Aerospace Propulsion

Lecture 14

Airbreathing Propulsion VI

IMAGINE

Airbreathing Propulsion: Part VI

- Turbomachinery
- Compressor
- Turbine
- Practical Considerations
- Summary

Turbomachinery

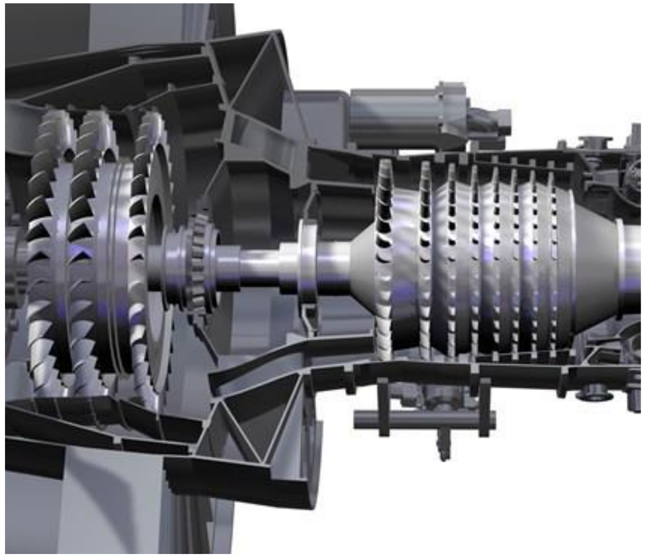
- “Machines that exchange energy with a fluid through shaft rotation”
  - Compressors and Turbines

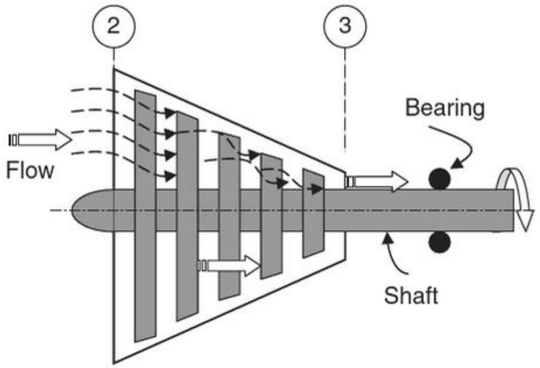
- Axial: Principal flow direction is parallel to turbomachine axis

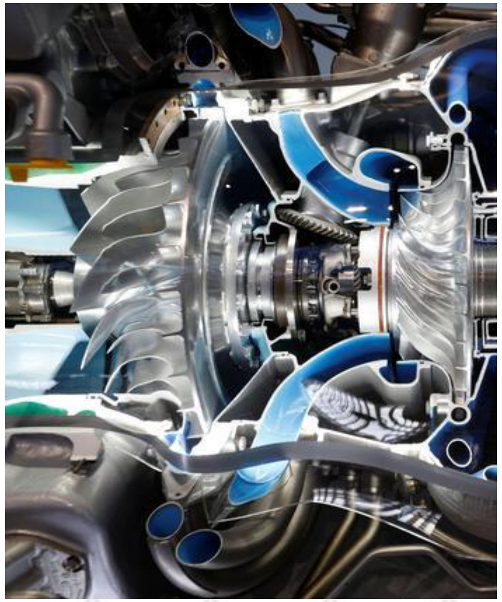
- Radial: Principal flow direction is perpendicular to turbomachine axis

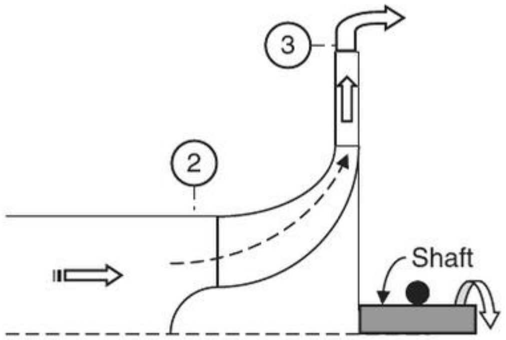
Turbomachinery

- Axial Turbomachinery
  - Primary form of turbomachinery in most aircraft applications
  - Relatively small entry area
    - Remains efficient even at high velocities
- Radial Turbomachinery
  - Not as common in aircraft engines, but does appear in slower aircraft
    - Often used in smaller turboprops
  - Flow turning requires larger entry area
    - Increased drag on engine



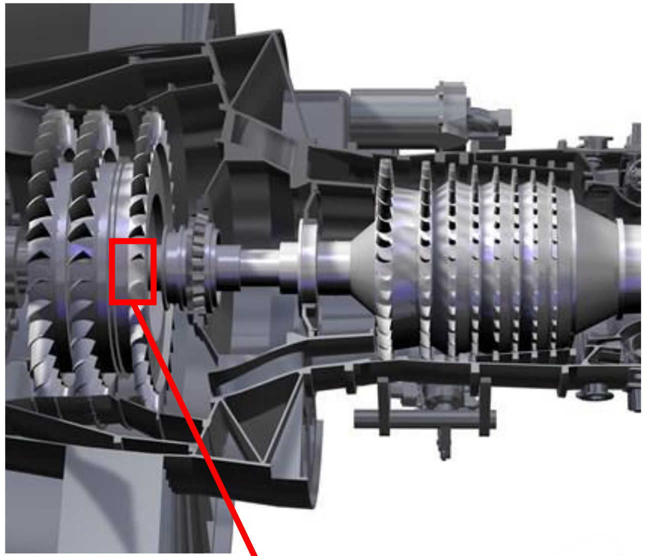


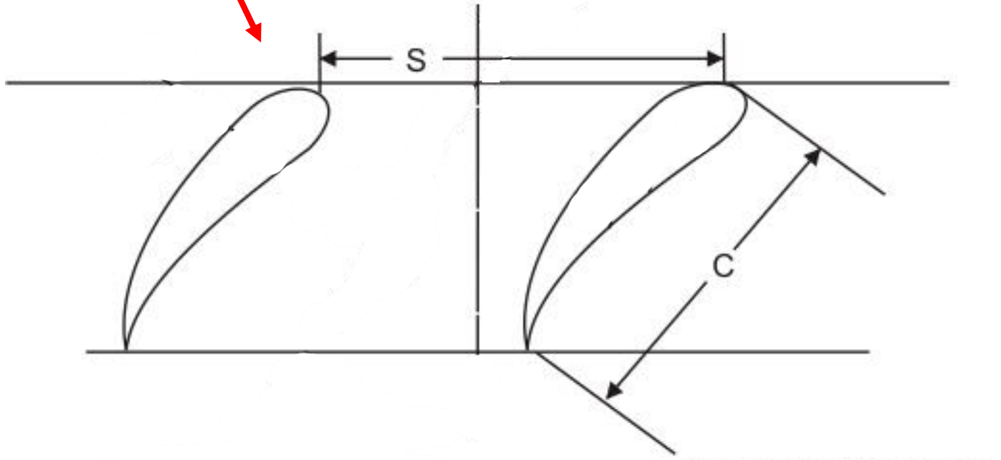




Turbomachinery

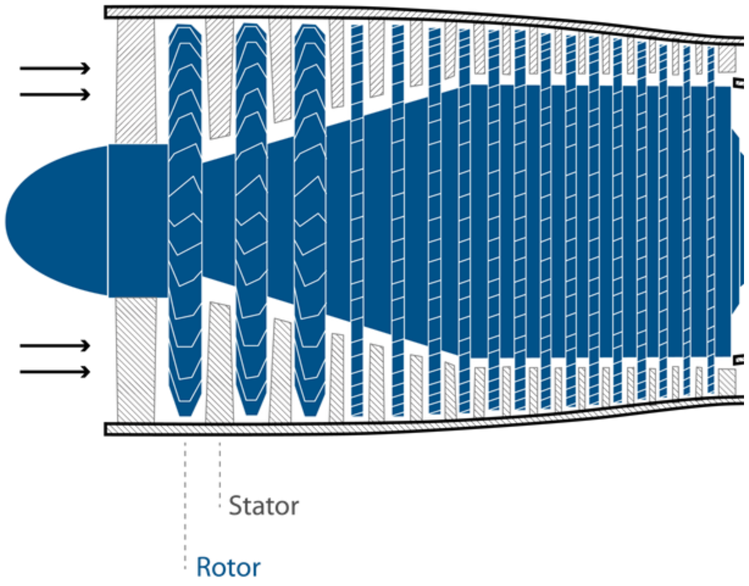
- Axial turbomachinery relies on a series of airfoil shaped “blades”
- Chord c: Longest linear distance of a blade
- Pitch s: Distance between consecutive blades
- Chord and pitch vary between stages

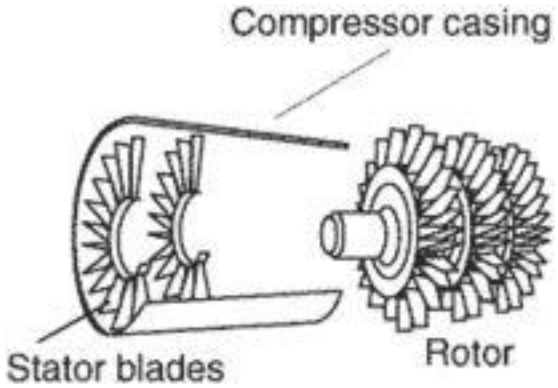




Turbomachinery

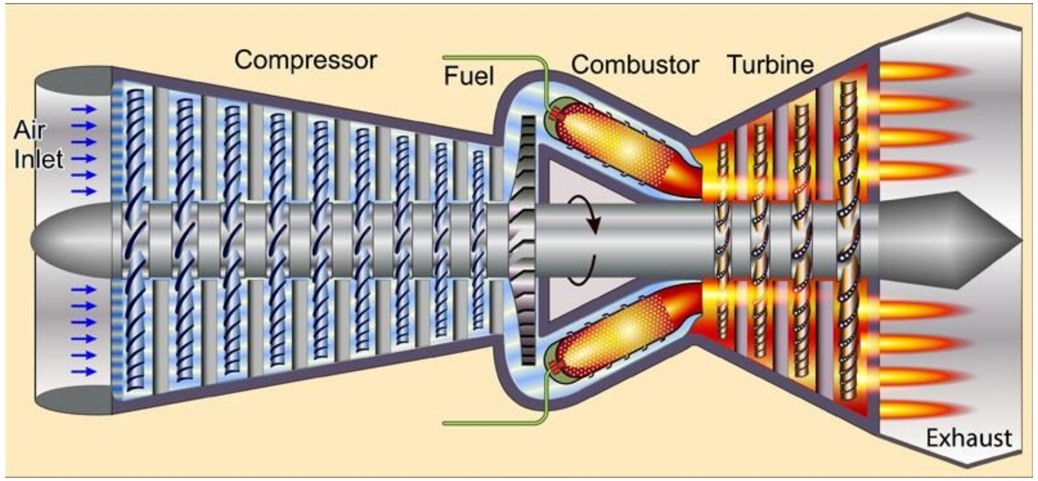
- Turbomachinery relies on a combination of stators and rotors
- Rotors
  - Moving blade that exchanges energy with fluid
- Stator
  - Stationary blade that turns flow
- A compressor/turbine "stage" is a single rotor/stator pair

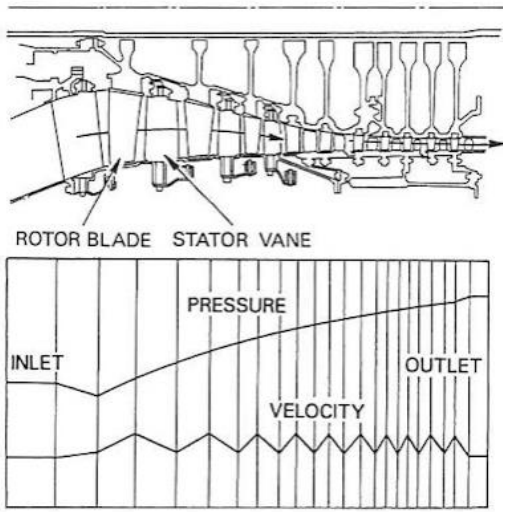




Turbomachinery

- What happens to flow as it travels through turbomachinery?
  - Compressor
    - Density increasing
    - Flow area decreasing
  - Turbine
    - Density decreasing
    - Flow area increasing
- Conservation of mass
  - Essentially constant axial velocity through compressor/turbine



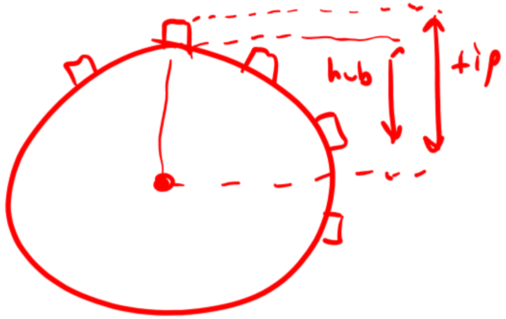


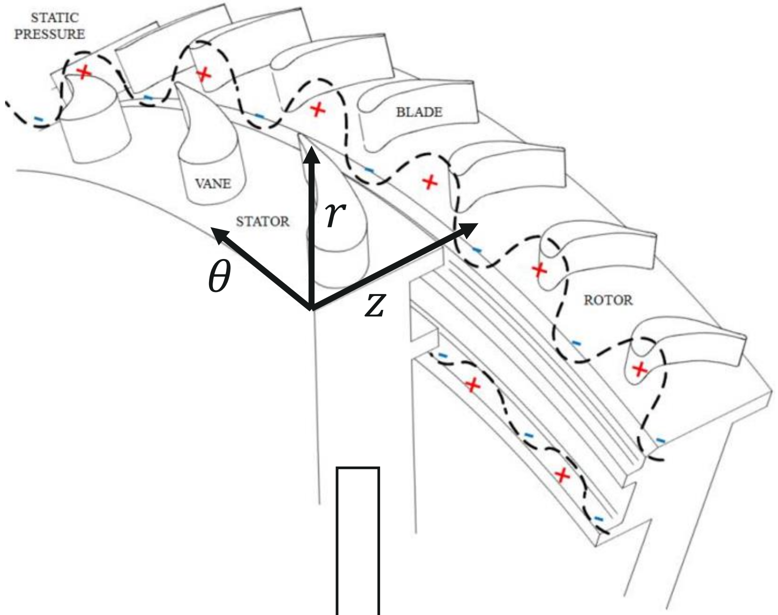
$$\dot{m} = \rho U A$$

$\uparrow \quad \downarrow$

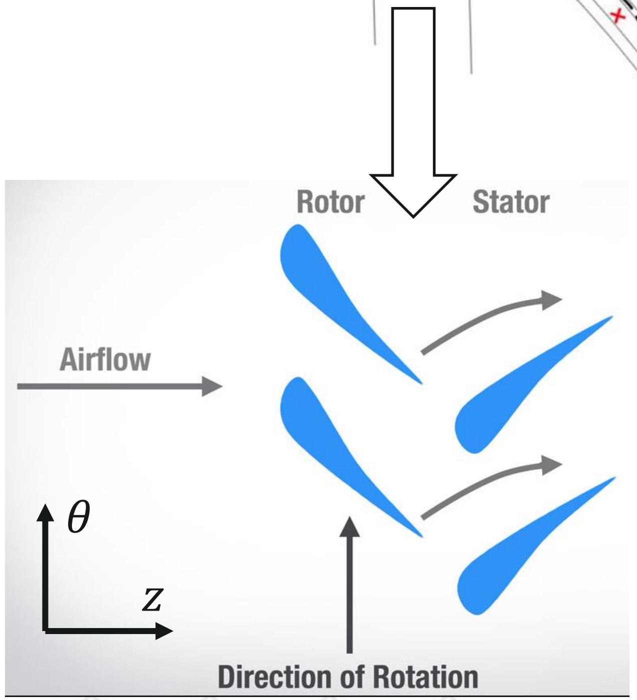
$U \approx$ constant

Turbomachinery





- Analyze turbomachinery by “unwrapping” it
  - Hub to tip ratio can be as small as 0.5 at lowest pressure stages but 0.9 or greater at high pressure stages
    - Neglect curvature effects
  - Neglect change in radius through a stage

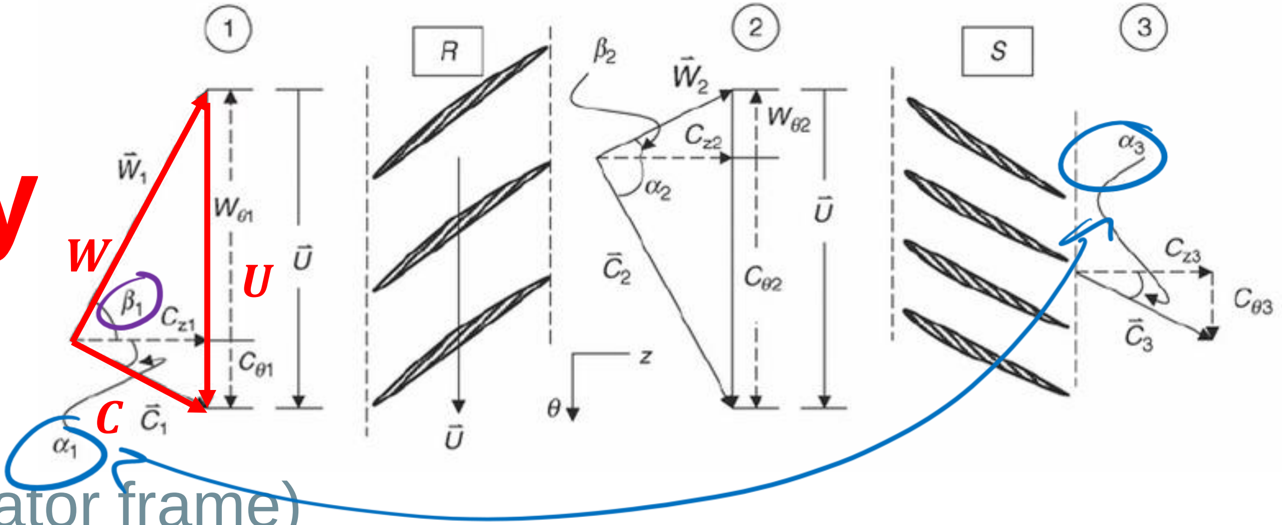


- Rotational velocity of blade
  - $\boldsymbol{U} = \omega r \hat{\boldsymbol{e}}_{\boldsymbol{\theta}}$
  - ω: rotational velocity
  - r: distance from centerline (radius)

Turbomachinery

- Two reference frames used when analyzing turbomachinery
  - Absolute reference frame (stator frame)
    - Observer in a lab watching the machine run
    - Rotor spins
    - Stator does not move
  - Relative reference frame (rotor frame)
    - Observer attached to spinning rotor
    - Rotor does not move
    - Stator spins

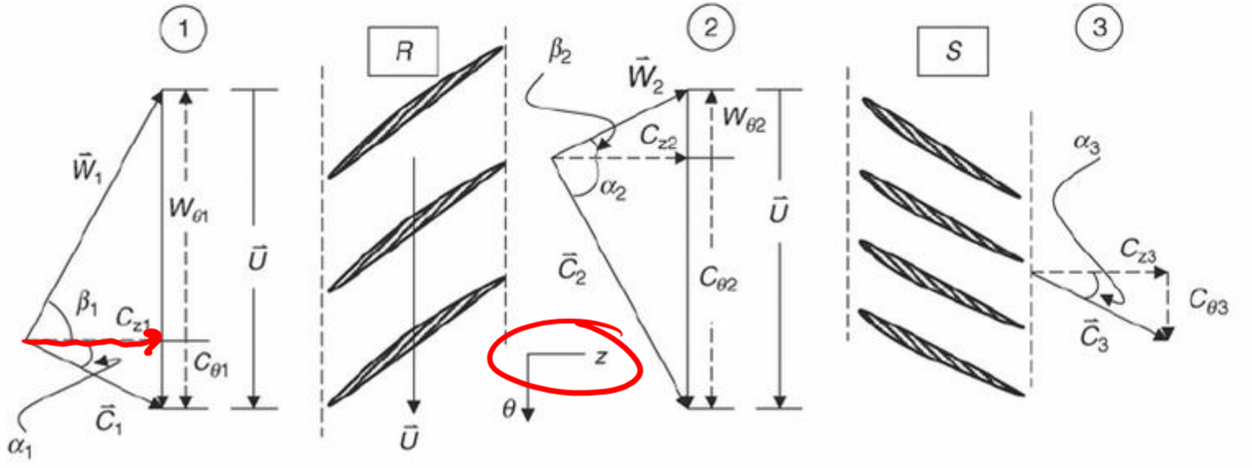
Turbomachinery



- Velocity triangles
  - $\boldsymbol{U}$: Velocity of the rotor (stator frame)
  - $\boldsymbol{C}$: Absolute velocity of flow (stator frame)
  - $\boldsymbol{W}$: Relative velocity of flow (rotor frame)
  - $\boldsymbol{C} = \boldsymbol{U} + \boldsymbol{W}$

  - α: Angle of absolute velocity relative to axial direction
    - At design point, this is same at entrance/exit angle of stage
  - β: Angle of relative velocity relative to axial direction
    - At design point, this is same at entrance/exit angle of stage

Compressor



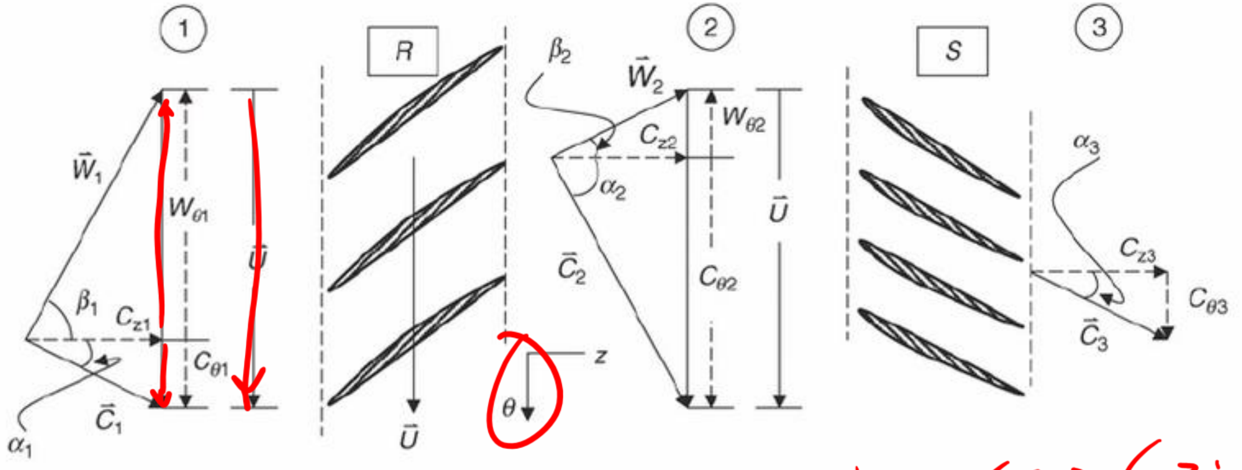
Axial velocity component

- Compressor is constant
  - Mechanically compresses air in gas turbine
  - Rotor imparts angular momentum and power to fluid → $\dot{W} = FV = T\omega$
  - Stator removes angular momentum from fluid
- Velocity triangles
  - $C_{zi} = C_i \cos \alpha_i$
  - $W_{zi} = W_i \cos \beta_i$
  - Axial Velocity: $C_{z1} = C_{z2} = C_{z3} = W_{z1} = W_{z2} = W_{z3}$
  - $\frac{C_1}{C_2} = \frac{\cos \alpha_2}{\cos \alpha_1}$ and $\frac{W_1}{W_2} = \frac{\cos \beta_2}{\cos \beta_1}$

equal
$C_{z1} = C_1 \cos \alpha_1$
$C_{z2} = C_2 \cos \alpha_2$
$\Rightarrow C_1 \cos \alpha_1 = C_2 \cos \alpha_2$
$\frac{C_1}{C_2} = \frac{\cos \alpha_2}{\cos \alpha_1}$

equal
$W_{z1} = W_1 \cos \beta_1$
$W_{z1} = W_2 \cos \beta_2$
$\Rightarrow \frac{W_1}{W_2} = \frac{\cos \beta_2}{\cos \beta_1}$

Compressor



- Velocity triangles
  - $C_{\theta i} = C_i \sin\alpha_i = C_{zi}\tan\alpha_i$
  - $W_{\theta i} = W_i \sin\beta_i = W_{zi}\tan\beta_i$
  - $C_{\theta i} = W_{\theta i} + U$

$C_{\theta i} = C_i \sin\alpha_i$ from last slide, $C_i = \frac{C_{zi}}{\cos\alpha_i}$

$C_{\theta i} = C_{zi}\tan\alpha_i$

$C_{\theta 1} = C_1 \sin\alpha_1 = C_{z1}\tan\alpha_1$
$C_{\theta 2} = C_2 \sin\alpha_2 = C_{z2}\tan\alpha_2$ $\Rightarrow \frac{C_{\theta 1}}{C_{\theta 2}} = \underbrace{\boxed{\frac{C_{z1}}{C_{z2}}}}_{=1}\frac{\tan\alpha_1}{\tan\alpha_2}$

$W_{\theta 1} = W_1 \sin\beta_1 = W_{z1}\tan\beta_1$
$W_{\theta 2} = W_2 \sin\beta_2 = W_{z2}\tan\beta_2$ $\Rightarrow \frac{W_{\theta 1}}{W_{\theta 2}} = \underbrace{\boxed{\frac{W_{z1}}{W_{z2}}}}_{=1}\frac{\tan\beta_1}{\tan\beta_2}$

- $\frac{C_{\theta 1}}{C_{\theta 2}} = \frac{\tan\alpha_1}{\tan\alpha_2}$ and $\frac{W_{\theta 1}}{W_{\theta 2}} = \frac{\tan\beta_1}{\tan\beta_2}$

Assume constant radius for each stage

Compressor

- Torque and Power
  - Torque
    - Both rotor and stator apply a torque to the flow (angular momentum)
    - $\tau_{in} = \dot{m}(r_2 C_{\theta 2} - r_1 C_{\theta 1}) = \dot{m} r (C_{\theta 2} - C_{\theta 1}) = \dot{m} r C_z (\tan\beta_2 - \tan\beta_1)$
  - Power
    - Only the rotor applies power to the flow
    - $\dot{W}_{in} = \tau_{in}\omega = \dot{m} r \omega (C_{\theta 2} - C_{\theta 1}) = \dot{m} U (C_{\theta 2} - C_{\theta 1})$

- Torque and Power
  - Torque ($\tau = Fd = \Delta$ Angular momentum)

    Angular Momentum $= \dot{m} r V$
    - Both rotor and stator apply a torque to the flow (angular momentum)
    - $\tau_{in} = \dot{m}(r_2 C_{\theta 2} - r_1 C_{\theta 1}) = \dot{m} r (C_{\theta 2} - C_{\theta 1}) = \dot{m} r C_z (\tan\beta_2 - \tan\beta_1)$

$\tau_{in} = \dot{m} r (C_{\theta 2} - C_{\theta 1})$

$\tau_{in} = \dot{m} r C_z (\tan\alpha_2 - \tan\alpha_1)$

$\tau_{in} = \dot{m} r C_z (\tan\beta_2 - \tan\beta_1)$

$C_{\theta i} = W_{\theta i} + U$

$C_{zi}\tan\alpha_i = W_{zi}\tan\beta_i + U$

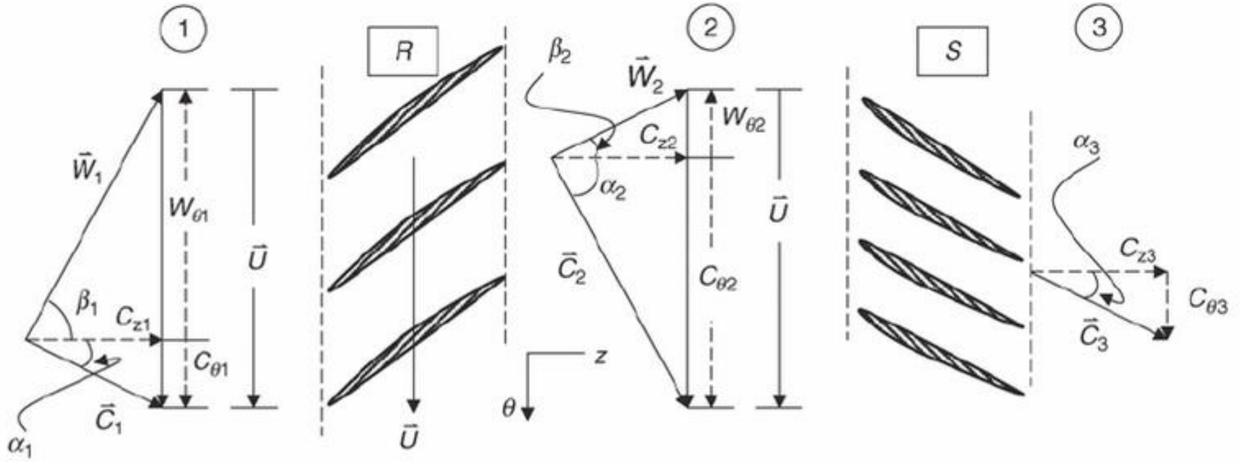
$\Downarrow$

$C_z \tan\alpha_2 = W_z \tan\beta_2 + U \quad (W_z = C_z)$

$\tan\alpha_2 = \tan\beta_2 + \frac{U}{C_z}$

- Power ($\dot{W} = FV = \tau\omega$)
  - Only the rotor applies power to the flow
  - $\dot{W}_{in} = \tau_{in}\omega = \dot{m} r \omega (C_{\theta 2} - C_{\theta 1}) = \dot{m} U (C_{\theta 2} - C_{\theta 1})$

Compressor



- Stagnation Pressure
  - Applying first law and combining with our power equation
  - $\dot{W}_{12} = \dot{m}(h_{t2} - h_{t1})$

1 → 2 Adiabatic, work: $\dot{W}_{12} = \dot{m}(h_{t2} - h_{t1})$

2 → 3 Adiabatic, no work $h_{t3} = h_{t2}$

Combine: $\dot{W}_{12} = \dot{m}(h_{t3} - h_{t1})$

$= \dot{m} c_p (T_{t3} - T_{t1}) = \underbrace{\dot{m} U (C_{\theta 2} - C_{\theta 1})}_{\text{prev. slide}}$

$T_{t3} = T_{t1} + \frac{U}{c_p}(C_{\theta 2} - C_{\theta 1})$

$\frac{T_{t3}}{T_{t1}} = 1 + \frac{U}{c_p T_{t1}}(C_{\theta 2} - C_{\theta 1})$ 1

$\eta_{cs} = \frac{h_{t3s} - h_{t1}}{h_{t3} - h_{t1}} = \frac{T_{t3s}/T_{t1} - 1}{T_{t3}/T_{t1} - 1}$

$\frac{T_{t3s}}{T_{t1}} = 1 + \eta_{cs}\left(\frac{T_{t3}}{T_{t1}} - 1\right)$ 2

$\frac{T_{t3s}}{T_{t1}} = \left(\frac{p_{t3}}{p_{t1}}\right)^{\frac{\gamma-1}{\gamma}}$ 3

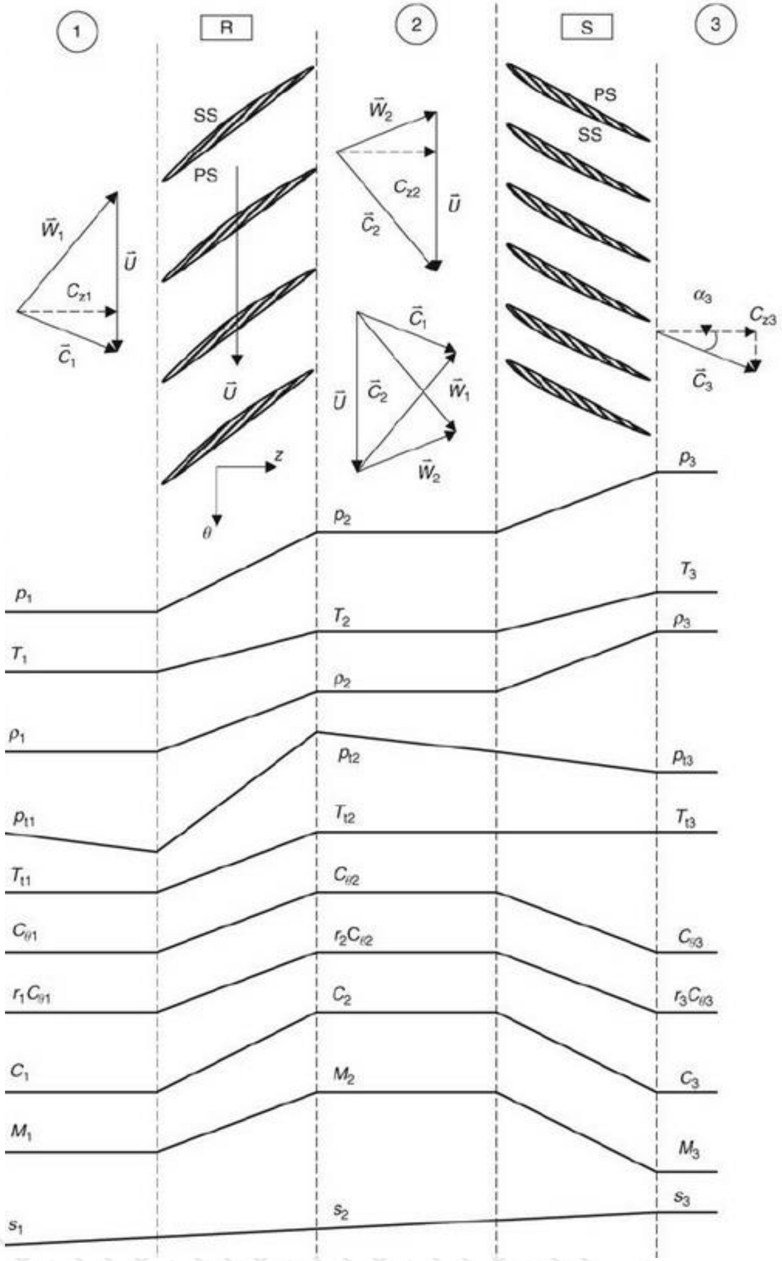
1 2 3
  - $\frac{p_{t3}}{p_{t1}} = \left[1 + \eta_{cs} \frac{U}{c_p T_{t1}} (C_{\theta 2} - C_{\theta 1})\right]^{\frac{\gamma}{\gamma - 1}}$

Compressor

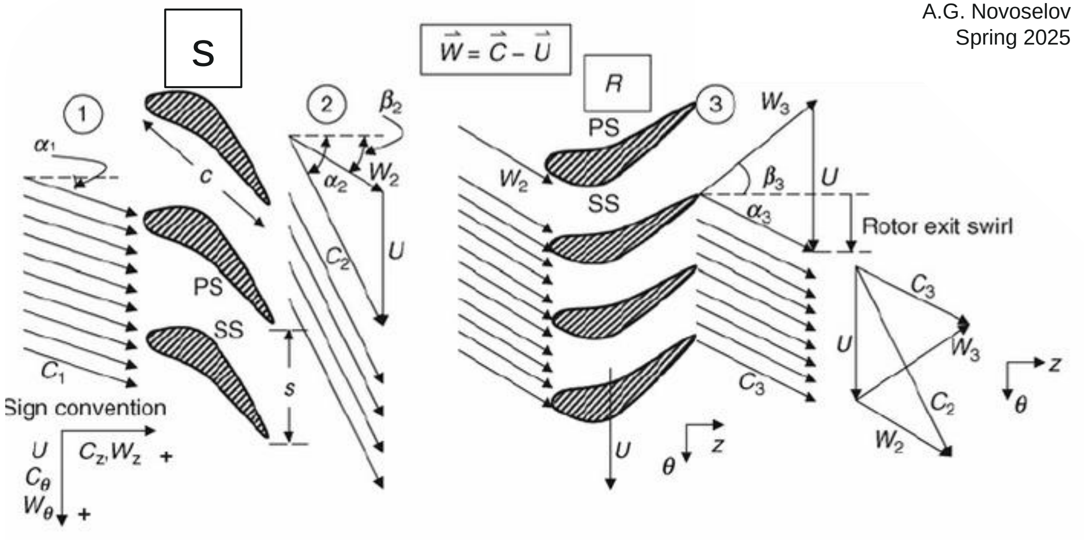
- Stagnation Temperature
  - Previously derived stagnation temperature change across an arbitrary compressor
    - $\frac{T_{t3}}{T_{t1}} = 1 + \frac{1}{\eta_{cs}}\left(\frac{p_{t3}}{p_{t1}}^{\frac{\gamma-1}{\gamma}} - 1\right)$

can apply to each stage

- Each compressor stage
  - Increases stagnation pressure
  - Increases stagnation temperature
  - Does not change velocity (approximately)
  - Requires work input



Turbine

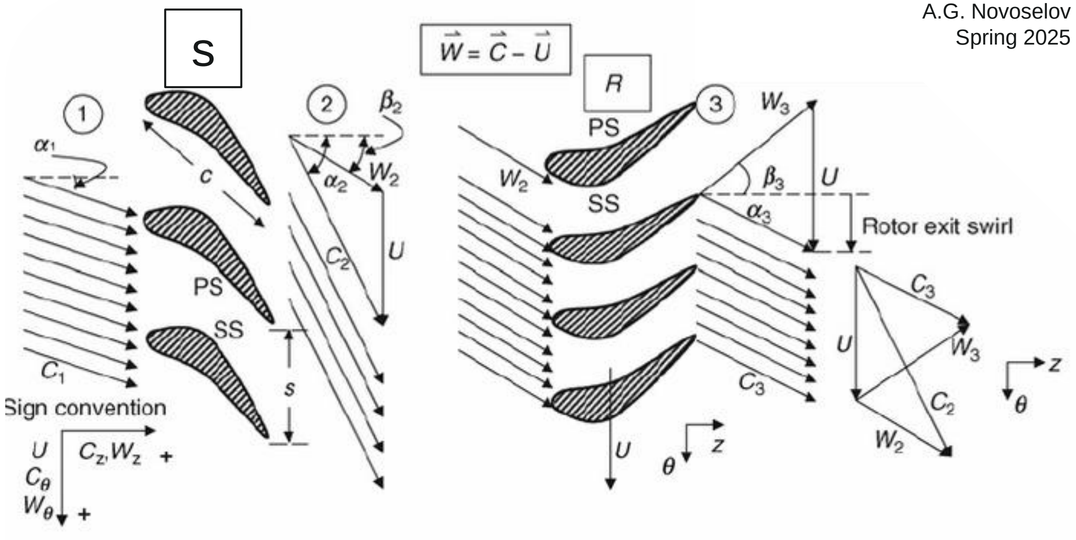


- Turbine extracts energy from flow
  - Stator adds angular momentum to fluid
  - Rotor removes angular momentum and power from fluid
- Velocity triangles
  - Axial velocity: $C_{z1} = C_{z2} = C_{z3} = W_{z1} = W_{z2} = W_{z3}$
    - $C_{zi} = C_i \cos\alpha_i$
    - $W_{zi} = W_i \cos\beta_i$
  - Tangential velocity
    - $C_{\theta i} = C_i \sin\alpha_i = C_{zi}\tan\alpha_i$
    - $W_{\theta i} = W_i \sin\beta_i = W_{zi}\tan\beta_i$
    - $C_{\theta i} = W_{\theta i} + U$

Stator first

Stator accelerates flow (in θ)
So rotor can extract the energy

Turbine



- Torque and Power
  - Torque
    - $\tau_{out} = \dot{m}r(C_{\theta 2} - C_{\theta 3})$
  - Power
    - $\dot{W}_{out} = \tau_{out}\omega = \dot{m}U(C_{\theta 2} - C_{\theta 3})$
- Stagnation Pressure
  - First law + power
  - $\frac{p_{t3}}{p_{t1}} = \left[1 - \frac{1}{\eta_{ts}} \frac{U}{c_p T_{t1}} (C_{\theta 2} - C_{\theta 3})\right]^{\frac{\gamma}{\gamma - 1}}$

$h_{t1} = h_{t2}$ (no work/heat)

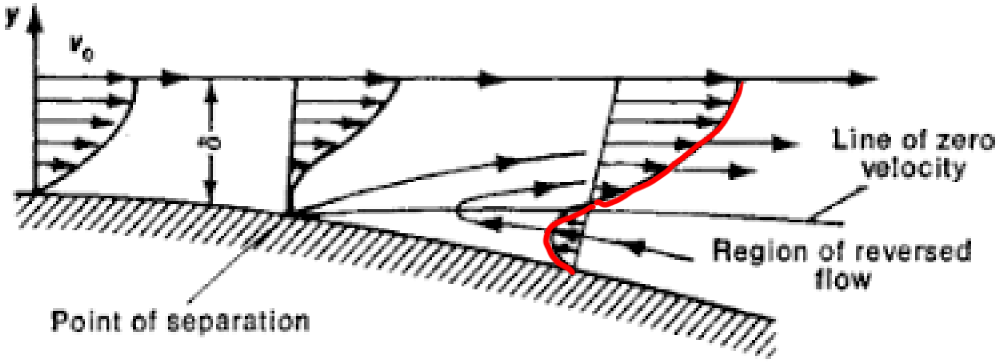
$\dot{m} c_p (T_{t1} - T_{t3}) = \dot{m} U (C_{\theta 2} - C_{\theta 3})$

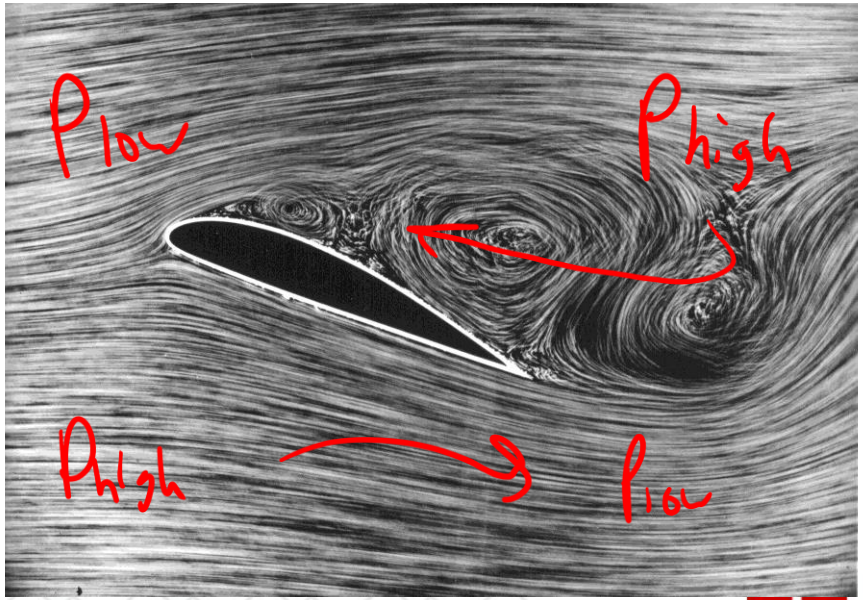
$T_{t3} = T_{t1} - \frac{U}{c_p}(C_{\theta 2} - C_{\theta 3})$

$\eta_{ts} = \frac{h_{t1} - h_{t3}}{h_{t1} - h_{t3s}}$

Practical Considerations

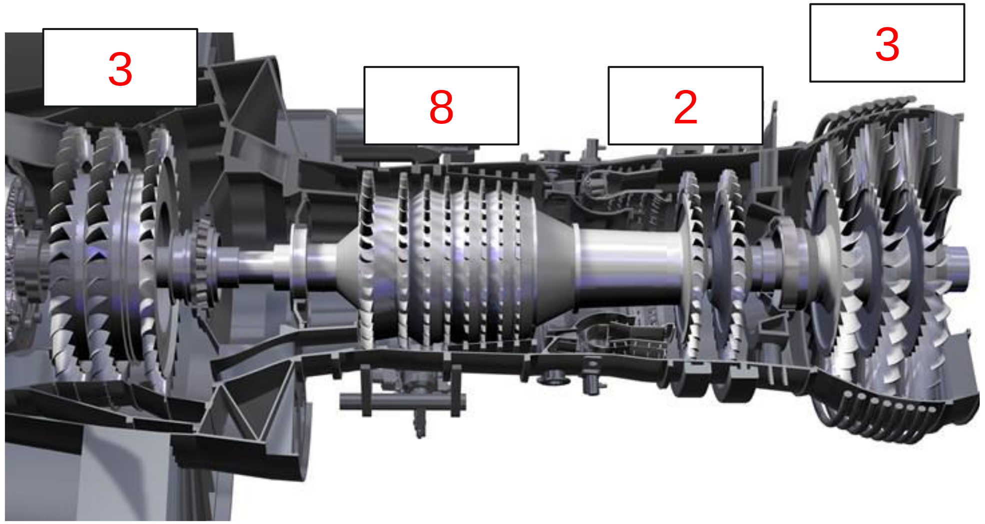
- Boundary layer separation
  - Detachment of a boundary layer from surface leading to a wake
    - Highly non-isentropic and inefficient
    - Leads to "stall"
  - Promoted by large turning angles
  - Promoted by increasing pressure and inhibited by decreasing pressure
    - Compressor: Pressure increases each stage
    - Turbine: Pressure decreases each stage





Practical Considerations

- Compressor stall
  - Can only handle small pressure jump and turning angle each stage
  - Many compressor stages
- Turbine stall
  - Can handle large pressure jumps and turning angles each stage
  - Few turbine stages
- Turbine blade cooling
  - To be discussed after combustors



Summary

- In the stator reference frame:
  - Stator and rotor turn flow (apply a torque)
  - Only rotor exchanges power
  - Stagnation temperature and pressure constant across (lossless) stator
  - Stagnation temperature and pressure change across rotor
- Compressor vs. Turbine
  - Stagnation pressure/temperature increase in compressor stage
  - Stagnation pressure/temperature decrease in turbine stage
  - Compressor order is rotor-stator
  - Turbine order is stator-rotor