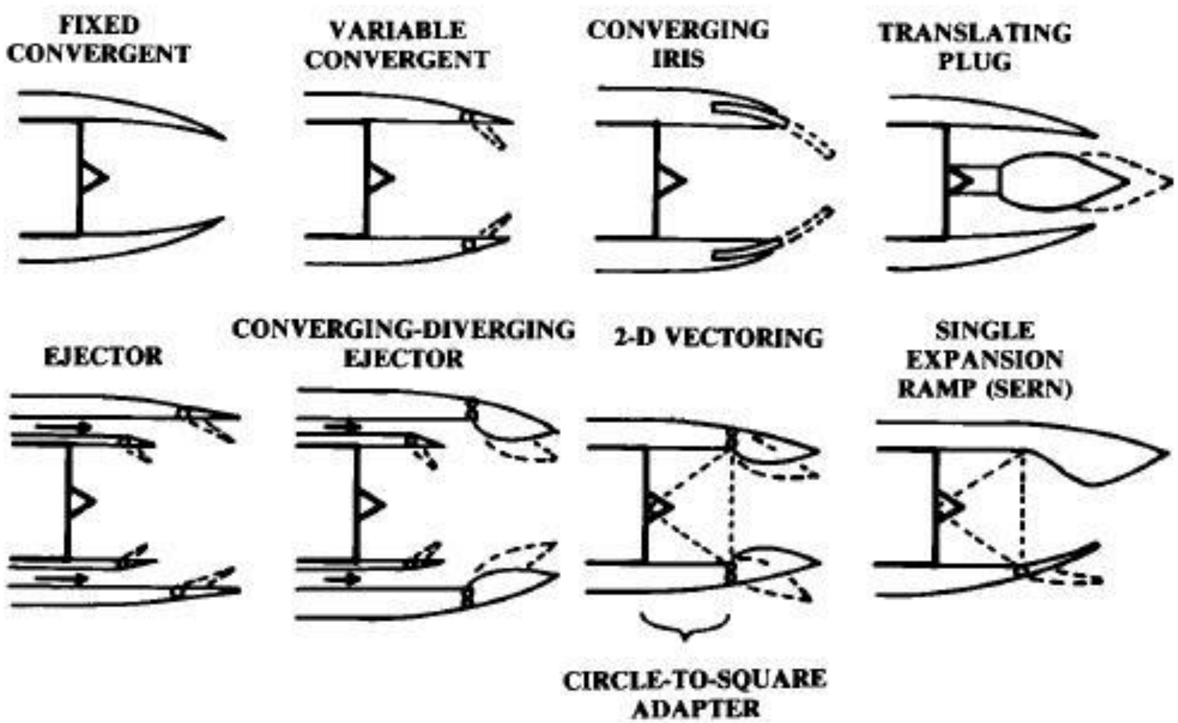


Fig. 10.20 Types of nozzles.

Part power operation

- Turbojet and turbofan engines would like to operate at **maximum thrust setting**.
- When the throttle is reduced, **reduction in thrust is more than the reduction in fuel flow**. Therefore the specific fuel consumption increases.

$$\frac{C}{C_{max,dry}} = \frac{0.1}{\left(\frac{T}{T_{max,dry}}\right)} + \frac{0.24}{\left(\frac{T}{T_{max,dry}}\right)^{0.8}} + \left(0.66\frac{T}{T_{max,dry}}\right)^{0.8}$$

$$+0.1M\left[\left(\frac{T}{T_{max,dry}}\right)^{-1} - \left(\frac{T}{T_{max,dry}}\right)\right]$$

Part power operation

- When the throttle is at idle, neither the fuel flow, nor the thrust is zero.
- If $\frac{T}{W} \geq \frac{1}{L/D}$ the airplane cannot descend.
- $C_{idle} \approx 1.5 C_{max,dry}$.

Piston engine performance

- Power produced ~ mass flow of air into the intake manifold.
- $hp = 620\dot{m}$ (lb/s) or $kW = 1019\dot{m}$ (kg/s).

$$\frac{P}{P_{SL}} = \left(\frac{\rho}{\rho_{Sl}} - \frac{1-\rho/\rho_{SL}}{7.55}\right)$$

- $P@$ intake manifold $\approx P_{atm}$.
- Manifold pressure can be increased by a **supercharger** or a **turbosupercharger**.
- Supercharger is a centrifugal air compressor driven by a shaft from the engine.
- Turbocharger is driven by a turbine placed in the exhaust pipe.

Piston engine performance

- Supercharging or turbocharging is usually used to **maintain sea-level pressure in the intake manifold** as the airplane climbs.

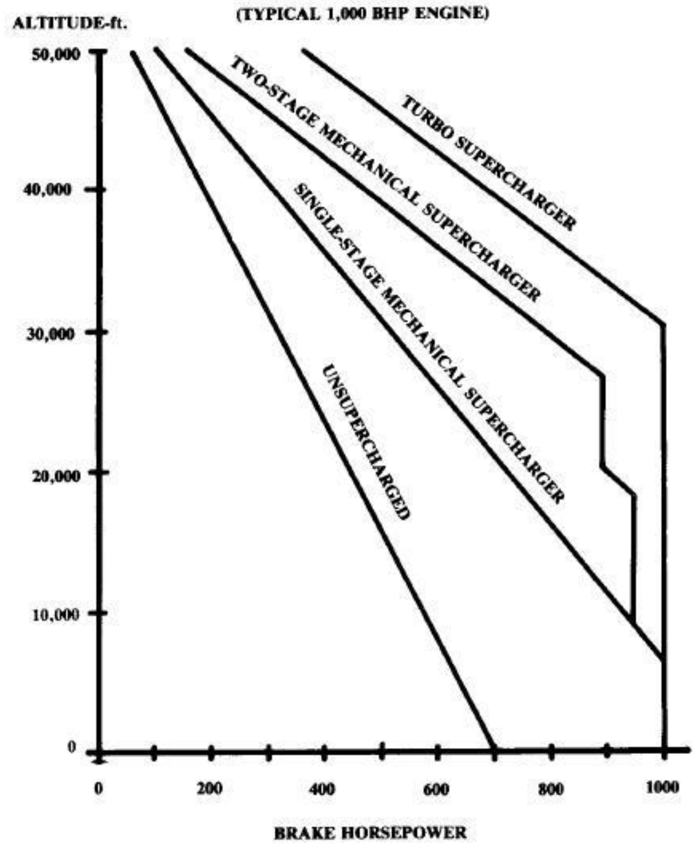


Fig. 13.7 Effects of supercharging.

Propeller performance

- A propeller is a **rotating wing** that generates thrust just like a wing produces lift.
- Like a wing, a propeller is designed for a particular flight condition, i.e. lift coefficient, which is usually around 0.5.
- The **twist** of the propeller is selected to yield the optimal airfoil angle of attack at the design condition.
- **Overall pitch** of a propeller refers to the blade angle at 75% of radius.

Propeller performance

- Advance ratio; $J = \frac{V_\infty}{nD}$: the distance the airplane moves with one turn of the propeller.
- Power coefficient; $C_p = \frac{P}{\rho n^3 D^5} = \frac{550bhp}{\rho n^3 D^5}$
- Thrust coefficient; $C_T = \frac{T}{\rho n^2 D^4}$
- Speed-power coefficient; $C_s = V_\infty \sqrt[5]{\rho / P n^2}$. Does not involve the propeller diameter, useful for comparison between different propeller sizes.

Propeller performance

- Activity factor is a measure of blade width and width distribution on the performance of the propeller and it is a measure of the propeller's ability to absorb power.

$$AF_{per\ blade} = \frac{10^5}{D^5} \int_{0.15R}^{R} c r^2 dr = \frac{10^5 c_{root}}{16D} [0.25 - (1 - \lambda) 0.2]$$

- Typical activity factors: 90-200, 100 for a light aircraft, 140 for a turboprop.

Propeller performance

- Propeller efficiency; $\eta_p = \frac{TV_\infty}{P} = \frac{TV_\infty}{550bhp}$
- Thrust; $T = \frac{P\eta_p}{V_\infty} = \frac{550bhp\eta_p}{V_\infty}$; forward flight

  $T = \frac{c_T}{c_P}\frac{P}{nD} = \frac{c_T}{c_P}\frac{550bhp}{nD}$; static

Propeller performance

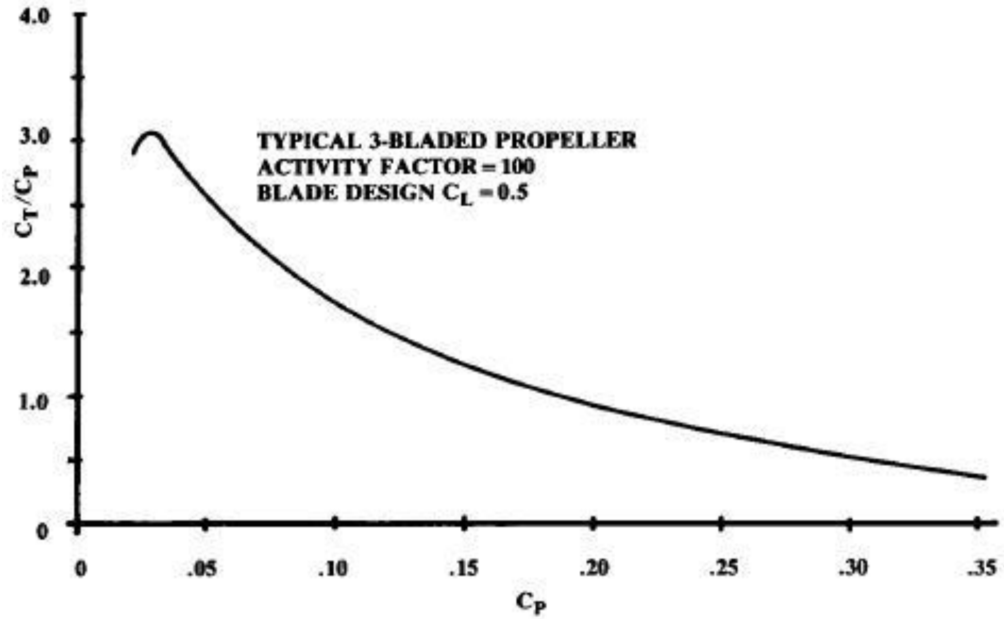


Fig. 13.8 Static propeller thrust. (after Ref. 50)

Propeller performance

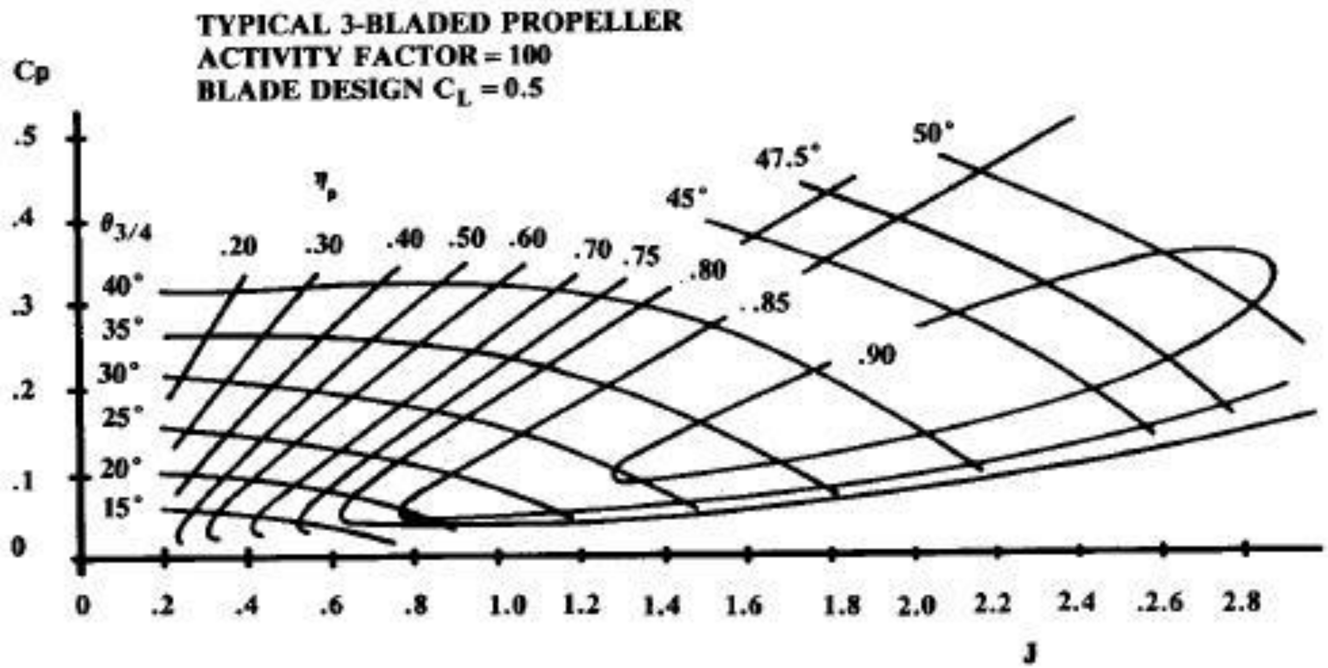


Fig. 13.9 Forward flight thrust and efficiency. (after Ref. 50)

Propeller performance

- For 2-blades: $\eta_p = +3\%,\quad T_{static} = -5\%,$
- For 4-blades: $\eta_p = -3\%,\quad T_{static} = +5\%.$
- For variable pitch propelers, pitch is adjusted such that engine RPM is constant regardless of P.

  $\Rightarrow c_p$ and J are independent of each other,

  $\Rightarrow \eta_p$ can be read from the previous chart for any c_p and J combination that can occur, also $\theta_{3/4}$.
- For $0 < V_\infty < 50$ knots, static thrust and thrust in forward flight can be joined by a smooth curve.

Piston-prop thrust corrections

- Propeller efficiency must be corrected for:
  i. Blockage effects,
  ii. Mach # effects,
  iii. Scrubbing drag,
  iv. Cooling drag.

Piston-prop thrust corrections

- **Blockage effect:** nacelle immediately behind the propeller blocks the airflow causing it to slow down before it reaches the propeller.

  $J_{corrected} = J(1 - 0.329S_c/D)$

  S_c: maximum cross-sectional area of cowling immediately behind the propeller.

Piston-prop thrust corrections

- **Mach # effects:** will reduce thrust at high flight speeds and/or high RPM.

$$\eta_{p,corr} = \eta_p - (M_{tip} - 0.89)\left(\frac{0.16}{0.48-3t/c}\right) \text{ for } M_{tip} > 0.89.$$

$$M_{tip} = \frac{\sqrt{V_\infty^2 + (\pi n D)^2}}{a} = \frac{helical\ tip\ speed}{speed\ of\ sound}$$

Piston-prop thrust corrections

- **Scrubbing drag:** it is the increase in aircraft drag due to higher velocity and turbulence experienced by the airframe components within the propwash.

$$\eta_{p,eff} = \eta_p \left[1 - \frac{1.558}{D^2}\frac{\rho}{\rho_{SL}}\sum\left(C_{fe}S_{wet}\right)_{washed}\right]$$

C_{fe}: equivalent skin friction (parasite) drag coefficient referenced to wetted area.

Piston-prop thrust corrections

- **Cooling drag:** is related to the momentum loss of the air passing around the engine for cooling.

$$\left.\frac{D}{q}\right)_{cooling} = 4.9 * 10^{-7}\frac{bhp\,T^2}{\sigma V_\infty}\,(ft^2) = 6 * 10^{-9}\frac{PT^2}{\sigma V_\infty}\,(m^2)$$

$\sigma = \rho/\rho_{SL}$, T is the temperature in Kelvin!

- **Miscellaneous drag:** drag of the oil cooler, air intake, exhaust pipes, etc.

$$\left.\frac{D}{q}\right)_{misc} = (2 * 10^{-4})bhp\,(ft^2) = 2.5 * 10^{-5}P\,(m^2).$$

Actual drag may be 2-3 times the values estimated.