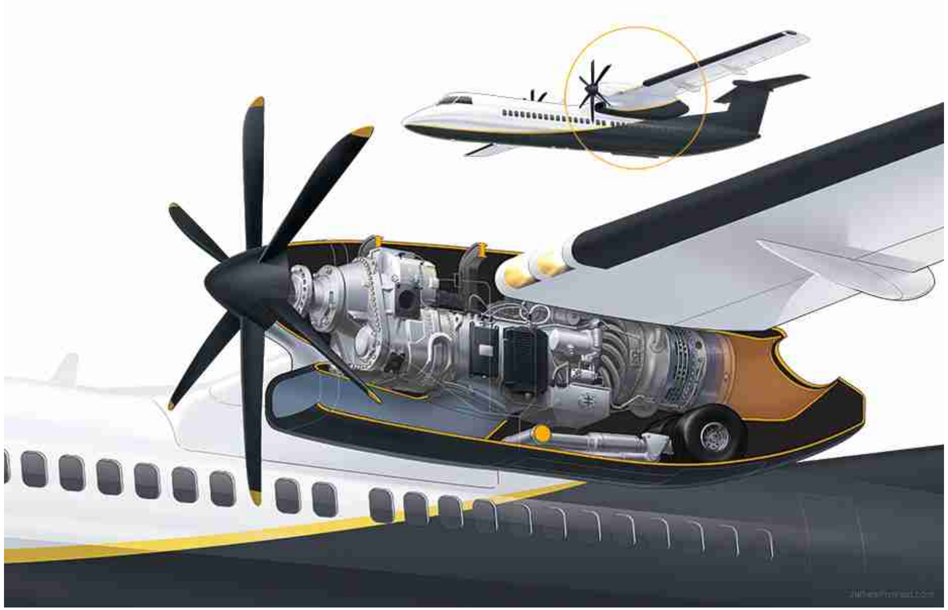
Introduction to airbreathing propulsion systems

APRI0004:

Integrated project aerospace design



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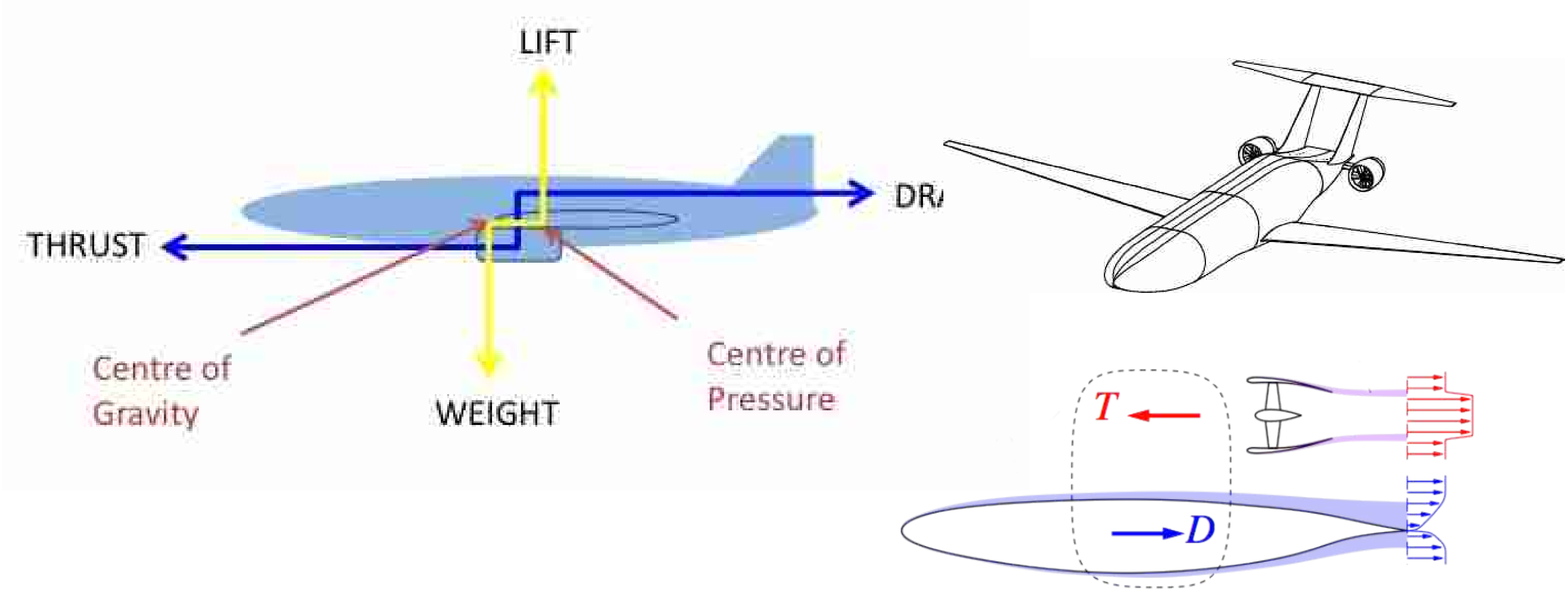
1. Balances, thrust and performance

Drag / thrust definition



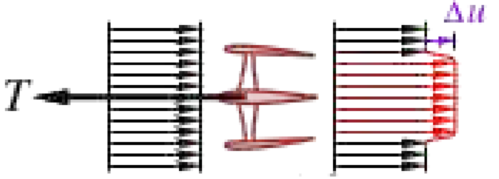
1. Balances, thrust and performance

Airbreathing engines: acceleration of (clean) air mass flow

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

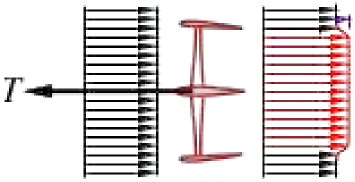
$$\mathcal{T} = \dot{m}_a(v_j - v_f)$$

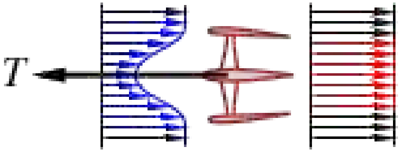
- **Powers**
  - Propulsive power → airplane acceleration : $\mathcal{P}_p = \mathcal{T} u_f = \dot{m}_a(u_j - u_f)u_f = \dot{m}_a \; \Delta u \; u_f$
  - Mechanical power → fluid acceleration : $\mathcal{P}_m = \dot{m}_a \Delta \mathcal{E}_k = \dot{m}_a \dfrac{u_j^2 - u_f^2}{2}$
  - Lost power $\mathcal{P}_l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



- **Propulsive efficiency:**

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

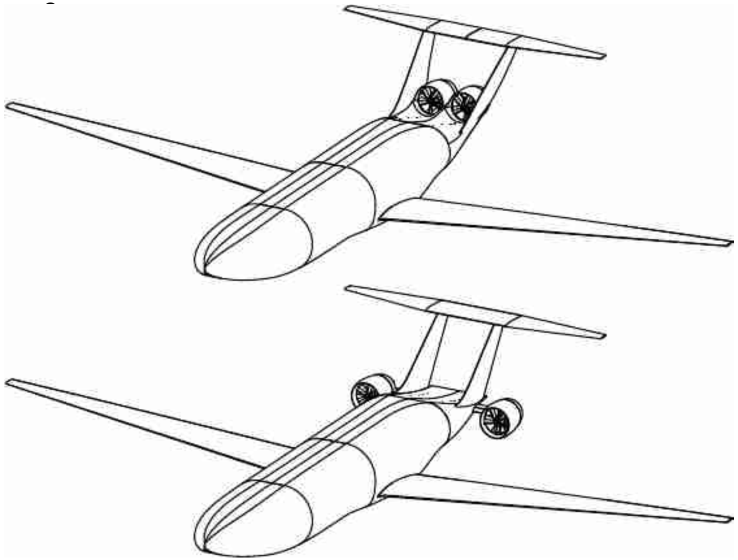


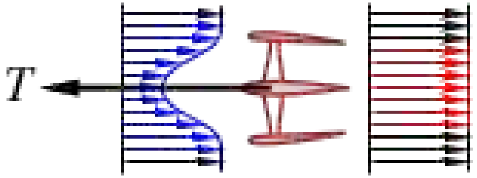


- **Increasing propulsive efficiency for constant thrust:**
  - increase mass flow, decrease jet velocity
  - Ingest flow at speed lower than flight speed $\mathcal{T} = \dot{m}_a(v_f - v_i)$

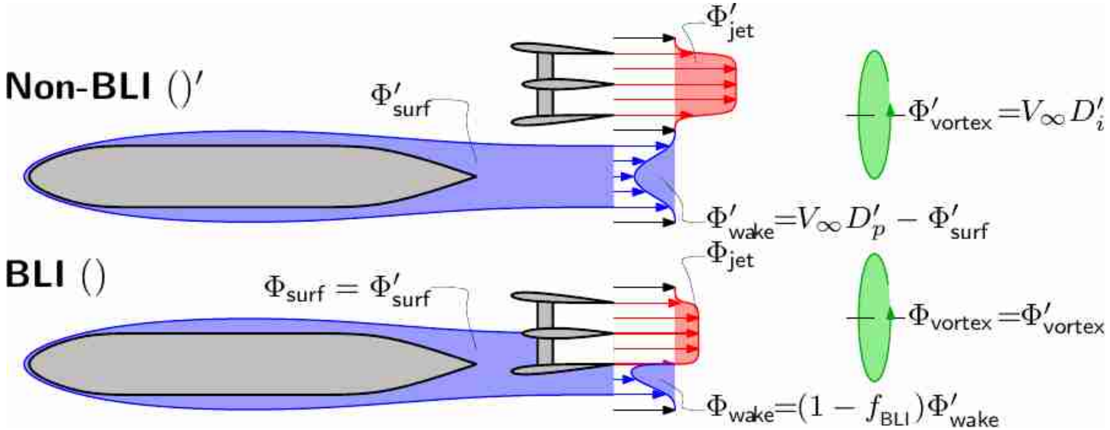
1. Balances, thrust and performance

Airbreathing engines: Boundary Layer Ingestion





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



1. Balances, thrust and performance

Airbreathing engines: classical performance parameters

- **Thermal energy $Q = m_f \Delta h_f$**
  - Fuel mass flow rate: $\dot{m}_f$
  - Fuel to air ratio: $far = \dot{m}_f / \dot{m}_a$
  - Fuel lower heating value: $\Delta h_f \approx 43 MJ/kg$
- **Overall efficiency : propulsive power P_p versus thermal energy Q**
  - Propulsive efficiency:

$$\eta_p = \frac{\mathcal{P}_p}{\mathcal{P}_m} = \frac{2 v_f}{v_f + v_j}$$

  - Thermal efficiency:

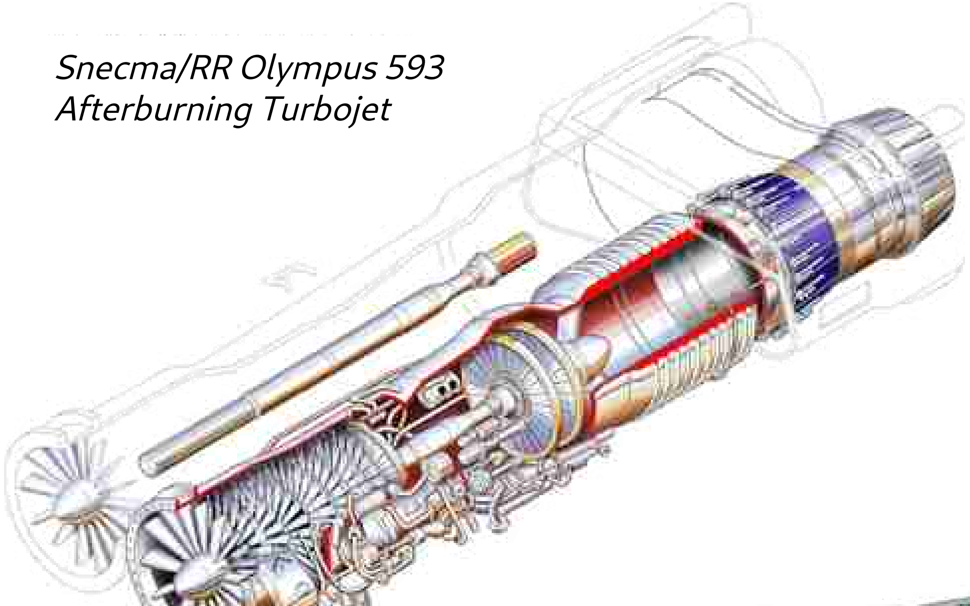
$$\eta_t = \frac{\mathcal{P}_m}{\mathcal{Q}} = \frac{\mathcal{P}_m}{\dot{m}_f \Delta h_f}$$

$$\eta = \frac{\mathcal{P}_p}{\mathcal{Q}} = \eta_p \eta_t$$

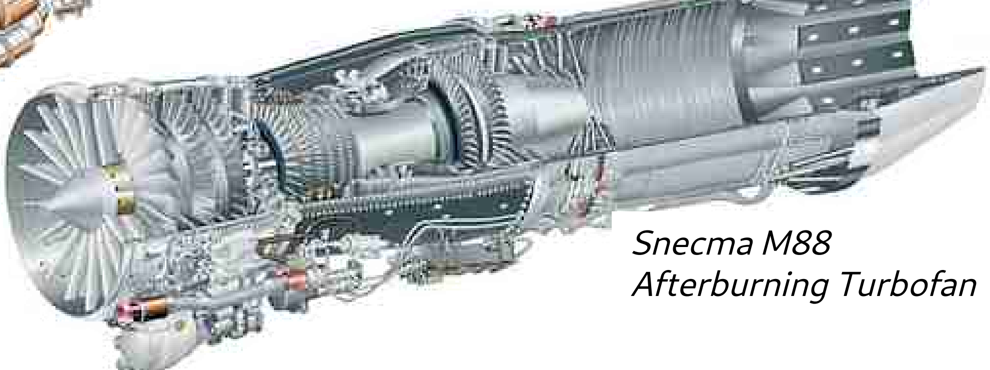
- **Efficiency → *Thrust specific fuel consumption (TSFC)*** $TSFC = \dfrac{\dot{m}_f}{\mathcal{T}}$
- **Compacity → *Specific thrust*** $\mathcal{T}_s = \dfrac{\mathcal{T}}{\dot{m}_a}$

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

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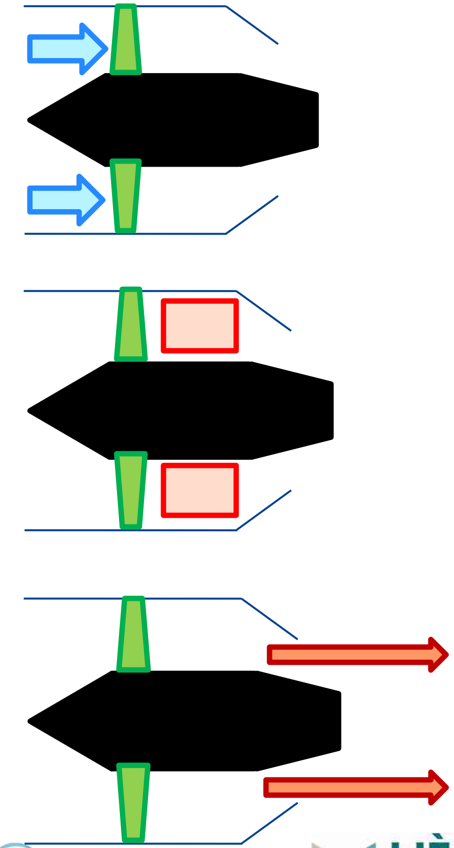
2. Jet engines

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

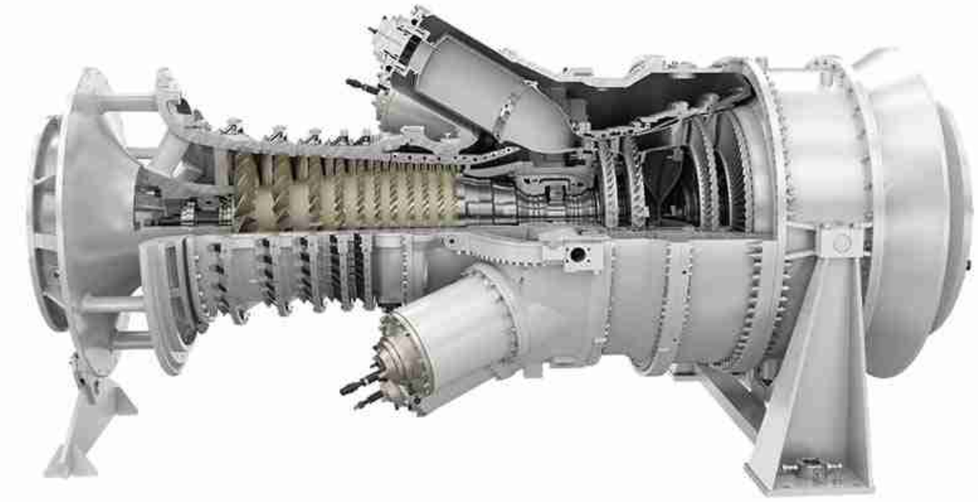
$$T^\circ = T_a\left(1+\frac{\gamma-1}{2}M_f^2\right) \qquad p^\circ = p_a\left(\frac{T^\circ}{T_a}\right)^{\frac{\gamma}{\gamma-1}}$$

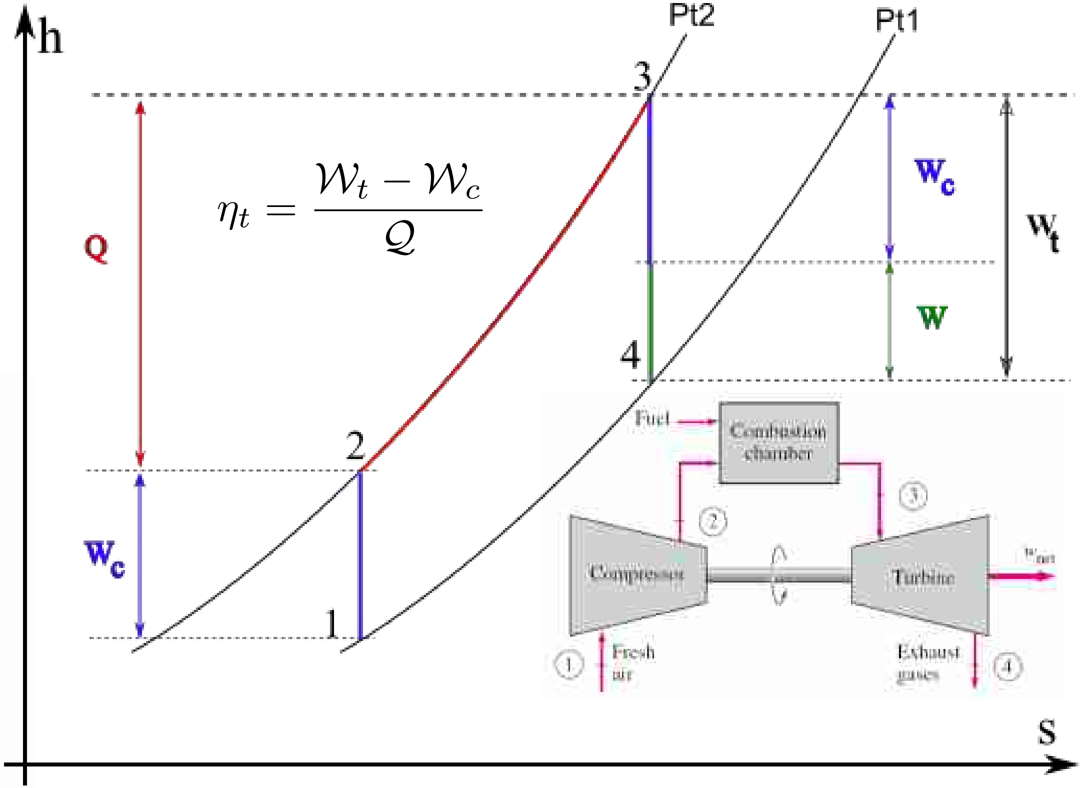
- **Increase total pressure and temperature**
    - Mechanical : fan
    - Thermal : gas generator / Brayton
    - Afterburning
- **Expansion over exhaust nozzle to ambient pressure**
    - Choked
    - Adapted

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 : $W_t = \dot{m}\Delta H_{43}$

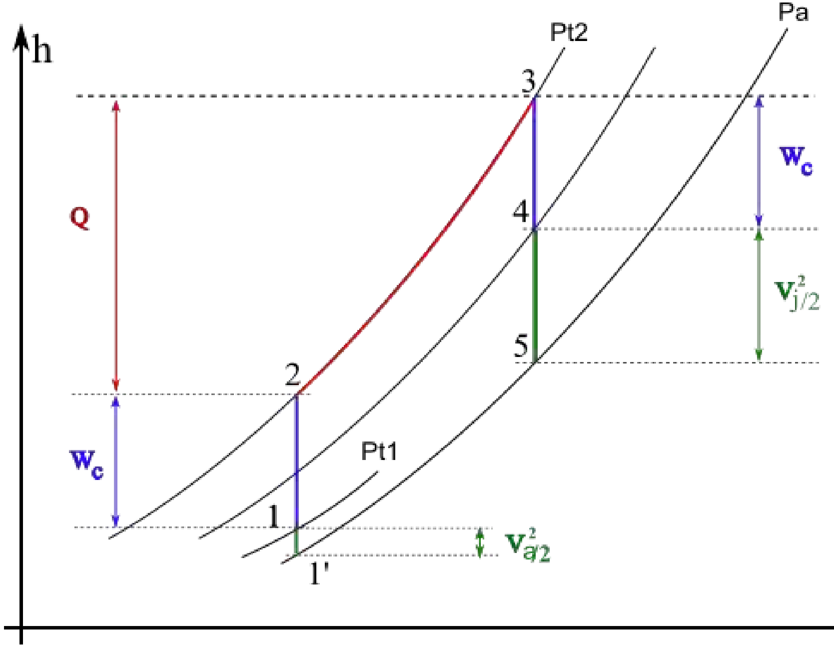


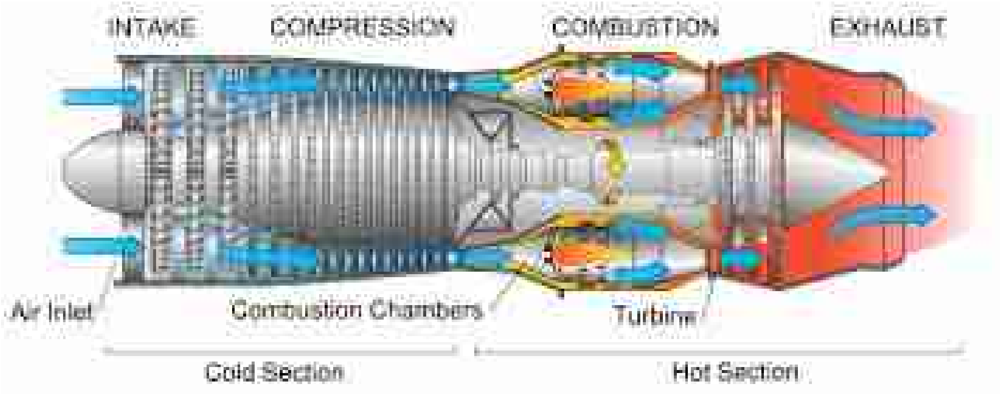


2. Jet engines

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**

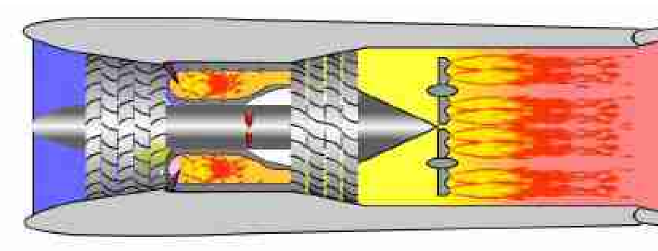


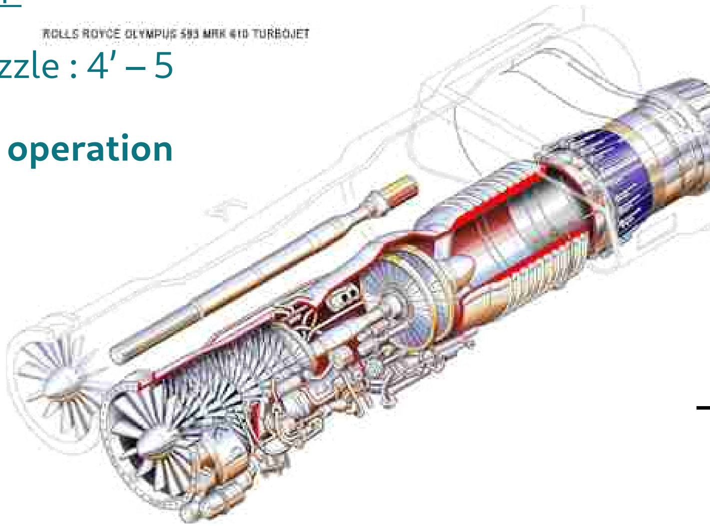


2. Jet engines

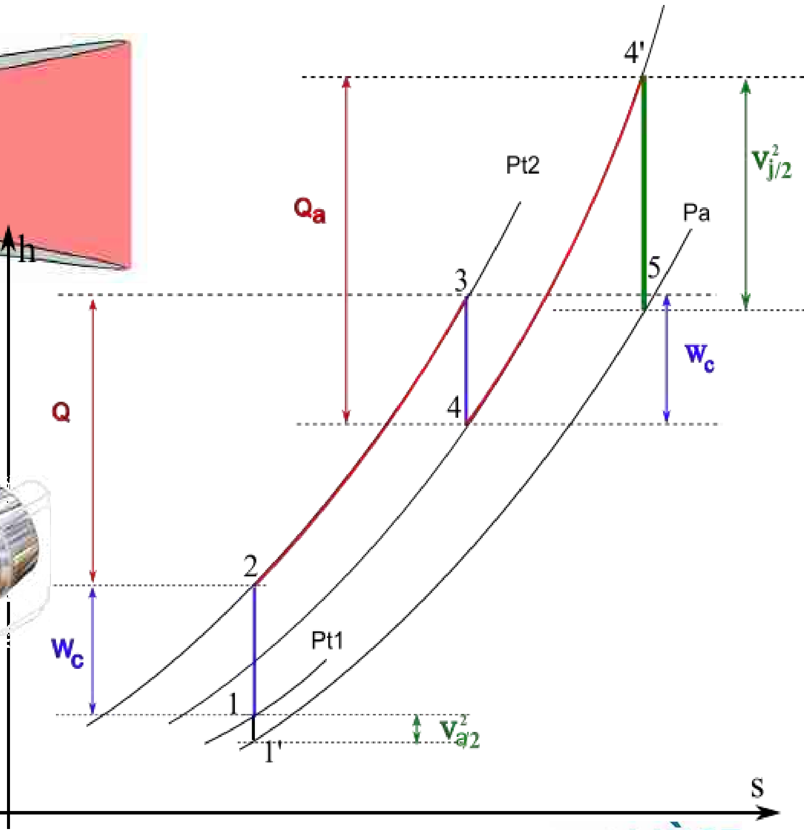
Afterburning turbojet: dry and wet operation

- **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
- **Nearly double thrust in “wet” operation**



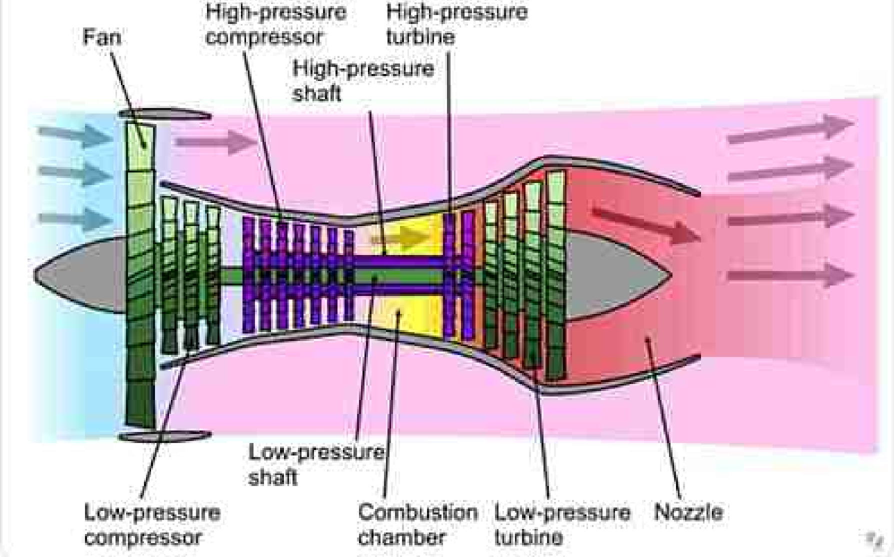


ROLLS ROYCE OLYMPUS 593 MRK 610 TURBOJET



2. Jet engines

Civil turbofan : high subsonic/transonic



- **Core m_c and bypass m_b flow rate**
  - Bypass ratio (BPR): $\alpha = m_b/m_c$
- **Core / primary : mech. power**
  - Fan + compressor : 1 - 2
  - Combustion : 2 - 3
  - Turbine → fan & compressor 3 - 4
  - Exhaust jet : 4 – 5

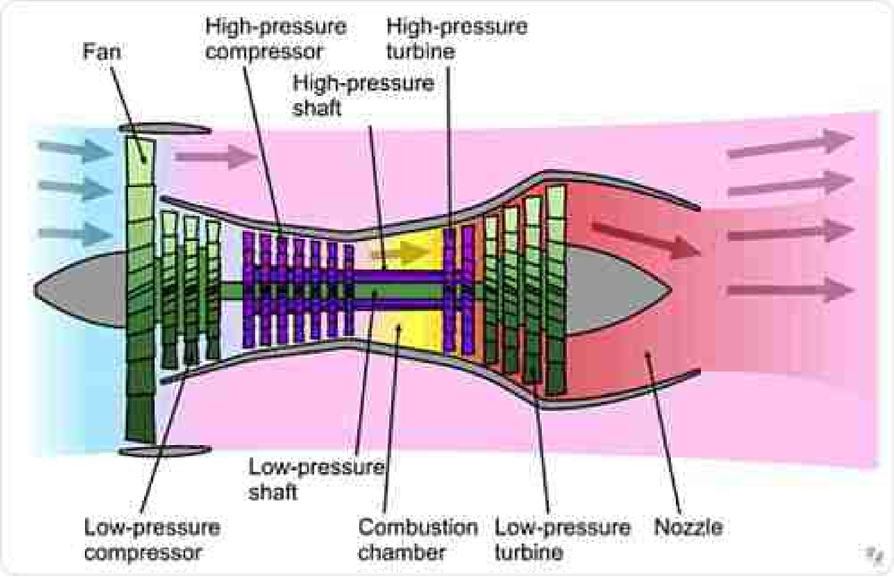
- **Bypass / secondary flow : thrust**
  - Compression by fan 1 – 2'
  - Exhaust nozzle 2' - 5

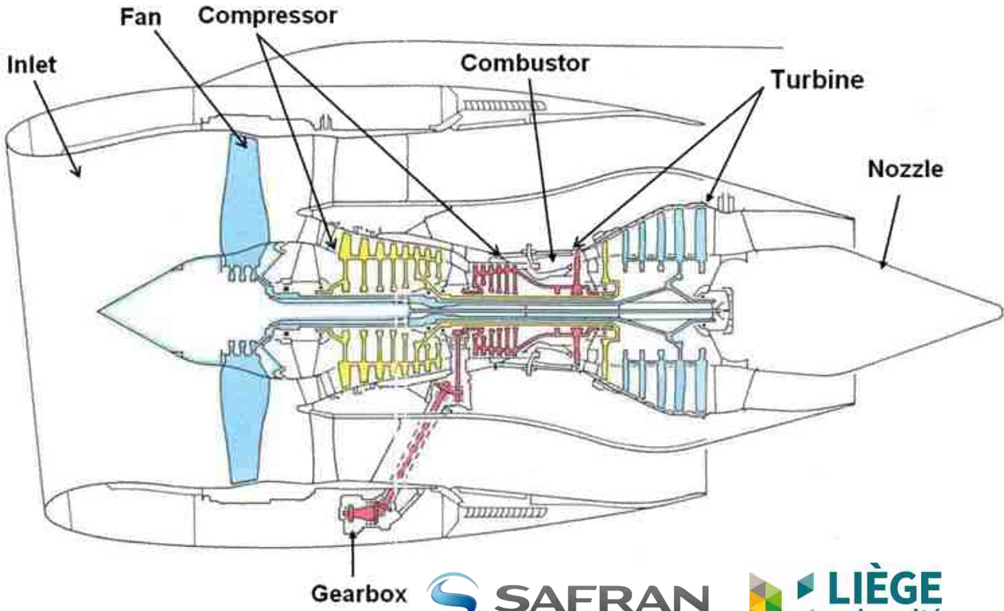
- **High propulsive efficiency: small acceleration of high mass flow rate**

2. Jet engines

Civil turbofan: multispool turbofans

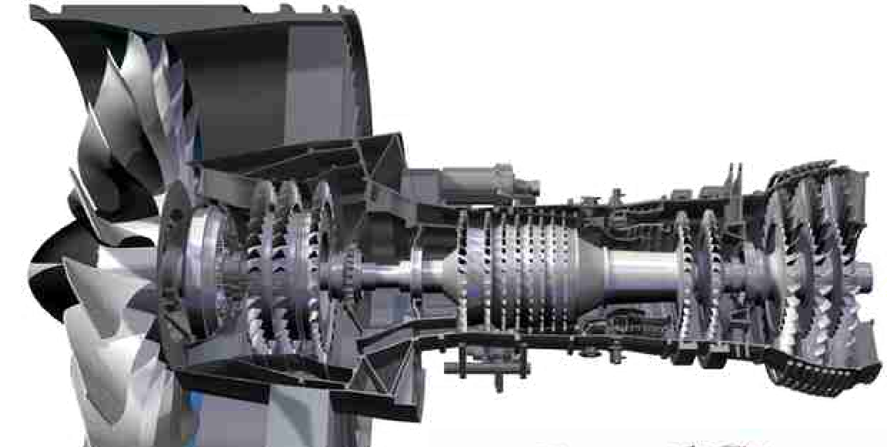
- **Optimal rotation speed = slightly supersonic at the tip**
- **Different spools / shafts → optimise rotation speed**
- **LP spool drives fan → large LP turbine**

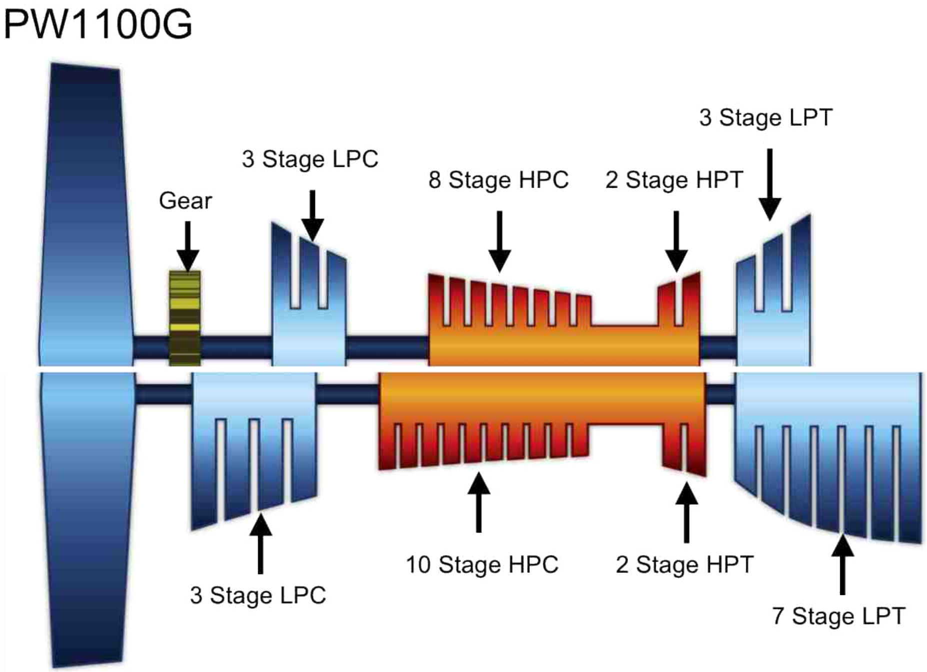




2. Jet engines

Civil turbofan : geared turbofan (GTF)





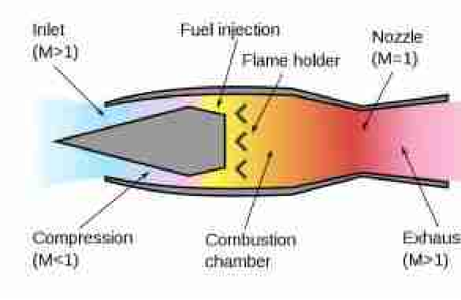
PW1100G
BPR = 12.5

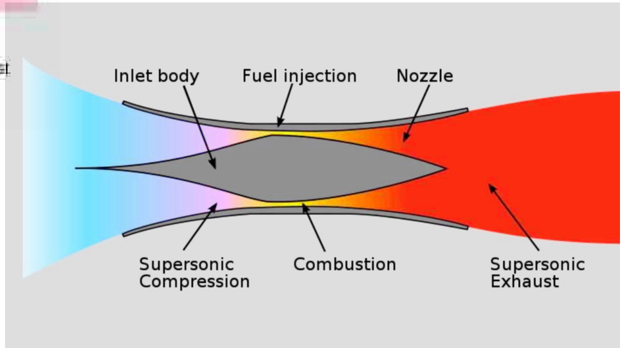
CFM Leap
BPR = 9 .. 11

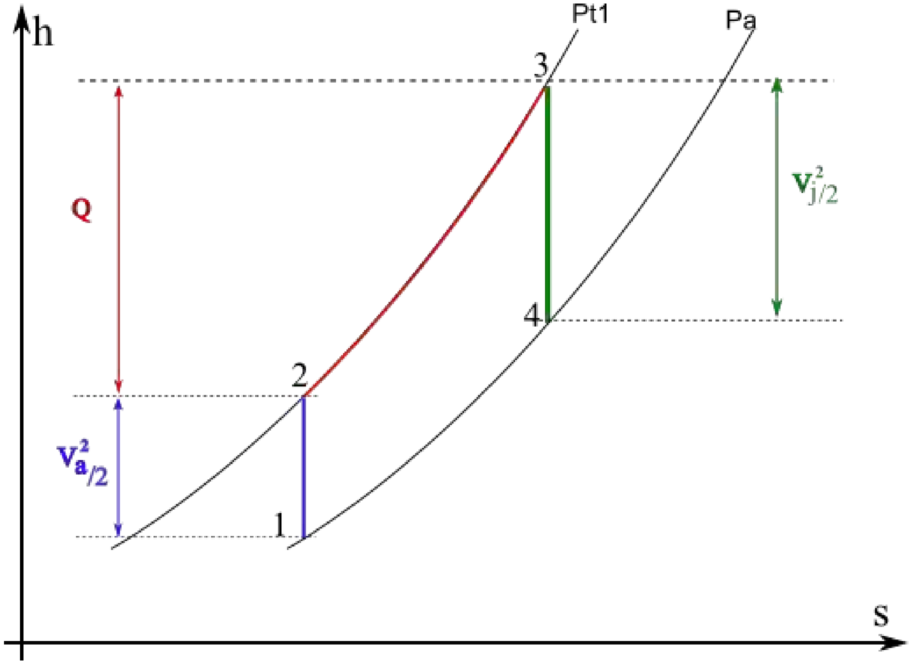
2. Jet engines

2.4 RAM/ScramJet: supersonic flight M > 3

- **Cycle without machines**
  - Convert kinetic energy va in pressure Pt by “RAM” effect : 1 - 2
  - Combustion : 2-3
    - **RAMJET** : subsonic combustion
    - **S**upersonic **C**ombustion **RAMJET**
  - Expand in nozzle to form jet : 3 – 4

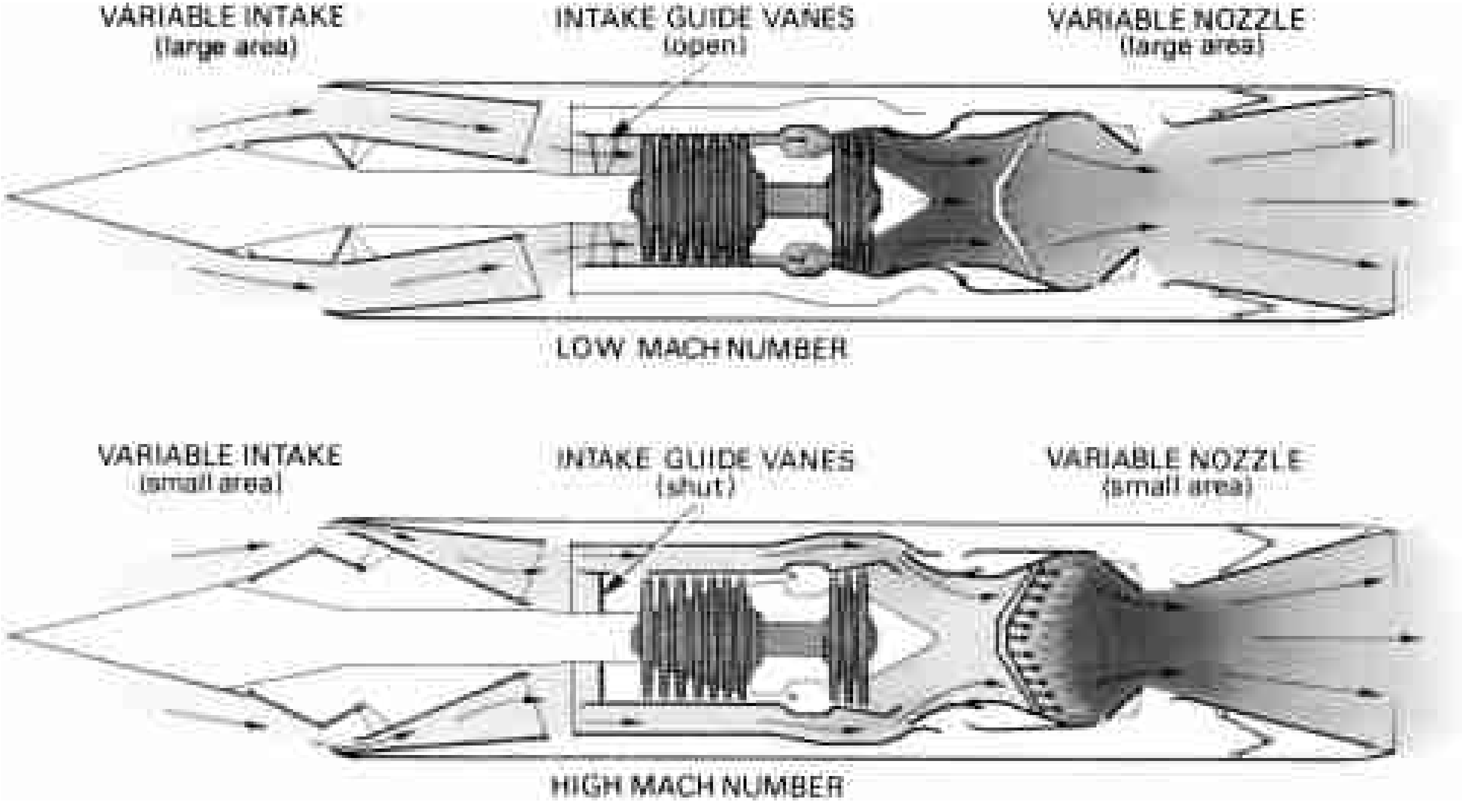






2. Jet engines

Combined afterburning turbojet & ramjet



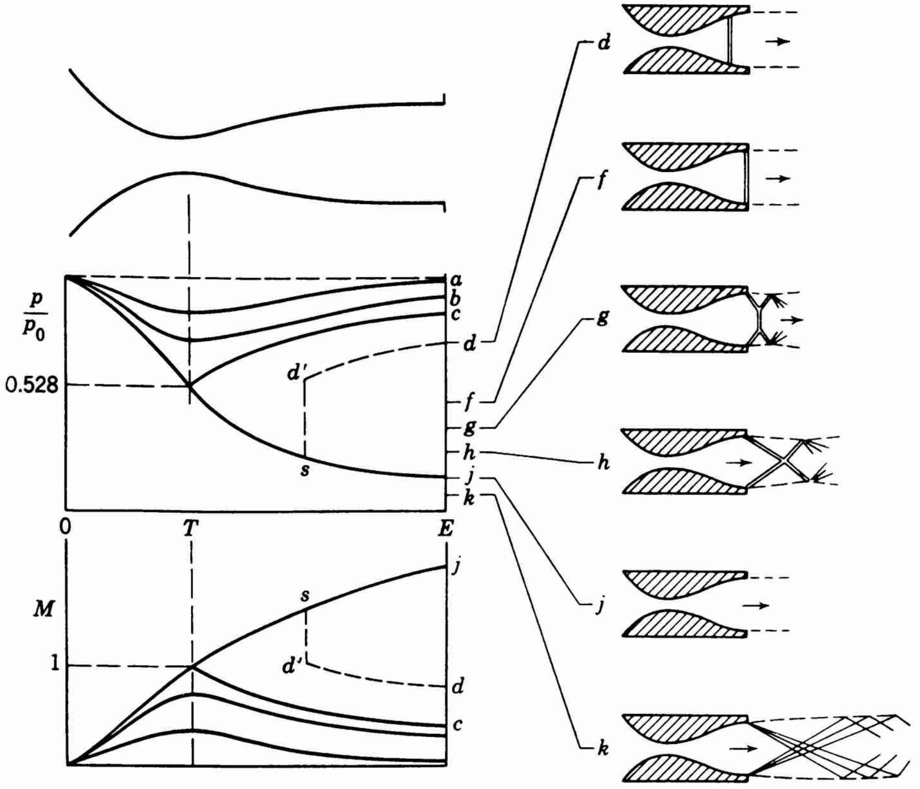
2. Jet engines

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**

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

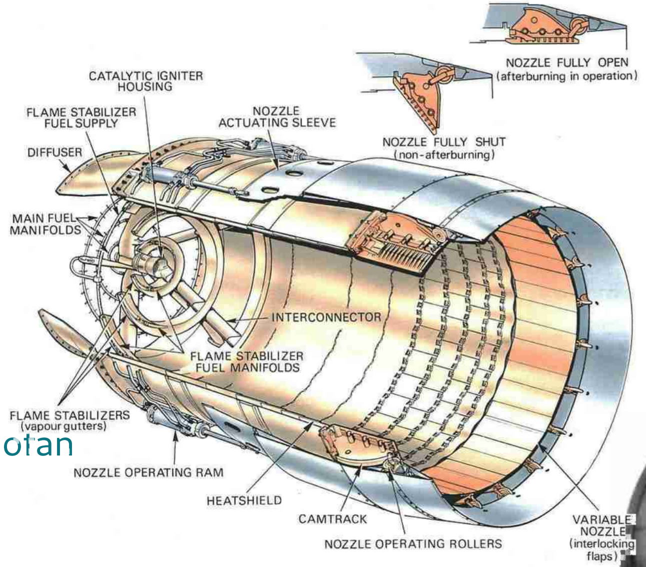
- **Maximal thrust if *adapted* ($p_j = p_a$)** $T = \dot{m}(v_j - v_f)$
- **Engine operating point = match GG and nozzle**
  - GG determines p° and T° upstream of nozzle
  - Nozzle limits maximum mass flow rate
  - Thrust can be optimized by varying throat (and expansion ratio)
  - Area needs to be variable to accommodate large variations in T°

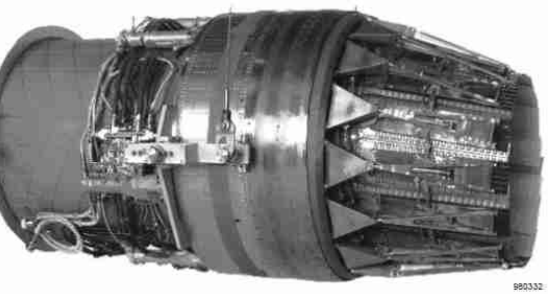


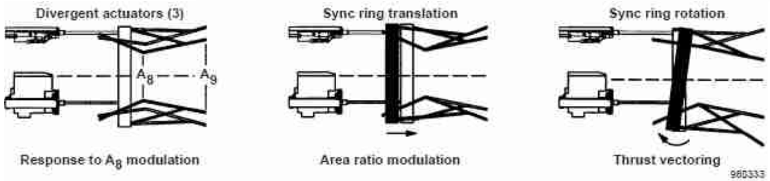
2. Jet engines

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

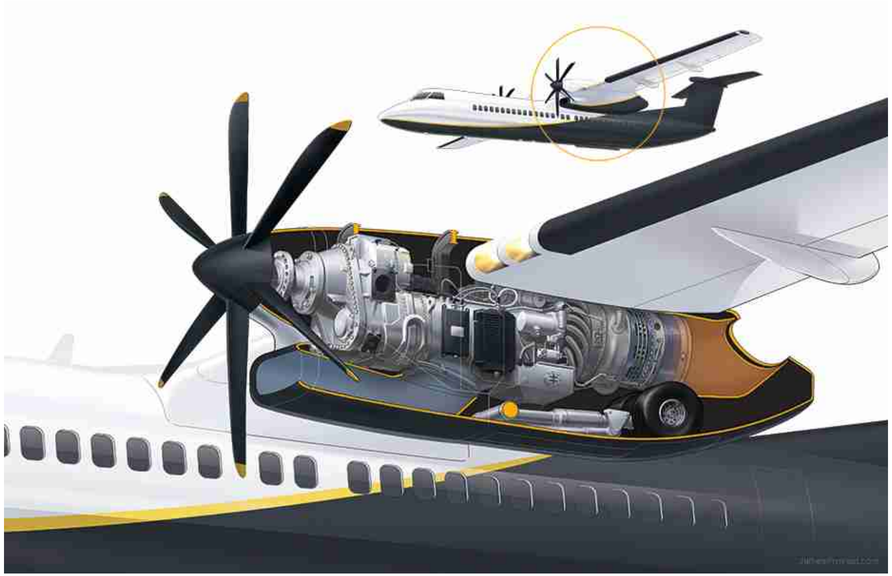


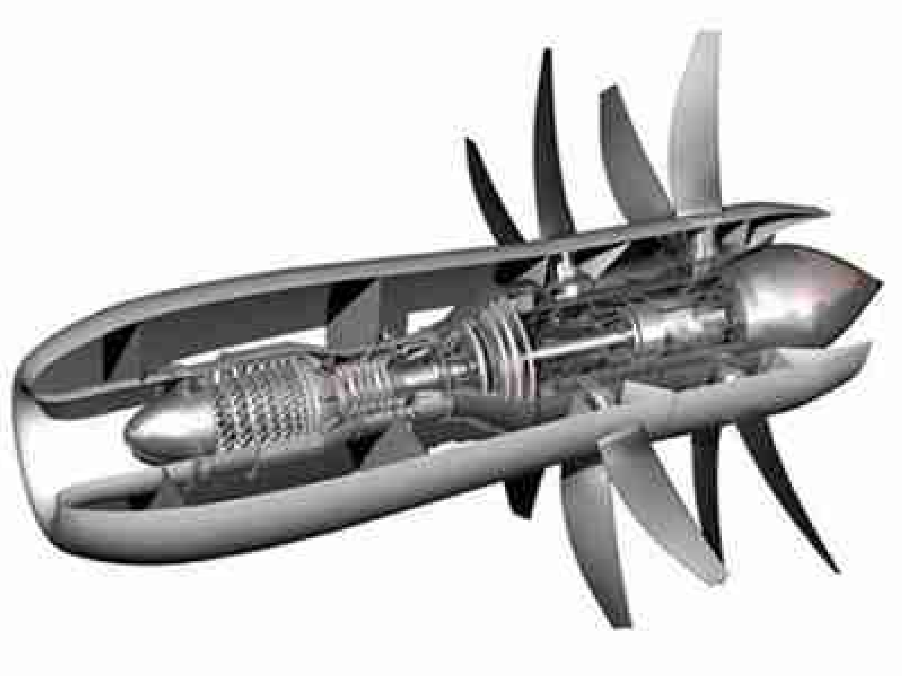




3. Propellers

Mechanical acceleration by lift forces on propeller blades





3. Propellers

Global operation: Rankine-Froude theorem

- **Accelerating / contracting stream tube**

$$\dot{m} = \rho v_0 S_0 = \rho v_1 S_1 = \rho v_2 S_2$$

- **Thrust** $T = \dot{m}(v_2 - v_0)$

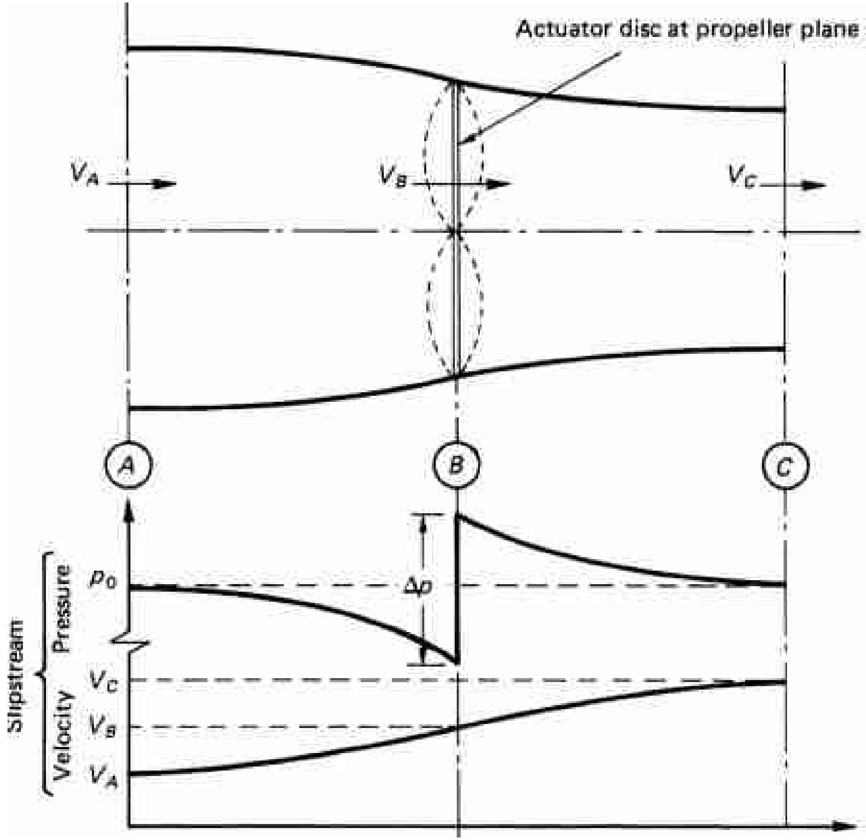
- **Propeller = actuator disk – pressure jump**

$$p_{1+} = p_{1-} + \Delta p$$

- **No losses up/down - Bernoulli**

$$p_{1+} = p_\infty + \frac{1}{2}\rho(v_2^2 - v_1^2)$$

$$p_{1-} = p_\infty + \frac{1}{2}\rho(v_0^2 - v_1^2)$$



3. Propellers

Global operation: Rankine-Froude theorem + induced velocity

- **Induction factor a**

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

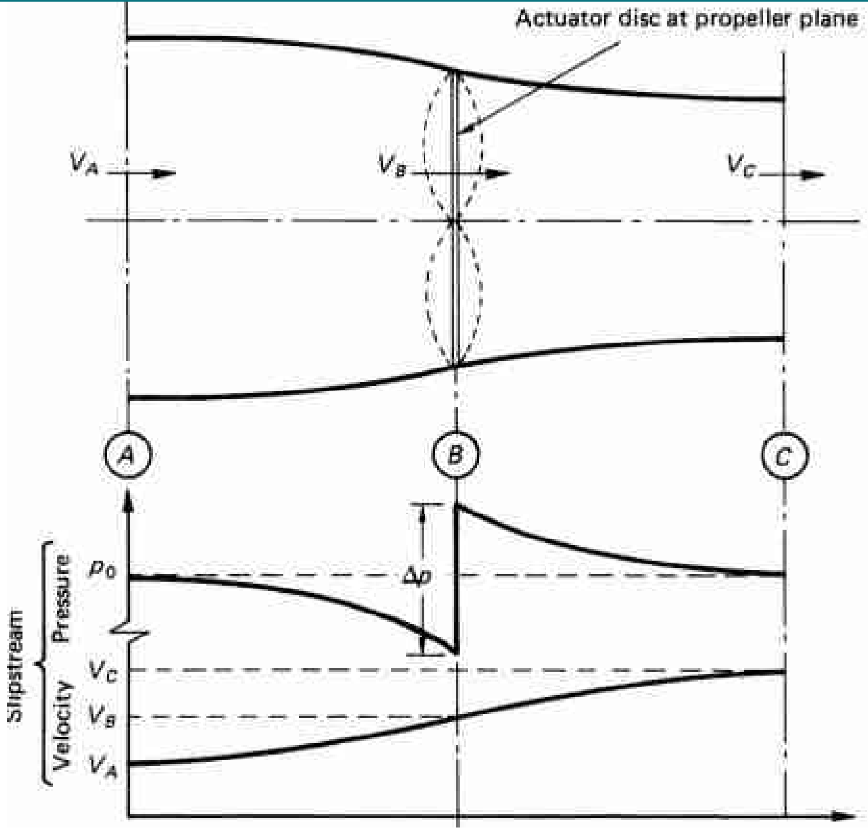
- **Thrust computed two ways**
  - stream tube control volume

$$T = \dot{m}(v_C - v_A) = \rho v_B S_1 (v_C - v_A)$$

  - pressure difference

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

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



3. Propellers

Global operation: thrust, power and propulsive efficiency

- **Thrust**

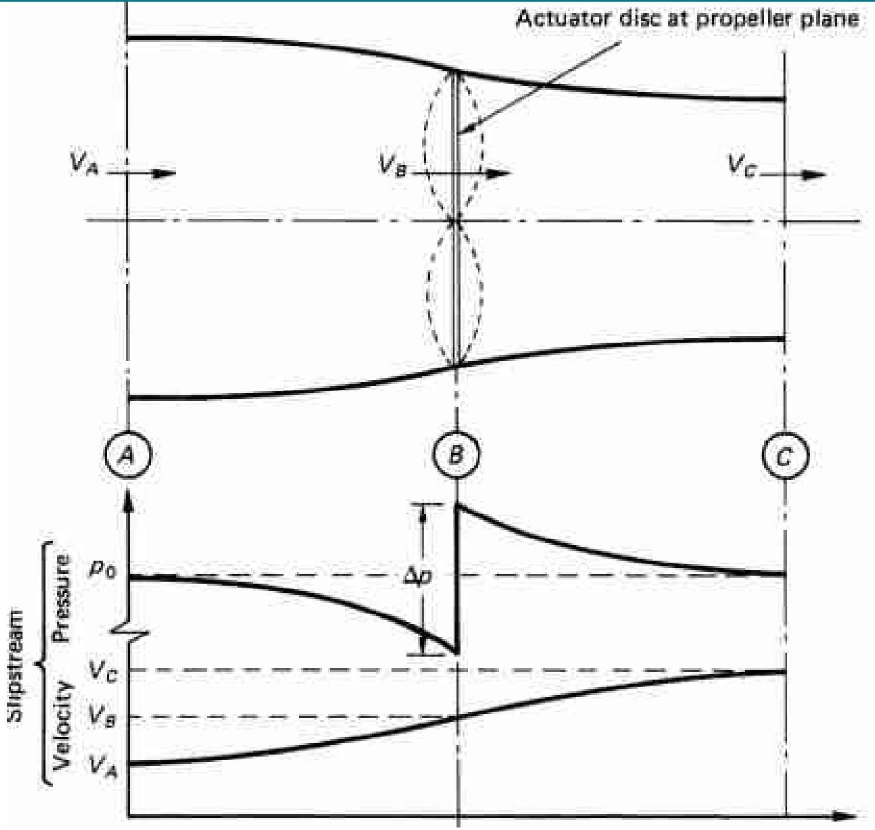
$$T = \dot{m}(v_C - v_A) = \rho v^2 S \cdot 2a(1+a)$$

- **Power**

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

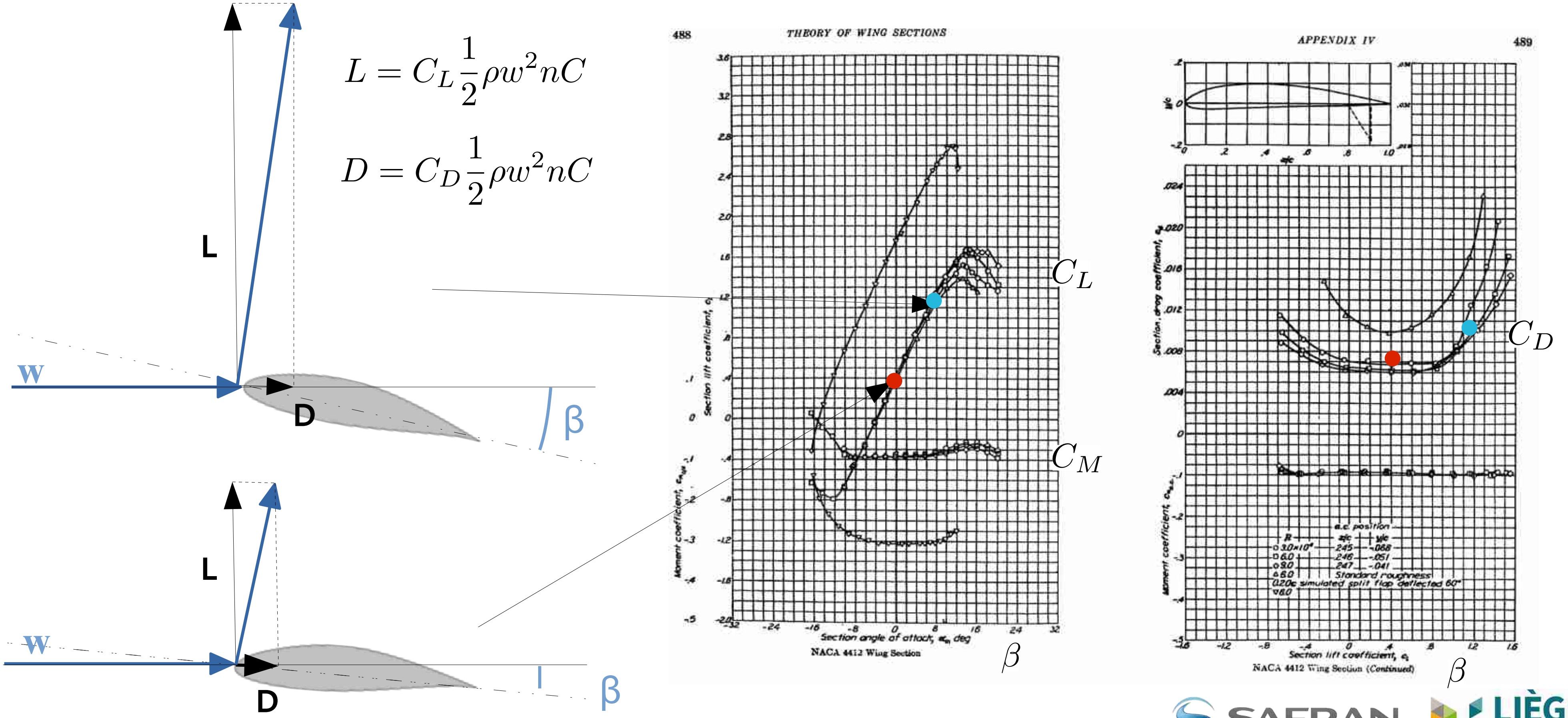
- **Propulsive efficiency**

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



3. Propellers

Blades : airfoil lift/drag polars



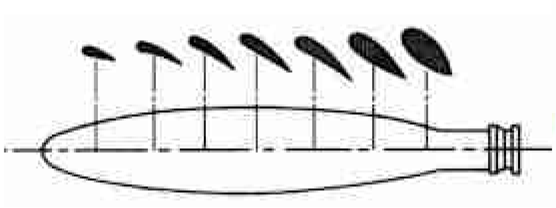
$$L = C_L \frac{1}{2} \rho w^2 n C$$

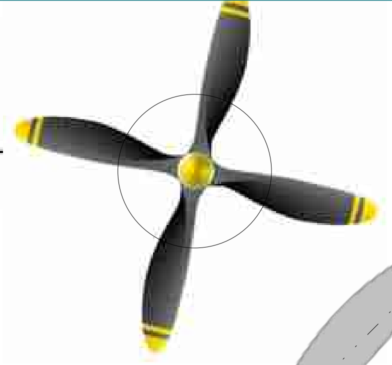
$$D = C_D \frac{1}{2} \rho w^2 n C$$

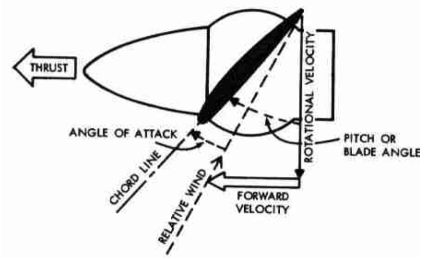
3. Propellers

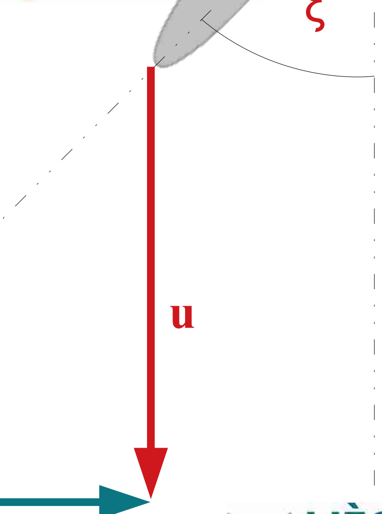
Blades – layout and operating parameters

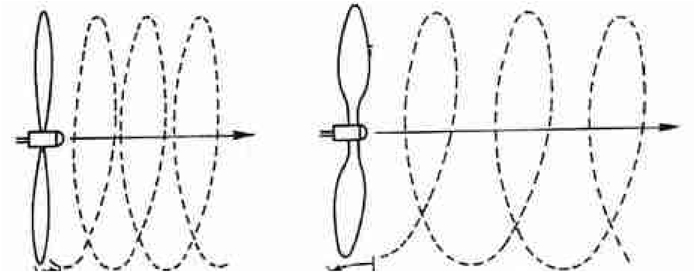
- **Geometry**
  - Tip radius R_t
  - (Radial distribution of) blade profile
  - Radial distribution of chord $C(r)$ / Solidity $\sigma(r) = N\,C(r)/2$
- **Operating parameters**
  - *Stagger* or *pitch* angle ξ
  - Rotation speed $\Omega \rightarrow$ local blade speed $u = \Omega\, r$
  - *Advance ratio* $J = v_a/u_t = v_a/\Omega\, r_t$











3. Propellers

Blade element method / Rotare - principle

- **Induction factor a at disk → v = v$_0$(1+a)**
- **Relative velocity w, flow angle β**

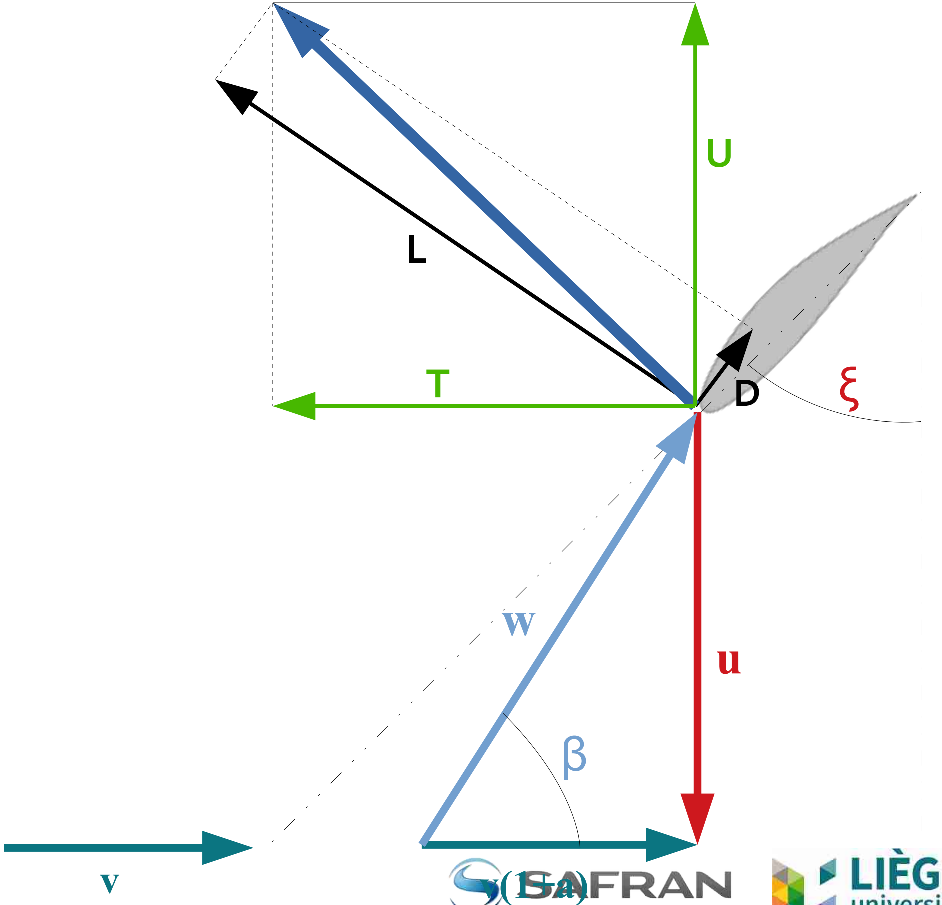
$$\mathbf{w} = (1+a)v_0\mathbf{e}_x + u\mathbf{e}_y$$

- **Lift/drag forces L & D as a function of**
  - Relative velocity w
  - Incidence i = ξ - β
- **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**



3. Propellers

Operation: performance parameters

- **Thrust coefficient**

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

- **Power coefficient**

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

3. Propellers

Operating point

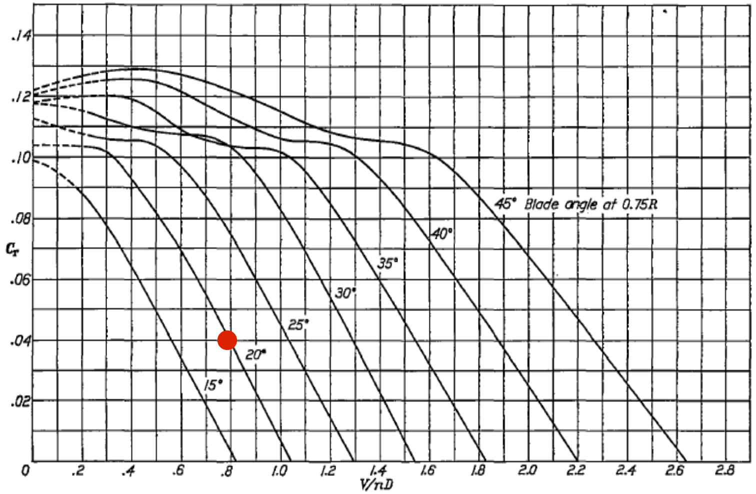


FIGURE 3.—Thrust-coefficient curves for propeller 5868-9, Clark Y section, 2 blades.

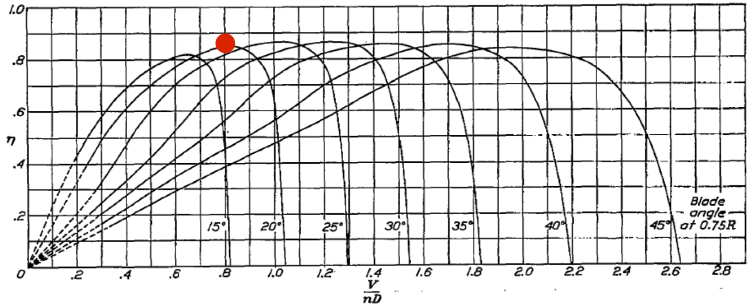
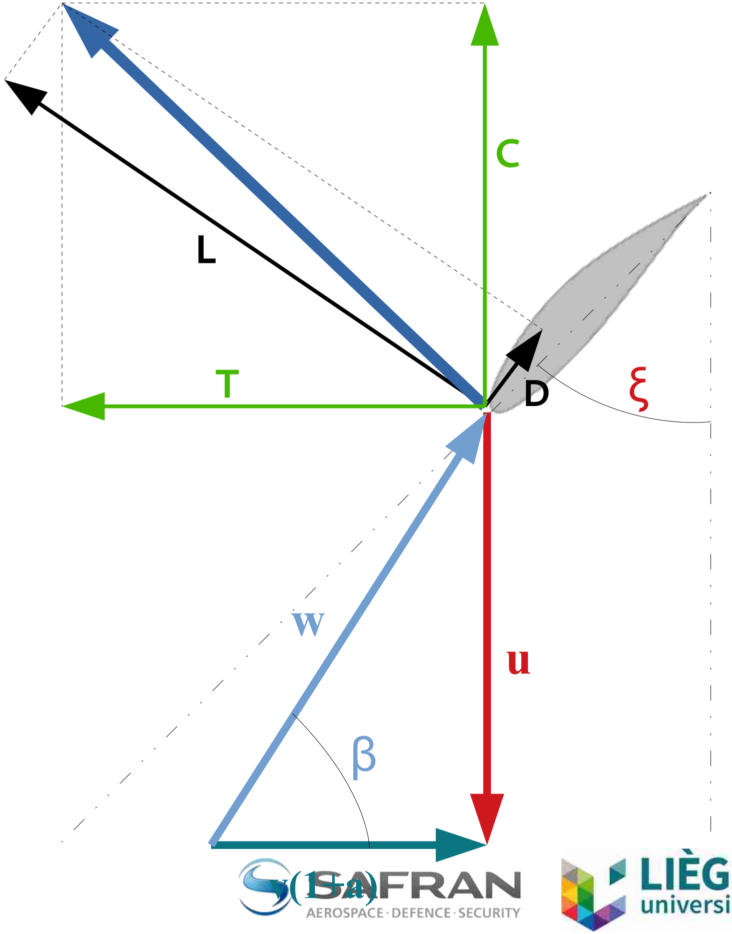


FIGURE 5.—Efficiency curves for propeller 5868-9, Clark Y section, 2 blades.



3. Propellers

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

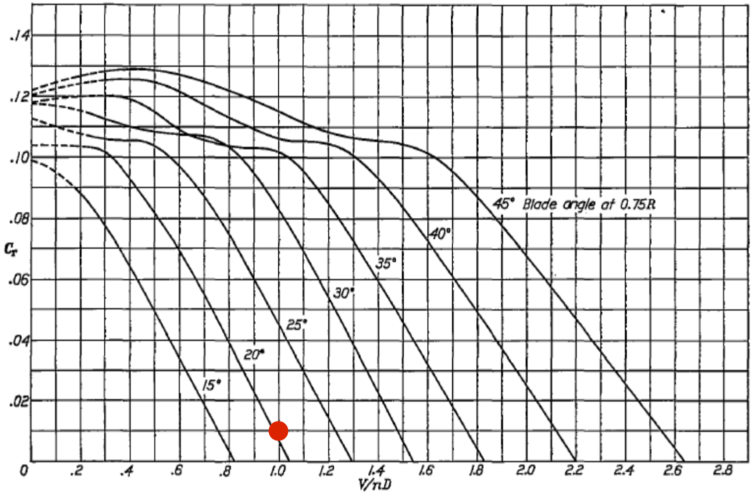


FIGURE 3.—Thrust-coefficient curves for propeller 5868-9, Clark Y section, 2 blades.

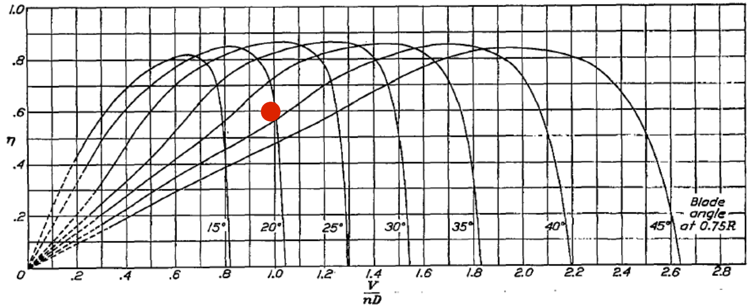
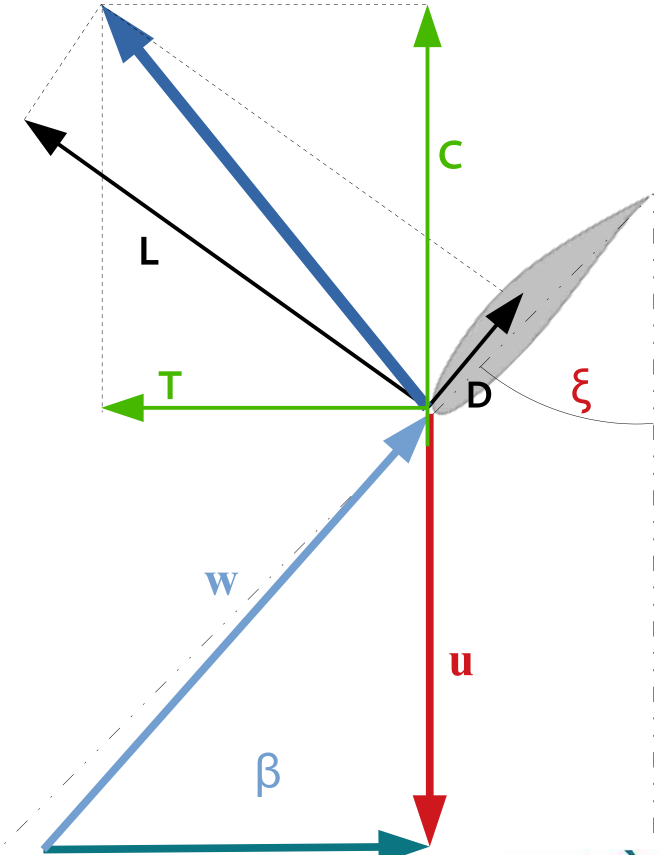


FIGURE 5.—Efficiency curves for propeller 5868-9, Clark Y section, 2 blades.



3. Propellers

Operation: pitch control

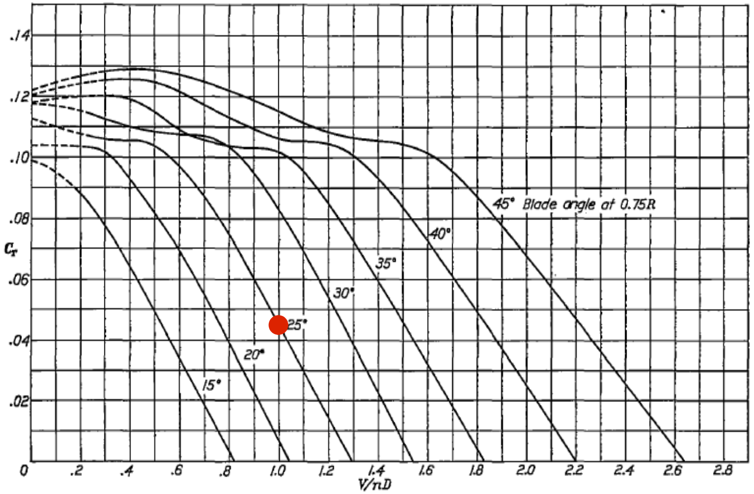


FIGURE 3.—Thrust-coefficient curves for propeller 5868-9, Clark Y section, 2 blades.

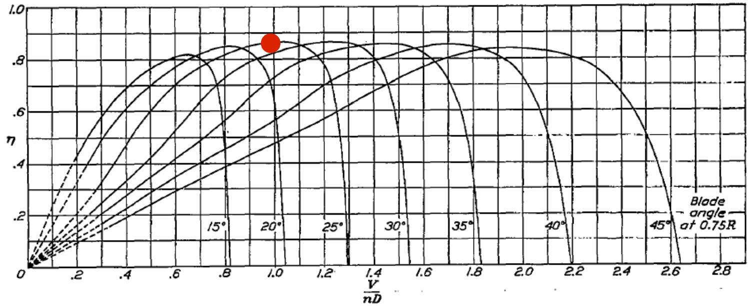
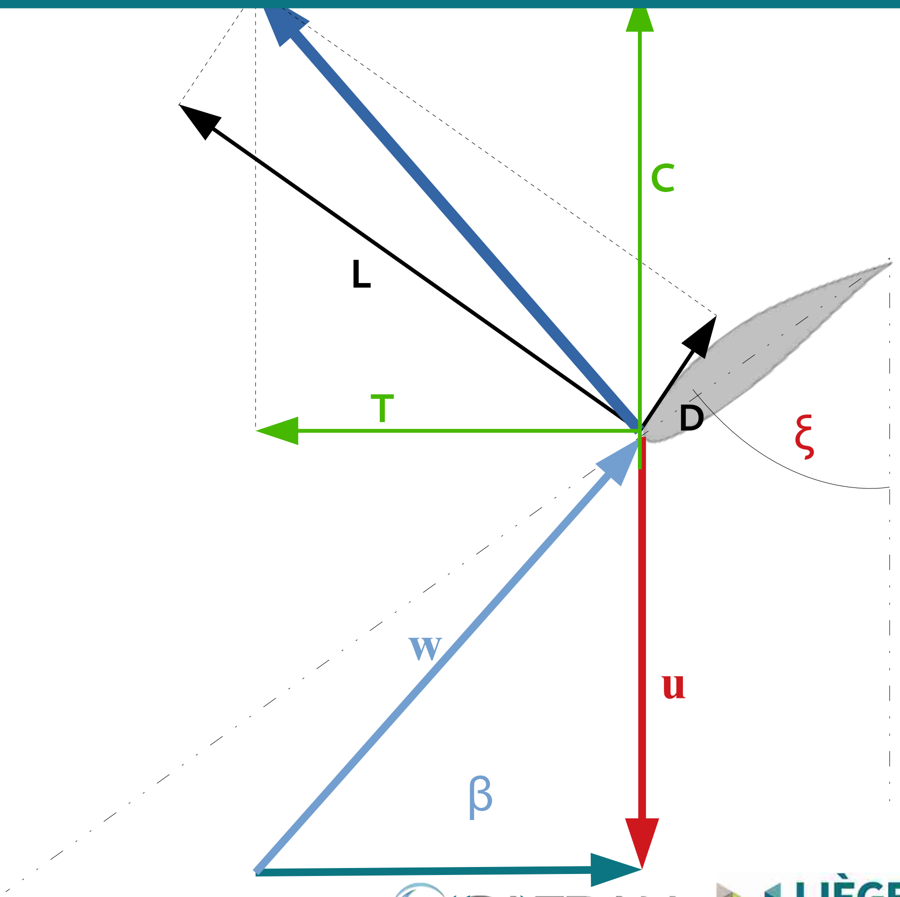


FIGURE 5.—Efficiency curves for propeller 5868-9, Clark Y section, 2 blades.



3. Propellers

Operation: pitch control

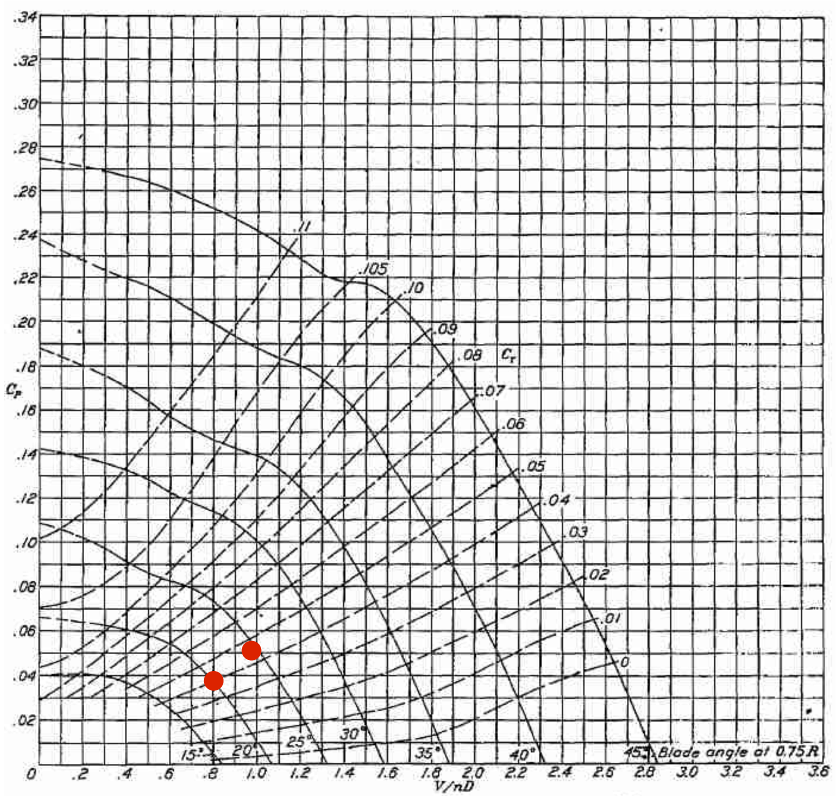
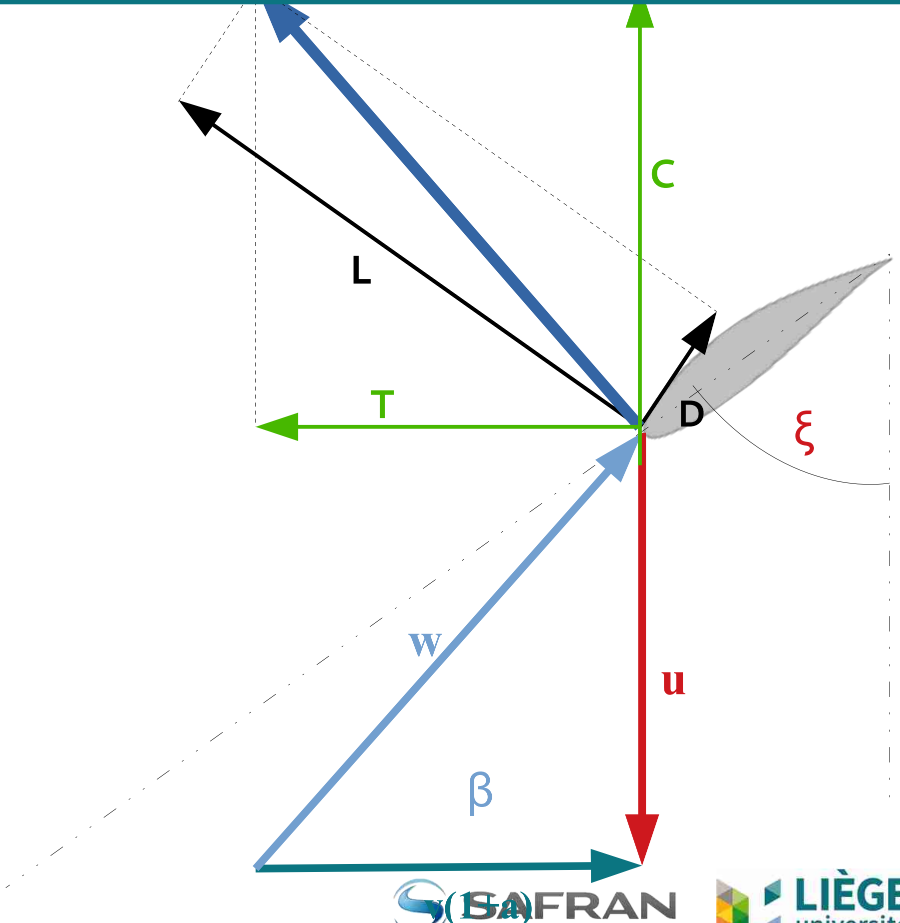


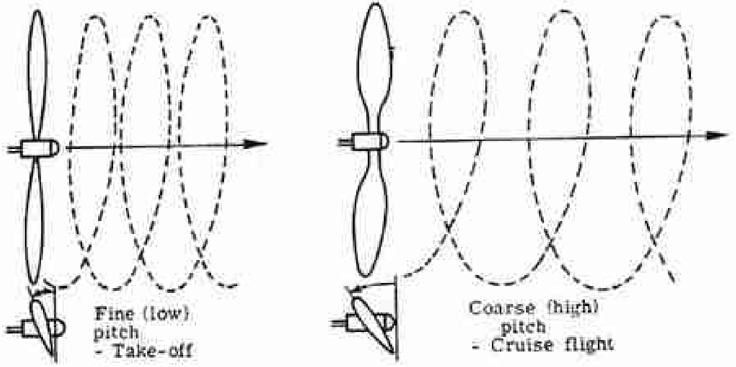
FIGURE 6.—Power-coefficient curves for propeller 5868-9, Clark Y section, 2 blades.



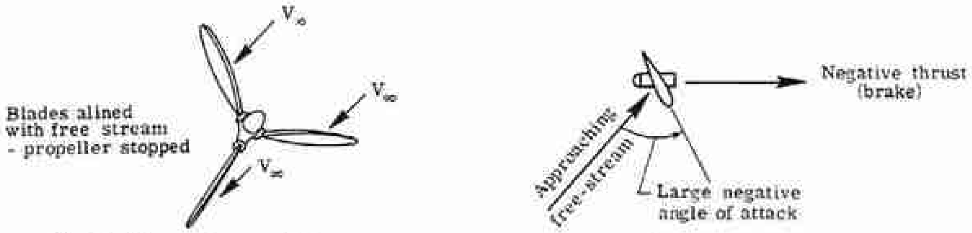
3. Propellers

Control

- **Means of control**
  - Engine power / rotation speed : T ~ n^2, P ~ 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.



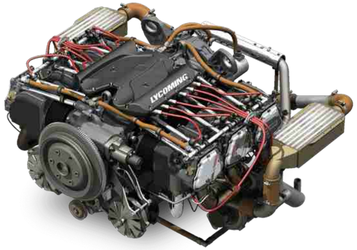
(b) Feathered propeller.

(c) Landing brake.

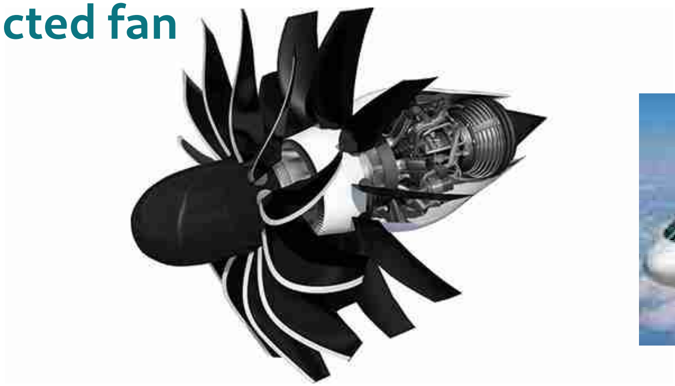
3. Propellers

Power generators

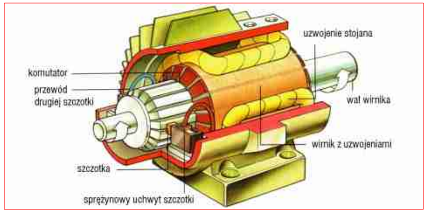
- **Internal combustion engine**



- **Gas turbine: turboprop & unducted fan**

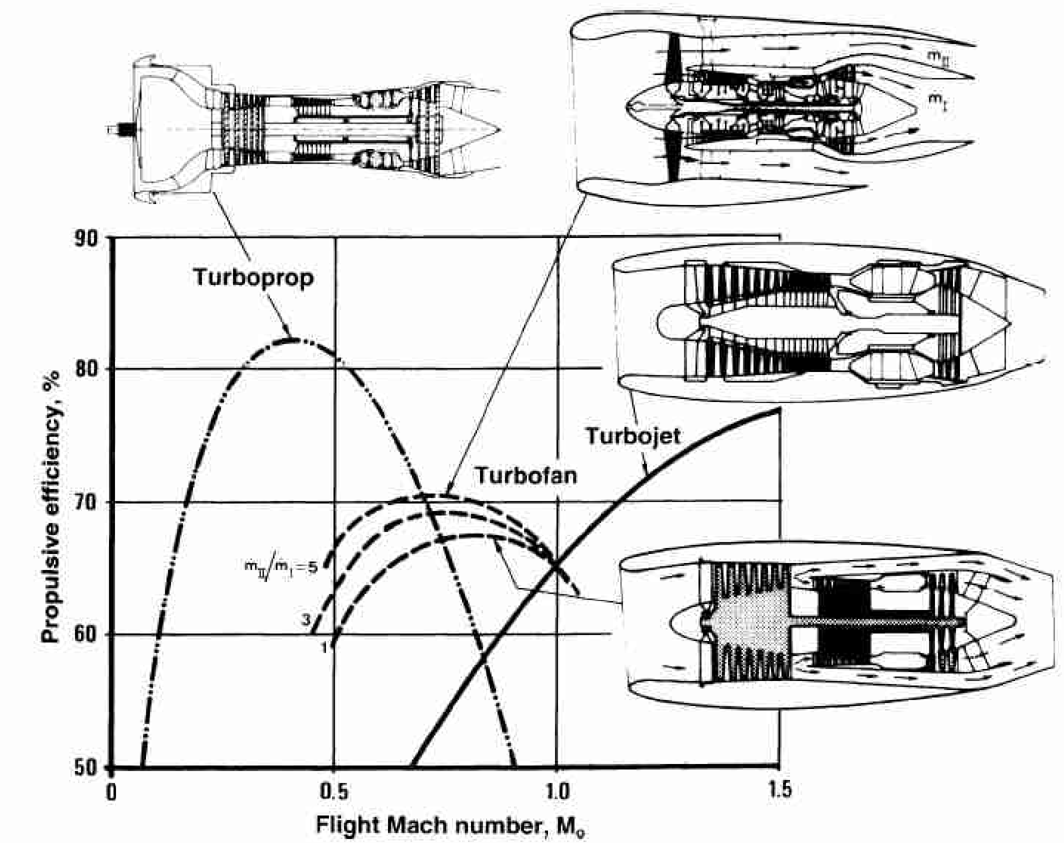


- **Future of propulsion systems : electric or hybrid, distributed …**



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 ?