AAE 538: Air-Breathing Propulsion

Lecture 14: Compression Systems

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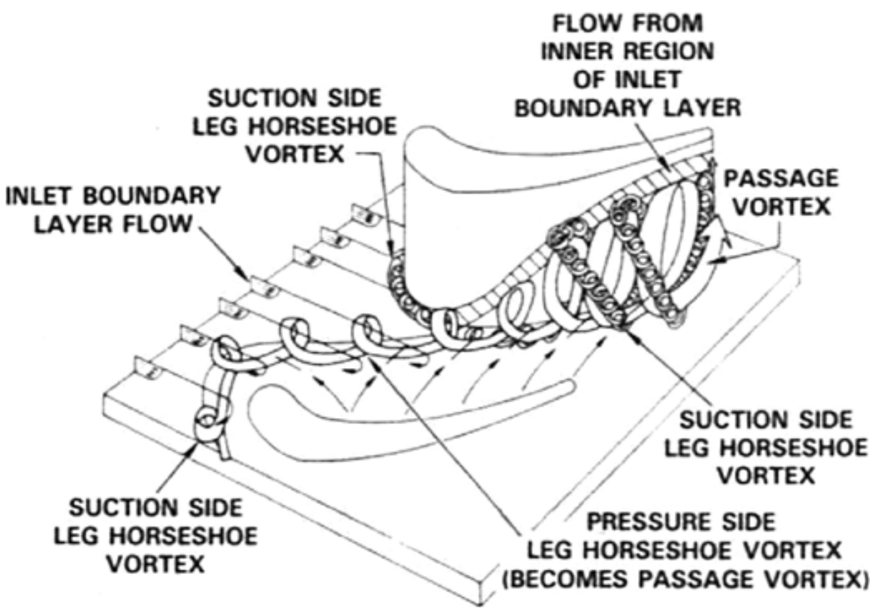
Elementary Analysis

Forces and Torques on a Blade Row

- The flow through turbomachinery is truly three-dimensional in nature.



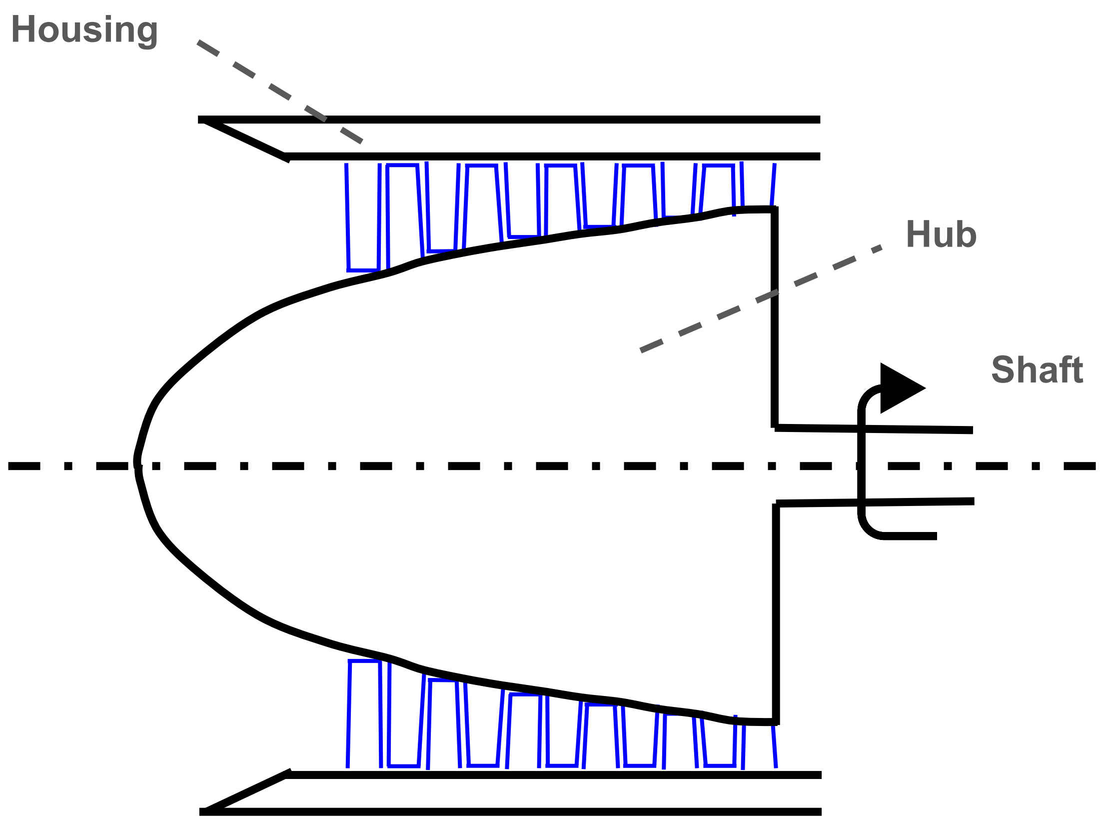
Schematic illustration of passage vortex structure

Image of cascade end-wall with oil-tracers showing presence of passage vortex

- However, considerable information can be obtained by assuming ________________ ____________________________ in properties.
  - Therefore, we can utilize properties corresponding to the average radius of the blade passage.

Elementary Analysis

- This assumption is referred to as the ‘through-flow’ approximation
  - As long as the blade length is a small percentage of the housing radius, the approximation can be quite good.



The mean radius is used for the through-flow approximation

Elementary Analysis

- Taking a slice along the mean radius, we can construct a control volume for a generic blade passage to investigate the forces on a pair of blades.
  - c_1 and c_2 represent the ___________________entering and leaving the channel.
  - The entire channel control volume is moving (_________________________) at speed $U = \Omega r$, where r is assumed to be the average channel radius measured from the engine centerline and Ω is the rotational speed (in rpm or rad/s)

Elementary Analysis

- Since we are interested in computing the forces relative to the row of rotating blades, it is useful to define w as this velocity.
  - Of course, we can relate the three principal velocities entering and exiting this control volume as
    - Again, note that we are considering a cascade; i.e. an 'unwrapped' blade passage. The C.V. can be considered planar and the motion of the C.V. can be considered steady because we do not have a through-plane centrifugal force to the centerline.
- Also note the forces exerted on the control volume.
  - We have, in general, ___________________________ that act on the inlet and exit control surfaces (the ends of the channel)
    - These forces arise due to cross-stream gradients in the flow and are therefore zero under one-dimensional flow assumptions (and nearly zero in practice).
  - For this reason, the only next __________________________, since we have neglected viscous forces in this derivation.
    - Note that the pressure forces resulting from pressure distributions on the blade walls are composed of axial and azimuthal (tangential) components, F_a and F_t, respectively.

Elementary Analysis

- Now we can write down our momentum equation for both the axial and tangential directions.
  - Starting with the axial forces relative to the blades and assuming steady flow,

    From conservation of mass, we know

    So the net axial force on the blade row can be written as

  - Similarly, the net tangential force can be simplified to give

Elementary Analysis

- Now let's look at the sum of the forces in the axial and tangential directions.
  - In the axial direction, we can write

    So that the net axial force ________________ is simply

    Where we have used the fact $F_z = \dot{m}(w_{z2} - w_{z1})$ to simplify the expression
  - In the tangential direction, there is ______________________ force because we have neglected the shear forces at the exit planes. Therefore $F_\theta = F_t$ and combining this result with the result that $F_\theta = \dot{m}(w_{\theta 2} - w_{\theta 1})$ gives the net tangential force on the fluid as

    Which can also be written in terms of the change in absolute velocity components

Elementary Analysis

- This tells us that the net torque acting on the fluid moving through the curved blade passage is then simply

  or

- The torque can then be related to the ____________________ change across the stage where, assuming an adiabatic flow, we can write

  Where w_{12} is the work per unit mass done ______________________

- From this, the power output can be expressed as

  or

  Where Ω represents the angular velocity of the fluid, which is assumed to be equal to the angular velocity of the device.

Elementary Analysis

- By equating these two definitions of power, we can write

Where $U = r\Omega$ is the is the average blade velocity in the passage.

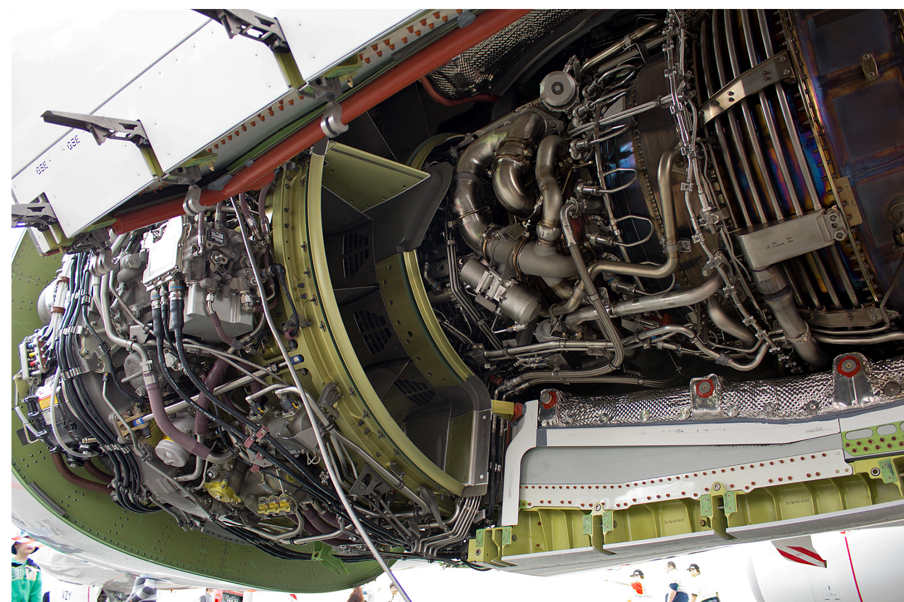
- This result shows that the work required to drive the compressor (or the work output of the turbine) is proportional to the change in the circumferential velocity across the stage.
- Since changes in the meridional velocity are attributed to flow turning, we can see the importance of the absolute flow angles entering and leaving the set of blades.
- No work is done in the stator passages, so the energy equation simply gives __________________ where we have assumed that the exit of the stator is denoted as stage 3.
- Since flow turning is still present in the stator passage, the stator blade will still sense a ______________________, which can be generally represented as

Introduction

PURDUE AERONAUTICS & ASTRONAUTICS

Compressor Design

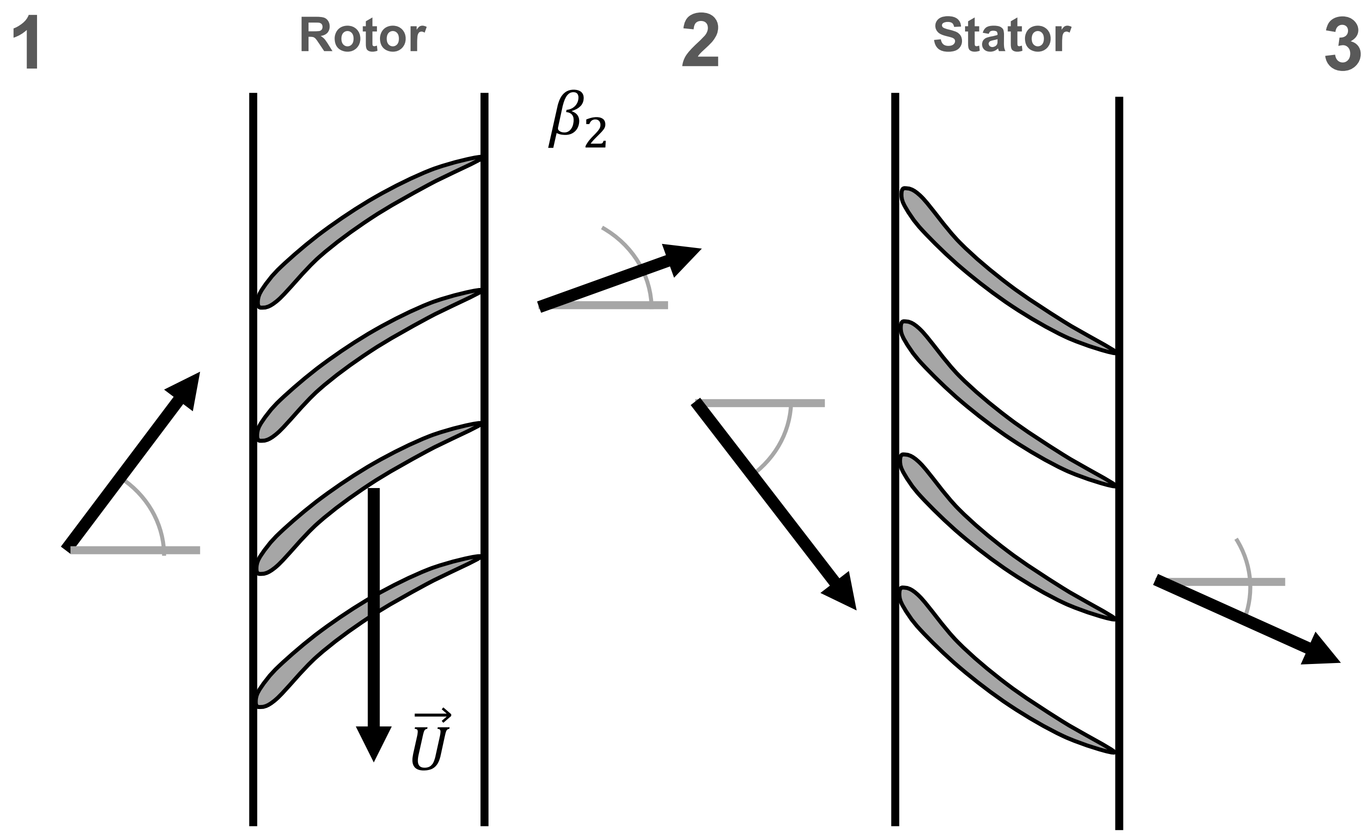
- Engineers designing axial compressors are faced with a typical challenge: multi-dimensional design trade-offs and a balance of compromises.
  - Minimization of engine frontal-area and weight will require ____________________ ________________ through the device to maintain a fixed engine mass flow rate.
  - Higher velocities result in greater losses (____________________________)
- To gain more understanding of the ramifications of this design trade, let us consider a single-stage axial compressor



CFM 56 Engine Installed on a Boeing 737 (with cowling removed, left) where numerous design complexities were undertaken to maximize the engine bypass ratio.

Single-Stage Axial Compressor

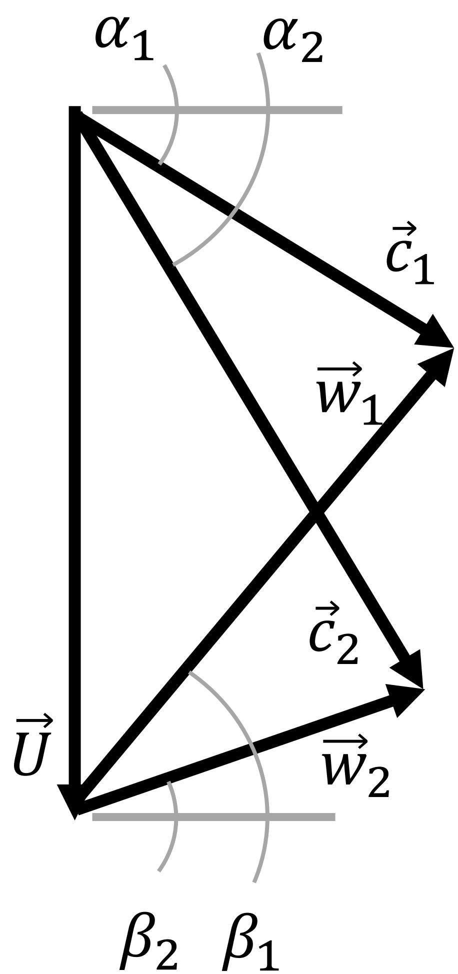
- We return to our cascade diagram, which highlights the velocity vector relationships through our single-stage device.



Single-Stage Axial Compressor

- Note that the incoming flow is assumed to have swirl.
  - The flow will not be completely axial as some degree of swirl is always introduced by the ______________________.
  - This tangential component of velocity is necessary to provide the correct flow angle to the first rotor in a real compressor.
    -
    - The flow angle β_1, in combination with the rotor blade geometry, determines the ______________________ for the flow encountering the rotor.
    - Similarly, β_2 determines the angle of attack of the flow encountering the stators.
- The combined graphical representation of the velocity vectors is typically referred to as a ______________________ since, by definition, $\vec{U}$, $\vec{c}$, and $\vec{w}$ must form a triangle.
  - The inlet and outlet velocity triangles for the rotor are related, since $\vec{U} = U_1 = U_2$ for an axial device
  - Overlaying the inlet and exit velocity triangles, we get a physical sense of the flow velocity change across rotor

Single-Stage Axial Compressor



- This is a well-designed stage
  -
- The main effect of the rotor is to change the ____________________ velocity of the fluid.
- Note also that the magnitude of the absolute velocity ($|\vec{w}|$) is increased through the stage.
  - This can be related back to _______________________, if we neglect the effects of blade twist as a function of radius from the rotor shaft.
    -

Single Stage Axial Compressor

- Therefore, the torque on the fluid can be specified as in the derivation of the Euler turbomachinery equation

  And the power required to drive this rotor is simply

  Where a negative sign results from the fact that we are prescribing the power generated ________________. Since we are interested in work done **on** the fluid in our compressor, we manipulate our equation to show.

- Since the stator row is not rotating ($U = 0$), there is no work done on the fluid in the stator row. However, since the fluid is turned by the stator, there is still a torque on this row of vanes.

Single Stage Axial Compressor

- One important matter to note is that the actual flow at stations 1-3 is not actually steady.
  - The fluctuations are periodic so that, on average, the conditions at these points are steady...
- Once we assume that the flow is steady, it is typically also a good assumption to neglect heat transfer in comparison to the large amount of work done on the fluid.
  - Under these conditions, the first law can be written
  - Combining with our equation for the compressor rotor power, we obtain
  - Assuming a constant specific heats, we can specify the dimensionless temperature rise across the rotor

Single Stage Axial Compressor

- Because the flow through the stator is also ________________, we know that $T_{o,3} = T_{o,2}$ and the stagnation temperature rise for the entire stage is given by the previous equation.

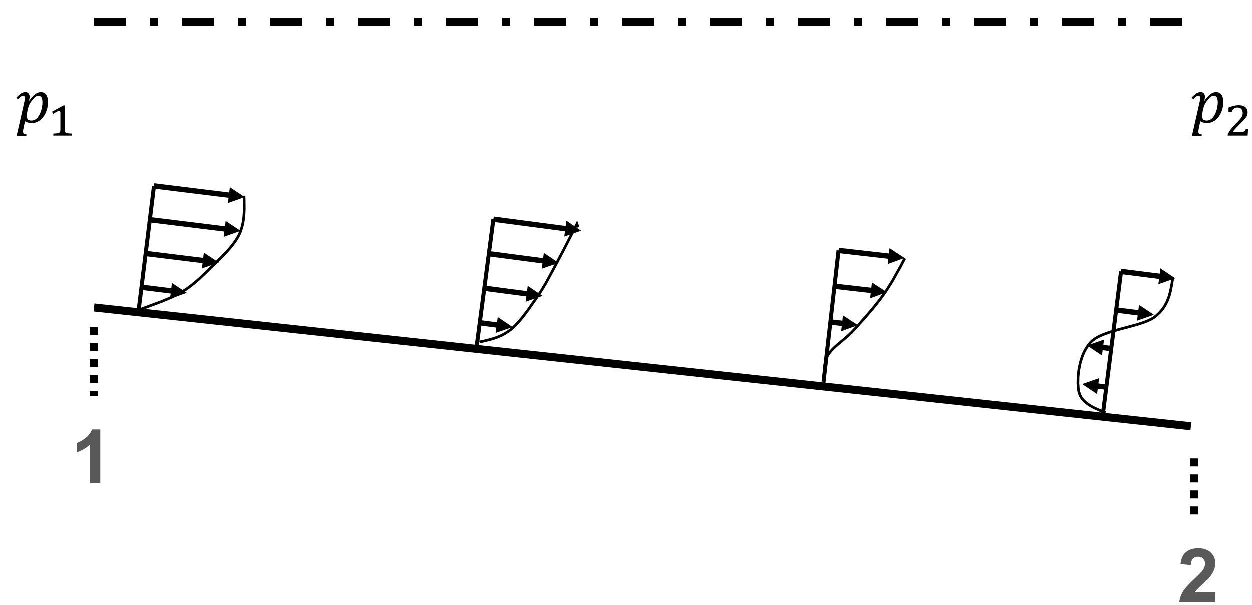
- Of course, frictional processes in the stator will still lead to ____________________ losses in this region. If we define the stage efficiency as η_{st}

$$\eta_{st} = \frac{h_{o,3s} - h_{o,1}}{h_{o,3} - h_{o,1}} = \frac{\left(\frac{p_{o,3}}{p_{o,1}}\right)^{\frac{(\gamma-1)}{\gamma}} - 1}{\frac{\Delta T_o}{T_{o,1}}}$$

so that the stagnation pressure rise (with losses subtracted) becomes

Pressure Rise Limitations

- As we've pointed out throughout the course, the flow through a compressor is analogous to a diffuser in that the boundary layers must work against adverse pressure gradients.



- Considering the developed boundary layer flow in a subsonic flow through an expanding channel.
  -

Pressure Rise Limitations

- Experiments have shown that separation on a flat plate will occur when the pressure coefficient reaches a specified value
  - Typically this value falls in the range from $0.4 < C_p < 0.8$.
- In terms of flow over a rotor, this requirement can be expressed as

  Where the maximum allowable pressure ($p_2 = p_{2,max}$) can be determined if the critical pressure coefficient is known.

  - Designers typically limit the static pressure rise in real machines to $C_p < 0.6$
- For an incompressible fluid, pressure changes can be related to velocity changes through the Bernoulli equation.
  - For the rotor and stator, we can write that

  where we can obviously see that restrictions on C_p imply restrictions on the velocity changes through the stage.

Compressibility Effects

- It is usually desirable to maintain a subsonic speed, _________ ____________________________, over the entire blade length.
  - If the ____________________________ of the flow approaching the blade exceeds unity, then shocks will form on the surface of the blade.
  - The most detrimental aspect of the shock presence is not the stagnation pressure loss across the shock itself, but the tendency ______________________ __________________________________ at the base of the shock.
    - This separation leads to high airfoil drag and associated losses in compressor performance.
- Typically, designers employ the criteria:

$$0.6 < \left(M_{1,rel} = \frac{w_1}{a_1}\right) < 0.85$$

  - Extending this limit is the focus of significant research effort, thereby increasing the mass-flow possible for a given frontal area and reducing the compressor weight.
    -
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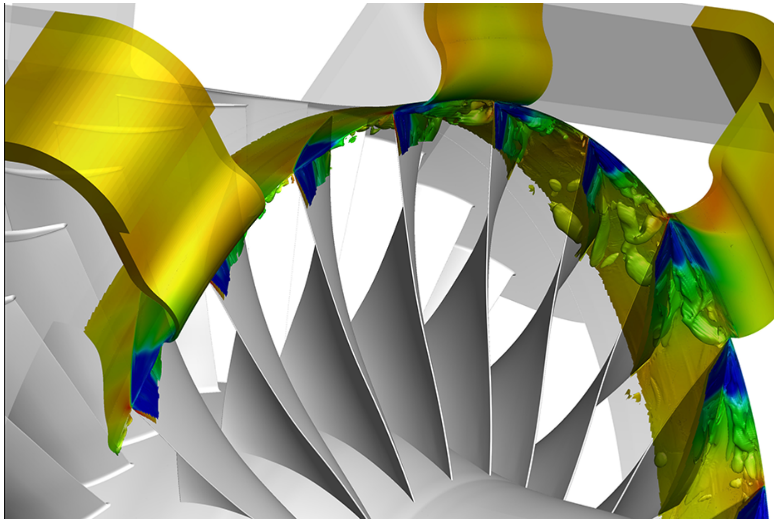


Oak Ridge Leadership Computing (2014)

'Ramgen Takes Turbomachine Designs for a Supersonic Spin on Titan'

Compressibility Effects

- Static pressure and Mach number limits tend to also place an upper-bound on the ______________________________ across a given compressor stage.
- Employing the definition of Mach number, we can re-write our incompressible form of critical pressure coefficient definition as

  Which gives a maximum pressure ratio of _____, assuming $c_p = 0.6$ and $M_{1,rel} = 0.8$.

- If similar limits are present for the stator, we may write

- Real machines have static pressure ratios considerably below this limit; typically around 1.3.
  - Since the speed of sound increases due to the temperature increases in successive stages, compressibility effects are generally most pronounced on the ______________________________ in the compressor.

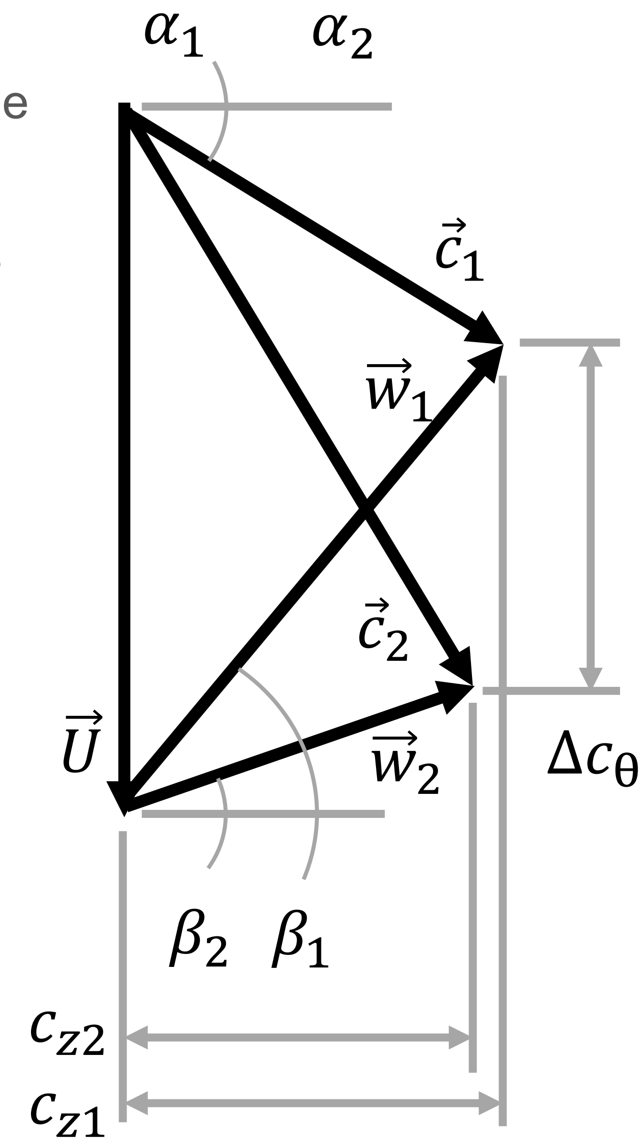
Compressibility Effects

- Current state-of-the-art axial velocities are on the order of ___________ ft/s.
- Current state-of-the-art blade tip velocities are on the order of ___________ ft/s.

- Of course, it is desirable to express the limiting pressure coefficient in terms of some restriction on the blade angles. We can accomplish this for the velocity triangles shown, if we assume that the axial velocity is roughly constant. We can write

  And, combining with the incompressible pressure coefficient gives:

  Similarly for the stator, we can write



Degree of Reaction

- The degree of reaction, R, is defined as the percentage (or fraction) of the total stage static pressure rise which occurs in the rotor.
- If we assume that the flow in the rotor is approximately isentropic, then the second law of thermodynamics gives:

$$Tds = dh - \left(d\frac{p}{\rho}\right) = 0$$

- Further, if we assume that, for a single rotor, the flow is approximately ________________________, we can write:

$$h_2 - h_1 = \frac{(p_2 - p_1)}{\rho}$$

- Combining with the energy equation relative to the rotor gives:

Degree of Reaction

- Recalling that $\Delta h_o = U \Delta c_\theta$, and noting that $h_{o,2} = h_{o,3}$, the energy equation for the entire stage can be written

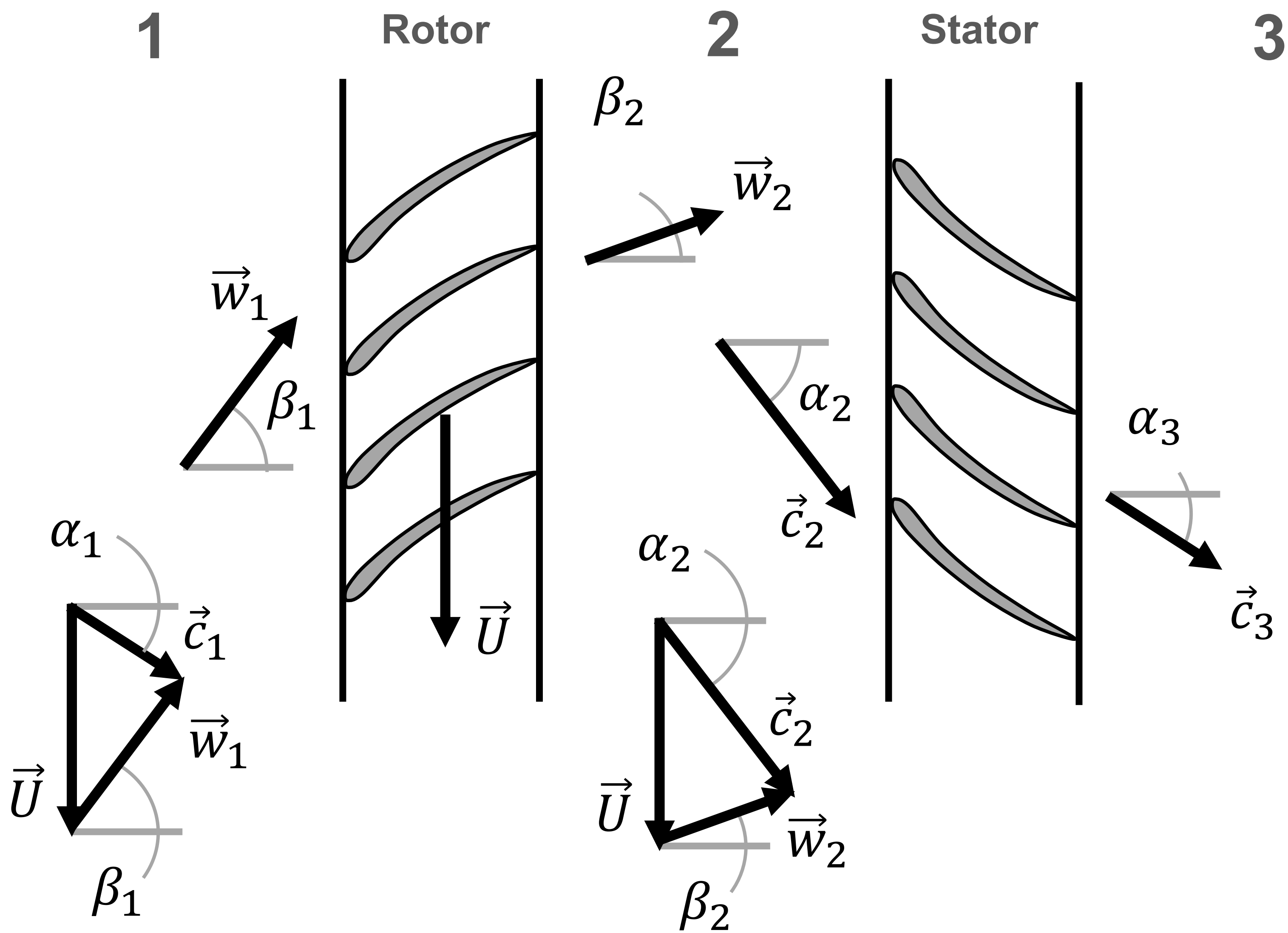
$$h_{o,3} - h_{o,1} = h_3 - h_1 + \frac{1}{2}\left(c_3^2 - c_1^2\right) = U\left(c_{\theta,2} - c_{\theta,1}\right)$$

- As a design objective, we can often assume that the initial and final absolute velocities for a given stage are approximately equal __________________. Using this assumption and simplifying the enthalpy difference as above gives:

- Combining this result with our expression for the pressure change in terms of the absolute velocity, we develop our expression for R the degree of reaction.

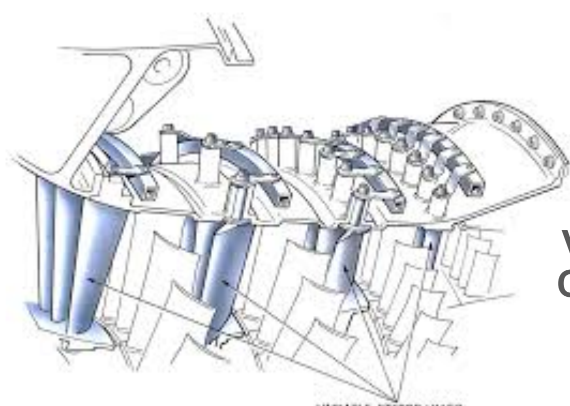
- Real machines have degrees of reaction near 0.5.
  -

Degree of Reaction

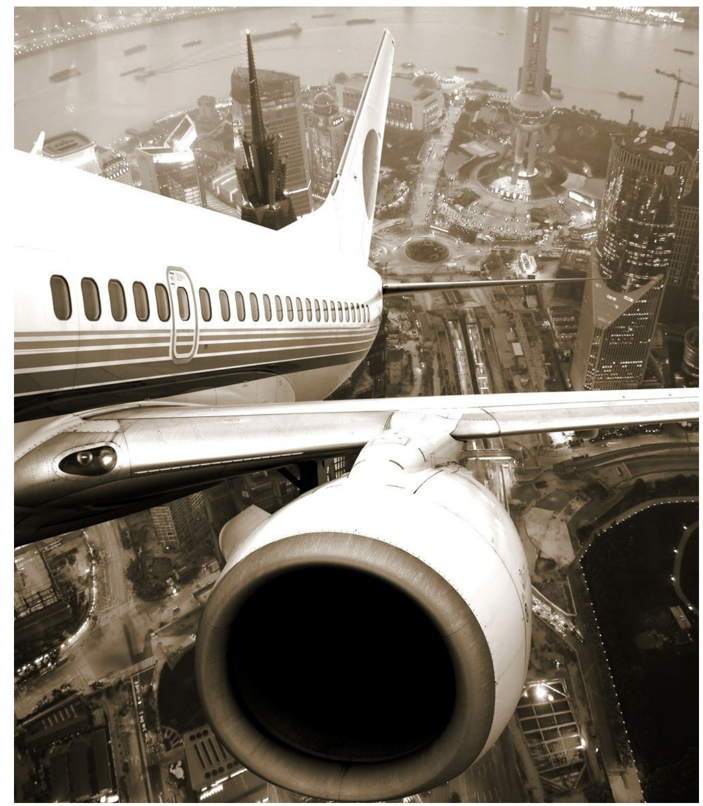


Performance of Real Compressors

- In these previous sections, we have discussed techniques to optimize the performance of a single stage compressor at a given operating condition.
  - Real compressors utilize multiple stages and must operate under a variety of conditions.
  - Inlet Guide Vanes are used to provide an appropriate angle of attack for the first rotor row in the compressor



Variable Geometry Compressor Stator Vane Mechanism



Take-off from Shanghai

Performance of Real Compressors

- Engine manufacturers generally specify the compressor performance in terms of measurable quantities that effect the overall pressure ratio, Π_c.
  - Hill and Peterson show that the exit pressure of the combustor, $p_{o,3}$, can be written as a function of the following variables:

$$p_{o,3} = fn(\dot{m}, p_{o,2}, T_{o,2}, \gamma, \Omega, R, \nu, A_2)$$

    Where R is the gas constant, ν is the kinematic viscosity of the air entering the compressor, and A_2 is the flow area, which could also be represented as D^2 with D being some dimension characteristic of the size of the device.

  - Performing a dimensional analysis on the above functional relationship yields:

Performance of Real Compressors

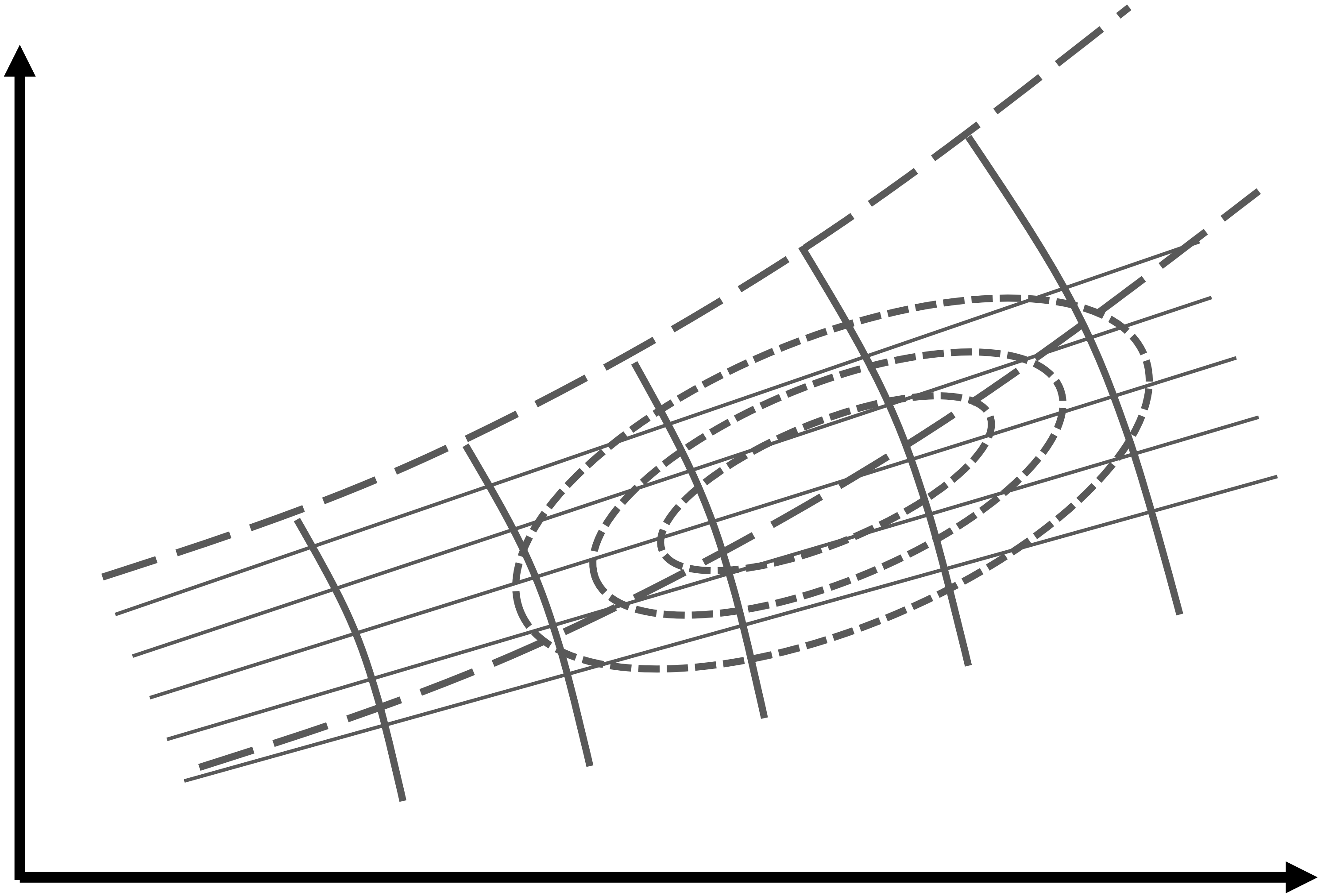
Performance of Real Compressors

- Since D is fixed for a given engine design, the mass-flow and engine-speed parameters can eliminate the dependence on D.
- As an additional simplification, we can nondimensionalize the pressure and temperature against sea level static conditions.
  - Creating two new dimensionless variables:

    where the subscript sls refers to a 'sea-level static' reference condition. Using these variables, we can write:

- These are the typical variables to represent the performance of a compressor on a ______________________________ .
  - The first term is called the ______________________________.
  - The second term is called the ______________________________.

Compressor Map



Surge and Stall

- Surge is a complex condition which is brought about by the inlet and back pressure conditions for the device.
  - Specifically, compressor surge occurs when the ___________________________ after the compressor is actually higher than what the compressor itself can maintain.
  - An instability is generated as the flow 'backs-up' (_________________), the axial velocity (_________________) drops, then the pressure relieves, leading to a flow increase, and so on… The engine 'gulps', then releases large quantities of air
    - Massive resultant stresses
    - Often lead to full compressor failure.
    - Combustion components can also couple to this instability - thermoacoustics
  - Prevention

C17 with a compressor stall during thrust reversal (top)
Severe blade damage to axial flow compressor due to vibration-induced crack formation

Surge and Stall

- Stall is an ________________________confined to the turbo-compressor internals that is usually characterized by a distortion of the flow patterns.
  - Often called rotating stall, these ______________________ can extend from a few blades to 180 degrees around the compressor annulus. They tend to rotate around the annulus at some fraction of the rotation speed (usually around half).
  - Local stall within the cascade can block the flow through the stalled passage.
    -
  - The condition is normally not catastrophic, unless the frequency of the stress oscillations caused by this unsteady aerodynamic loading happens to be near a natural frequency of the blade itself.