TURBOMACHINERY AERODYNAMICS

Lect - 30

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Axial Flow Turbine

3-D blade design

Design Steps : Design steps in brief are

- Selection of parameters
- Design at mean diameter, *Dm*
- Radial variation of parameters
- Profiling of stator and rotor blades

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1. Design at Dm

a) Parameters to be selected from the preliminary cycle (thermodynamic) calculations are: (@ flt velocity & altitude), T_g, $\dot{m}_g$, P_a , T_a at design point P_g^*, π_T^*, P_T^*
and the engine parameters

η_T^* = 0.88 – 0.90 for one stage
= 0.91 – 0.94 for each stage for multi-stage

b) Parameters selected from compressor-turbine matching are:

Exit U_{mean}, D_{mean}, D_{tip}, $\bar{d}$, λ_2 or M_2

[**λ** is a total temperature based critical speed ratio, **λ =V/a$_{cr}$**]
and, $a_{cr} = \sqrt{\gamma_g R T_{0i}}$

All these should lead to a work distribution, $H_T = \sum_{1}^{z} H_i$
and number of stages Z.

2. Design at *Dm*

Matching : Peripheral velocity, *u* is selected from turbine-compressor matching criteria. The outlet velocity from the nozzle may be supersonic, but inlet relative velocity to rotor is generally brought down below sonic speeds. The respective sonic speeds are:

At nozzle exit

$$a_2 = \sqrt{\gamma R T_2}$$

At rotor exit

$$a_3 = \sqrt{\gamma R T_3}$$

Total Temp based critical speed at the nozzle exit

$$a_{cr2} = \sqrt{\gamma_g R.T_{02}}$$

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Blade passage wall temperature at *Dm*

$$T_{wt} = T_{0t} - \frac{C_2^2 - V_2^2}{2C_p} = T_{0t} - \frac{\gamma - 1}{2\gamma R}\left(C_2^2 - V_2^2\right)$$

$$V_2^2 = C_2^2 + U^2 - 2UC_2 \sin\alpha_2$$

$$\frac{T_{wt}}{T_{0t}} = 1 - \frac{\gamma - 1}{\gamma + 1}\left(2\lambda_2 . \lambda_u . \sin\alpha_2 - \lambda_u^2\right)$$

and
$$\frac{\lambda_{2\text{-}abs}}{\lambda_{2\text{-}rel}} = \frac{\cos\beta_2}{\cos\alpha_2}\sqrt{\frac{T_{wt}}{T_{0t}}}$$

where

$\lambda_{2\text{-}abs} = C_2 / a_{cr}$

$\lambda_{2\text{-}rel} = V_2 / a_{cr}$

$\lambda_u = U / a_{cr}$

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Choice of velocity triangle for the rotor inlet is obtained by the relation,

$$M_{2\text{-}rel} = J_1\left(M_2 - M_{2u}\right), \qquad \text{where}$$

$$J_1 = \sqrt{1 + \frac{1 - \sin\alpha_1}{\frac{M_1 / M_{1u} + M_{1u} / M_1}{2} - 1}}$$

$$= 1.2 \text{ to } 1.4, \text{ is a flow coefficient}$$

At the exit of the stage, Mach number can be expressed as,

$$M_3 = J_2 \left(M_{3\text{-}rel} - M_{3u} \right)$$

Where, another flow coefficient J_2 is used,

$$J_2 = \sqrt{1 + \frac{1 - \sin\beta_3}{\dfrac{M_{3\text{-}rel}/M_{3u} + M_{3u}/M_{3\text{-}rel}}{2} - 1}} = 2.5 \text{ to } 4.5$$

$$M_{3u} = M_{2u} \cdot \sqrt{\frac{T_2}{T_3}}$$

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For moderate pressure drops (π <2.0) the flow in the rotor may be entirely subsonic. However for high pressure drops (π >2.5), the flow becomes transonic at the stator trailing edge.

Stator Exit flow conditions:

From continuity, for an unit length of the blade, at throat

$$\rho_t . V_t . s_t . 1 = s.1.\rho_3 . V_3 . sin\beta_{3eff}$$

s = blade spacing or pitch

$s_t = O$ = Throat width,

Subscript ***t*** for throat

β_3' = blade exit angle

β_3 = flow exit angle

$\beta_{3\text{-}eff}$ = Mass - averaged effeective flow exit angle

Generally, because of diffusion

$$\rho_t . V_t > \rho_3 . V_3$$

Subscript t for throat

$$sin\beta_{3\text{-}eff} = \frac{s_t}{s}$$

Throat area ratio

The exact relationship between β_2 *and* s_t / s can be found experimentally by accurate cascade analysis

$$\beta_3 = sin^{-1}\left(k_2 \frac{s_t}{s}\right)$$

Initially assume $K_2 = 1$

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a) Actual R_x ,

$$R_x = \frac{h_{rotor}}{h_{rotor} + h_{stator}} = \frac{h_{rotor}}{h_T} = \frac{V_3^2 - V_2^2}{2h_T}$$

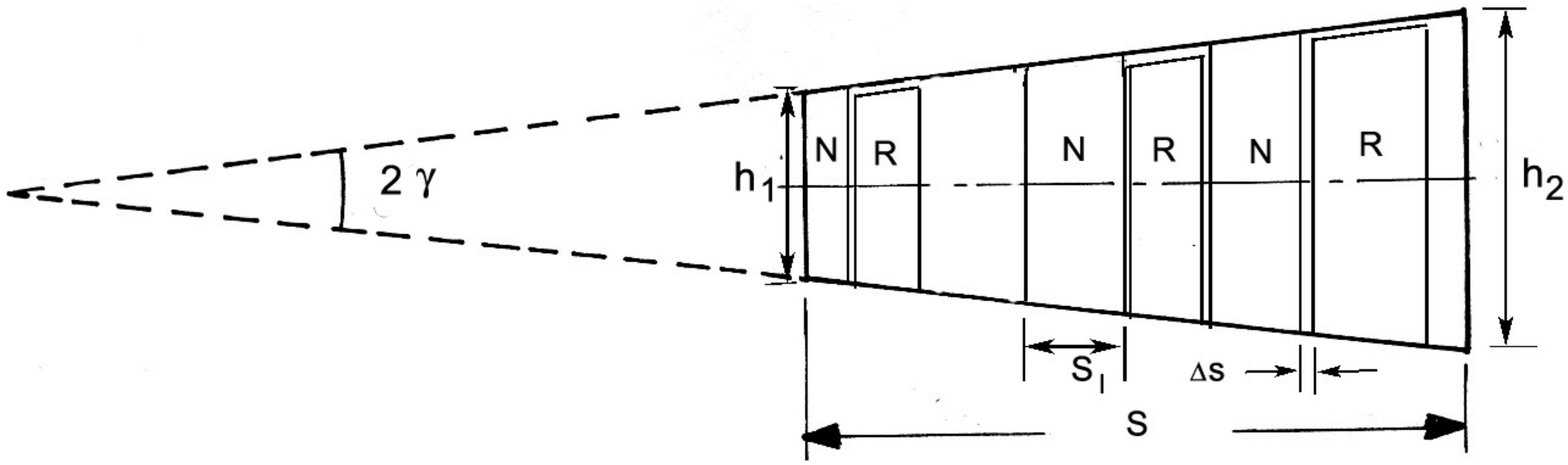
Degree of Reaction - ideal to actual change

DR	0	0.1	0.25	0.35	0.45	0.5
DR_{act}	0.03	0.073	0.226	0.33	0.433	0.485

b) Distribution of work in a multi-stage turbine

$$H_T = \sum_{1}^{z} H_i$$

c) Selection of flow track i.e. λ angle (local)



d) Velocity triangle and other parameters.

i) $$H_T = \frac{H_{T\text{-}actual}}{\overline{w}_{rotor}} \quad , where\ \overline{w}_{rotor} = 0.97 - 0.98$$

(Loss coefficient)

ii) $$C_{2w} + C_{3w} = \frac{H_T}{U}$$

$$C_{2w} - C_{3w} = 2U\left(1 - DR\right)$$

From which C_w are selected at mean diameter

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iii) Select three probable values of α_2 and for each one of them calculate the velocity triangle parameters at various radial stations

$$C_{2a} = \frac{C_{2w}}{tan\alpha_2} \qquad where,\ C_2 = \frac{C_{2a}}{cos\alpha_2}, \qquad \lambda_2 = \frac{C_2}{a_{cr2}}$$

And , λ_{cr2} = 0.85 to 0.9

iv) Assume velocity coefficient ϕ, and calculate pressure loss coefficient δ_{noz}

$$\delta_{noz} = \frac{\pi\left(\dfrac{\lambda_2}{\phi}\right)}{\pi(\lambda_2)}; \qquad P_{02} = P_{01}.\delta_{noz}$$

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v) $$A_2 = \frac{\dot{m}_g}{\rho C_{2a}}$$

From which Blade height $$h_{2_{bl}} = \frac{A_2}{\pi D_{m2}}$$

$$h_{2_{passage}} = h_{2_{bl}} \left(1 + \overline{\Delta r}\right)$$

the rotor tip radial gap $$\overline{\Delta r} = \frac{\Delta r}{h_{1_{bl}}} = 0.010 - 0.015$$

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vi)
$$\bar{d} = \frac{\left(D_{m2} / h_{2_{bl}} \right) - 1}{\left(D_{m2} / h_{2_{bl}} \right) + 1}$$

vii)
$$\beta_2 = tan^{-1}\left(\frac{C_{2w} - U}{C_{2a}} \right)$$

Find V_2 and $\lambda_{2\text{-}rel}$

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viii) **C_{2a}, C_2, and V_2, leads to** $\lambda_{3,}\ \alpha_3$ and β_3 **. Calculate for blade geometry and check for** λ_2, α_2 **within limits mentioned.**

also $\lambda_{2\text{-}rel} \leq 1.0 - 1.1$

ix) **Assume ψ for rotor, calculate $P_{02\text{-}rel}$ and calculate $P_{03\text{-}rel}$**

From empirical rotor loss correlations, e.g. those given here:

$$P_3^* = P^*_{3\text{-}rel} \frac{\pi\left(\lambda_{3\text{-}rel}\right)}{\pi\left(\lambda_3\right)}; \quad P_3 = P_3^* \cdot \left(\quad 3 \right) \quad \pi_T^* = \frac{P_{01}^*}{P_{03}^*}$$

The stage efficiency is calculated from :

$$\eta_{T_i} = \frac{H_{T_i}}{\frac{k_g}{k_g+1} R_g T^*_{g_i} \left(1 - \frac{1}{\pi_T^{*\frac{k_g-1}{k_g}}} \right)}$$

The best efficiency consideration often determines the selection of α_2 from the three initial considered. In some cases e.g. military a/c engine, best pressure ratio π_{0T} may be used for making the final decision on α_2

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Exit area A_3 may now be found from various aerothermodynamic parameters and using the continuity condition.

$$h_{3_{bl}} = \frac{D}{2} - \sqrt{\frac{D^2}{4} - \frac{A_3}{\pi}}$$

For D_{tip} = const

$$d = D_m - h_{bl}$$

$$h_{3_{bl}} = \sqrt{\frac{d^2}{4} - \frac{A_3}{\pi}} - \frac{d}{2}$$

For d_{hub} = const

$$D = d + 2h_{bl}$$

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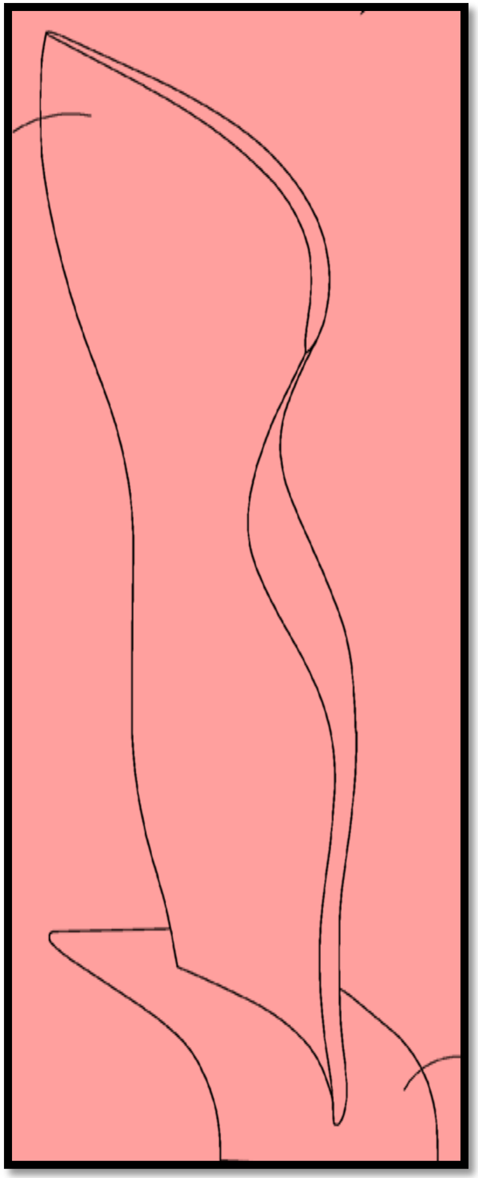
After these calculations divergence angle is checked and if $\gamma > 15^o$, the blades angles are modified to allow for more expansion.

Radial variation: **either use α_2 as constant from hub to tip or use some vortex law e.g. constant reaction law or the free vortex law**

Profiling: **same as in last lect use turbine specific airfoils *e.g.* T6 (HPT) or T106 (LPT) airfoils**



A modern turbine blade obtained through design, optimization and stress calculations

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