Engine Selection

Aerospace Design

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Engine Selection

- Knowing already the total drag from the wing, fuselage and tail, calculated for the different mission phases, the required thrust is known and an engine may be selected from the available set, where cost is also an important factor.
- Developing a new engine or using existing ones (the last option is preferred for cost reasons and for minimization of design problems and uncertainties in early design stages).
- For instance, for long range aircraft where efficient cruise is the main objective, engine is selected based on cruise conditions (Mach number and altitude).
- Also, the geometry and dimensions of the engine are important (to fit the design).

Engine Selection

A good aircraft engine is characterized by:

- **Enough power** to fulfill the mission -> Take-off, climb, cruise etc
- **Low weight**
  High weight increases the necessary lift and therefore the drag.
- **High efficiency**
  Low efficiency increases the amount fuel required and therefore the weight and therefore the drag.
- **High reliability**
- **Ease of maintenance**

Engine Selection - Type

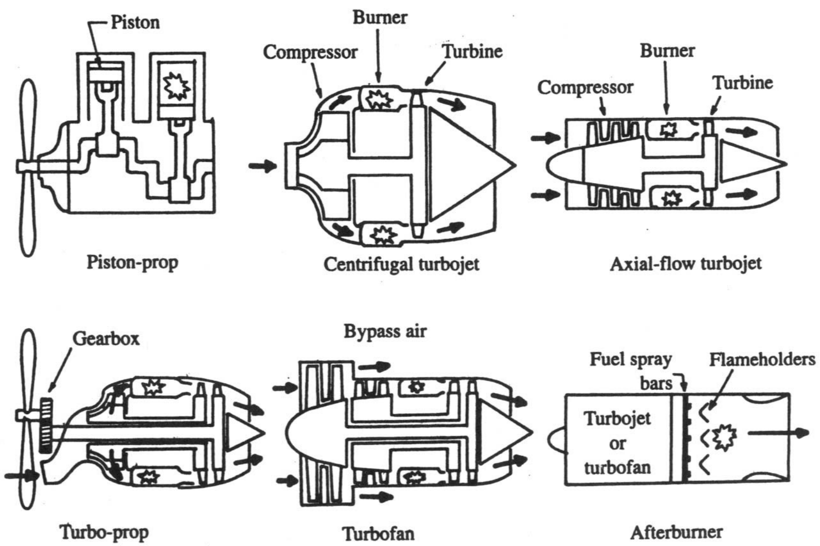
- **Engine type:** piston, turboprop, turbofan, etc.
- **Number of engines:** required thrust and probability of failure.
- **Engine installation:** underwing, fuselage sides, tail, inside fuselage etc.
- **Choice of propellers:** for piston and turboprop engines.

Engine Type

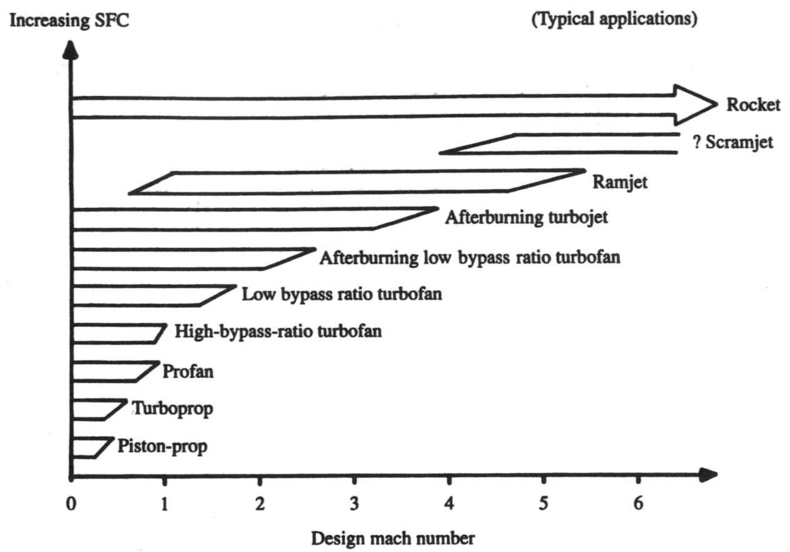
- This usually depends on the aircraft specification
- **Transport aircraft** at $M < 0.7$: Specific Fuel consumption is paramount -> Turboprop.
- **Transport aircraft** at $0.7 < M < 1$: Specific Fuel consumption is paramount -> Turbofan.
- **Supersonic aircraft** $M>1$: Thrust is paramount. • Turbojet.
- **Supersonic aircraft** $M>3$: Thrust is paramount. • Ramjet.
- **Hypersonic aircraft** $M>4$: Thrust is paramount. • Scramjet.

Typical Propulsion Systems

- All aircraft engines operate by compressing outside air, mixing it with fuel, burning the mixture, and extracting energy from the resulting high-pressure hot gases
- In a piston prop, these steps are done intermittently in the cylinders via the reciprocating pistons
- In a turbine engine, these steps are done continuously, but in the three distinct parts of the engine

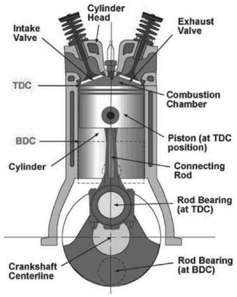


Propulsion system options



Propulsion system speed limits

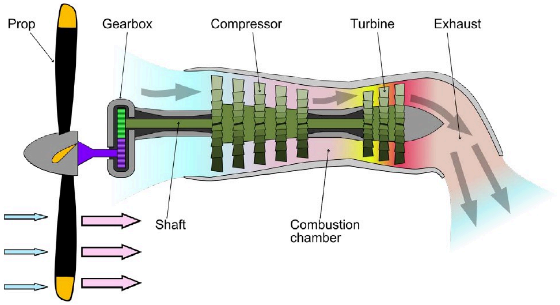
Piston



- Lowest SFC and lowest cost
- Appropriate for light aircraft
- Low *T/W* and higher levels of noise and vibration
- The power loss with altitude (decrease of air density) can be avoided with use of turbo/super chargers

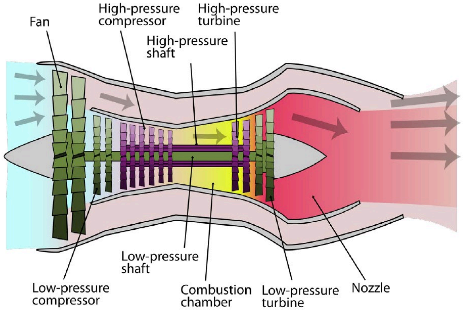
Turboprop

- The engine uses a turbine mainly to extract the energy from the flow after combustion to rotate the propeller
- The jet exhaust contributes with about 20% for thrust
- Higher efficiencies compared to piston engines, at higher Mach numbers
- Appropriate for mid-range commuter aircraft
- Higher *T/W*, higher possible operational altitudes and lower vibration levels



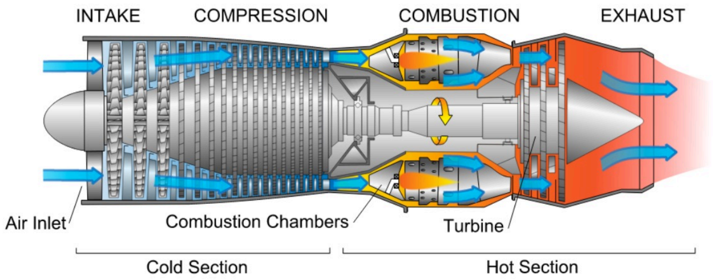
Turbofan

- Best efficiency at high subsonic Mach numbers
- Bypass ratios typically from 0.25 to 6
- High bypass ratios mean better fuel efficiency, but less thrust/lower exit velocity



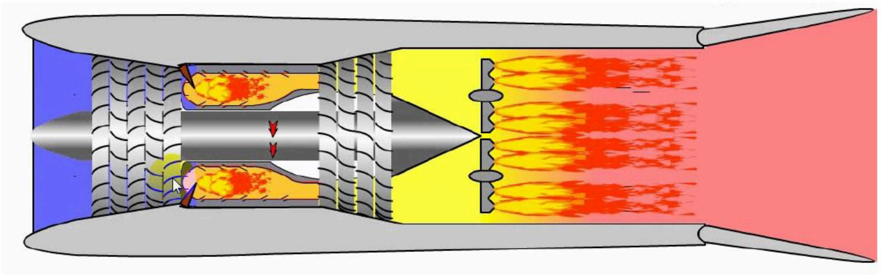
Turbojet

- About 25% of the air is used in the combustion process (in order to maintain the temperatures below the material property temperature limits in the turbine blades)



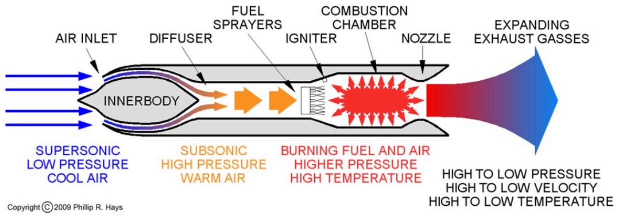
Turbojet with afterburner

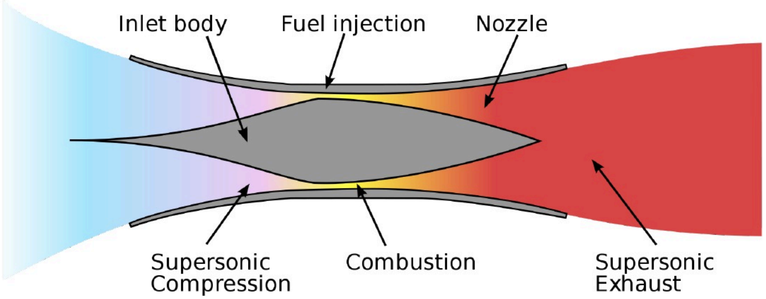
- Additional fuel introduced downstream from turbine stages
- Can increase the thrust by a factor of two to three
- Very high fuel consumption
- Usually used in combat, take-off and high speed intercept



Ramjet and Scramjet

- Uses aircraft's forward motion to compress air before combustion
- Cannot be used at Mach numbers lower than 2





Number of Engines

- The number of engines is usually determined by the amount of thrust needed and the available thrust per engine
- When possible, use the minimum number of engines
  - Leads to a simpler, lighter, more efficient and less expensive aircraft
- FAA requires at least two engines in commuter and commercial aircraft
  - Engine redundancy increases safety
  - The aircraft performance must be demonstrated with one engine inoperative

Number of Engines

- Increasing the number of engines increases the maximum thrust.
- It also increases the probability of at least one engine failing.

- P is the probability of one engine failing per flying hour. It is a small number.
- Doubling the number of engines doubles the probability of failure of 1 engine but multiplies by 6 the probability of failure of 2 engines.

	Probability of engine failure (per flying hour)		
Failure of	1 engine	2 engines	3 engines
twin-engine aircraft	2P	P^2	-
three-engine aircraft	3P	$3P^2$	P^3
four-engine aircraft	4P	$6P^2$	$4P^3$

Engine Ratings

Take-off engine rating

- Maximum thrust that the engine is certified to produce, for short periods of time (around 5 min)
- It is usually specified at sea level static thrust (SLST)
- The take-off rating is generally used when sizing an engine for a design

Climb engine rating

- 90% to 93% of the take-off rating

Maximum cruise engine rating

- 80% of the take-off rating, continuous operation, with no time limits

Turbojet Engine Sizing

- The ideal situation in a new design is to find an existing turbojet engine that meets the mission requirements perfectly
- However, in most cases, this will not happen
- The designer would start with an existing engine with characteristics that are close to those needed in the design and scale it up or down
- It is possible to develop scaling laws based on conservation of mass and momentum for fluid flows

$$T = \dot{m}\left(V_e - V_a\right) + A_e\left(P_e - P_a\right), \quad \text{with } \underset{\textit{Exit}}{P_e} \approx \overset{\textit{Atmospheric}}{P_a}$$

- Considering the static thrust

$$T = \dot{m}V_e, \quad V_a = 0$$

- Hence, the thrust of a turbojet engine should vary with respect to that of a reference engine as

$$\frac{T}{T_{\mathrm{ref}}} = \frac{(\dot{m}V_e)}{(\dot{m}V_e)_{\mathrm{ref}}} \Leftrightarrow T = T_{\mathrm{ref}}\frac{(\dot{m}V_e)}{(\dot{m}V_e)_{\mathrm{ref}}} = T_{\mathrm{ref}}\frac{\dot{m}}{\dot{m}_{\mathrm{ref}}}$$

- Where it was assumed that the jet-exit velocity is not a function of the thrust

Turbojet Engine Sizing

- The mass flow rate through engine is

$$\dot{m} = (\rho A V)_e = \left[\rho V \frac{\pi d^2}{4}\right]_e$$

- Relating mass flow rate to the reference engine the ***diameter ratio*** is given by

$$\dot{m} = \dot{m}_{\text{ref}} \left[\frac{d}{d_{\text{ref}}}\right]_e^2 \Leftrightarrow \left[\frac{d}{d_{\text{ref}}}\right]_e = \left[\frac{\dot{m}}{\dot{m}_{\text{ref}}}\right]^{1/2} = \left[\frac{T}{T_{\text{ref}}}\right]^{1/2}$$

- The ***weight*** and ***length*** of a turbojet engine are based on empirical relations

$$W_{\text{eng}} = W_{\text{eng}_{\text{ref}}} \left[\frac{\dot{m}}{\dot{m}_{\text{ref}}}\right]^a = \left[\frac{T}{T_{\text{ref}}}\right]^a, \quad 0.8 \leq a \leq 1.3$$

$$L_{\text{eng}} = L_{\text{eng}_{\text{ref}}} \left[\frac{\dot{m}}{\dot{m}_{\text{ref}}}\right]^{(2a-1)/2} = \left[\frac{T}{T_{\text{ref}}}\right]^{(2a-1)/2}, \quad 0.8 \leq a \leq 1.3$$

Turbojet Engine Sizing

- The previous equations are accurate if the scale factor T/T_{ref} falls in the approximate range

$$0.5 \leq T/T_{ref} \leq 1.5$$

- Outside this range, it is preferable to use completely empirical relations

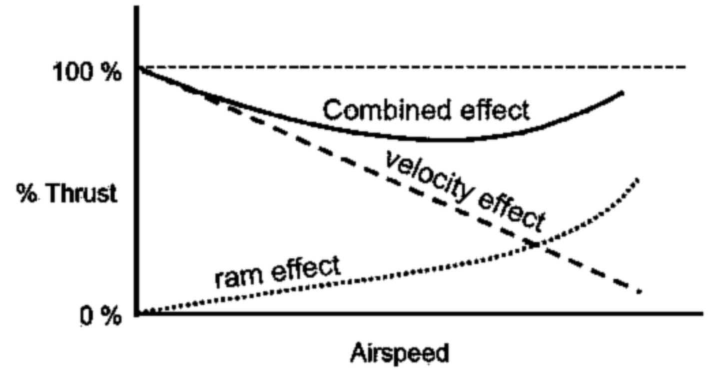
Non-after-burning, $M < 1$, $0 \leq \text{BPR} \leq 6$:
$W = 0.084T^{1.1}e^{(-0.045\text{BPR})}$
$L = 2.22T^{0.4}M^{0.2}$
$D = 0.393T^{0.5}e^{0.04\text{BPR}}$
After-burning, $1 \leq M \leq 2.5$, $0 \leq \text{BPR} \leq 1$:
$W = 0.063T^{1.1}M^{0.25}e^{-0.81\text{BPR}}$
$L = 3.06T^{0.4}M^{0.2}$
$D = 0.288T^{0.5}e^{0.04\text{BPR}}$

Empirical scaling relations for turbojet engines

$$T/T_{ref} < 0.5, \quad T/T_{ref} > 1.5$$

Altitude and Velocity Effects

- TSFC is the fuel mass used per hour divided by thrust
- Thrust decreases with altitude, mainly due to the decrease in air density
- Since the density decreases and less oxygen is available for combustion, the fuel mass must decrease also
- For subsonic turbojet engines, TSFC reaches a minimum at an altitude of around 36000 ft – **optimum altitude for most efficient cruise**
- The exhaust velocity is usually kept constant and nearly sonic, when the flight velocity increases, the difference between the two decreases, what would imply a decrease in thrust
- However, with the increase in the flight velocity, the air compression at the intake (ram effect) increases, increasing thrust



Altitude and Velocity Effects

- The thrust value provided by the engine manufactures corresponds to the uninstalled sea-level static thrust (SLST)
- If the engine is being sized based on the thrust required for cruise, the sea-level thrust needs to be corrected for altitude
- Assuming an ideal gas relation, the air density is given by

$$\rho = \frac{P}{R\theta}$$

where R is the gas constant for air, P is pressure and ϑ is temperature.

- The thrust at an altitude H is related to the thrust at sea-level as

$$T_H = T_{SL} \frac{P_H}{P_{SL}} \frac{\theta_{SL}}{\theta_H}$$

Installed Thrust Corrections

- Installed thrust is the thrust the engine produces when installed on the aircraft
  - Manufacturers supplied thrust is measured in a test cell
- Installed thrust tends to be lower than stated thrust due to many factors
  - Inlet pressure recovery
  - Inlet airflow distortion effects
  - Bleed air and power extraction
  - Exit nozzle performance
  - Exit nozzle drag
  - Trim drag
- The above can be hard to quantify at this stage but we can estimate the two most significant effects
  - Inlet pressure recovery
  - Bleed air and power extraction

Installed Thrust Corrections

- For $M < 1$ we can assume that the inlet pressure recovery is 1 (same as uninstalled value)
- Otherwise, using a reference pressure recovery ratio based on MIL-E-5008B and for an ideal isentropic compression inlet, the thrust loss is given by

$$\text{Loss}\,(\%) = C_{\text{ram}} \left[\left(\frac{P_i}{P_\infty} \right)_{\text{ref}} - \left(\frac{P_i}{P_\infty} \right)_{\text{act}} \right] \times 100$$

where

$$\left(\frac{P_i}{P_\infty} \right)_{\text{ref}} = 1 - 0.075\,(M_\infty - 1)^{1.35}$$

$$\left(\frac{P_i}{P_\infty} \right)_{\text{act}} = \begin{cases} 1.0, & M_\infty < 2.5 \\ -0.1M_\infty + 1.25, & M_\infty \geq 2.5 \end{cases}$$

$$C_{\text{ram}} = 1.35 - 0.15\,(M_\infty - 1)$$

Installed Thrust Corrections

- Air is usually bled from combustion chamber or inner turbine stage
  - Usually between 1% to 5% of the total engine mass flow
  - Circulate inside the cabin in commercial aircraft
  - Used in anti-icing boots in wing and inlets
- Since thrust is proportional to mass flow, the thrust loss is

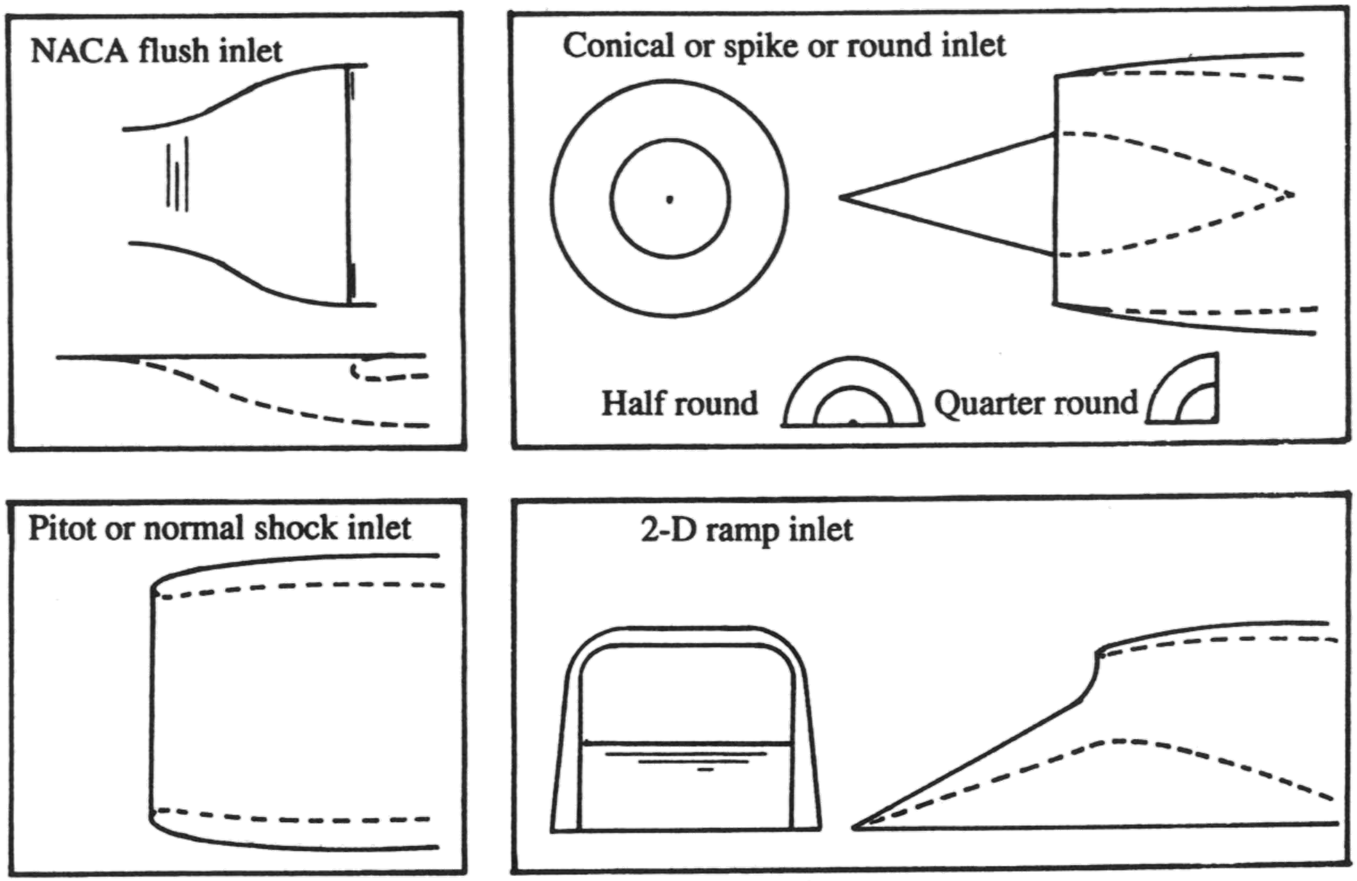
$$\text{Loss}\,(\%) = C_{\text{bleed}}\left[\frac{\dot{m}_{\text{bleed}}}{\dot{m}_{\text{engine}}}\right] \times 100 \qquad C_{\text{bleed}} \approx 2.0$$

Air Inlets

- ***Inlet tasks***
  - Allow for the engine required mass flow without separations
  - Allow for a Mach number reduction to about 0.4 to 0.5 while increasing the static pressure
- ***Subsonic air inlets***
  - NACA – allow for a pressure recover of about 90% and are used mainly as cooling air inlets and in APUs
  - Pitot – allow for a pressure recover of 100%
- ***Supersonic air inlets***

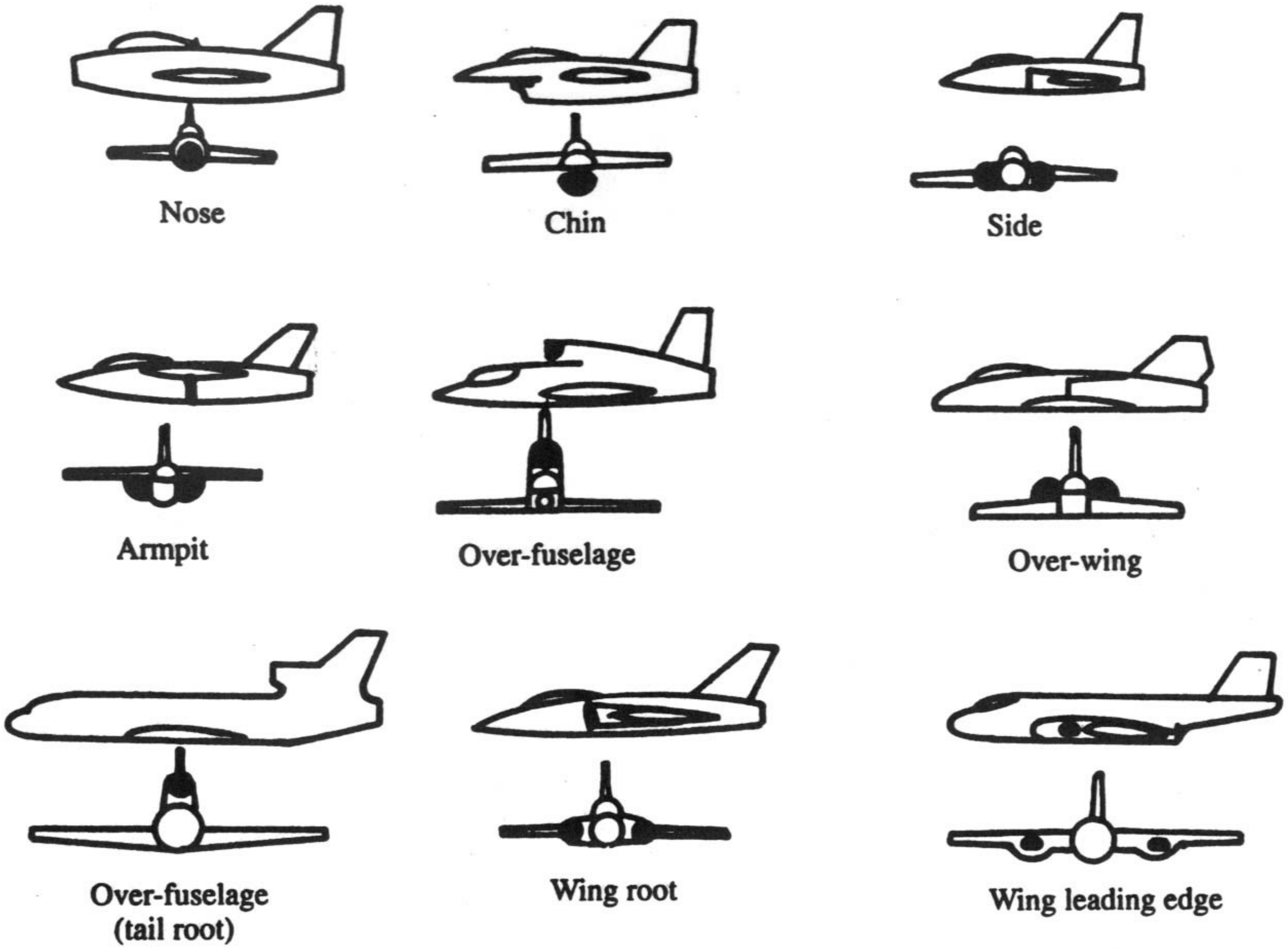
Air inlet type	Pressure recover	Weight	Drag contribution	Complexity	Mach
Cone	+	+	-	-	> 2
Ramp	-	-	+	+	< 2

Air Inlets

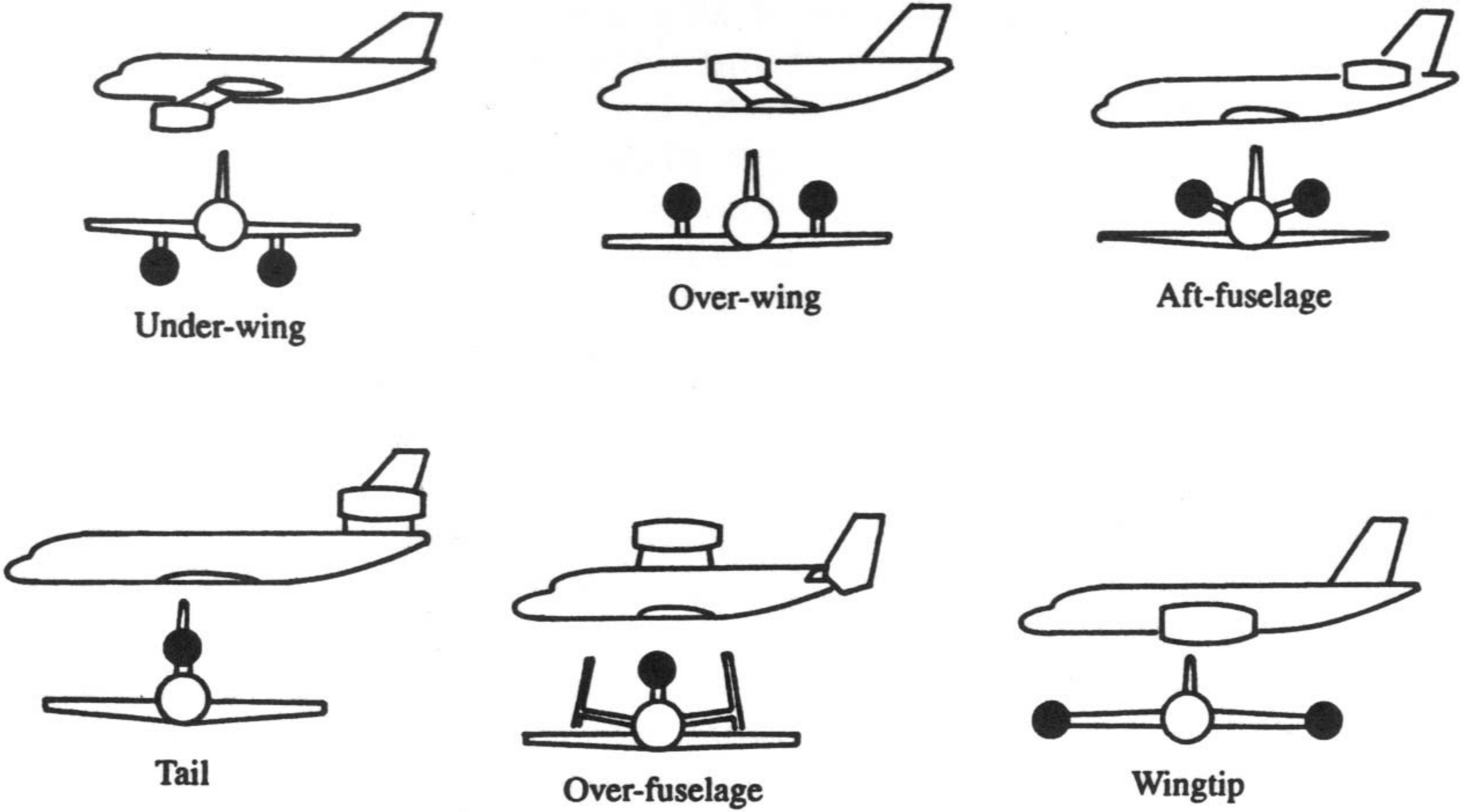

NACA flush inlet
Conical or spike or round inlet
Half round
Quarter round
Pitot or normal shock inlet
2-D ramp inlet

Inlet Position

- ***Integrated engines***

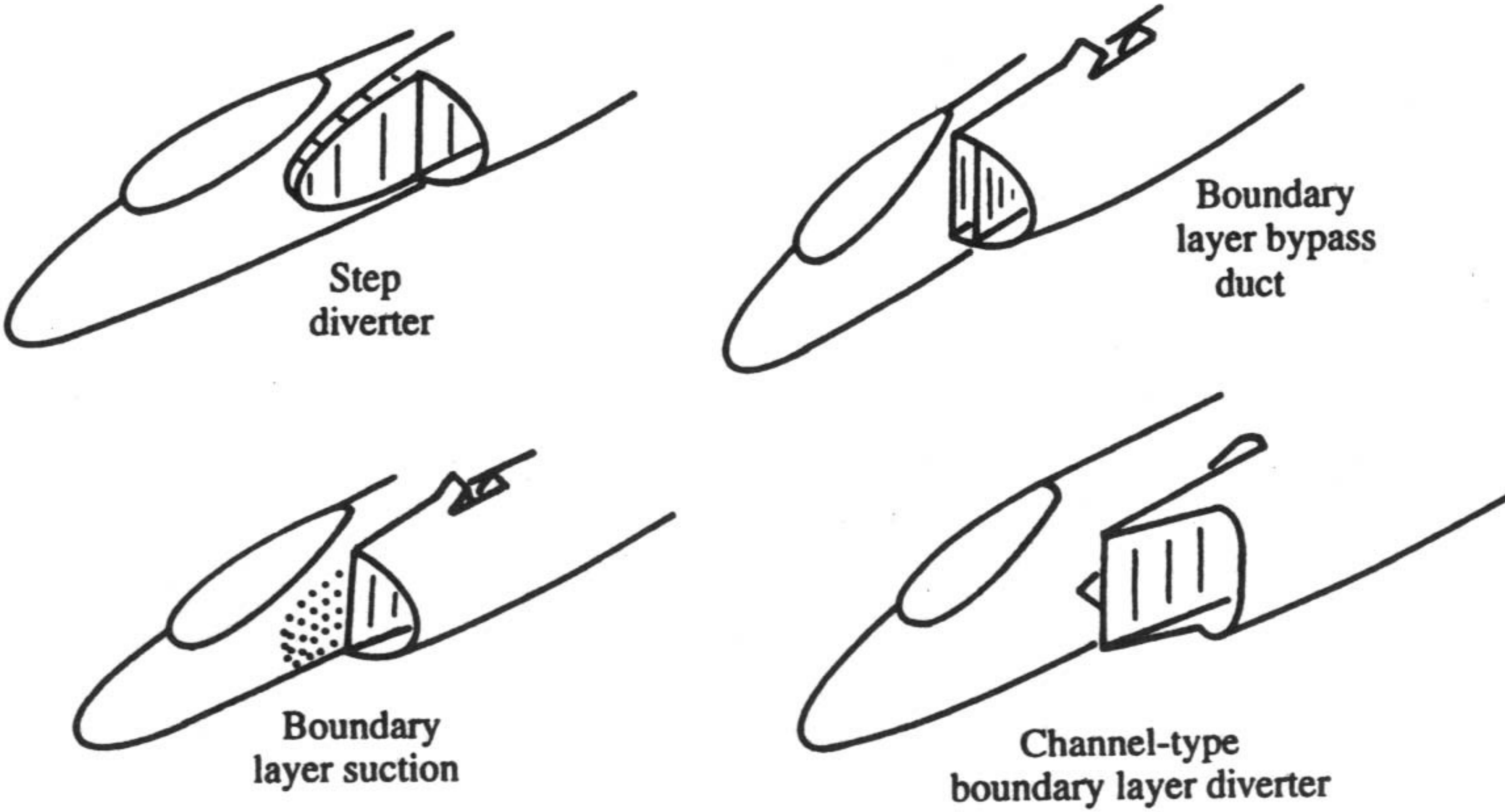


- ***Nacelle and pylon mounted engines***

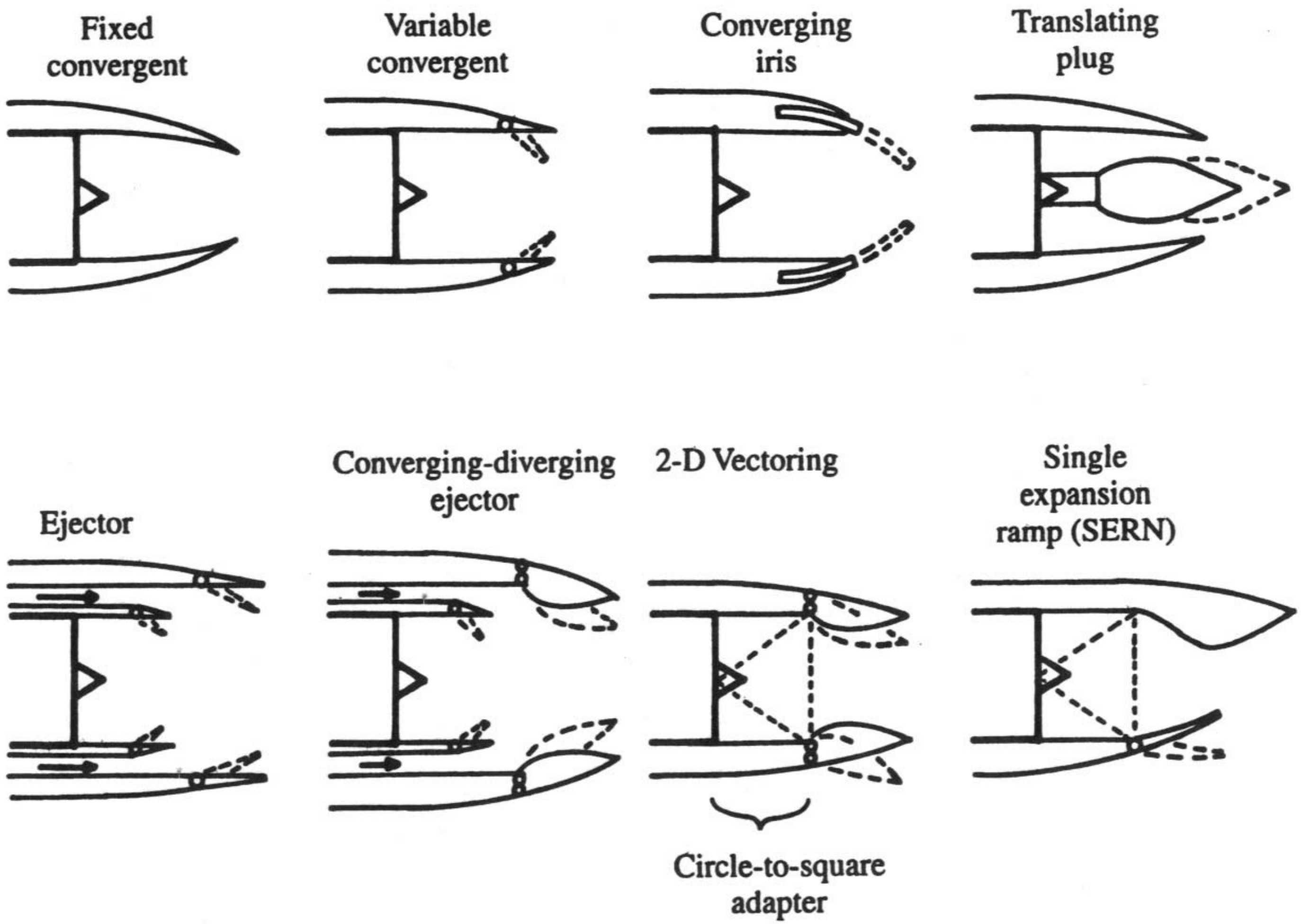


Inlet Splitters

- ***Boundary layer splitters***



Exhaust Types



- For a propeller-driven aircraft, the important design parameters that need to be determined are the propeller diameter and the engine shaft horsepower
- As with the wing, the propeller is designed for a particular flight condition (cruise, take-off, *etc.*)
- The thrust coefficient C_T and power coefficient C_P for a propeller are given by

$$C_T = \frac{T}{n^2 D^4} \qquad C_P = \frac{P}{\rho n^3 D^5}$$

- Where n is the propeller rotational velocity with units of rev/s, D is the propeller diameter and ρ is the air density

- The propulsive, or propeller, efficiency is defined as

$$\eta_P = \frac{\text{Thrust Power Output}}{\text{Shaft Power Input}} = \frac{T\,V}{P}$$

- The tip speed of the propeller is

$$V_{\text{tip}} = \left[(\pi\, n\, D)^2 + V^2\right]^{0.5}$$

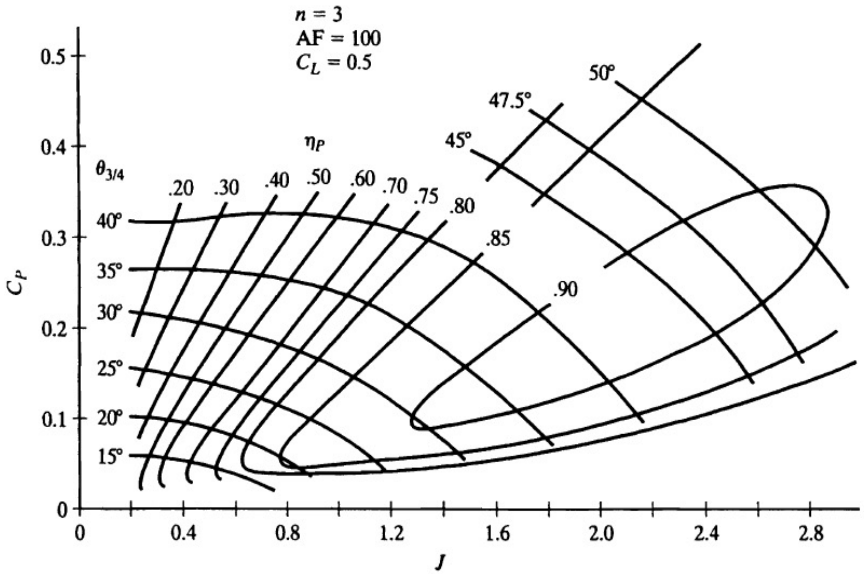
- M_{tip} should be lower than 0.85 to avoid local shocks
- The ratio of the true airspeed to the tip speed is defined as the advance ratio

$$J = \frac{V}{n\,D}$$

- Combining the previous equations, the propeller efficiency and thrust can then be expressed as

$$\eta_P = J\frac{C_T}{C_P} \qquad\qquad T = \frac{P}{n\,D}\frac{C_T}{C_P}$$

- ***Cruise conditions***
  - Use the graph with design (initial) C_P and J to determine θ, and efficiency. Then determine C_T and T



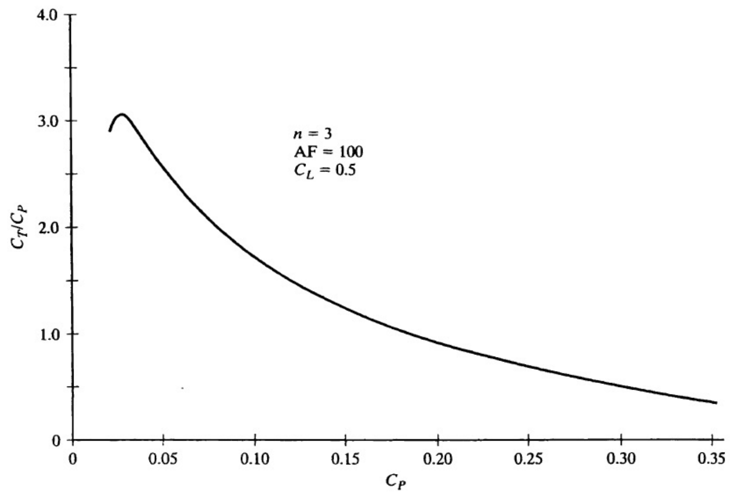
$$\eta_P = J\frac{C_T}{C_P}$$

$$T = \frac{P}{nD}\frac{C_T}{C_P}$$

- Using as reference a three bladed propeller, the performance of two or four bladed propellers may be estimated by
  - For wood propellers, higher thickness airfoils are required, hence the efficiency of the following table must be multiplied by 0.9

Performance	2 blades	3 blades	4 blades
Efficiency	$1{,}03\eta_P$	η_P	$0{,}97\eta_P$
Thrust	0,95T	T	1,05T

- ***Static conditions (take-off)***



$$C_P = \frac{P}{\rho\, n^3 D^5}$$

$$T = \frac{P}{n\,D}\frac{C_T}{C_P}$$

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Thrust	0,95T	T	1,05T

Propeller Performance

- ***Blocking correction***
  - An engine nacelle behind the propeller decelerates the airflow before it reaches the propeller, then

$$J_{\mathrm{cor}} = J\left(1 - 0.329\frac{S_C}{D^2}\right)$$

S_C, maximum frontal area of the nacelle or fuselage

D, propeller diameter

- ***Compressibility correction***
  - At high flight velocities, or high engine rpm, thrust is reduced due to compressibility effect

$$\eta_{P_{\mathrm{cor}}} = \eta_P - \left(M_{\mathrm{tip}} - 0.89\right)\frac{0.16}{0.48 - 3\,t/c}, \quad M_{\mathrm{tip}} > 0.89$$

t/c, propeller airfoil relative maximum thickness

- ***Friction correction***
  - The aircraft components in the propeller wake will be subjected to higher airflow velocities and turbulence, increasing their friction drag
  - For ***pusher propellers*** an efficiency loss of 2% to 5%, due to the fuselage, wing and/or tail wake on the propeller, may be observed
  - For ***tractor propellers***, an effective efficiency may be used in calculations

$$\eta_{P_{\text{eff}}} = \eta_P \left[1 - \frac{1.558}{D^2 \left(\frac{\rho}{\rho_0}\right) \sum (C_F S_{\text{wet}})_{\text{wake}}} \right]$$

C_F, friction coefficient

S_{wet}, wetted area of propeller wake

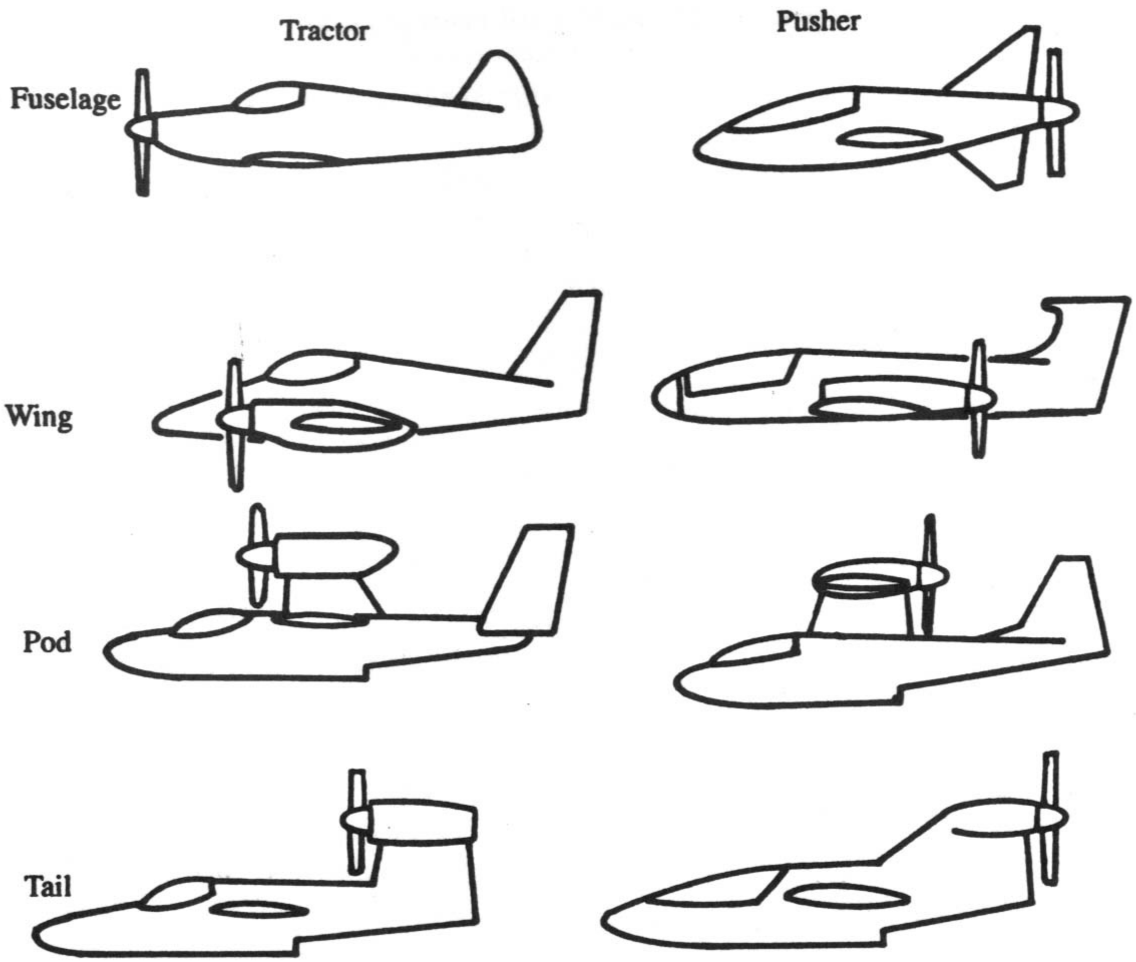
Propeller Types

- ***Tractor propeller***
  - Engine in front: better stability, allowing for smaller tail
  - Less chance of prop strike on rotation
  - The propeller is not inside the fuselage wake
  - Can blow air over wing increasing lift at low speed
- ***Pusher propeller***
  - Fuselage is not in the propeller wake, reducing the fuselage friction drag
  - Fuselage wetted area may be reduced (larger fuselage angles allowed due to favorable pressure gradient)
  - Arguably less drag at cruise due to “clean” air over surfaces
  - Noise reduction in the cabin
    - Engine exhaust in the back of the aircraft
    - Propeller wake doesn’t affect the fuselage
  - Longer landing gear to maintain the propeller clearance to the ground in rotation phase of take-off
  - The propeller is prone to be damaged by objects on the runway, coming from the landing gear
  - Engine cooling less efficient

Propeller Position

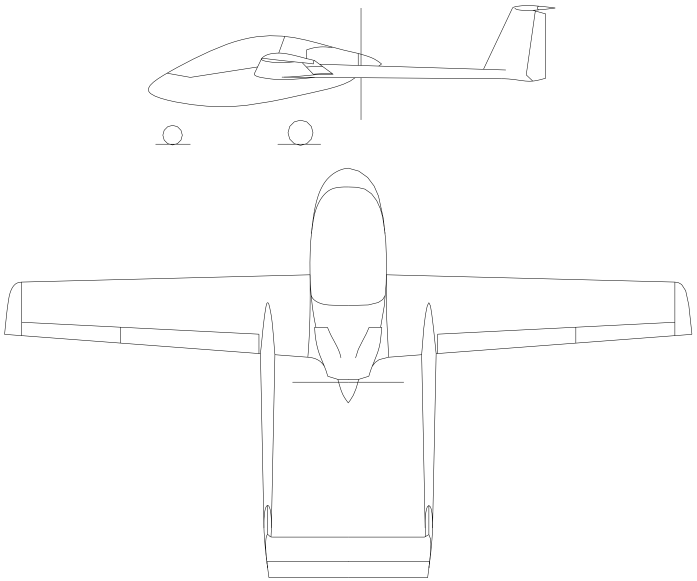
- ***Propellers on main wing***
  - Decreases the friction drag on the fuselage, since the fuselage is not affected by the propeller wake
  - Generally, engines on the wing allow for a decrease in the wing structural weight – since engine weight and bending moment oppose the wing lift and respective bending moment
  - In the event of a blade fracture, this might hit the fuselage
  - Higher vibration levels on the wing – related to the pressure difference between the upper and lower wing surfaces
- ***Suspended propellers***
  - Used in hydroplanes
  - The thrust line is usually high above the CG, possibly causing stability and control problems (pitching moment variation) when thrust is changed. This usually forces a correction with higher horizontal stabilizer area

Propeller Position



- Aircraft design known characteristics

Total length	5,86 m
Total height	1,98 m
Span	9,99 m
Wing area	9,76 m^2
Engine Power	80 hp = 59,7 kW
Regime	5500 rpm = 91,67 rot/s
Max Speed	216 km/h = 60,0 m/s
Propeller Diameter	1,60 m
Number of blades	3
Pitch	fixed
Air density	1,225 kg/m^3
Air temperature	288,25 K
Speed of Sound	340,29 m/s



Example

- Assure that the Mach number on the propeller tip is less than 1

For $M_{tip} = 0.8$

$n = 91.67/2.27 = 40.38$ rpm

$D = [(M_{tip}a)^2 - V^2]^{0.5}/(pn);$

$D = [(0.8 \text{ x } 340.29)^2 - 60.0^2]^{0.5}/(40.38 \text{ p}) = 2.09$ m

$$M_{tip} = [V^2 + (p \ n \ D)^2]^{0.5}/a$$

$$M_{tip} = [60.0^2 + (40.38 \text{ x } 1.6p)^2]^{0.5}/340.29 = 0.62$$

Example

- Calculate the propeller pitch

$J = V/(nD) = 60.0/(40.38 \times 1.6) = 0.929;$
$C_P = P/(rn^3D^5) = 59700/(1.225 \times 40.38^2 \times 1.6^5) = 0.071$

From graph:

theta = 22.5º

$n_P = 0.875$

- Assuming a pusher propeller, no correction is needed for J to obtain J_{cor}
- Assuming a pusher propeller, no correction is needed for η_P to obtain $\eta_{P\text{eff}}$. However, it is necessary to apply the factor of 0.95 to 0.98, due to the influence of the fuselage wake on the propeller (efficiency)

Example

- Propeller design assumptions

$$\eta_{P\text{design}} = 0.95 \times 0.875 = 0.831$$
$$J_{\text{design}} = 0.929$$

- Calculate the thrust dependence on velocity

V [m/s]	J	J/J_{design}	$\eta_P/\eta_{Pdesign}$	η_P	T [N]	
5	0,077	0,083	0,092	0,076	913	
25	0,387	0,417	0,500	0,416	992	
40	0,619	0,667	0,777	0,646	964	
50	0,774	0,833	0,930	0,773	923	
60	0,929	1,000	1,000	0,831	827	Design
70	1,083	1,167	0,896	0,745	635	