Turbomachinery

Axial Compressors

Axial Compressors

Cascade Flow Angles and Velocity Triangles

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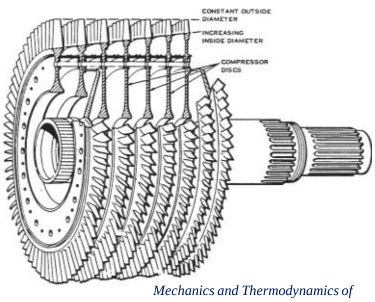
Compressor Analysis

- From Euler turbomachinery (conservation) equations need to understand change in tangential velocity to relate to forces on blades and power

$$\mathrm{T} = \dot{m}\Delta\left(rc_\theta\right)$$

$$\dot{W}/\dot{m} = \Delta\left(uc_\theta\right)$$



Mechanics and Thermodynamics of Propulsion, Hill and Peterson

- Analyze cascade flow to find values for c_θ (azimuthal or swirl velocity) through a compressor stage

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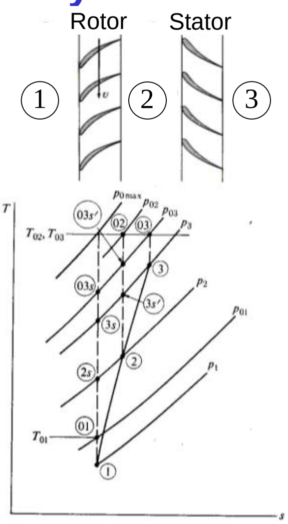
Compressor Cascade Analysis

- Compressor stage consists of moving (rotor) and stationary (stator) blades
  - – state change across each blade row
    $1 \rightarrow 2$ rotor
    $2 \rightarrow 3$ stator
- Use flow angles and velocity triangles to visualize transition between reference frames

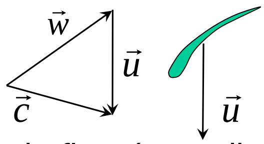


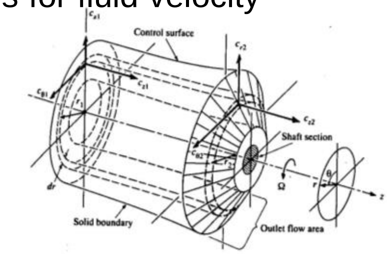
Mechanics and Thermodynamics of Propulsion, Hill and Peterson

Compressor (Cascade) Flow Angles

- Recall, two reference frames for fluid velocity
  - engine's $\vec{c}$
  - blade's $\vec{w}$
- Difference due to rotor motion

$$\vec{w} = \vec{c} - \vec{u}$$
$$\vec{c} = \vec{w} + \vec{u}$$

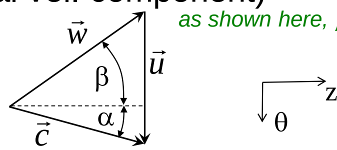




"abs" swirl downward can still have swirl upward relative to rotor

- For cascade flow (no radial vel. component)
  - use u to define +θ dir.*
  - define angles for each ref. frame (α and β)

as shown here, $\beta < 0$



*sometimes (e.g., in UK) α >0 in U direction, β >0 in opposite direction

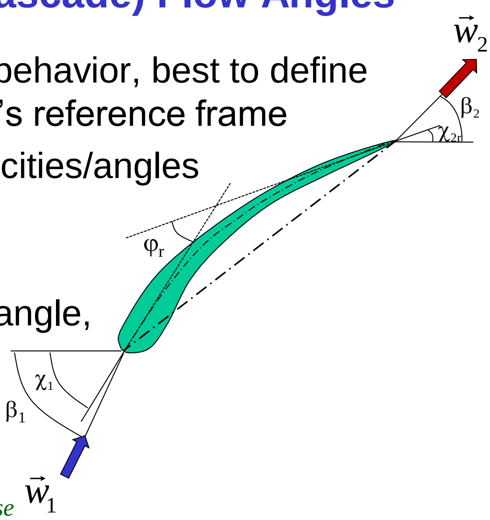
Compressor (Cascade) Flow Angles

- To examine airfoil behavior, best to define flow angle in blade's reference frame
- For **rotor**, use velocities/angles in rotating frame
  - w, β
  - net flow turning angle,

$$\boxed{\beta_1 - \beta_2} \quad \textbf{(II.9)}$$

  - will equal φ_r if flow matches blade angles

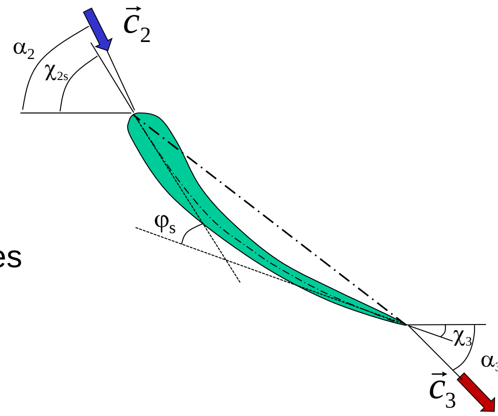
generally ≠, but could be close



Compressor (Cascade) Flow Angles

- For **stator**, use engine reference frame
  - c, α
  - net flow turning angle, $\alpha_2 - \alpha_3$ **(II.10)**
    - will equal φ_s if flow matches blade angles

      generally ≠, but could be close



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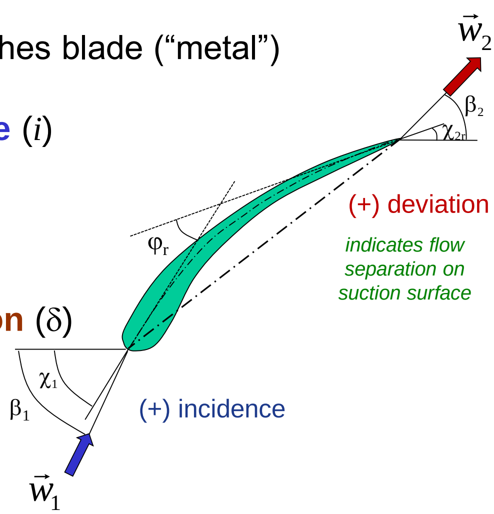
Flow vs. Blade Angles

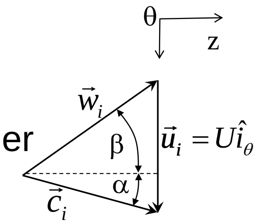
- How well flow matches blade ("metal") angles is given by
  - inflow: **incidence** (i)

    (II.11)
    $i \equiv -(\beta_1 - \chi_1)$ (rotor)
    $i \equiv \alpha_2 - \chi_{2s}$ (stator)
  - outflow: **deviation** (δ)

    (II.12)
    $\delta \equiv -(\beta_2 - \chi_{2r})$ (rotor)
    $\delta \equiv \alpha_3 - \chi_3$ (stator)



Velocity Triangles



$\vec{c}_i = \vec{w}_i + \vec{u}$

- Rotor motion in θ direction, so ref. frame change has no effect on other directions $\Rightarrow$ $\boxed{w_{zi} = c_{zi}}$ **(II.13)**
- Rotor vel. constant in cascade flow (like fixed r), and let $|u_i| = U$

  as shown here, $w_{\theta i} < 0$

  $\Rightarrow \boxed{c_{\theta i} - w_{\theta i} = U}$ **(II.14)**
- Also have general trigonometric relations
  - e.g.,

$$\begin{aligned} c_{\theta i} &= c_i \sin \alpha_i = c_{zi} \tan \alpha_i \\ w_{\theta i} &= w_i \sin \beta_i = w_{zi} \tan \beta_i \\ w_{zi} &= w_i \cos \beta_i = c_{zi} = c_i \cos \alpha_i \end{aligned} \qquad \textbf{(II.15)}$$

Velocity Triangle Analysis

θ z

- Apply (II.12-14) to both blade rows of compressor stage
- 1: rotor inlet

  $(13) \Rightarrow c_{\theta_1} = c_{z_1} \tan \alpha_1$
- 2: between rotor and stator

  $(13,15) \Rightarrow w_{\theta_2} = c_{z_2} \tan \beta_2$

  $(14) \Rightarrow c_{\theta_2} = U + w_{\theta_2}$

  $\boxed{c_{\theta_2} = U + c_{z_2} \tan \beta_2}$ **(II.16)**

  with (15) $\Rightarrow \boxed{\tan \alpha_2 = \dfrac{U}{c_{z_2}} + \tan \beta_2}$ **(II.17)**
- 3: stator outlet

  $(15) \Rightarrow c_{\theta_3} = c_{z_3} \tan \alpha_3$

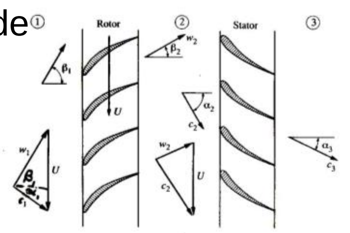


FIGURE 7.7 Mean radius section of a compressor stage. The absolute exit angle fror

Mechanics and Thermodynamics of Propulsion, Hill and Peterson

$w_{zi} = c_{zi}$ (13)

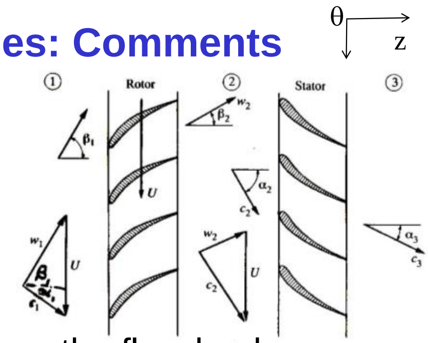
$c_{\theta i} - w_{\theta i} = U$ (14)

$c_{\theta i} = c_i \sin \alpha_i = c_{zi} \tan \alpha_i$

$w_{\theta i} = w_i \sin \beta_i = w_{zi} \tan \beta_i$ (15)

Velocity Triangles: Comments

- In axial compressor,
  - the rotor blades increase absolute swirl (push flow downward)
  - the stator blades reduce the swirl (return the flow back towards the axial direction)



Repeated (or Normal) Stage

≡ velocities at inlet and exit of stage are the same
$(c_{z3}=c_{z1},\ c_{\theta 3}=c_{\theta 1},\ \alpha_3=\alpha_1)$

Zero exit swirl

≡ no azimuthal velocity at exit of stage $(\alpha_3=0)$

Swirl Velocity Change Example

- **Given**:
  - Repeating axial flow compressor stage with pitchline radius of 0.50 m, rotational speed of 4050 rpm, inflow axial velocity of 155 m/s and inlet flow angle of 10.2° (in same direction as rotor wheel motion). The rotor blade exit angle is -22.5° and the deviation is 2°.
- **Find:**
  1. Change in swirl velocity across rotor ($\Delta c_{\theta 1,2}$)
  2. Change in swirl vel. ($\Delta c_{\theta\ 2,3}$) across stator
- **Assume:**
  - axial velocity constant through stage

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Swirl Velocity Change Example

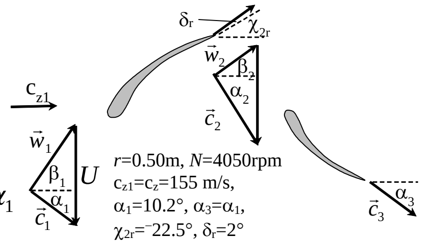
- $\Delta c_{\theta_{1,2}} = ?$

from (14) $c_{\theta_1} = c_{z_1} \tan\alpha_1$

from (15) $c_{\theta_2} = U + c_{z_2} \tan\beta_2$

$c_{\theta_2} - c_{\theta_1} = U + c_{z_2} \tan\beta_2 - c_{z_1} \tan\alpha_1$

$$\boxed{\Delta c_{\theta_{1,2}} = \overset{?}{U} + \overset{\checkmark}{c_z}\left(\tan\overset{?}{\beta_2} - \tan\overset{\checkmark}{\alpha_1}\right)}\ \textbf{(II.18)}$$



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Swirl Velocity Change Example

- $\Delta c_{\theta_{2,3}} = ?$

$$\Delta c_{\theta_{2,3}} = c_{\theta_3} - c_{\theta_2}$$