Lezione 24 - Axial-Flow Compressors

Numero di Mach si calcola con la temperatura statica, ma si può usare la temperatura totale, cambia solo il numero! Il mach definito è con quello statica.

Axial-Flow Compressor Architecture

Axial Compressors are normally multistage due to their limits for β_T. Some need several stage.

Applications:
- Aero-engine
- Gas-turbine based power-generation

Max pressure ratio (β) for axial compressor ≈ 1.4

We generally look at a stage in the middle of the

<! Meridial view for aero-engine "Bypass 6">

We have different D and b through the compressor.
At a certain point we have an anular combustion chamber.

The number of stages is significant and can have implications.

Blade Aerodynamics and Load Limitations

Axial Compressors $\rightarrow \Delta U \simeq 0$

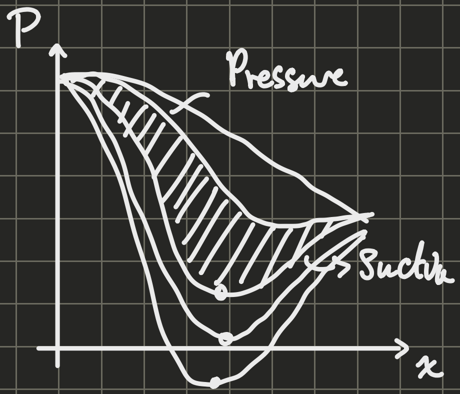
$$L^{\cdot} = \dot{m}\left(u_2 V_{2t} - u_1 V_{1t}\right) = \dot{m} u \left(V_{2t} - V_{1t}\right) = \dot{m} u \left(w_{2t} - w_{1t}\right)$$

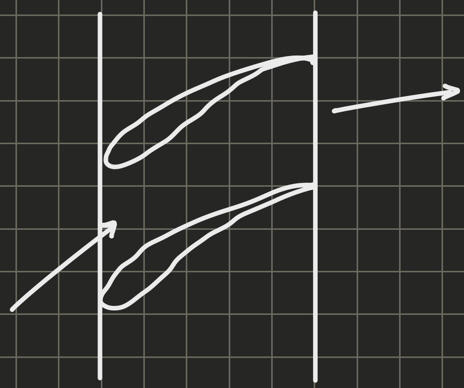
$$\overset{!}{=} \dot{m}\,\omega r\,(w_{2t} - w_{1t})$$

omega

$$\dot{L} = \omega C_{AERO,x} = \omega F_{t,aero}\, r \Longrightarrow \dot{m}\,\cancel{\omega}\cancel{r}\,(w_{2t} - w_{1t}) = \cancel{\omega} F_{aero}\,\cancel{r}$$

$$\Longrightarrow F_{aero,t} = \dot{m}\,(w_{2t} - w_{1t})$$





Once we want to exchange power, $\dot{L}$, we need a large pressure different, cause

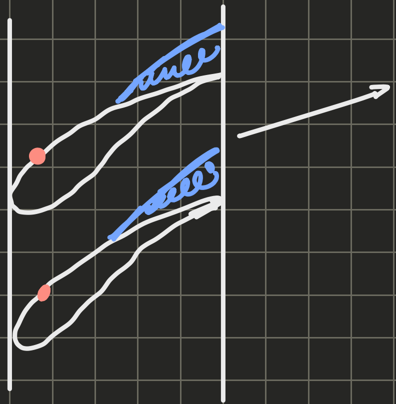
Higher the ΔP, the wider the Δw_t and the higher the $\dot{L}$

So there will be a connection between ΔP and β_T

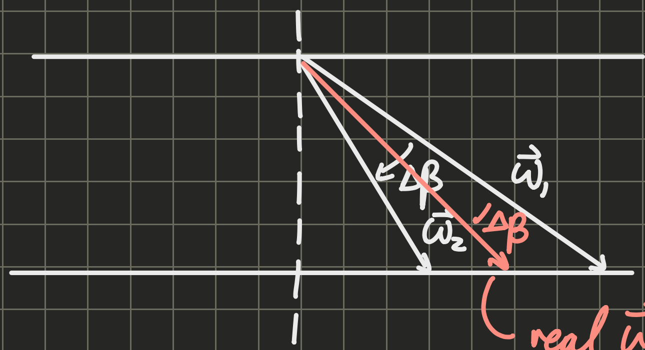
The greater the suction, the greater the adverse pressure gradient to get to P_{OUT}.

With an adverse pressure gradient you risk separation of the gas from the surface because the pressure there works with the friction.

• = point of maximum suction



The fluid separates, and begins to act like a wall for the flow.

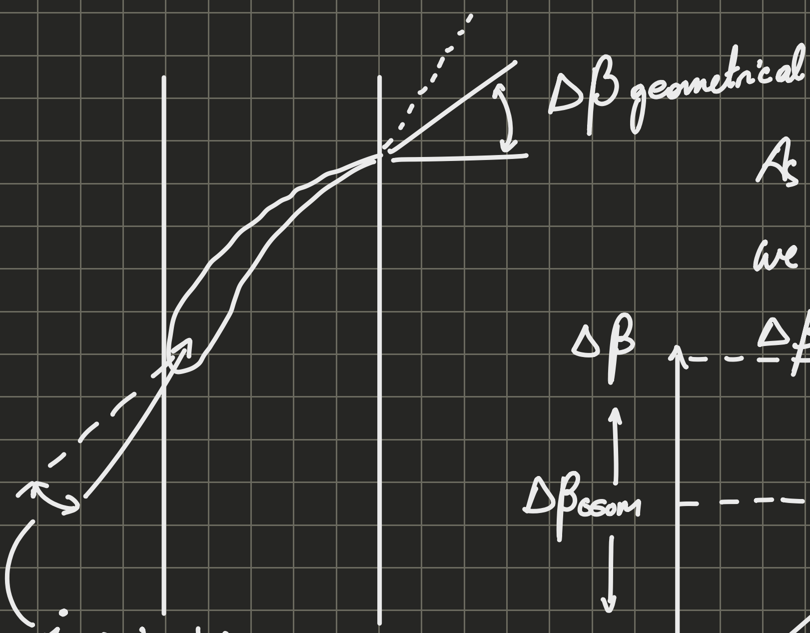


real $\vec{w}_2$ that is caused due to separation. The $\angle$ decreases from the expected and losses increase.

⇒ axial compressors cannot have separation, so we can only have a certain amount of deflection, limiting our β

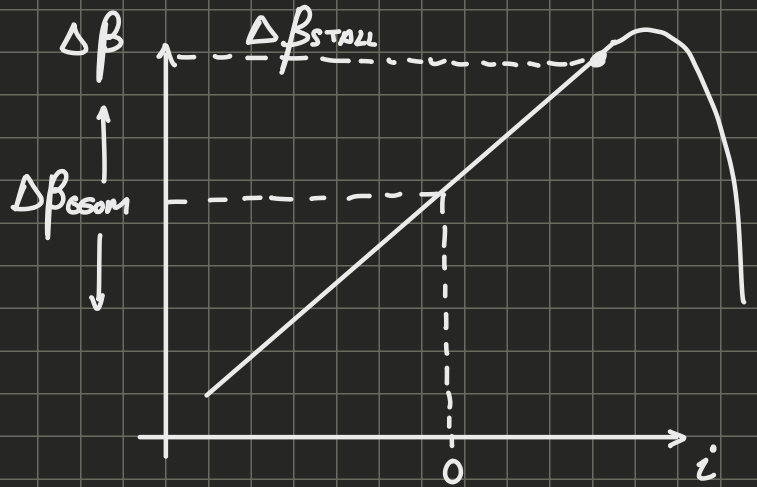
We could increase blades but then can also increase losses, so we have an optimum number of blades

15:05 → lead-in for this part



i → incidence
↳ caused by non-constructive angle

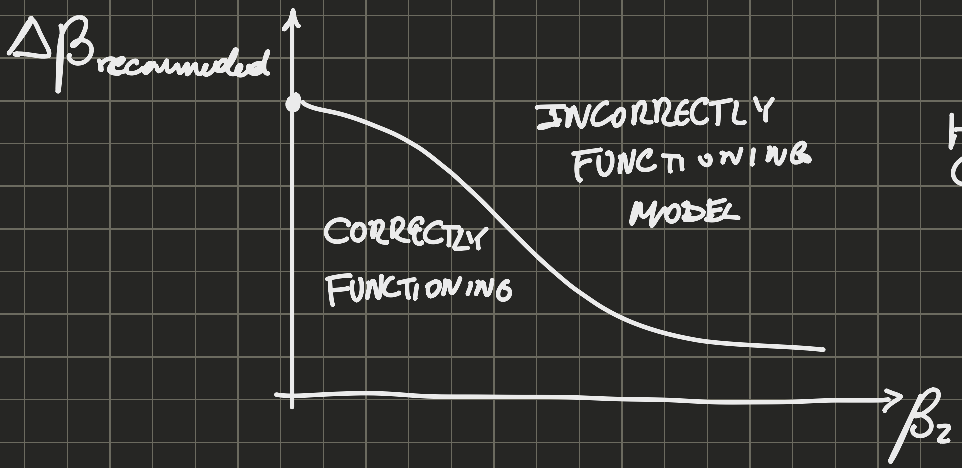
As we increase the incidence, we increase the flow deflection.



At a certain point, if we increase too much, ΔP causes detachment, decreasing the deflection.

Once we have separation we loose our constructive angles.
So $\Delta\beta$ would then become detached from, i

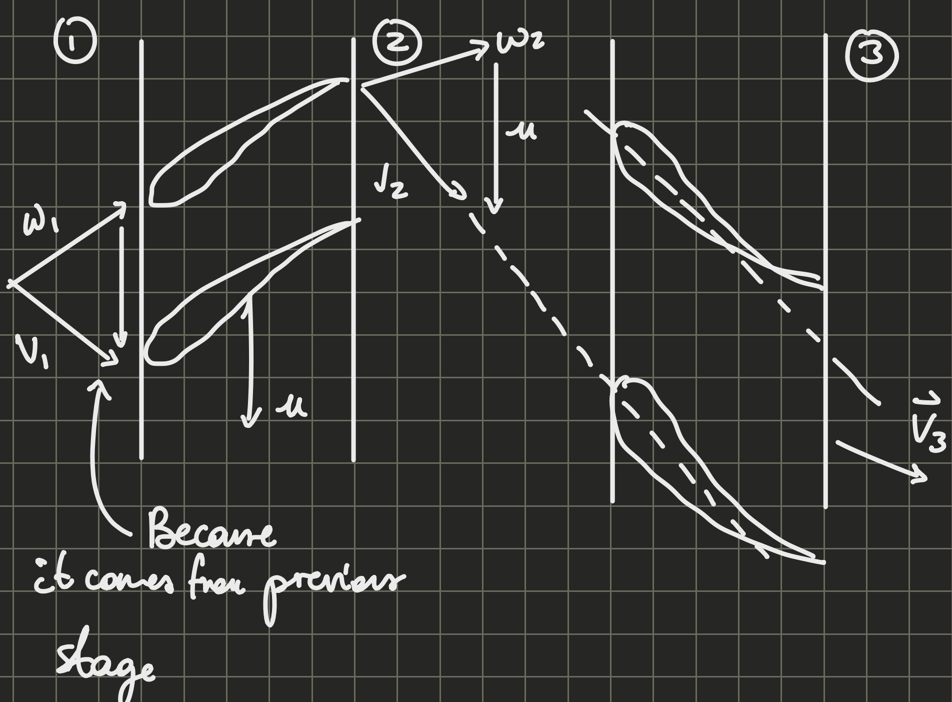
To not make things complicated, we work with
$\Delta\beta = .8\,\Delta\beta_{STALL}$

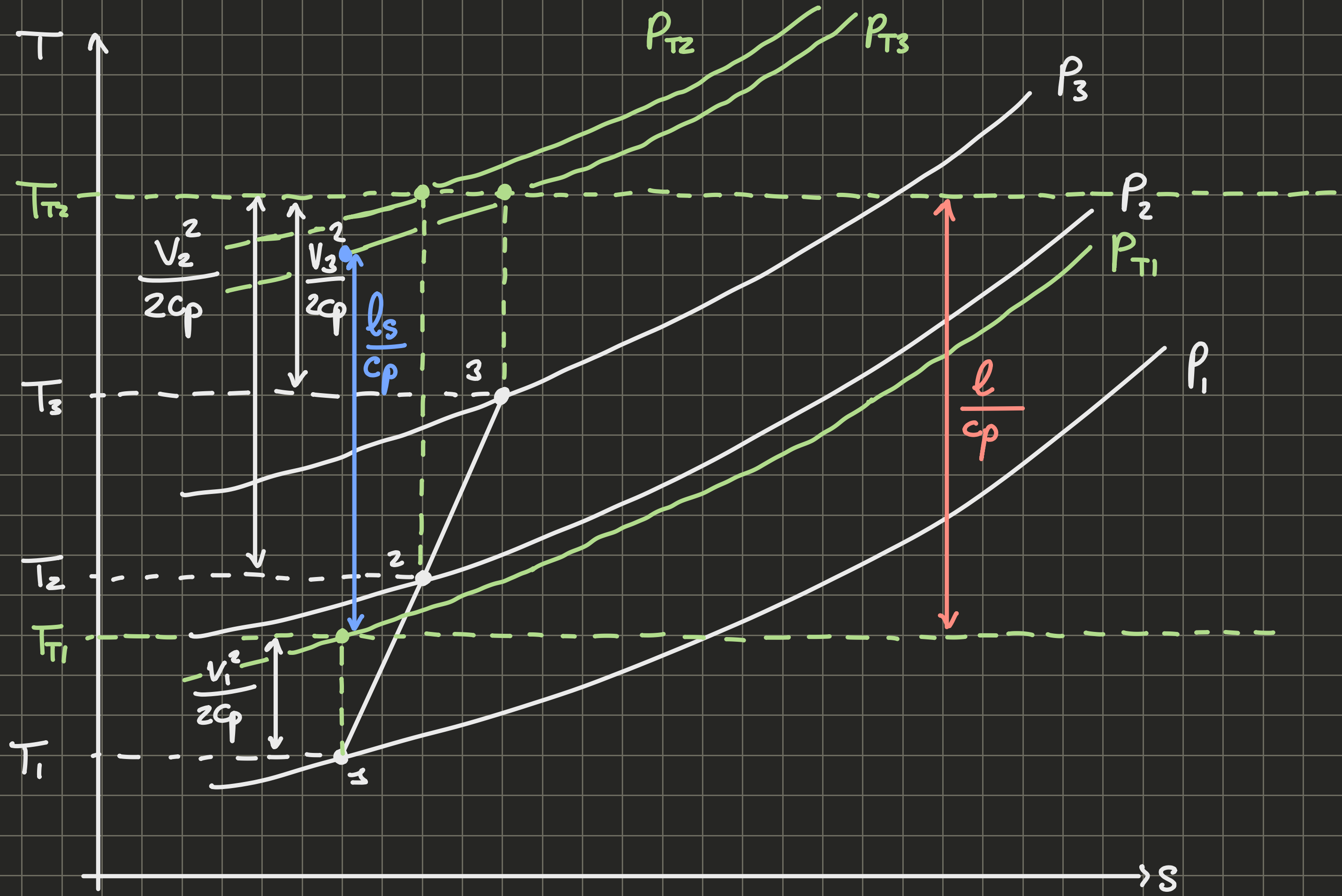


Howel Criterion

TF Diagram, η, Multi-stage from 1 stage
↳ Parts of rest of lesson

<u>Thermo-Fluid Diagram</u> for Axial Compressor





$l_s \rightarrow$ isoentropic work to rise from P_{T1} to P_{T3} in this case

$$\eta = \frac{l_s}{l} = \frac{c_p T_{T1}\left(\left(\frac{P_{T3}}{P_{T1}}\right)^{\gamma/\gamma-1} - 1\right)}{l}$$

$$\chi = \frac{\Delta h_R}{l} = \frac{h_2 - h_1}{l} = \frac{\omega_1^2 - \omega_2^2}{2l}$$

Enthalpy change in rotor

BERF: $\quad I = h + \frac{\omega^2}{2} - \frac{u^2}{2} = \text{const}$ if process is adiabatic

$\hookrightarrow$ Rothalpy

$$\Rightarrow h_1 + \frac{\omega_1^2}{2} = h_2 + \frac{\omega_2^2}{2}$$

$$\Rightarrow h_2 - h_1 = \frac{\omega_1^2 - \omega_2^2}{2}$$

To have an increase in enthalpy we need to decellerate the relative flow.

We can also develop l:

$$l = \frac{\Delta V^2}{2} - \frac{\Delta w^2}{2} + \frac{\Delta u^2}{2} = \frac{V_2^2 - V_1^2}{2} + \frac{w_1^2 - w_2^2}{2}$$

$$\Rightarrow \chi = \frac{w_1^2 - w_2^2}{V_2^2 - V_1^2 + w_1^2 - w_2^2} = \frac{\Delta h_R}{+\Delta h_R}$$

$$V_2^2 - V_1^2 + V_3^2 - V_3^2 = V_2^2 - V_3^2 + V_3^2 - V_1^2 = 2\Delta h_S + 2(V_3^2 - V_1^2)$$

BE across stator

$$\cancel{l}^{\to 0} + \cancel{q}^{\to 0} = \Delta h_T = h_{T3} - h_{T2} \Rightarrow h_3 + \frac{V_3^2}{2} = h_2 + \frac{V_2^2}{2} \Rightarrow \frac{V_2^2}{2} - \frac{V_3^2}{2} = h_3 - h_2$$

$$= \Delta h_{STATOR}$$

$$\overset{!}{=} \Delta h_S$$

$$= \frac{2\Delta h_R}{2\Delta h_S + 2\Delta h_R + V_3^2 - V_1^2}$$

It would be best if $V_3^2 = V_1^2$, this would also mean V_3 would be the V_1 for the next stage, allowing us to do an approach of designing all the stages the same.

Changing b with ρ, we can keep V_m constant, simplifying our calculations.

How to put together all the stages?

Repeated stage strategy, all the velocities are the same, with $V_m = \text{const}$, keeping the same kinematics but different thermodynamics.

Repeated Stage Strategy $\rightarrow \vec{V}_3 = \vec{V}_1$, all velocities identical

$\rightarrow l_{ST} = \text{const}$

↳ work exchanged in stage

Normal Stage : $V_m = \text{const}$

$$\chi = \frac{\Delta h_R}{\Delta h_R + \Delta h_S} = \frac{w_{1t}^2 - w_{2t}^2}{V_{2t}^2 - V_{1t}^2 + w_{1t}^2 - w_{2t}^2} = \frac{\cancel{w_{1m}^2}\tan^2\beta_1 - \cancel{w_{2m}^2}\tan^2\beta_2}{\cancel{V_{2m}^2}\tan^2\alpha_2 - \cancel{V_{1m}^2}\tan^2\alpha_1 + \cancel{w_{1m}^2}\tan^2\beta_1 - \cancel{w_{2m}^2}\tan^2\beta_2}$$

$$= \frac{\tan^2\beta_1 - \tan^2\beta_2}{\tan^2\alpha_2 - \tan^2\alpha_1 + \tan^2\beta_1 - \tan^2\beta_2}$$

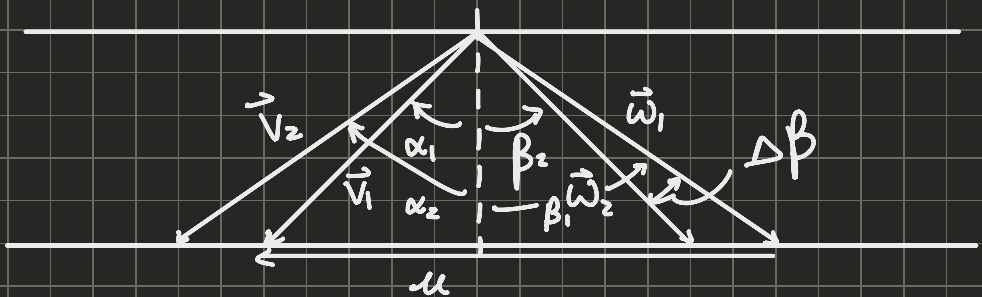
→ The reaction degree is the one which for axial compressors provides the highest performance.

$\chi = 0.5 \longrightarrow \Delta h_S = \Delta h_R$

Also $\Rightarrow \tan^2\alpha_2 - \tan^2\alpha_1 = \tan^2\beta_1 - \tan^2\beta_2$

$$\Rightarrow \begin{cases} \beta_1 = -\alpha_2 \\ \beta_2 = -\alpha_1 \end{cases}$$

→ Implication for velocity triangles:



This is an overly simple criteria to design a stage, → hoping $\Delta\beta$ is within Howel's criterion.
but this is only for the rotor since we want $v_3 = v_1$,
and so we need a $\Delta\alpha$ which follows Howell's criterion

Since the velocity angles are symmetric, $\Rightarrow |\Delta\alpha| = |\Delta\beta|$,
this means we can use one blade and just flip the blade for the stator so we only need one blade for all

the stages.

16:22 Missed lead-in

Once we have a multi-stage machine

$l_{ST} = \text{const}$

$\eta_{ST} = \text{const}\ ?$

$\eta_{ST} = f(\omega_s, D_s, \beta)$

↳ we have said this before, we can use the Baljè diagram

$l_{ST} = c_p T_{TIN,ST} \left(\beta_{TST}^{\frac{\gamma-1}{\gamma}} - 1 \right) / \eta_{ST}$

↳ Since l_s not l

not precisely

$\Rightarrow \beta_{T,ST} \neq \text{const}$

$\Rightarrow 1.1 < \beta_{T,ST} < 1.4$

↳ but low variability

$\beta_{T,ST} \approx \text{const}$

↳ at the level of the accuracy of the Baljè diagram

$\Rightarrow \eta_{ST} = f(\omega_s, D_s)$

η_{ST} can be kept const if $\omega_s, D_s = \text{const}$ along multistage-machine.

What do we have to do to keep it constant

$$\omega_s = \omega \frac{\sqrt{Q_{IN,ST}}}{l_{S,ST}^{3/4}} = \omega \sqrt{\frac{\dot{m}}{\rho_{IN,ST}}} \cdot \frac{1}{l_{S,ST}^{3/4} \cdot \eta_{ST}^{3/4}} \rightsquigarrow \omega_s \propto \frac{\omega}{\sqrt{\rho_{IN,ST}}}$$

$$D_s = D \frac{l_{S,ST}^{1/4}}{\sqrt{Q_{IN,ST}}} = D \frac{\eta_{ST}^{1/4}\, l_{ST}^{1/4}}{\sqrt{\dot{m}}} \sqrt{\rho_{IN,ST}} \rightsquigarrow D_s \propto D \cdot \sqrt{\rho_{IN,ST}}$$

If we can do this

$$\omega_s = \text{const} \iff \omega \propto \sqrt{\rho_{IN,ST}}$$

Where ρ is higher, the blades need to spin faster.

$$D_s = \text{const} \iff D \propto \frac{1}{\sqrt{\rho_{IN,ST}}}$$

To keep u the same as ω is increasing D needs to decrease.

Yes we can keep $\eta_{ST} = \text{const}$ at the cost of changing ω and D along the flow of the liquid.

While conceptually we can do it, in practice we cannot.

So we limit ourselves to at most 2 or 3 shafts for the same machine, independent on the number of stages.

$\boxed{16:54}$

It's possible to have a detached flow due to a reduced flow rate which can increase the incidence and so we begin to have problems.
When the aerodynamics of the machine fail there is nothing keeping the high pressure fluid from the low pressure one. This instability is called surge.
This is an oscillating behaviour of the fluid that can destroy the machine.