DESIGN OF AN AXIAL COMPRESSOR ROTOR

Notes for the class exercise (other comments during the class work)

Assumptions:

1. intermediate stage → inlet flow not axial (if possible normal stage)
2. Free vortex design for the blade: as $V_a \frac{\partial V_a}{\partial r} + \frac{V_t}{r}\frac{\partial (rV_t)}{\partial r} = 0$ → Va constant along the blade height
3. Constant density at inlet; constant blade height; constant mean diameter
4. Axial velocity may change in the stage.

INPUT DATA:

- Static to static pressure ratio: 1.25
- Mass flow rate: 120 kg/s
- Inlet static conditions: P = 1bar_A, T = 288 K

Draft PROCEDURE for the rotor design

Proposed procedure:

a. Application of Balje diagram
b. First choice according to Vavra results for the best efficiency point (ϕ , χ)
c. Check on Howell correlation
d. Design of rotor blades by Lieblein correlations

Velocity triangles:

1. By the pressure ratio → $L_{is,SS} = L_{is,TT}$ as in first approx, normal stage $V_1 = V_3$
2. By the mass flow + inlet conditions → volumetric flow rate
3. By step 1 and 2 and ω_S, Ds chosen on Balje → Rpm, Dtip, η_{TT}
4. By Dtip, λ_D = Dhub/Dtip (by Balje) → Dmean, Dhub and blade height
5. Chosen on Vavra at midspan: $\phi = 0.5$ → Vax and $\chi = \frac{h_2 - h_1}{Lu} = 0.5$
6. By mass flow rate → Vax: check with Vavra result and change in blade height (Iteration of steps 4 – 6, by changing λ_D to find out the correct blade height)
7. by ω and radii → U everywhere; given the Euler work , Vax, radii, ω → λ, φ can be calculated for all radii
8. to find out , α_{1M}: $\lambda = \frac{Lu}{U^2/2} = 2U\frac{(V_{2t} - V_{1t})}{U^2} = \left[V_{t\infty} = (V_{2t} + V_{1t})/2\right] = 4(V_{t\infty} - V_{1t})/U$

   but by the reaction coeff. definition: $\chi = 1 - V_{t\infty}/U$

$$V_{1t}/U = V_{t\infty}/U - \lambda/4 = 1-\chi-\lambda/4$$
$$tg\ \alpha_1 = V_{1t}/V_a = V_{1t}/U \cdot 1/\varphi$$
$$\alpha_1 = atg\left(\frac{1-\chi-\lambda/4}{\varphi}\right)$$

9. $V_{2t,M}$: $V_{2t} = Lu/U + V_{1t}$ *or* $V_{2t}/U = V_{1t}/U + \lambda/2$

$$V_{2t} = U(1-\chi+\lambda/4)$$

10. Free vortex application: V_{1t} * r = cost; V_{2t} * r = cost; all **Vt** upstream and downstream

11. Reaction degree, when free vortex applied and with Va=cost along the axial length:

$$\chi = 1 - V_{t\infty}/U = 1-(V_{2t}+V_{1t})/2U = 1-\frac{V_{2t,M}r_M + V_{1t,M}r_M}{2U\ r} = 1-\frac{V_{2t,M}r_M + V_{1t,M}r_M}{2\omega\, r^2}$$

$$\chi = 1 - K/r^2$$

12. Given the reaction degree, the temperature downstream of the rotor can be calculated; afterwards, by η_{TT}, T2is, P2is, rho2, new Vax, new reaction coefficient (that takes into account for the different axal velocity between inlet and outlet).

13. Since the Vax seems to be different along blade span, free vortex imposes the same Vax → new alfa2. After two iterations, of step 12, 13 the final Vax is achieved.
14. Given Vax, Vt, all W can be calculated → and also flow deflection on rotor/stator
15. Check on Howell correlation the loading → rotor can be loaded a bit
16. Change of Ds, ωs to find out RPM = 3000 (as we are close to it) and smaller diameters
17. Repeat steps from 4 to 15

blade calculation:

1. The first table reports kinematic quantities useful for Lieblein criterion application

2. The following parameter are set:
    - Max blade thickness with respect to chord (Th = 8)
    - Blade chord, constant along the blade height = 0.13 m
    - solidity =1 at midspan
    - camber angle (geometrical deflection) for 3 sections from Lieblein chart.

- Given the pitch and the mean radius → n° blades

- Given the blades count + radius → pitch, solidity at hub and tip

- Chosen the camber on draft charts, C_L can be calculated ($\theta_{eq} = 25\ C_L$)
- <u>Optimum incidence</u>: $i_{opt} = i_{0,10}\ K_{i,th} + n\ \theta$
    - By slides 10 → $i_{0,10}$
    - By slides 11 → $K_{i,th}$

- By slides 11 → n

- <u>Deviation angle</u>: $\delta = \delta_{0,10}\ K_{\delta,th} + {m\vartheta}/{\sigma^b}$
  - By slides 12 → $\delta_{0,10}$
  - By slides 12 → $K_{\delta,th}$
  - By slides 13 → m
  - By slides 13 → b

- <u>The kinematic deflection</u> can now be calculated and check if what required: $\Delta\beta = \varepsilon = \theta + i - \delta$
- if $\Delta\beta$ it not correct, θ_{eq} has to be modified and recalculated

- <u>Stagger</u>: given the NACA65, the difference between the mean line and the stagger is $\theta/2$. With reference to Slide 17 : $\beta_1 = \gamma - \theta/2 - i_{opt}$ —> $\gamma = \beta_1 + \theta/2 + i_{opt}$

- axial chord: $C_a = C \cos\gamma$ tangential chord: $C_t = C \text{ sen } \gamma$

- outlet kinematic angle check: since $\beta_{2,g} = \gamma - \theta/2$ → $\beta_{2,cin} = \beta_{2,g} + \delta$ and it is possible vthe check the actual outlet flow direction / deflection ($\Delta\beta_{nom}$; $\Delta\beta_{reale}$)

LOADING CRITERION: The Lieblein global diffusion factor is applied:

for rotors: $D = \frac{W_1 - W_2}{W_1} + \frac{|W_{1t} - W_{2t}|}{2W_1\sigma}$ Better to have: D < 0.6 ; for stator use absolute quantities.

PROFILE LOSSES EVALUATION: The formula proposed by Lieblein is applied

BLADE GEOMETRY BUILT UP

<u>Generic profile definition:</u>

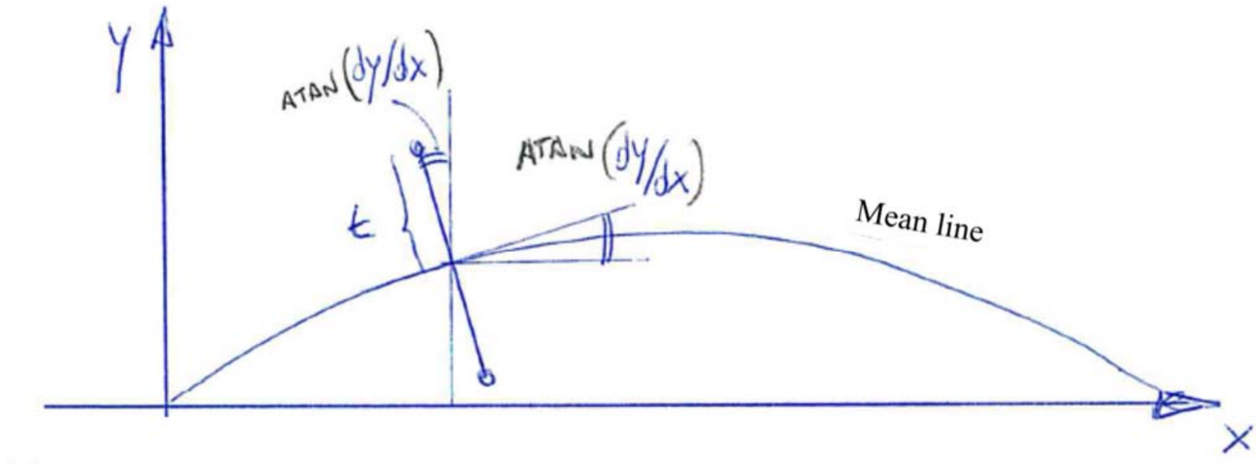
- from SLIDE 18 , The chord-wise thickness for the NACA 65 profile with max thickness of 8% can be calculated:

  t = t% * chord * TH/10 con TH = 8 (max thickness with respect of the chord)

- from SLIDE 19, the mean line can be determined, as well as the pressure side and suction side one

  y = y% * chord * CL in fact, $y = f(\theta)$, but $C_L = f(\theta)$ → $y = f(C_L)$
  x = x% * chord
  dy/dx = dy/dx * CL : mean line slope

  <u>warning:</u>
  1. the slope is positive up to 50% of the chord and then negative till 100%
  2. neglect the rounding of the leading and trailing edge



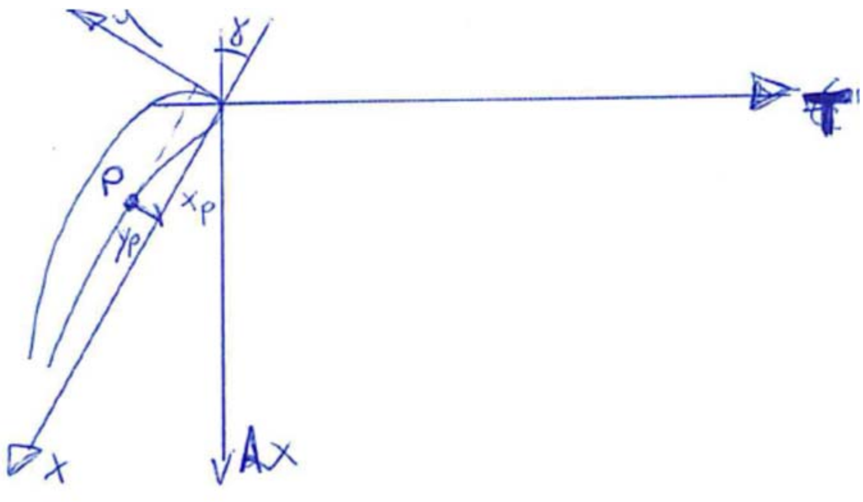
the generic coordinate is so far described by:

<u>pressure side</u>: $x_p = x + t * \sin(\text{atan}(dy/dx))$ $y_p = y - t * \cos(\text{atan}(dy/dx))$

<u>suction side</u>: $x_p = x - t * \sin(\text{atan}(dy/dx))$ $y_p = y + t * \cos(\text{atan}(dy/dx))$

<u>transfer of the profile into the machine coordinate system:</u>

It consists of the profile rotation from the intrinsic blade coordinate system to the machine one by applying a rotation: the angle of rotation is the stagger angle.



Tangential coordinate: $T = - x_p \text{ sen}(\gamma) - y_p \cos(\gamma)$

Axial coordinate: $Ax = x_p \cos(\gamma) - y_p \text{ sen}(\gamma)$

Values of T and Ax are different for each radial section - Hub, Mid and Tip

<u>Profile Stacking:</u>

the profile has to be stacked by keeping the chord mean points (each mean point for every radial section) to be coincident on the blade to blade plane.

Tangential shift: $\Delta C_t = C_{t,x} / 2$ with x = hub, mid, tip

Axail shift: $\Delta C_a = C_{a,x} /2$ with x = hub, mid, tip

$T = T - \Delta C_t$; $Ax = Ax + \Delta C_a$