Turbomachinery Overview

Georgia Tech College of Engineering

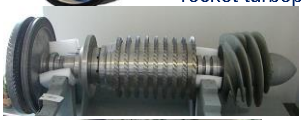
Definition

- Widely used in aerospace propulsion
  - propellers, fans, compressors, turbines, pumps, turbopumps,…
- Also energy/power conversion
  - gas turbines, wind turbines, water turbines, steam turbines, …
- **Turbomachinery definition**
  - devices that transfer energy through expansion/compression of a continuously moving fluid by blade rows (rotating blades)
  - so not piston-based compression/expansion devices

geaviation.com

bypass fan

rocket turbopump



power gas turbine

turbomachinery.com
nrel.com

wind turbine

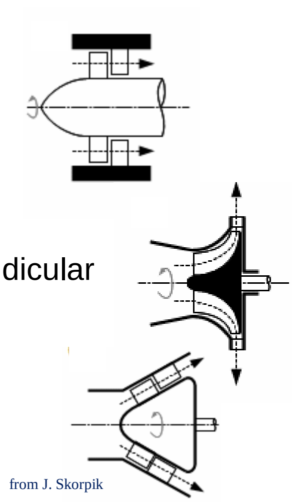
Turbomachinery Overview

Configurations and Nomenclature

Georgia Tech College of Engineering

Configurations

- Typically characterized by flow direction versus axis of rotation
  - – **axial**
    - flow primarily parallel to axis
  - – **radial**
    - entering or exiting flow perpendicular to axis
  - – mixed
    - in-between the two extremes

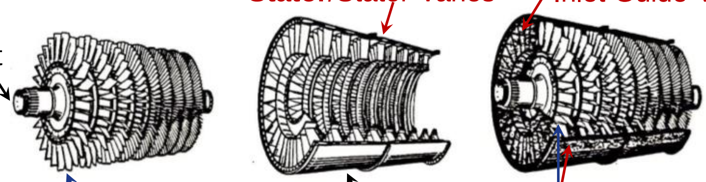


from J. Skorpik

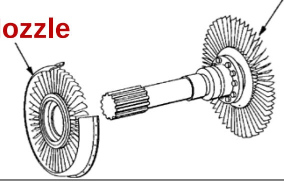
Georgia Tech College of Engineering

Axial (Flow) Compressors and Turbines

- Turbomachinery made up of many parts
  - compressor



  - turbine



Elements of Gas Turbine Propulsion, Mattingly

Georgia Tech College of Engineering

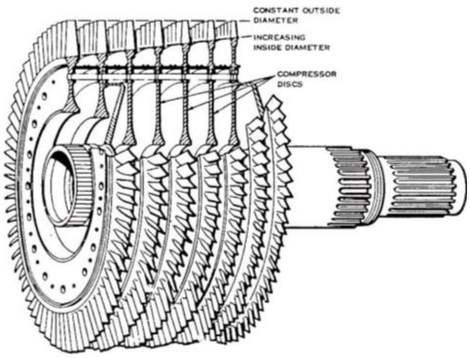
Axial Compressors and Turbines

- Turbomachinery made up of many parts

braytonenergy.net

Disk (blades attached to it)

- Blisk if blades integrated into disk



Elements of Gas Turbine Propulsion, Mattingly

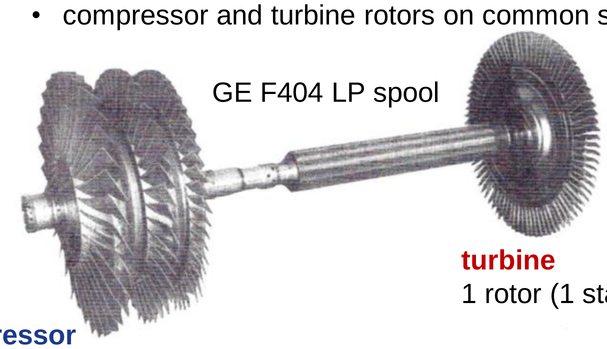
Georgia Tech | College of Engineering

Axial Compressors and Turbines

- Turbomachinery made up of many parts

Spool

- compressor and turbine rotors on common shaft



GE F404 LP spool

turbine
1 rotor (1 stage)

compressor
3 rotors (3 stages)

Mechanics and Thermodynamics of Propulsion, Hill and Peterson

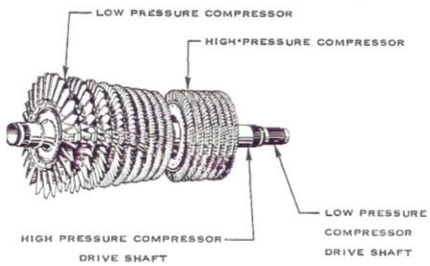
Turbomachinery -7

AE4451

Georgia Tech | College of Engineering

Axial Compressors and Turbines

- Turbomachinery made up of many parts
  - most engines have at least **two spools**
  - e.g., concentric shafts



Elements of Gas Turbine Propulsion, Mattingly

3 stage LP compressor

7 stage HP compressor

GE F404
Pr_c~26
Pr_{stage}~1.4

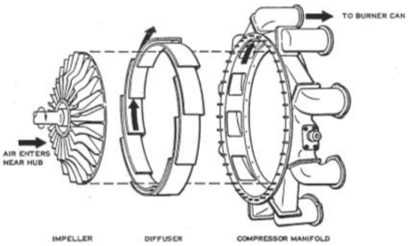
Mechanics and Thermodynamics of Propulsion, Hill and Peterson

Turbomachinery -8

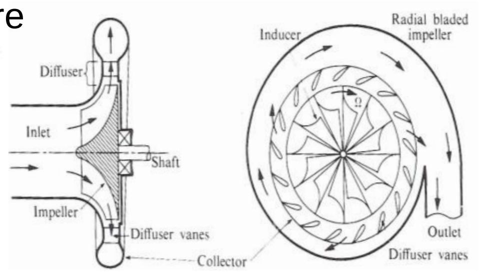
AE4451

Centrifugal (Radial) Compressor

- Modified nomenclature



Elements of Gas Turbine Propulsion, Mattingly



rotor/impeller
- PW100 LP compressor
- single piece

Mechanics and Thermodynamics of Propulsion, Hill and Peterson

Mixed (Axial-Centrifugal) Compressor

- Some engines use both axial and centrifugal components

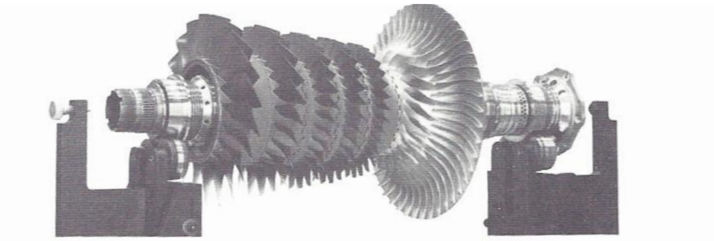


FIGURE 9.2 Axial-centrifugal compressor of the General Electric T700 engine. (Courtesy GE Aircraft Engines.)

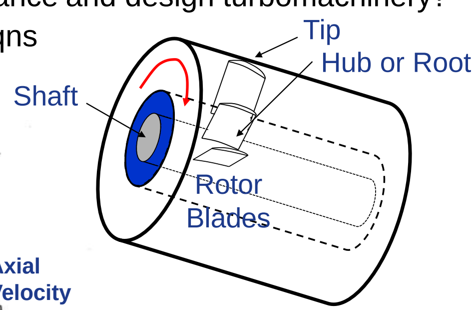
Mechanics and Thermodynamics of Propulsion, Hill and Peterson

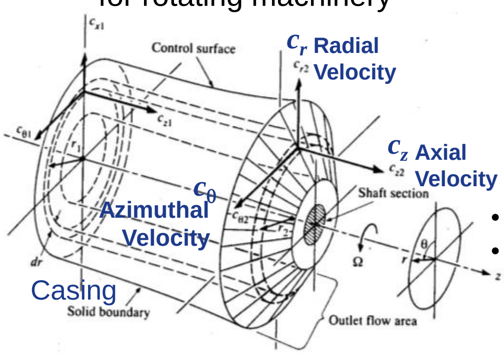
Turbomachinery Overview

Euler Turbomachinery Equations

Euler Turbomachinery Equations

- How to analyze performance and design turbomachinery?
- Develop conservation eqns
- Define appropriate CV for rotating machinery





Mechanics and Thermodynamics of Propulsion, Hill and Peterson

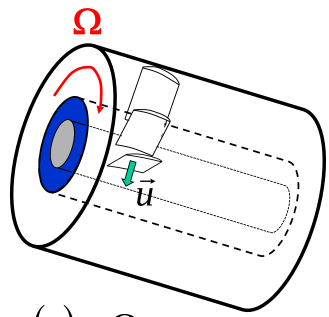
- Use axisymm. coord system
- Define 2 reference frames
  1. fixed (engine) ref. frame $\equiv \vec{c}$
  2. rotating ref. frame $\equiv \vec{w}$

Fixed vs. Rotating Frames of Reference

- How to we convert velocities from one ref. frame to another?
  - Galilean transform

$$\vec{v}_{new} = \vec{v}_{old} - \vec{v}_{rel}$$

$\vec{v}_{rel}$ is relative velocity of new reference frame with respect to old



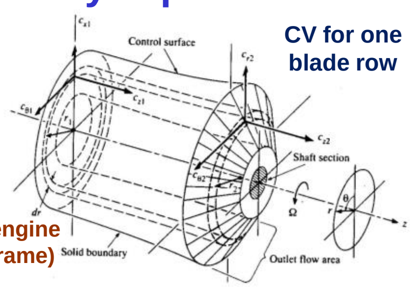
- What is the relative velocity between our 2 ref. frames?
  - the (local) blade velocity!

$$u(r) = \Omega r$$

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

Georgia Tech College of Engineering

Euler Turbomachinery Equations



CV for one blade row

- **Mass**

$$0 = \frac{d}{dt}\int_{CV} \rho dV + \int_{CS} \rho(\vec{c}\cdot\hat{n})dA$$

$$0 = 0 + \dot{m}_2 - \dot{m}_1 \qquad \textit{steady}$$

$$\boxed{\dot{m}_2 = \dot{m}_1 = \dot{m}}$$

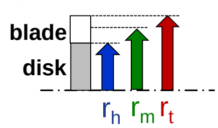
- **Angular Momentum** (engine frame)
  - CM law $\mathrm{T} = \frac{d}{dt}(mrc_\theta)$ (torque)

$$\mathrm{T} = \frac{d}{dt}\int_{CV} \rho r c_\theta dV + \int_{CS} \rho r c_\theta (\vec{c}\cdot\hat{n})dA$$

0 for steady…if we time avg. over high freq. fluctuations that result from blades going by

$$\mathrm{T} = \int_{CS} \rho r c_\theta (\vec{c}\cdot\hat{n})dA \equiv \dot{m}\left[(rc_\theta)_2 - (rc_\theta)_1\right]$$

(rc_θ) represents a spatially averaged (integrated) property



*for prelim. design, typically use the "mean" radius location (between tip and hub) ≡ **pitchline** (or meanline)*

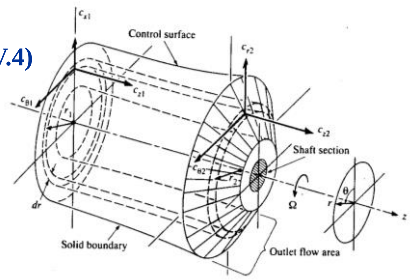
reasonable starting point if $r_m >> r_t - r_h$

Georgia Tech | College of Engineering

Euler Turbomachinery Equations

- So $\boxed{\mathrm{T} = \dot{m}\left[(rc_\theta)_2 - (rc_\theta)_1\right]}$ **(V.4)**
  - what about power?
- **Power/Energy**
  - from mechanics

$$\dot{W} = \mathrm{T}\Omega = \dot{m}\Omega\left[(rc_\theta)_2 - (rc_\theta)_1\right]$$



$\dot{W}/\dot{m} = \Omega\Delta(rc_\theta)_{1,2}$ **Ωr = blade speed ≡ u** $\boxed{\dot{W}/\dot{m} = \Delta(uc_\theta)_{1,2}}$ **(V.5)**

- from thermodynamics **(V.6)**

$\dot{W}/\dot{m} = h_{o2} - h_{o1} \Rightarrow \boxed{\Delta(h_0)_{1,2} = \Delta(uc_\theta)_{1,2}}$

steady, adiab., uniform

(or h_o is "averaged" value)

relates TD property changes across blade rows to the azimuthal velocity changes

$$\Omega = N\left(\frac{rev}{min}\right)\left(\frac{min}{60sec}\right)\left(\frac{2\pi}{rev}\right)$$
$$= N_{rpm}\,\pi/30$$

for equations as written

$\mathrm{T}, \dot{W} > 0$ for compressor

$\mathrm{T}, \dot{W} < 0$ for turbine

Georgia Tech | College of Engineering

Turbomachinery Overview

Degree of Reaction and Flowfields

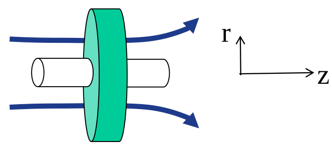
Georgia Tech | College of Engineering

Other Important Definitions

- **Reaction** (Degree of Reaction)

(V.7) $R \equiv \frac{\Delta h_{rotor}}{\Delta h_{stage}}$ ←energy change across rotor; ← energy change across stage $\sim \frac{\Delta p_{rotor}}{\Delta p_{stage}}$

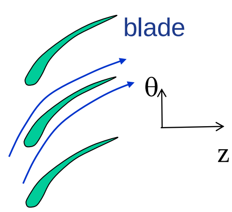
  – balance torque, p gradient between rotor/stator
- Flowfields (axial machines)
  – while real machines have 3-d flows, easier to consider 2-d flows (different “planes”)
- **Throughflow** Field (r-z plane)
  – not including θ variations
  – disk replaces blades (actuator disk theory)
  (useful for calculating $\dot{m}$ and linear forces)



Georgia Tech | College of Engineering

Other Important Definitions

- **Cascade** Field (θ-z plane)
  – not including r variations
  – like unwrapping blade to look at array of airfoil sections
  – **will focus on this for 2-d design**



- **Secondary** Field (r-θ plane)
  – not including z variations
  – low velocity in boundary layers along blades/walls
  – pressure gradients produce secondary (rotational) flows
  – leads to reduced performance (efficiency loss)