

Introduction to airbreathing propulsion systems

APRI0004:

Integrated project aerospace design



Koen Hillewaert

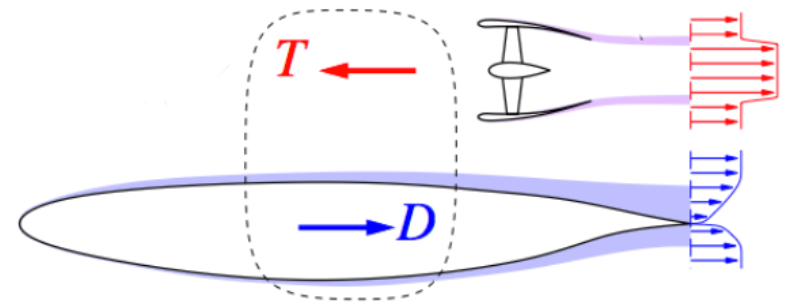
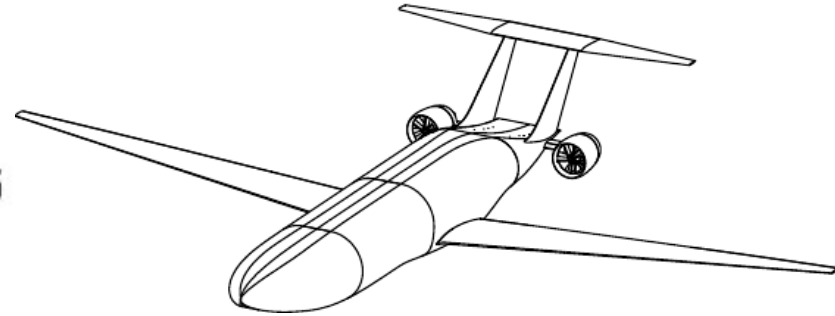
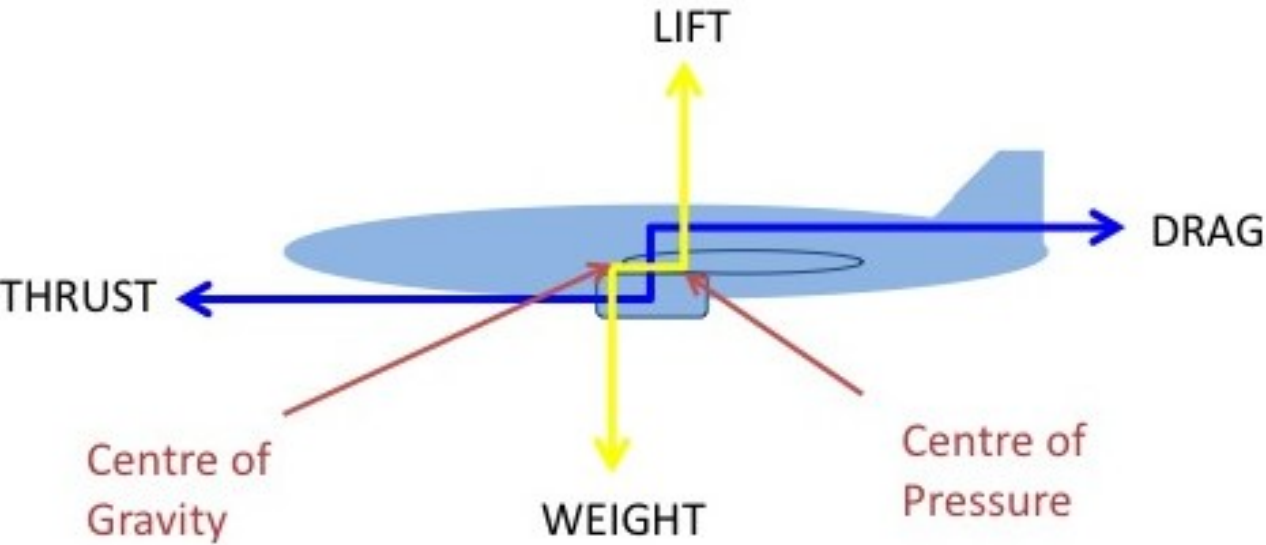
Design of Turbomachines & Propulsors
Aerospace & Mechanics Department
koen.hillewaert@uliege.be

Remy Princivale

BeCover
remy.princivale@becover.eu

1. Balances, thrust and performance

Drag / thrust definition



1. Balances, thrust and performance

Airbreathing engines: acceleration of (clean) air mass flow

- **Thrust = acceleration force of engine mass flow from flight v_f to jet velocity v_j**

$$\mathcal{T} = \dot{m}_a(v_j - v_f)$$

- **Powers**

- Propulsive power $\rightarrow$ airplane acceleration : $\mathcal{P}_p = \mathcal{T}u_f = \dot{m}_a(u_j - u_f)u_f = \dot{m}_a \Delta u u_f$
- Mechanical power $\rightarrow$ fluid acceleration : $\mathcal{P}_m = \dot{m}_a \Delta \mathcal{E}_k = \dot{m}_a \frac{u_j^2 - u_f^2}{2}$
- Lost power $\mathcal{P}_l = \mathcal{P}_m - \mathcal{P}_p = \dot{m}_a \frac{\Delta u^2}{2}$

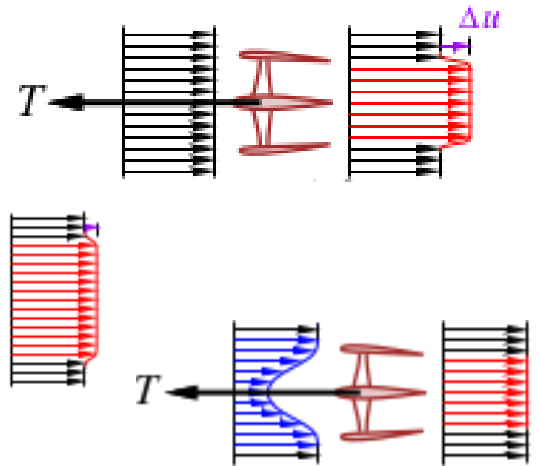
- **Propulsive efficiency:**

$$\eta_p = \frac{\mathcal{P}_p}{\mathcal{P}_m} = \frac{2u_f}{u_f + u_j}$$

- **Increasing propulsive efficiency for constant thrust:**

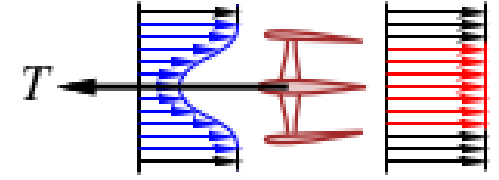
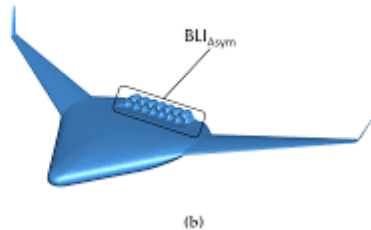
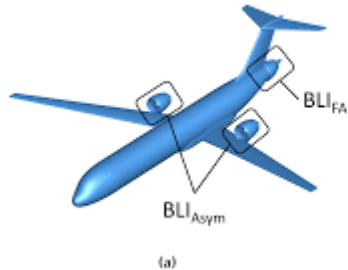
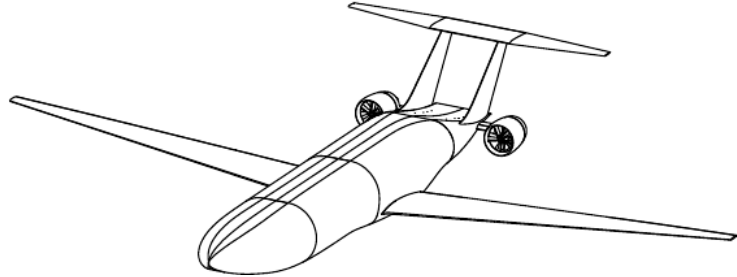
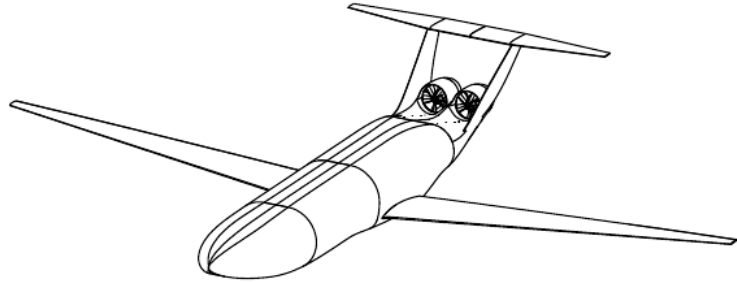
- increase mass flow, decrease jet velocity
- Ingest flow at speed lower than flight speed

$$\mathcal{T} = \dot{m}_a(v_f - v_i)$$



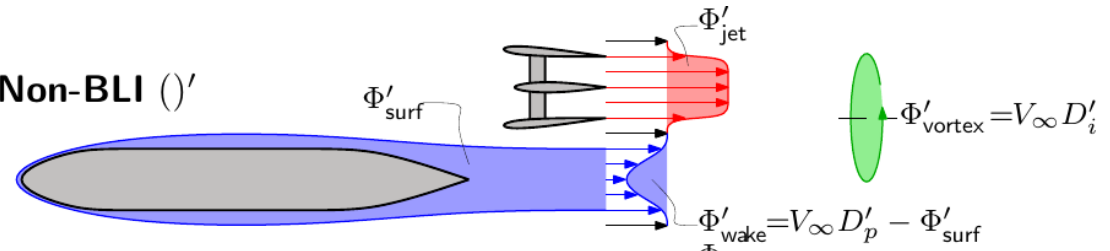
1. Balances, thrust and performance

Airbreathing engines: Boundary Layer Ingestion

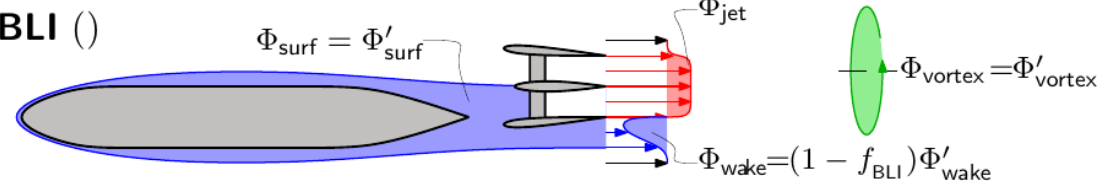


$$\mathcal{T} = \dot{m}_a (v_j - v_i)$$

Non-BLI ()'



BLI ()



1. Balances, thrust and performance

Airbreathing engines: classical performance parameters

- **Thermal energy $Q = \dot{m}_f \Delta h_f$**

- Fuel mass flow rate: $\dot{m}_f$
- Fuel to air ratio: $far = \dot{m}_f / \dot{m}_a$
- Fuel lower heating value: $\Delta h_f \approx 43 \text{ MJ/kg}$

- **Overall efficiency : propulsive power P_p versus thermal energy Q**

- Propulsive efficiency:

$$\eta_p = \frac{P_p}{P_m} = \frac{2v_f}{v_f + v_j}$$

- Thermal efficiency:

$$\eta_t = \frac{P_m}{Q} = \frac{P_m}{\dot{m}_f \Delta h_f}$$

$$\eta = \frac{P_p}{Q} = \eta_p \eta_t$$

- **Efficiency $\rightarrow$ Thrust specific fuel consumption (TSFC)**

$$TSFC = \frac{\dot{m}_f}{T}$$

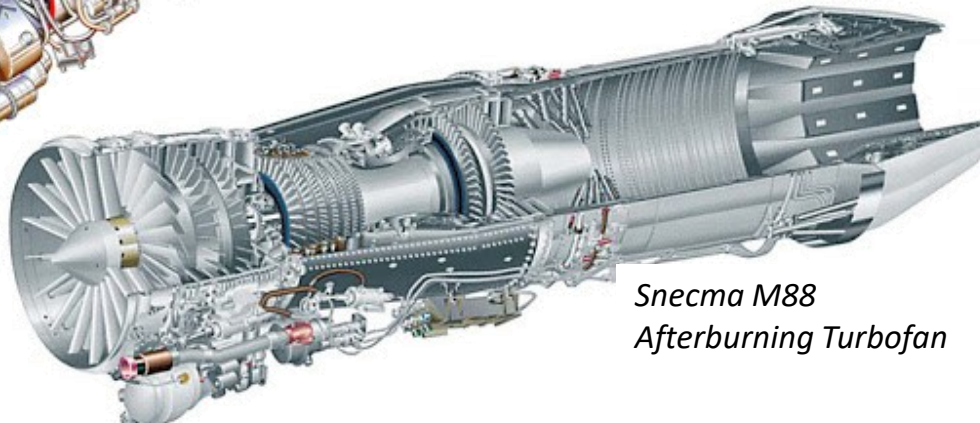
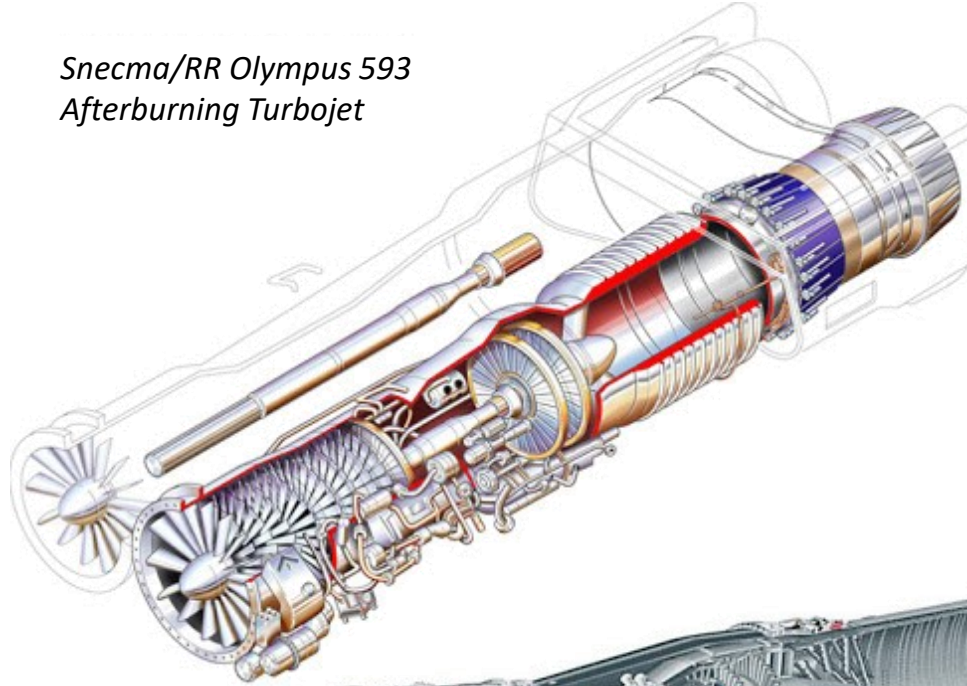
- **Compacity $\rightarrow$ Specific thrust**

$$\mathcal{T}_s = \frac{T}{\dot{m}_a}$$

2. Jet engines

Generation of “high” speed jet through expansion over nozzle

*Snecma/RR Olympus 593
Afterburning Turbojet*



*Snecma M88
Afterburning Turbofan*



*CFM Leap
Civil Turbofan*

2. Jet engines

Generation of “high” speed jet through expansion over nozzle

- **Ingestion of m_a air at flight speed in nacelle**

- Ram effect: increased total T and p due to relative Mach number M_f

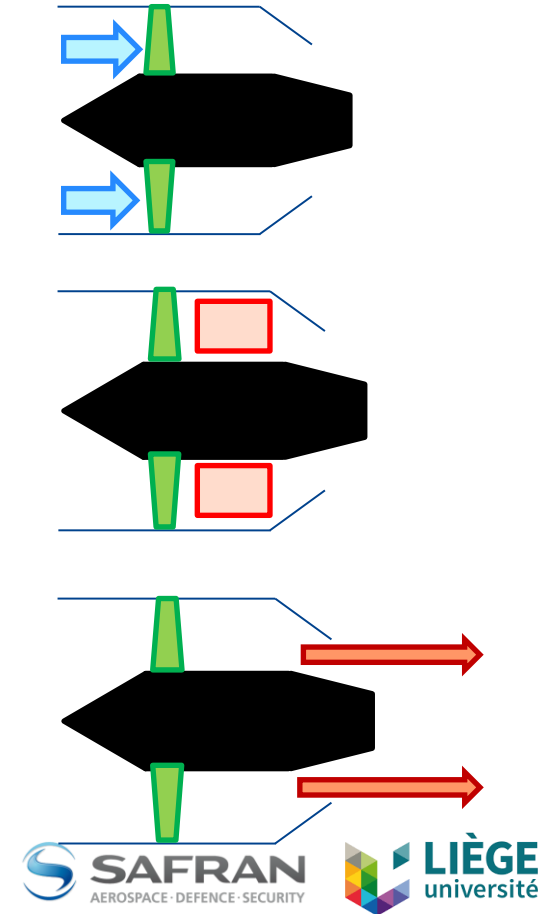
$$T^\circ = T_a \left(1 + \frac{\gamma - 1}{2} M_f^2 \right) \quad p^\circ = p_a \left(\frac{T^\circ}{T_a} \right)^{\frac{\gamma}{\gamma - 1}}$$

- **Increase total pressure and temperature**

- Mechanical : fan
- Thermal : gas generator / Brayton
- Afterburning

- **Expansion over exhaust nozzle to ambient pressure**

- Choked
- Adapted

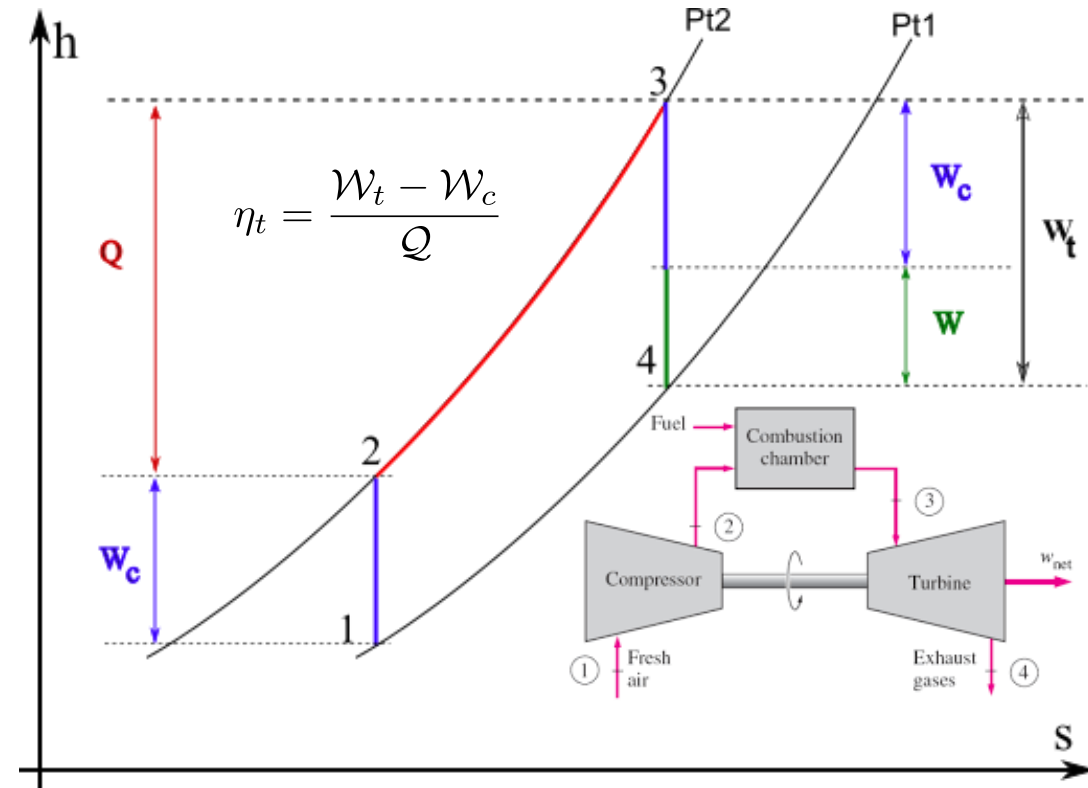
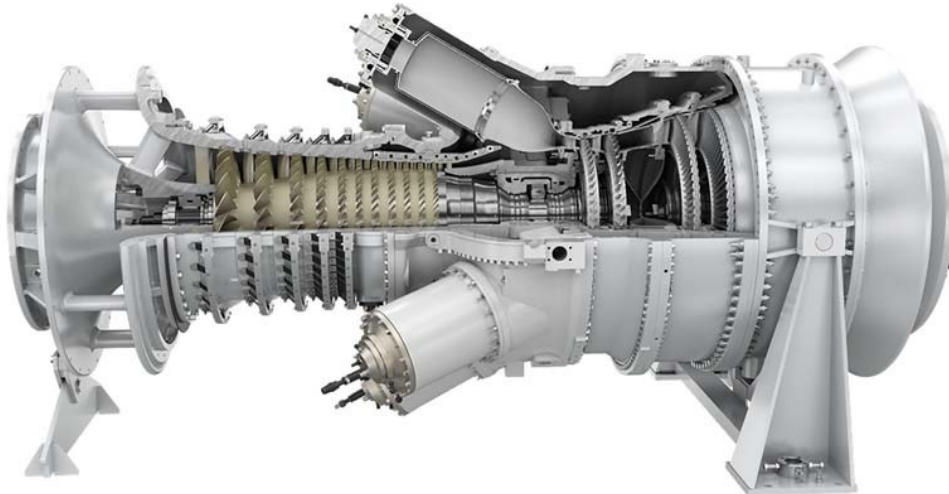


2. Jet engines

Core flow: Brayton thermodynamic cycle

- **Thermodynamic cycle**

- Adiabatic compression 1 → 2 : $W_c = \dot{m}\Delta H_{12}$
- Combustion 2 → 3 : $Q = \dot{m}\Delta H_{23}$
- Adiabatic expansion 3 → 4 : $W_t = \dot{m}\Delta H_{43}$



2. Jet engines

Core flow : efficiency of the non-ideal Brayton cycle

- Parameters affecting efficiency

- Overall pressure ratio (OPR) : $\Pi = \frac{P_2^\circ}{P_1^\circ}$

- Turbine Inlet Temperature (TIT)/ T_3°

Turbine Entry Temperature (TET)

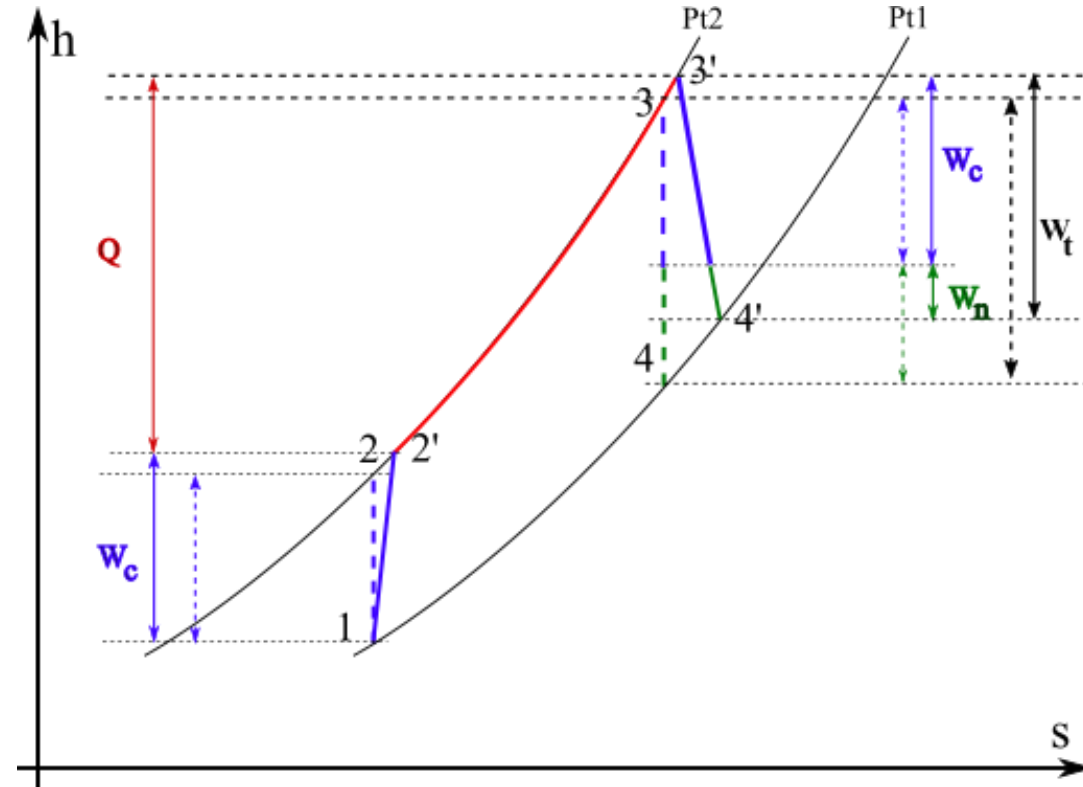
or Overall Temperature ratio: $\tau = \frac{T_3^\circ}{T_1^\circ}$

- Compressor efficiency

$$\eta_c = \frac{h_2^\circ - h_1^\circ}{h_{2'}^\circ - h_1^\circ}$$

- Turbine efficiency

$$\eta_t = \frac{h_3^\circ - h_{4'}^\circ}{h_3^\circ - h_4^\circ}$$



2. Jet engines

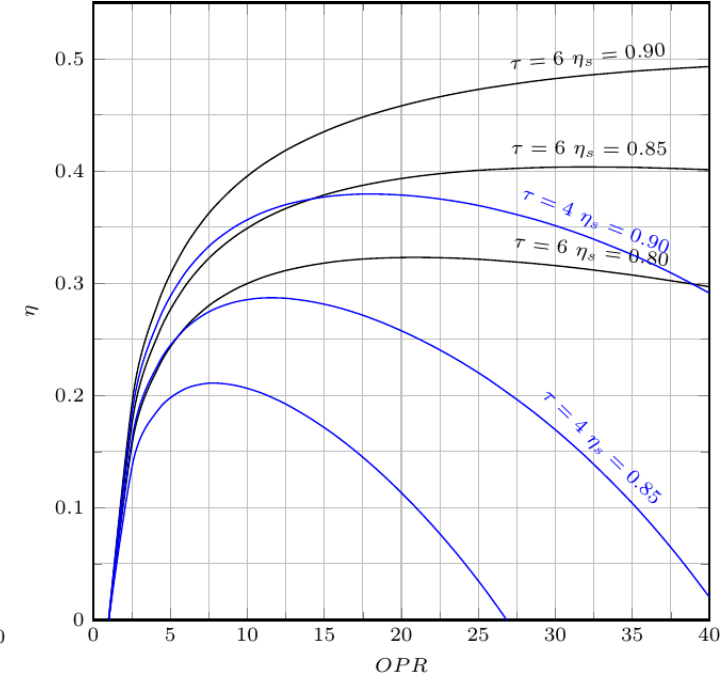
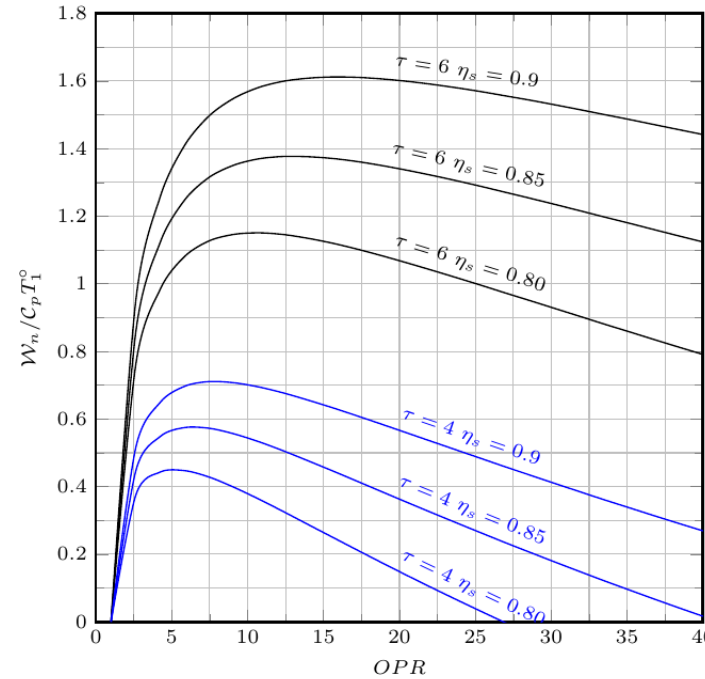
Core flow : efficiency of the non-ideal Brayton cycle

- **TiT**

- Determines specific work
- Limited by material resistance
- $\sim 1850 \text{ K} \gg 1400 \text{ K}$ (fusion)
- Requires film cooling

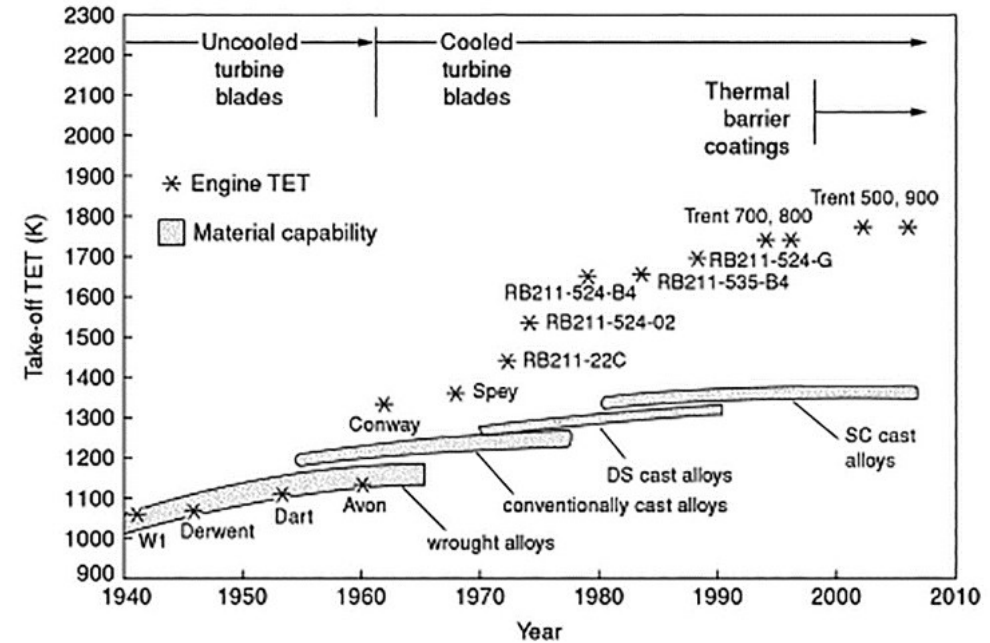
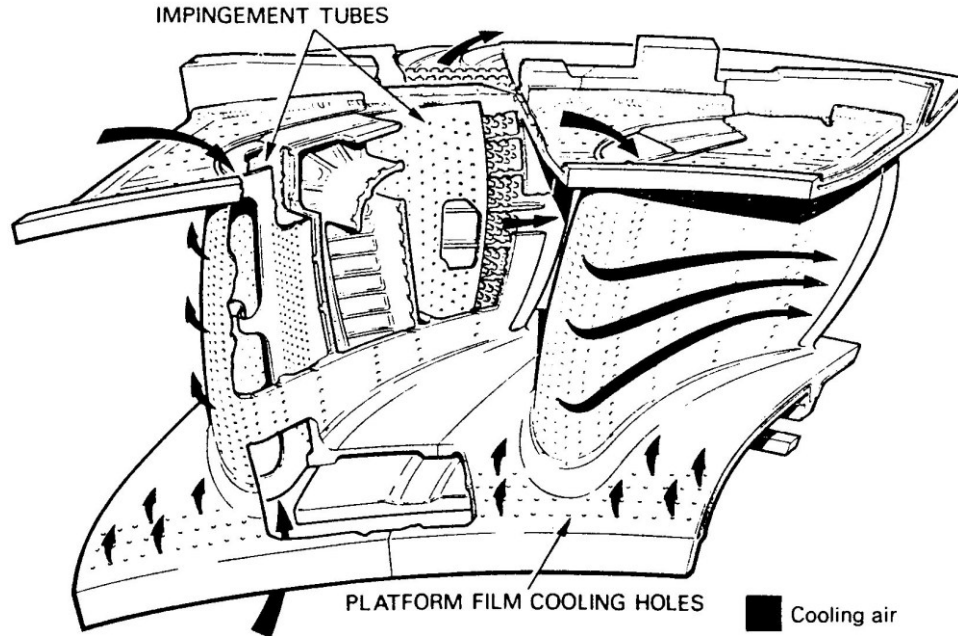
- **OPR**

- Determines efficiency
- Optimum $\sim$ TiT & efficiencies
- 30 ... 40



2. Jet engines

Core flow : Increasing TiT / TeT



2. Jet engines

Nozzle

- **Jet engine nozzle ~ de Laval nozzle**

- Nozzle pressure ratio $NPR = \frac{p^\circ}{p_a}$
- Critical pressure ratio ~ choking $NPR^* = \frac{p^\circ}{p^*} \approx 1.78$
- Choking mass flow rate $\dot{m}^* \approx 0.68 \frac{p^\circ A}{\sqrt{RT^\circ}}$

- **Thrust for imperfect expansion**

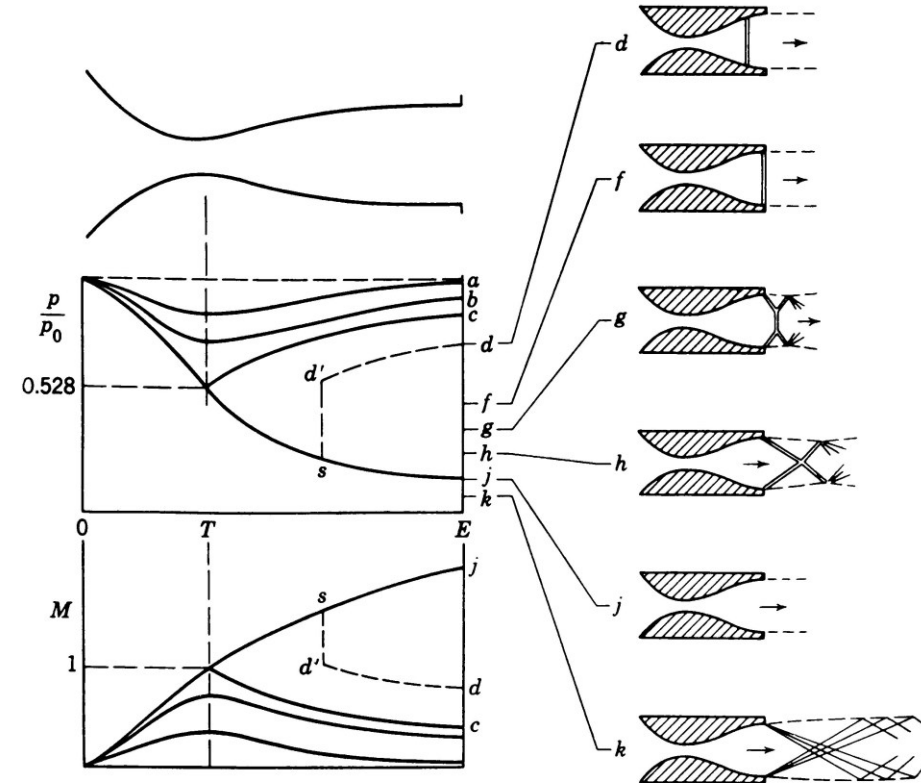
$$T = \dot{m}(v_j - v_f) + (p_j - p_a)A$$

- **Maximal thrust if *adapted* ($p_j = p_a$)**

$$T = \dot{m}(v_j - v_f)$$

- **Engine operating point = match GG and nozzle**

- GG determines p° and T° upstream of nozzle
- Nozzle limits maximum mass flow rate
- Thrust can be optimized by varying throat (and expansion ratio)
- Area needs to be variable to accommodate large variations in T°



2. Jet engines

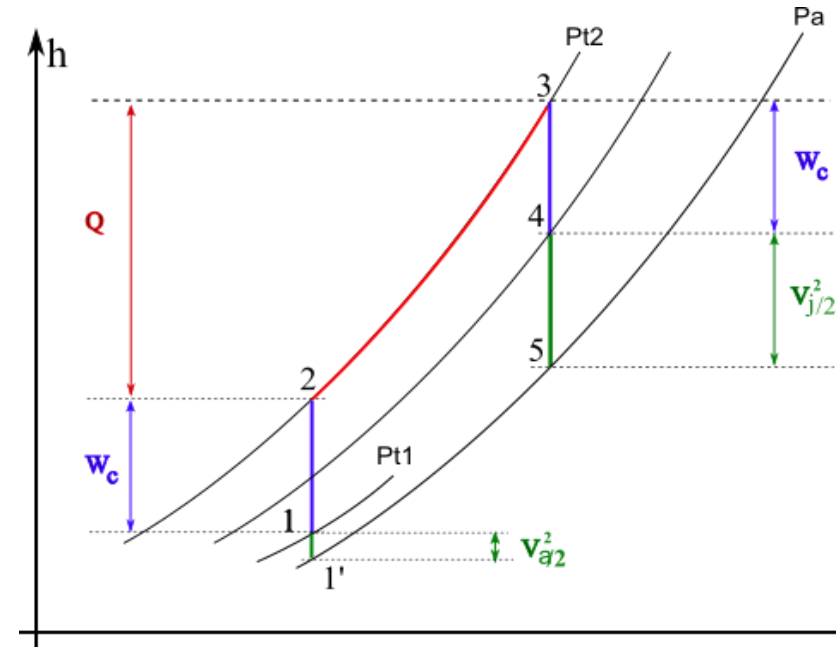
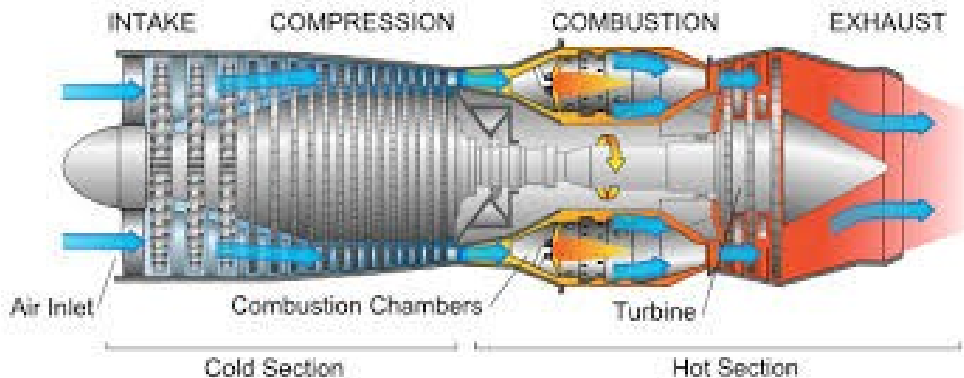
Turbojet : high subsonic through supersonic flow

- **Core flow**

- RAM effect : $1' - 1$
- Compressor : $1 - 2$
- Combustion : $2 - 3$
- Turbine expansion : $3 - 4$
- Exhaust nozzle jet : $4 - 5$



- **High specific thrust**

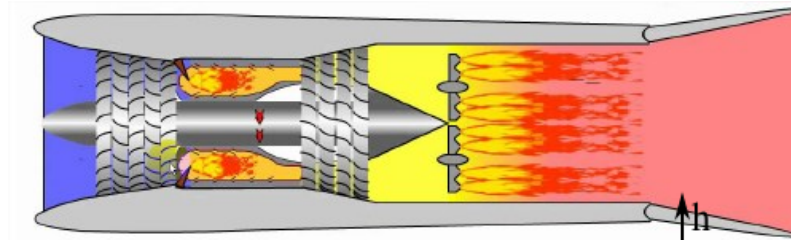


2. Jet engines

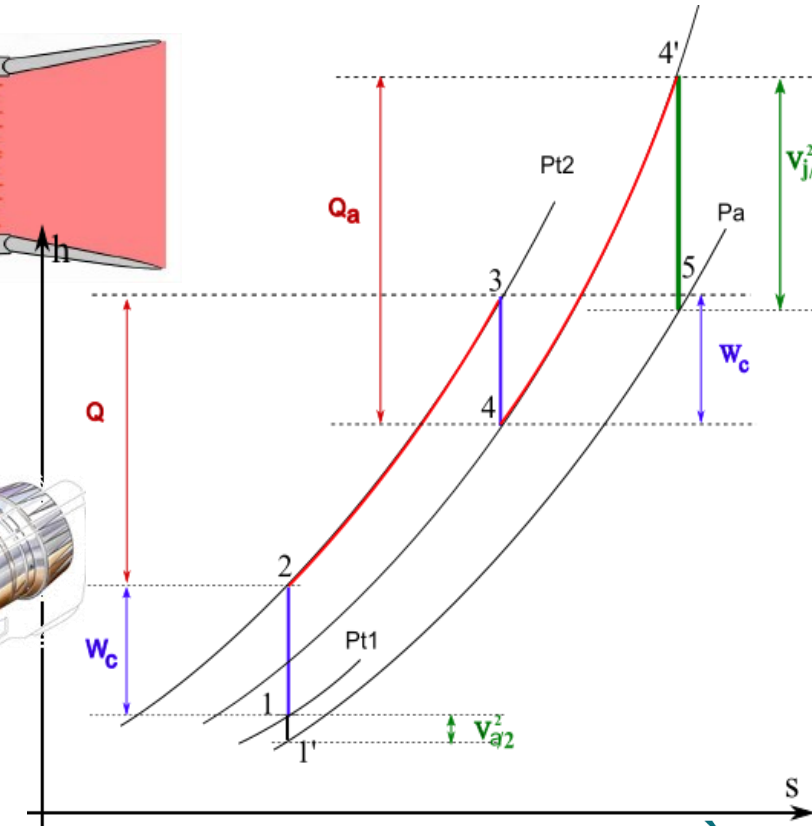
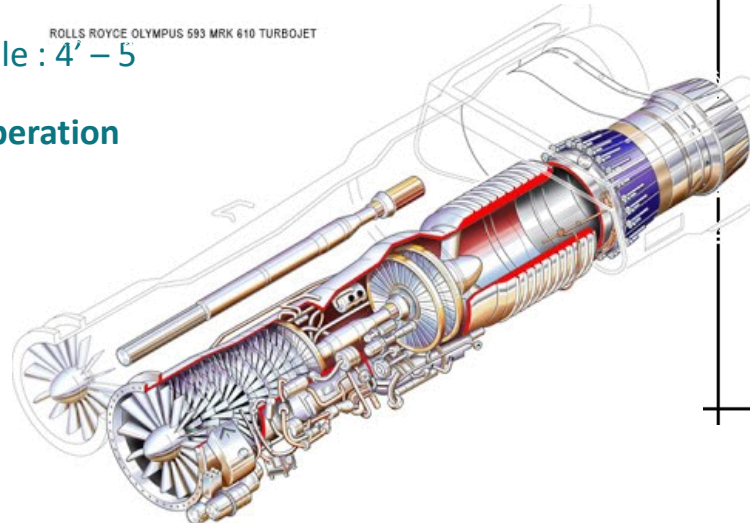
2.5 Afterburning turbojet: dry and wet operation

- Core flow

- Ram effect : $1' - 1$
- Compressor : $1 - 2$
- Combustion : $2 - 3$
- Expansion in turbine : $3 - 4$
- Wet / afterburning : $4 - 4'$
- Exhaust by adjustable nozzle : $4' - 5$



ROLLS ROYCE OLYMPUS 593 MRK 610 TURBOJET



- Nearly double thrust in “wet” operation

2. Jet engines

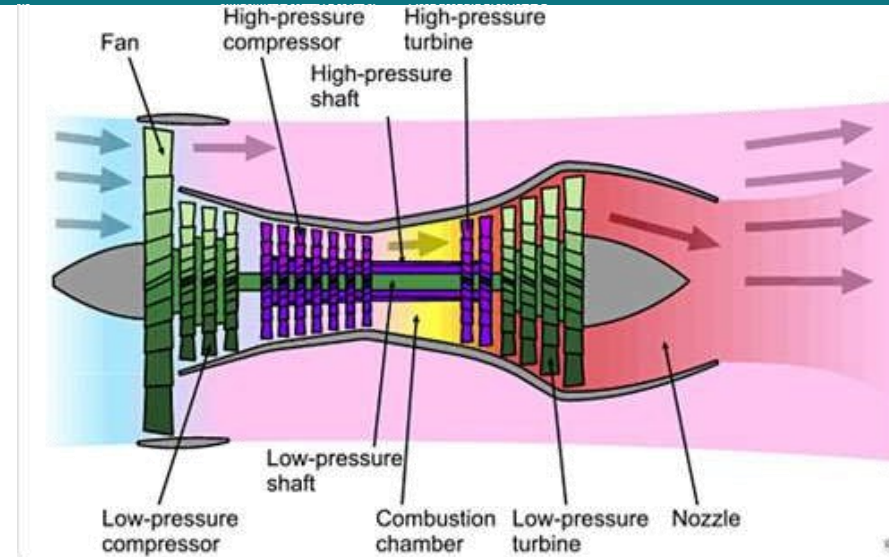
Civil turbofan : high subsonic/transonic

- **Core m_c and bypass m_b flow rate**

- Bypass ratio (BPR): $\alpha = m_b / (m_b + m_c)$

- **Core / primary : mech. power**

- Fan + compressor : 1 - 2
- Combustion : 2 - 3
- Turbine → fan & compressor 3 - 4
- Exhaust jet : 4 - 5



- **Bypass / secondary flow : thrust**

- Compression by fan 1 - 2'
- Exhaust nozzle 2' - 5

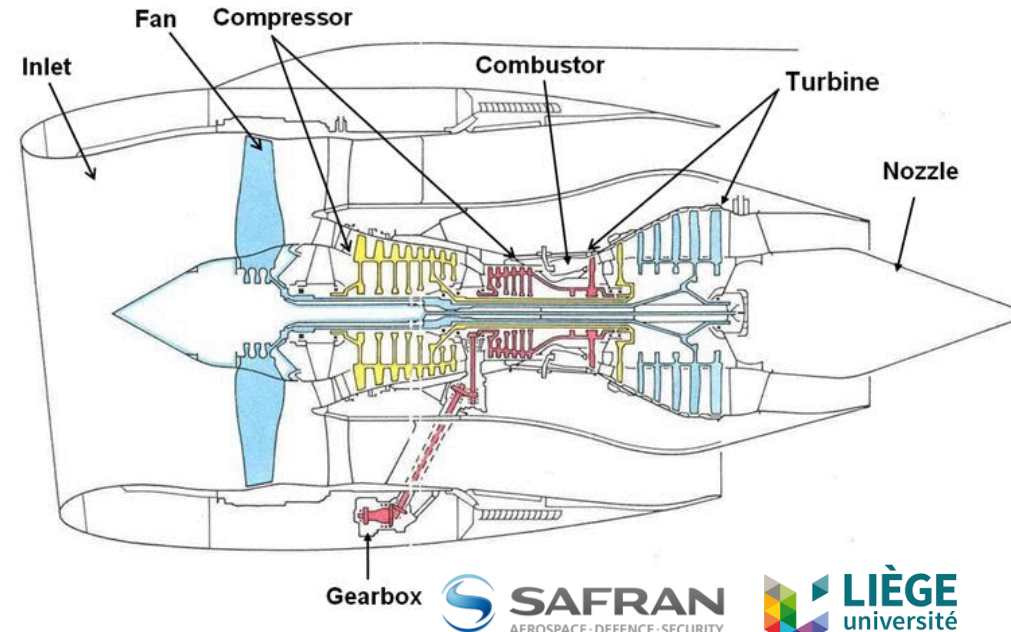
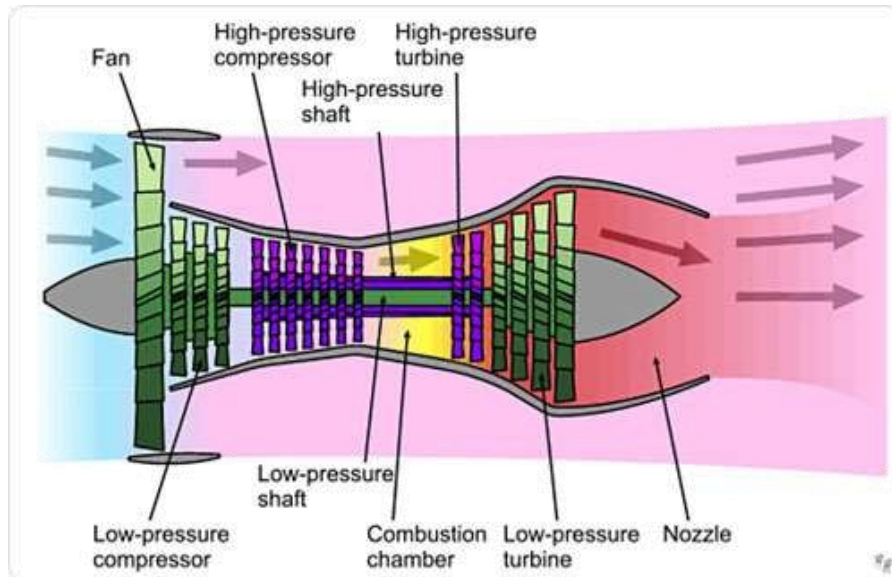


- **High propulsive efficiency: small acceleration, high flow rate**

2. Jet engines

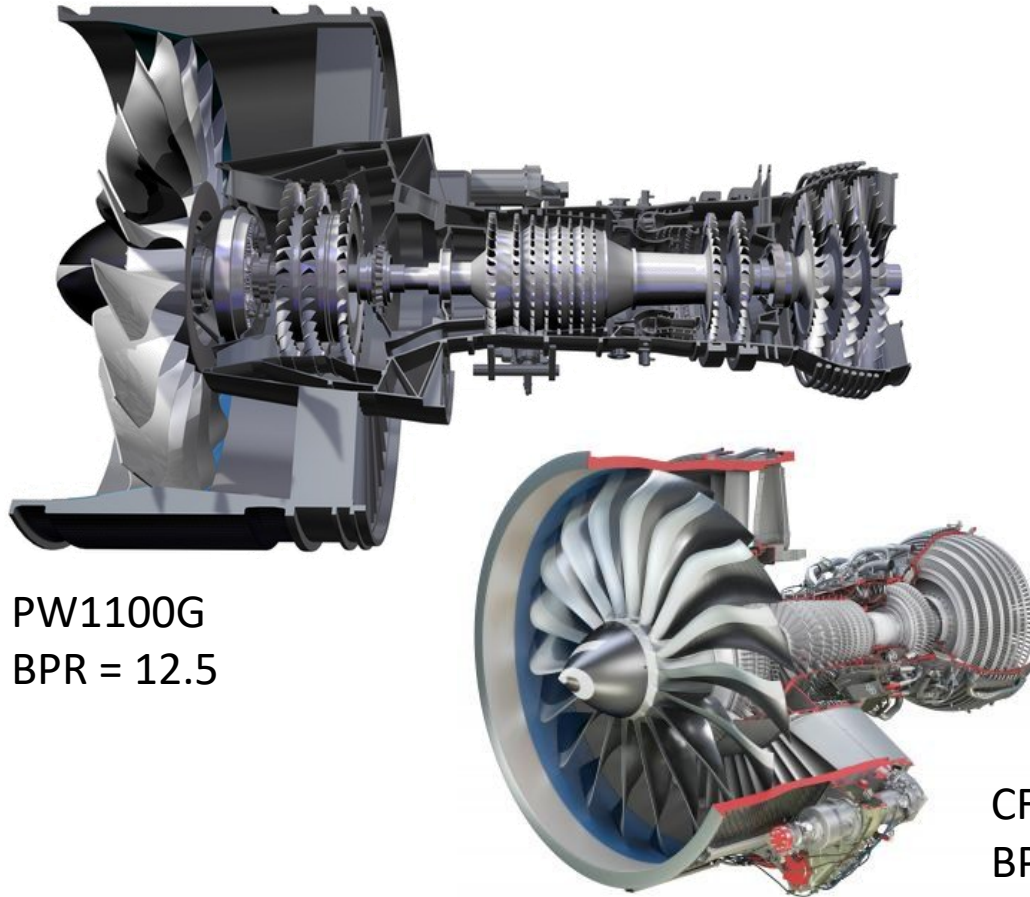
Civil turbofan: multispool turbofans

- Optimal rotation speed = slightly supersonic at the tip
- Different spools / shafts → optimise rotation speed
- LP spool drives fan → large LP turbine



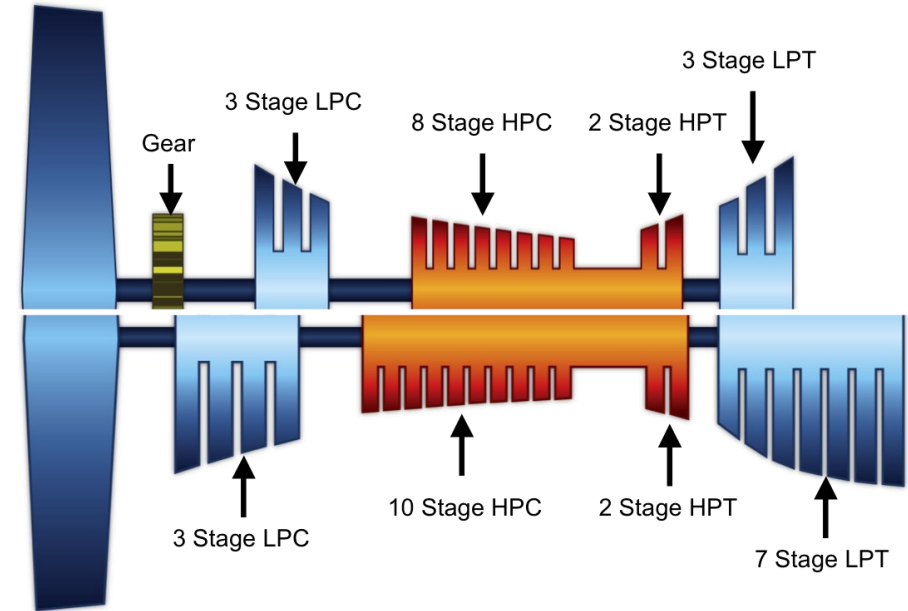
2. Jet engines

Civil turbofan : geared turbofan (GTF)

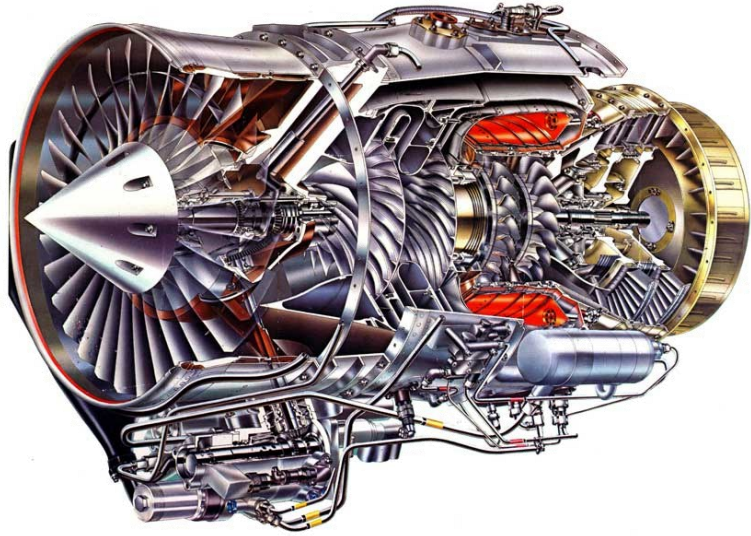


PW1100G
BPR = 12.5

PW1100G



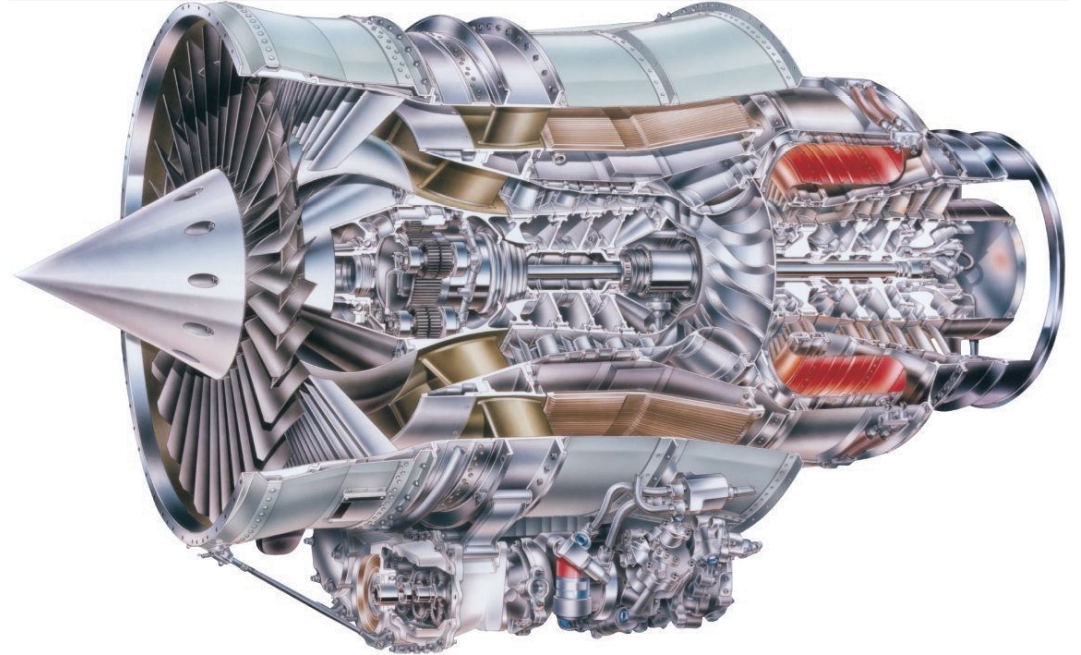
CFM Leap
BPR = 9 .. 11



Garret F109

$T \sim 6\text{kN}$

$\text{BPR} \sim 5$



Garret/Honeywell TFE731

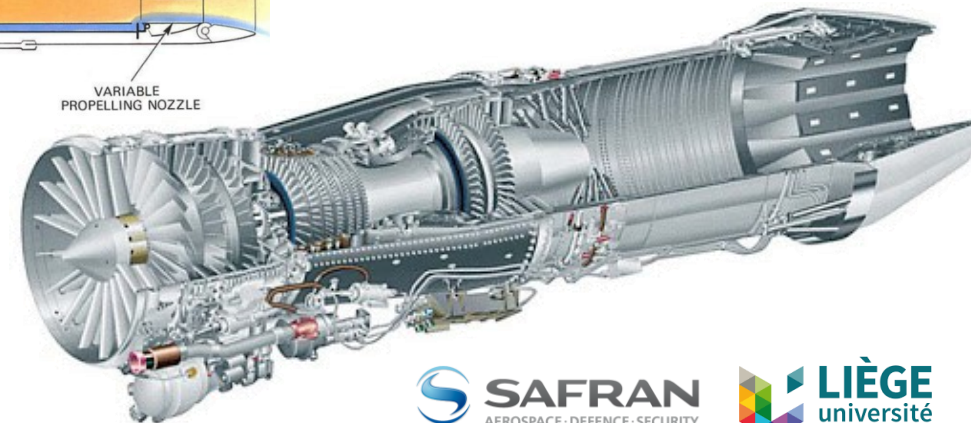
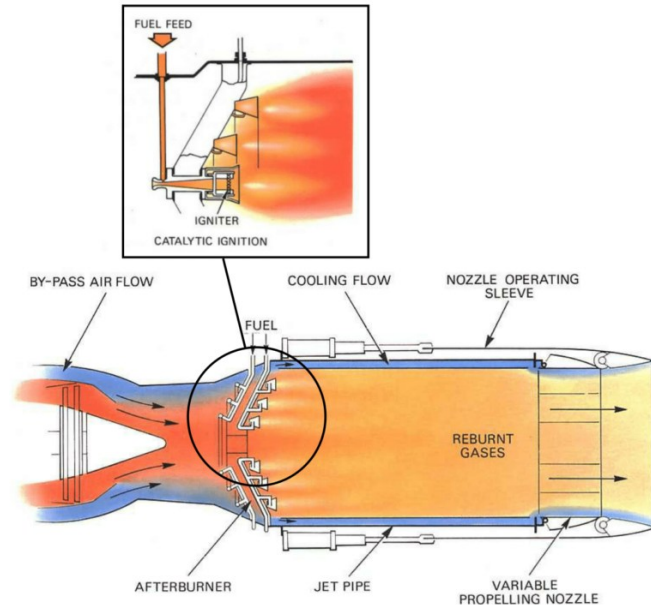
$T \sim 1.5 - 2.5\text{kN}$

$\text{BPR} \sim 2.8$

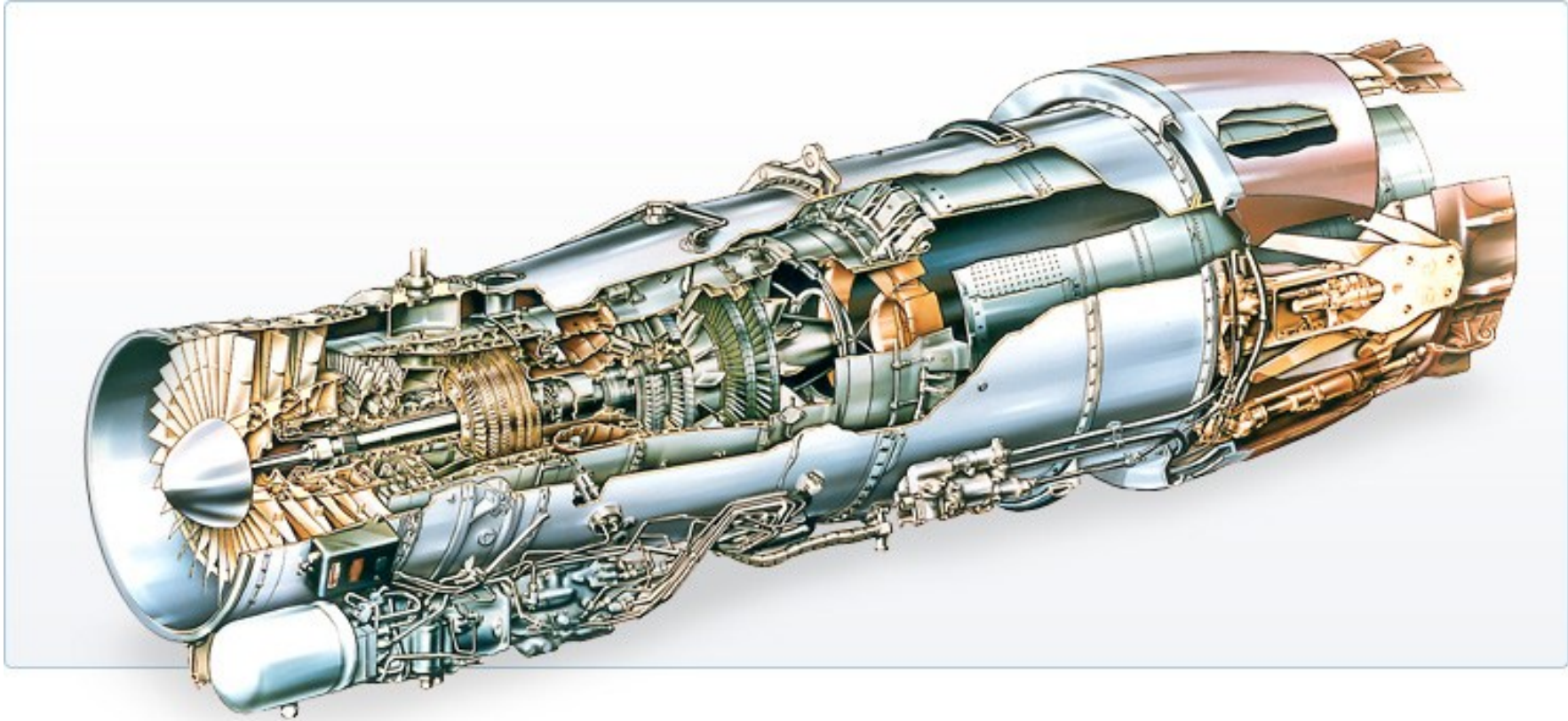
2. Jet engines

Afterburning turbofan: subsonic to supersonic flight

- **Ram effect : 1' - 1**
- **Core / primary flow**
 - LP + HP Compressor : 1 – 2
 - Combustion : 2 – 3
 - Expansion in turbine : 3 – 4
- **Bypass / secondary flow (below 1) :**
 - LP compression
 - Cooling of core
- **Mixer/Afterburner**
 - Mantle cooled by perspiration secondary flow
 - Mixing of primary and secondary flow
 - (Afterburning)
- **Exhaust by adjustable nozzle : 4' – 5**



Military turbofan w/ afterburning (J58)

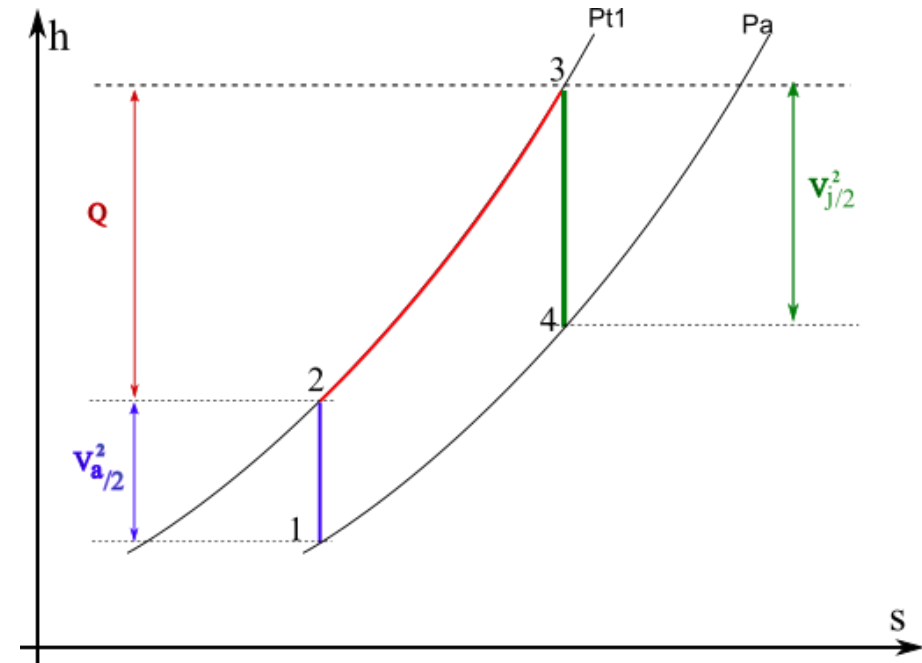
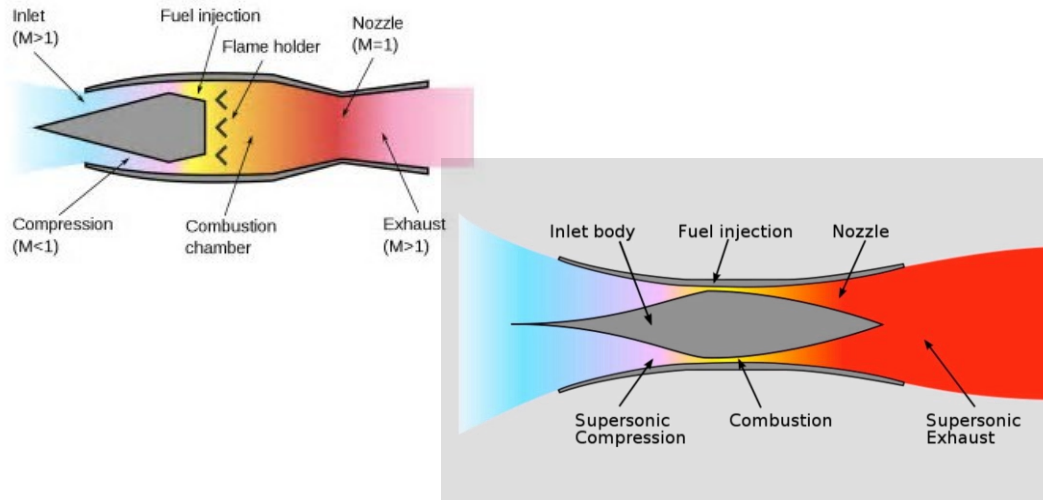


2. Jet engines

2.4 RAM/ScramJet: supersonic flight $M > 3$

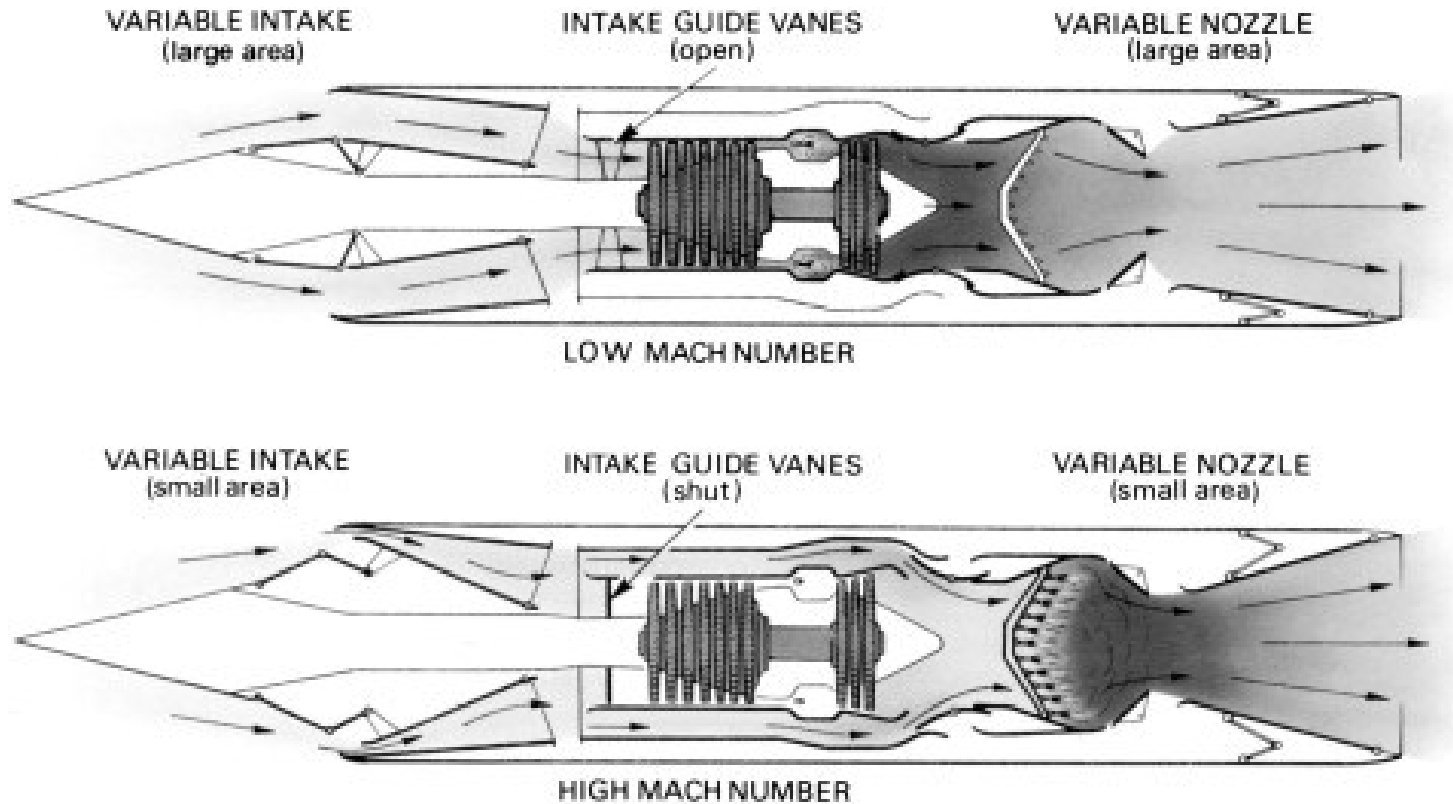
- **Cycle without machines**

- Convert kinetic energy v_a in pressure P_t by “RAM” effect : 1 - 2
- Combustion : 2-3
 - RAMJET : subsonic combustion
 - Supersonic Combustion RAMJET
- Expand in nozzle to form jet : 3 – 4



2. Jet engines

Combined afterburning turbojet & ramjet



2. Jet engines

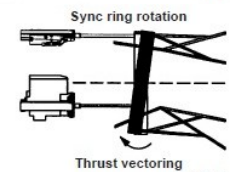
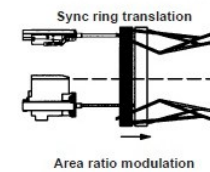
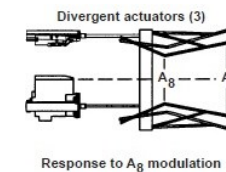
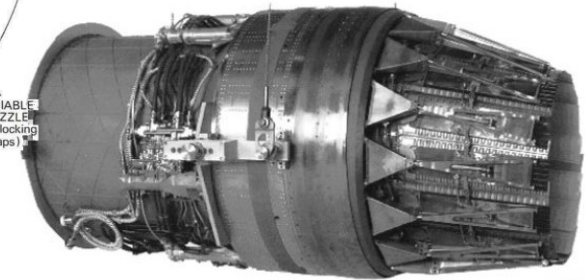
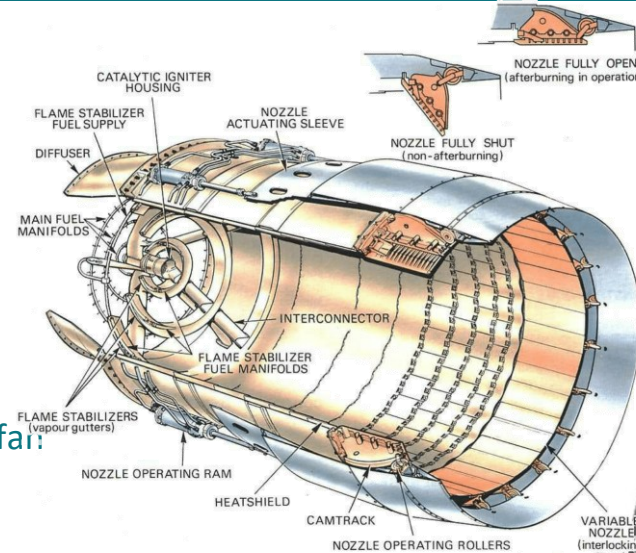
Nozzle

- **Converging**

- Sonic jet (wrt exhaust T) → lower speeds
- Choked if $NPR > NPR^*$
- Adapted if $NPR < NPR^*$
- Fixed for civil turbofan (this could change ...)
- Variable throat for military/afterburning turbofan:

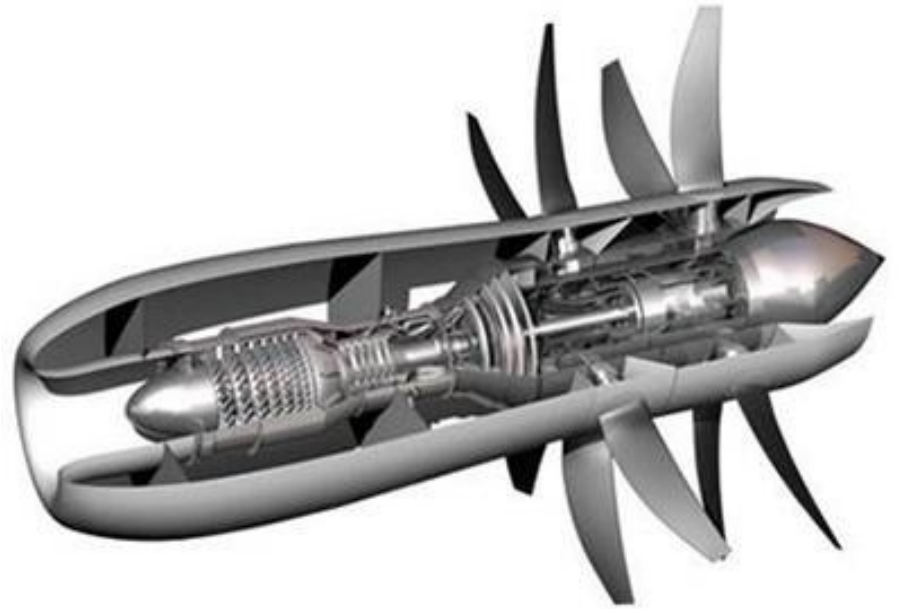
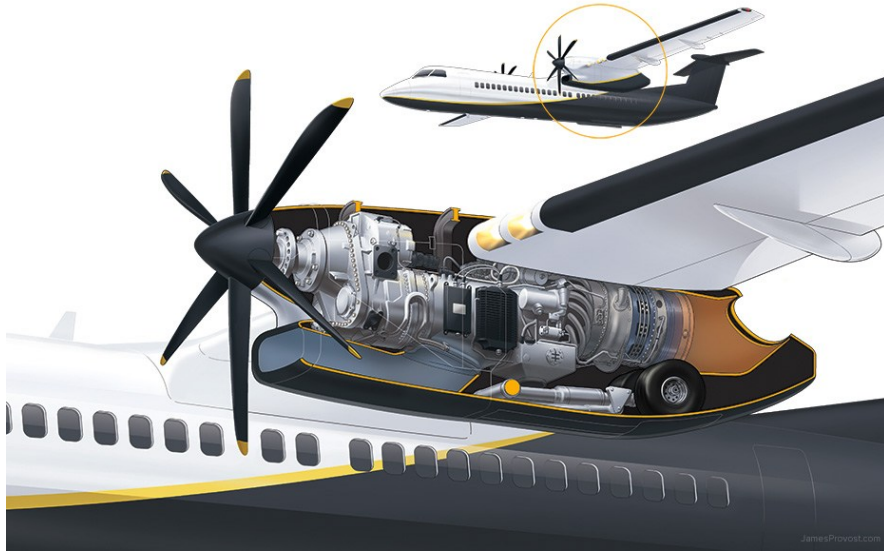
- **Converging-diverging**

- Higher speed range
- Variable throat and expansion area to adapt to GG and flight (thrust vectoring)
- Afterburning turbojet/turbofan



3. Propellers

Mechanical acceleration by lift forces on propeller blades



3. Propellers

Global operation: Rankine-Froude theorem

- **Accelerating / contracting stream tube**

$$\dot{m} = \rho v_A S_A = \rho v_B S_B = \rho v_C S_C$$

- **Propeller = power -> (total) pressure jump**

$$P = \dot{m} \Delta \mathcal{E}_m = \dot{m} \frac{p_{B+}^o - p_{B-}^o}{\rho} = \dot{m} \frac{p_{B+} - p_{B-}}{\rho}$$

- **Thrust computed on two control volumes**

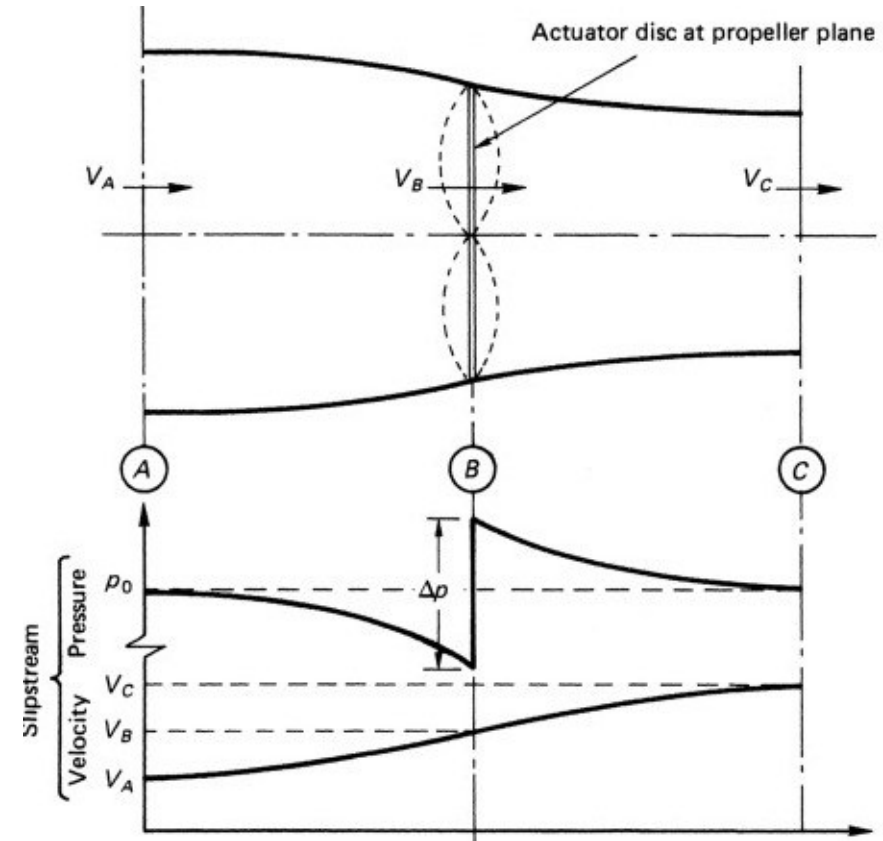
$$T = \dot{m} (v_C - v_A) = \dot{m} (v_C - v_\infty)$$

$$T = (p_{B+} - p_{B-}) S_B = \Delta p_B S_B$$

- **Bernoulli : conservation of total pressure**

$$p_{B-} = p_A + \frac{1}{2} \rho (v_A^2 - v_B^2) = p_\infty + \frac{1}{2} \rho (v_\infty^2 - v_B^2)$$

$$p_{B+} = p_C + \frac{1}{2} \rho (v_C^2 - v_B^2) = p_\infty + \frac{1}{2} \rho (v_C^2 - v_B^2)$$



3. Propellers

Global operation: Rankine-Froude theorem + induced velocity

- Induction factor a**

$$v_{B+} = v_{B-} = v_B = v_A(1 + a) = v(1 + a)$$

- Thrust computed two ways**

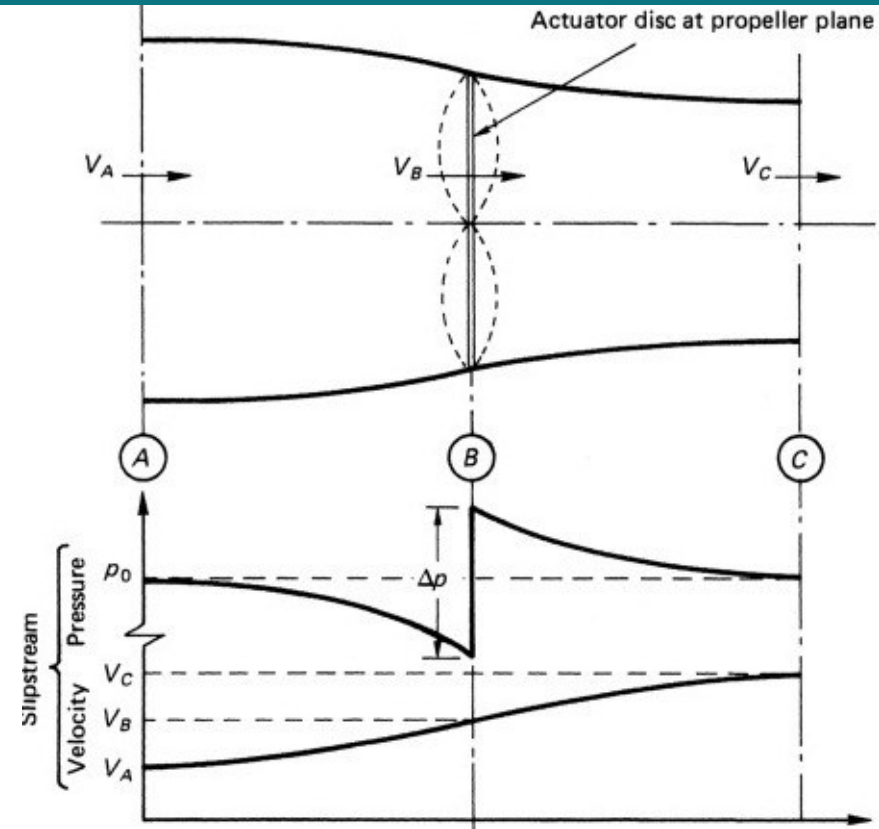
stream tube control volume

$$T = \dot{m} (v_C - v_A) = \rho v_B S_B (v_C - v_A)$$

- pressure difference

$$\begin{aligned} T &= (p_{B+} - p_{B-})S = \rho \frac{(v_C^2 - v_A^2)}{2} S \\ &= \rho \frac{(v_A + v_C)(v_C - v_A)}{2} S \end{aligned}$$

$$\Rightarrow v_B = \frac{v_A + v_C}{2} \Rightarrow v_C = (1 + 2a)v_A$$



3. Propellers

Global operation: thrust, power and propulsive efficiency

- **Thrust**

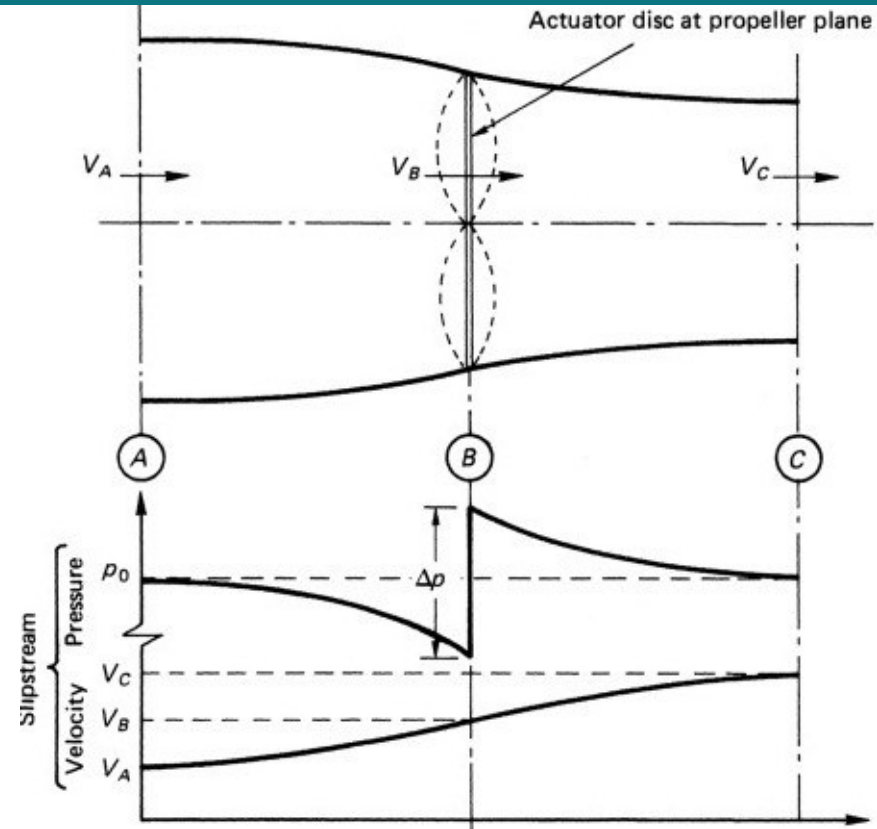
$$T = \dot{m}(v_C - v_A) = \rho v^2 S \cdot 2a(1 + a)$$

- **Power**

$$P = \dot{m} \frac{1}{2} (v_C^2 - v_A^2) = \rho v^3 S \cdot 2a(1 + a)^2$$

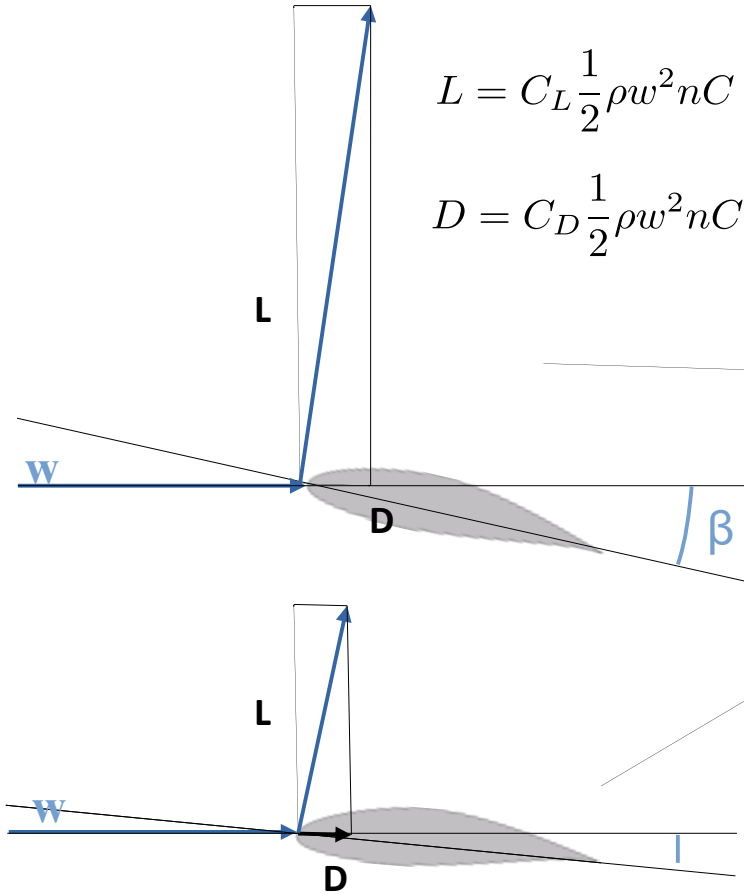
- **Propulsive efficiency**

$$\eta_p = \frac{Tv}{P} = \frac{1}{1 + a}$$



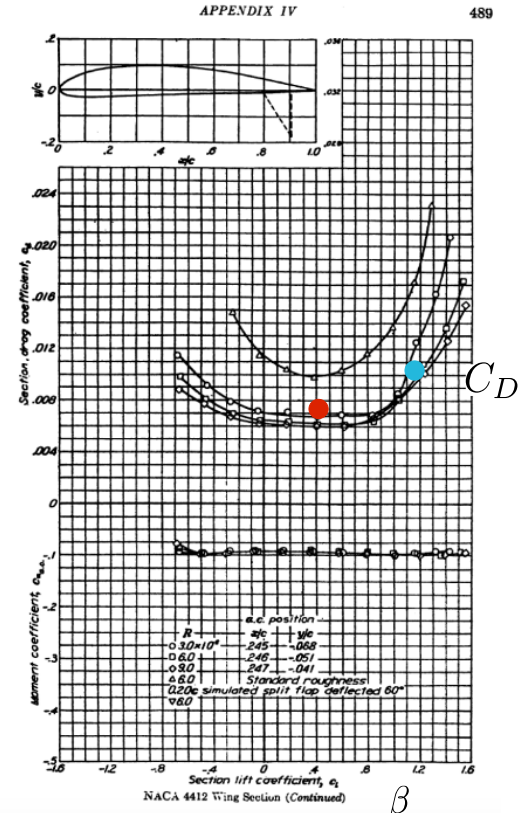
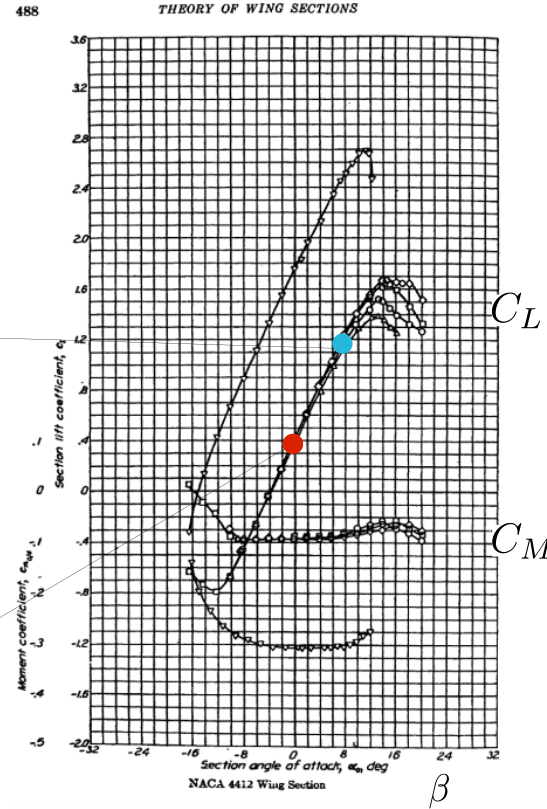
3. Propellers

Blades : airfoil lift/drag polars



$$L = C_L \frac{1}{2} \rho w^2 n C$$

$$D = C_D \frac{1}{2} \rho w^2 n C$$



3. Propellers

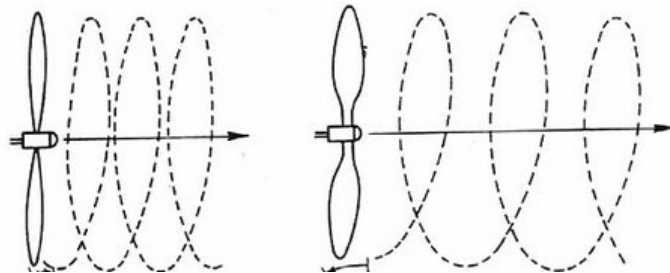
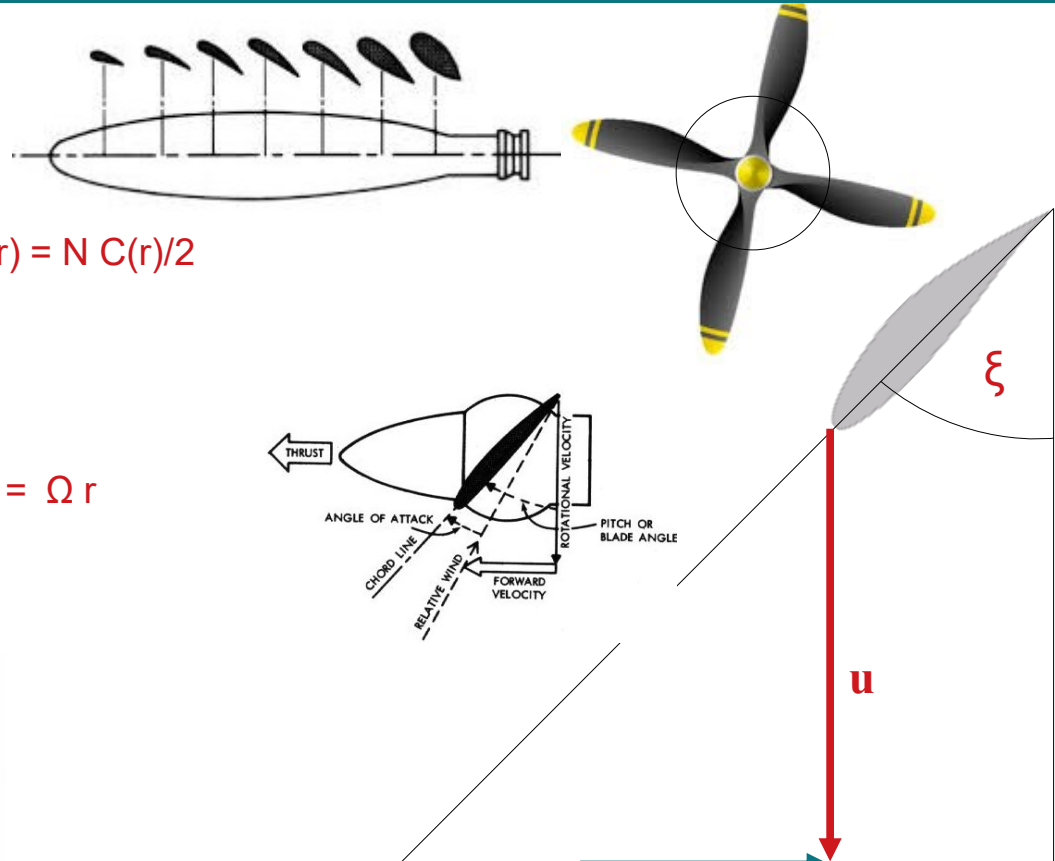
Blades – layout and operating parameters

- **Geometry**

- Tip radius R_t
- (Radial distribution of) blade profile
- Radial distribution of chord $C(r)$ / Solidity $\sigma(r) = N C(r)/2$

- **Operating parameters**

- Stagger or pitch angle ξ
- Rotation speed $\Omega \rightarrow$ local blade speed $u = \Omega r$
- Advance ratio $J = v_a/u_t = v_a/\Omega r_t$



3. Propellers

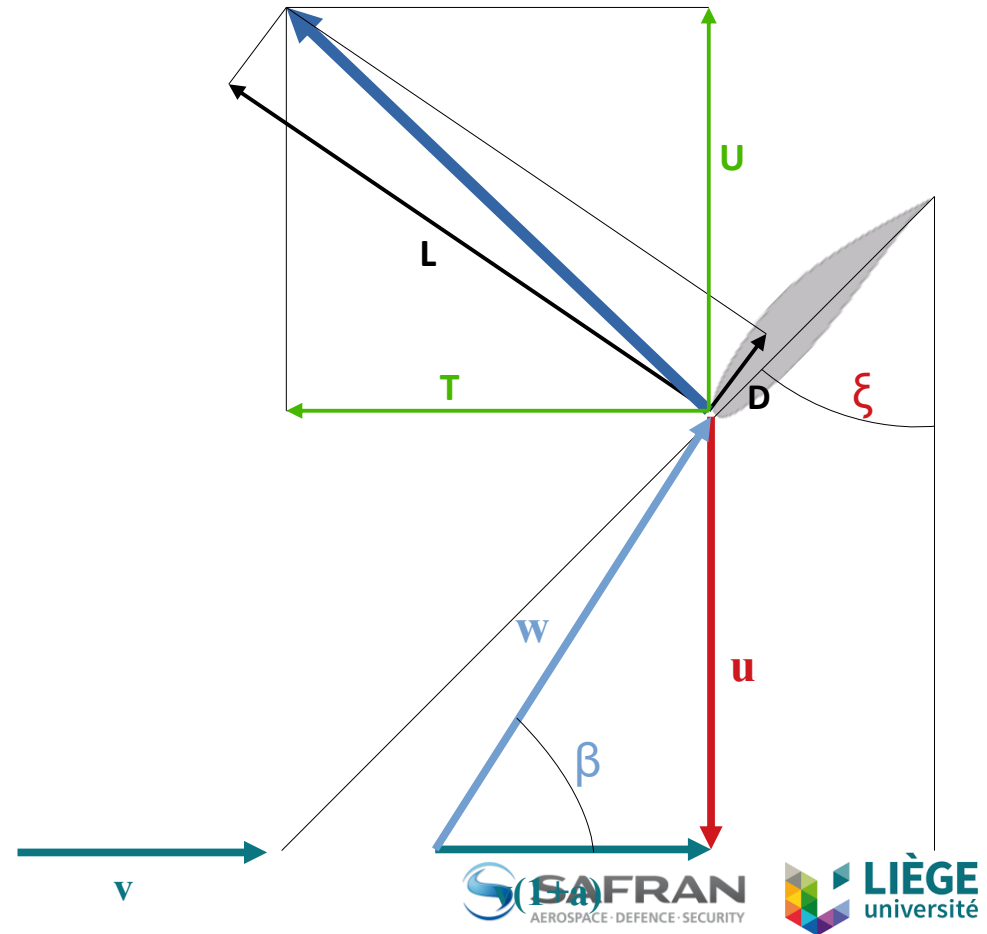
Blades : forces on blade element section

- Induction factor $a \rightarrow v(1+a)$
- Relative velocity w , flow angle β
- $\mathbf{w} = (1 + a)v_0\mathbf{e}_x + u\mathbf{e}_y$
- Lift/drag forces L & D as a function of
 - Relative velocity w
 - Incidence $i = \xi - \beta$
- Compute thrust T and tangential force U

$$T = L \sin \beta - D \cos \beta$$

$$U = L \cos \beta + D \sin \beta$$

- Recompute induction factor a from T



- **Thrust coefficient**

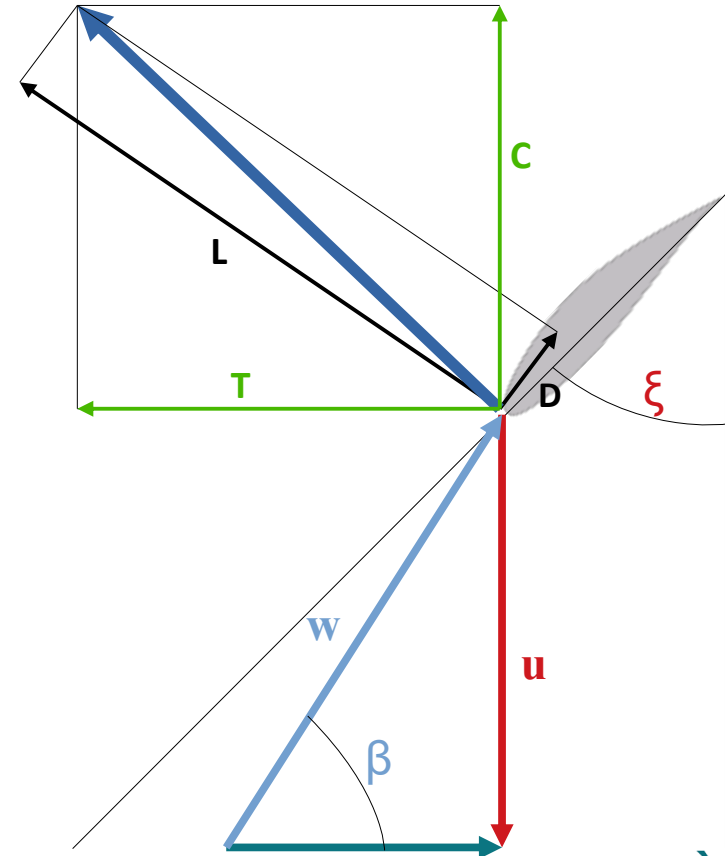
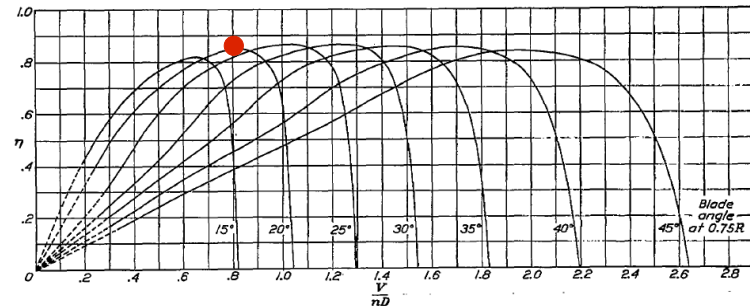
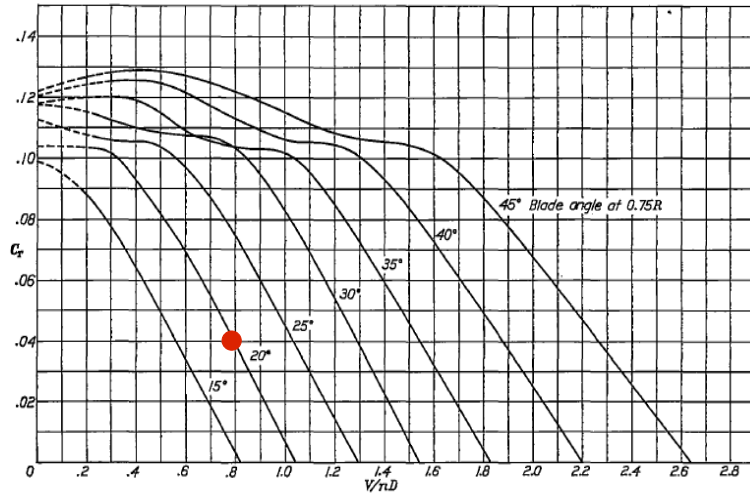
$$T = \dot{m}(v_C - v_A) = \rho v^2 S \cdot 2a(1 + a) \quad \Rightarrow C_T = \frac{T}{\rho S u_b^2} = J^2 \cdot 2a(1 + a)$$

- **Power coefficient**

$$P = \dot{m} \frac{1}{2} (v_C^2 - v_A^2) = \rho v^3 S \cdot 2a(1 + a)^2 \quad \Rightarrow C_P = \frac{P}{\rho S u_b^3} = 2a(1 + a)^2$$

3. Propellers

Operating point



3. Propellers

Operation point: variation of advance ratio (flight speed or rotation speed)

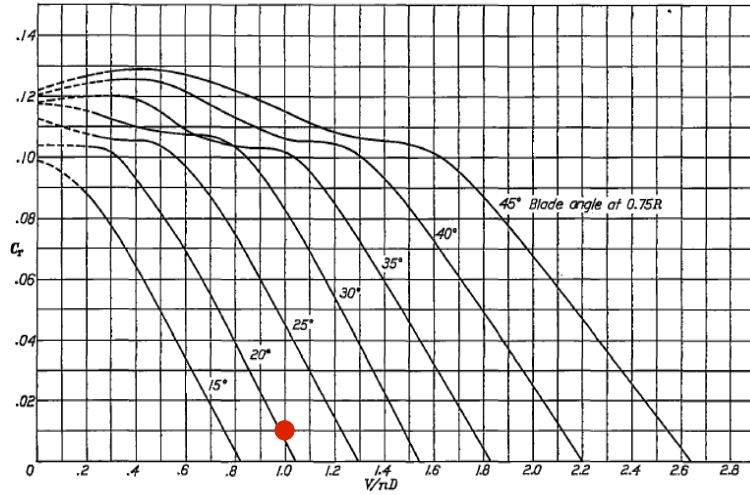


FIGURE 3.—Thrust-coefficient curves for propeller 868-0, Clark Y section, 2 blades.

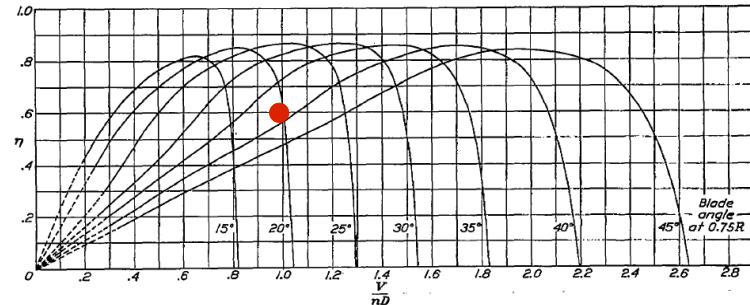
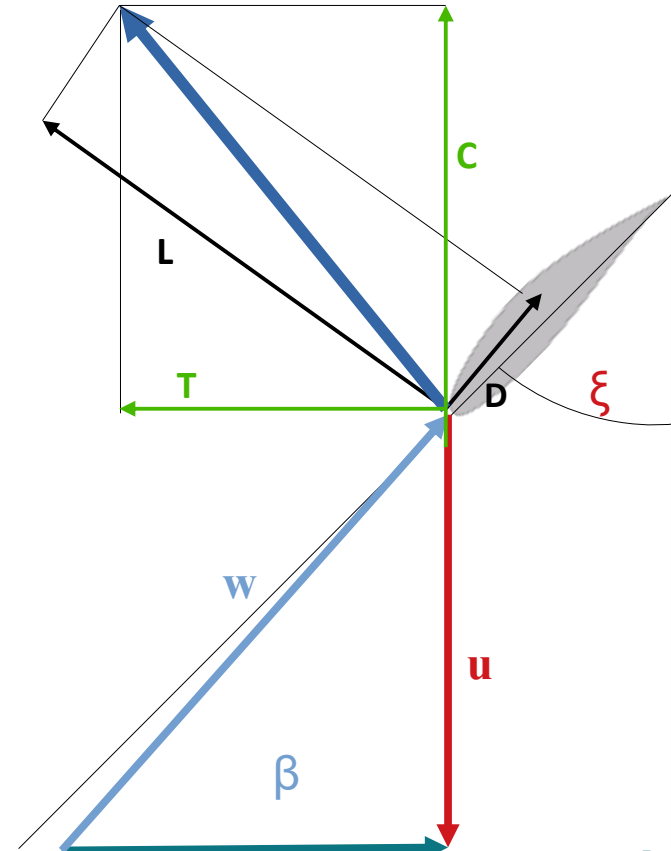


FIGURE 5.—Efficiency curves for propeller 868-0, Clark Y section, 2 blades.



3. Propellers

Operation: pitch control

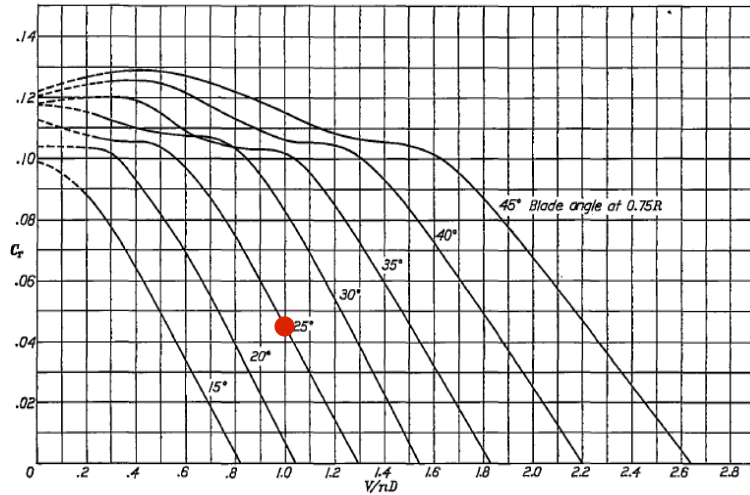


FIGURE 3.—Thrust-coefficient curves for propeller 5608-0, Clark Y section, 2 blades.

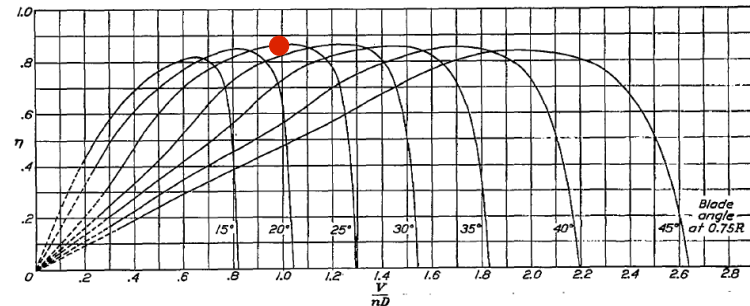
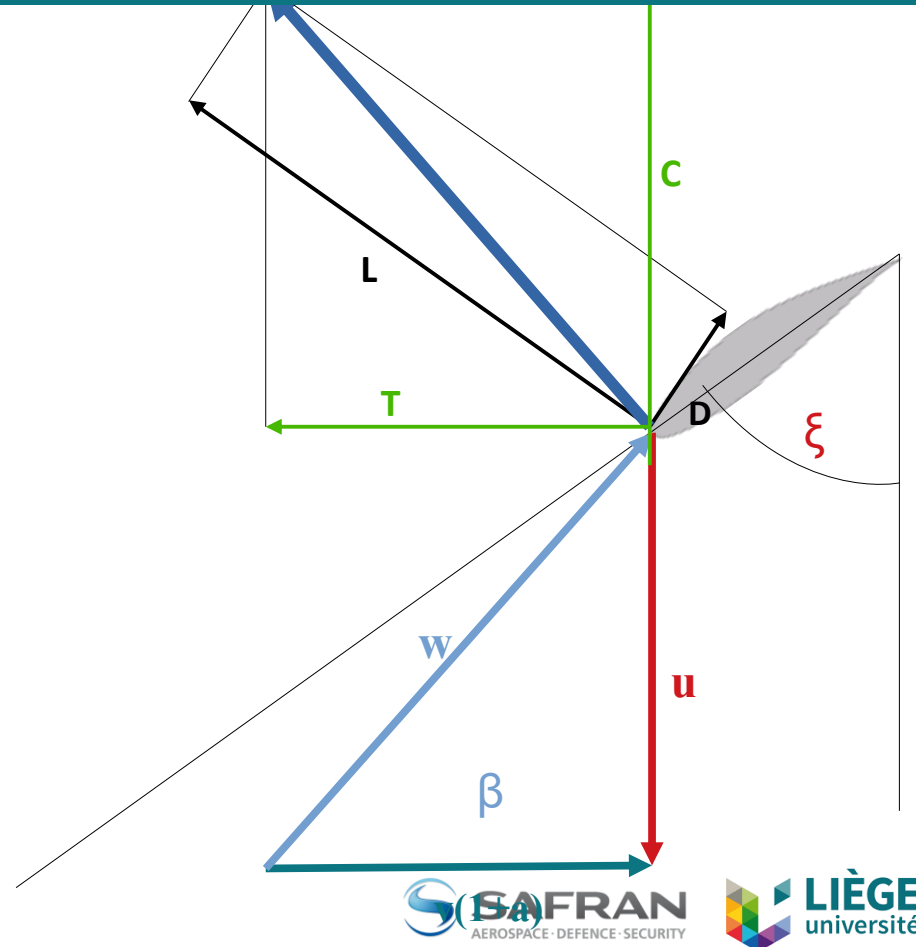
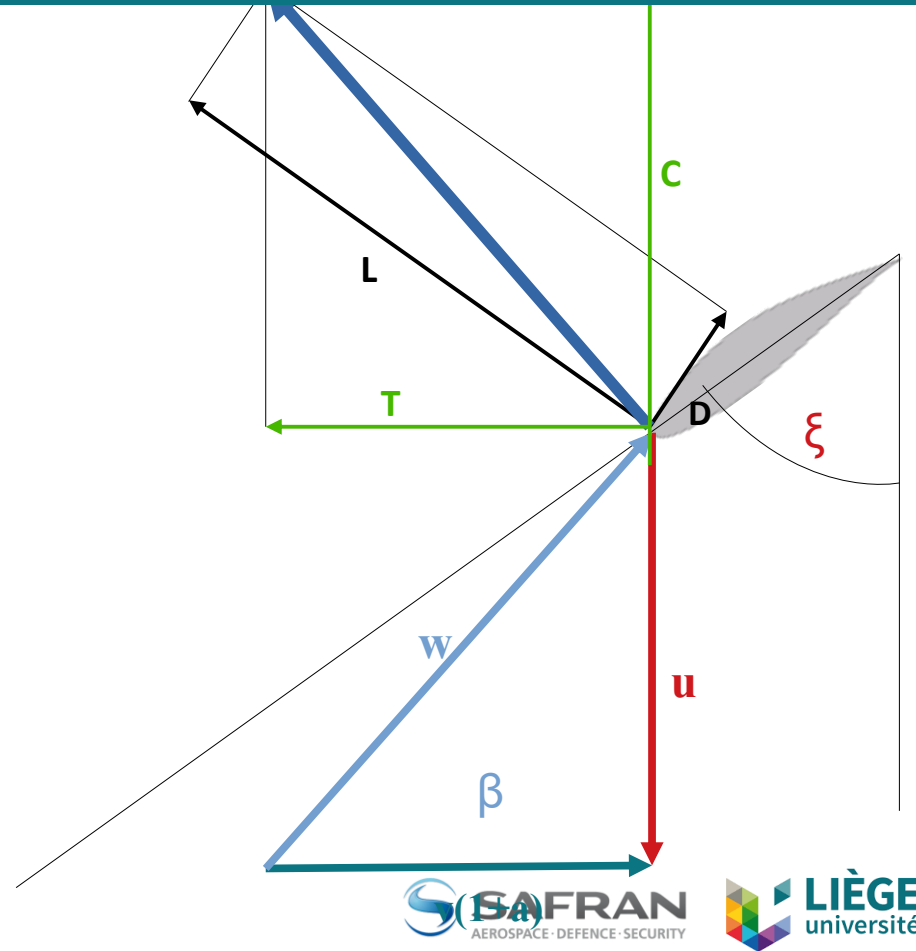


FIGURE 5.—Efficiency curves for propeller 5608-0, Clark Y section, 2 blades.



Operation: pitch control



3. Propellers

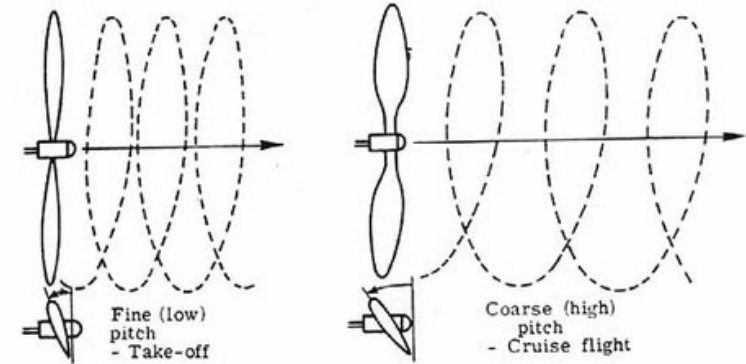
Control

- **Means of control**

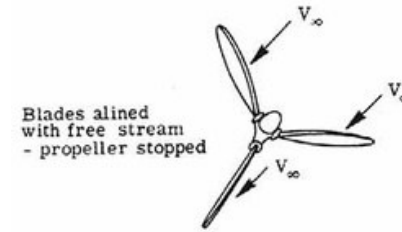
- Engine power / rotation speed : $T \sim n^2$, $P \sim n^3$
- Advance speed vs rotation speed : “gear box”
 - Fine pitch ~ low gear :
 - high thrust at low advance speed : take-off, taxi, ...
 - limited flight speed
 - Coarse pitch ~ high gear :
 - low thrust at take-off
 - higher air speeds

- **Propeller types**

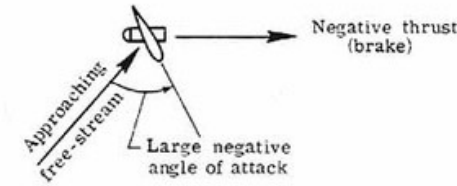
- Fixed pitch / ground adjustable ~ single gear
- Variable pitch propellers
 - Inflight adjustable: change throttle and pitch angle independently ~ manual gear box
 - Fixed velocity: governor adjusts pitch to keep constant rotation speed ~ automatic gearbox



(a) Pitch control.



(b) Feathered propeller.

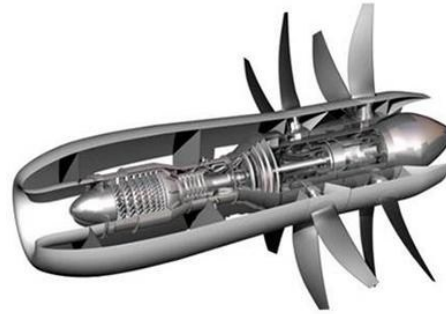


(c) Landing brake.

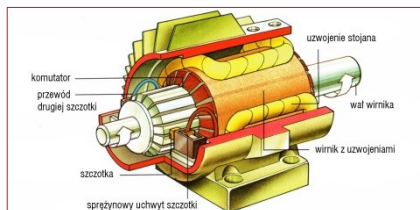
3. Propellers

Power generators

- Internal combustion engine
- Gas turbine: turboprop & CROR

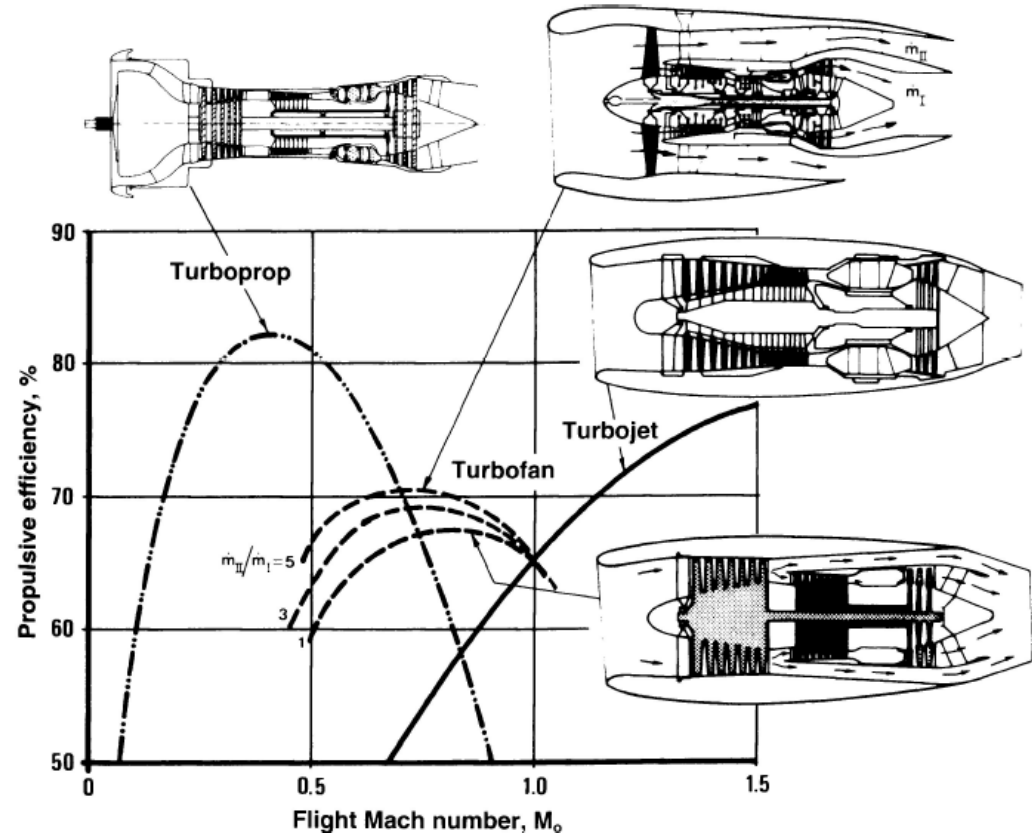


- Future of propulsion systems : electric or hybrid, distributed ...



4. Choosing the propulsion system

- **Typical : cruise speed**
 - Propeller : $0.1 < Ma < 0.7$
 - High BPR turbofan : $0.7 < Ma < 1$
 - Low BPR turbofan / turbojet : $Ma > 1$
 - RAMJET : $Ma > 2$
 - SCRAMJET : $Ma > 5$
- **Extension of operating range of propellers to transonic**
 - (Variable pitch turbofans)
 - Transonic open rotors (CROR)
 - Ducted fan for hybrid propulsion



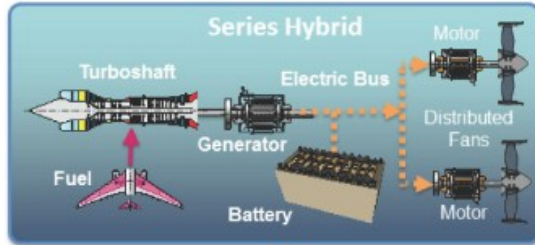
4. Choosing the propulsion system

Future: integrated / hybrid / distributed propulsion systems ?

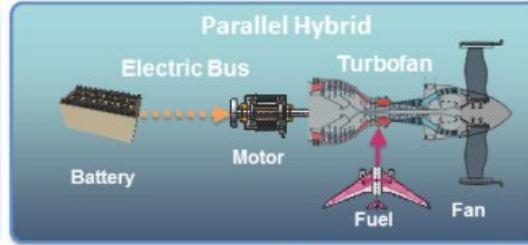


4. Choosing the propulsion system

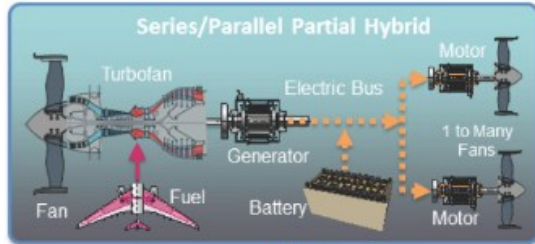
hybrid / new propulsion stems ?



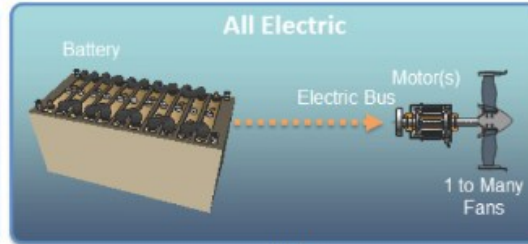
(a)



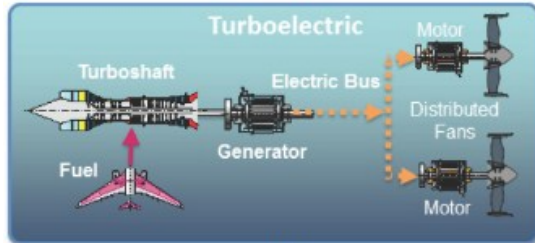
(b)



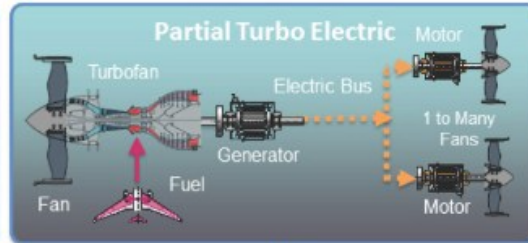
(c)



(d)



(e)



(f)

