AAE 538: Air-Breathing Propulsion

Lecture 13: Subsonic Inlets and an Introduction to Turbomachinery

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PURDUE AERONAUTICS & ASTRONAUTICS

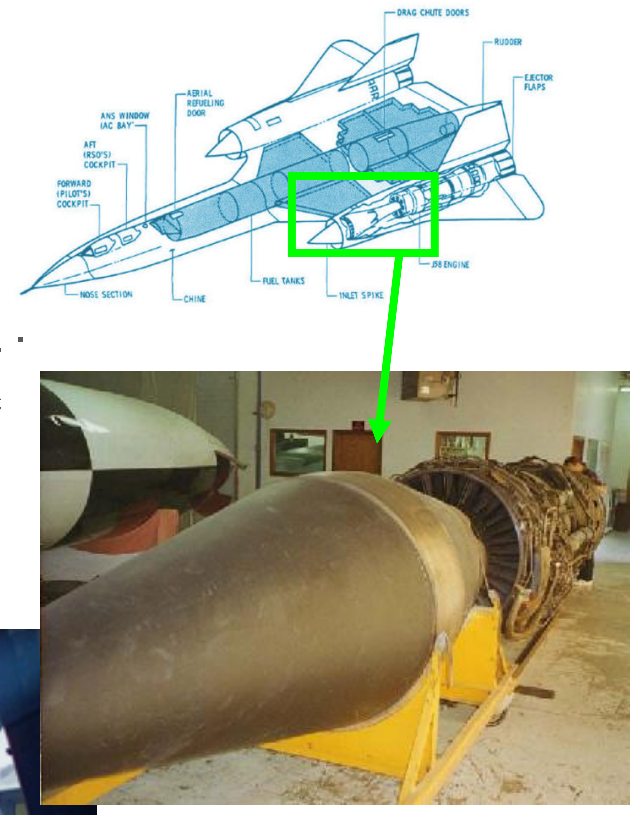
PURDUE PROPULSION

Introduction

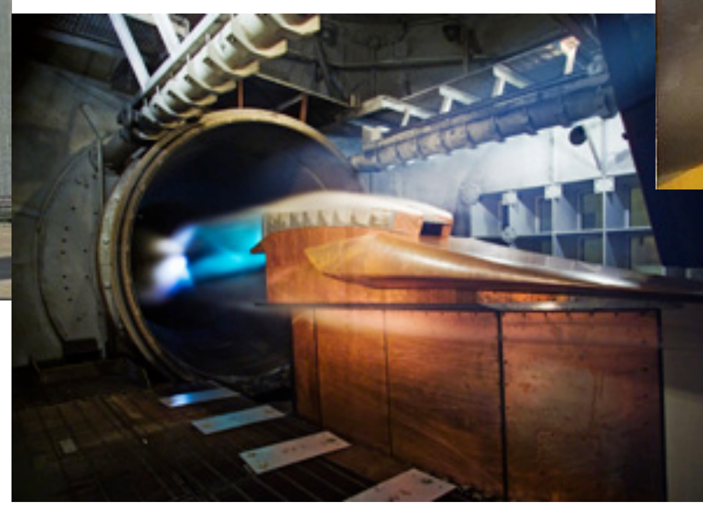
Engine Inlets

- Principal Functions:
    -
    -
    -
- Inlet Design is Highly-Dependent on __________________ .

Supersonic



Subsonic



Hypersonic

Introduction

- Design Criteria: Minimize Pressure Losses
  - Losses in $p_{o,2}$ cause a reduction in ________________ across the diffuser
    - The impact of this is compounded through the compressor, where
  - External losses from an inlet system are typically the result of drag due to
    -
    -
  - Internal losses are typically due to flow irreversibilities
    -
    -

- Supersonic inlets must be able to handle shock losses efficiently and still provide adequate performance at subsonic speeds.

- Subsonic inlets must turn and decelerate the fluid efficiently over the desired range of speed.

Introduction

- Until this point, we have always drawn the free-stream flow as being parallel to the axis of the engine.
  - Of course, in reality the inlet must be able to __________________ the flow in a reasonably uniform sense for a range of inlet angles of attack.
    - As an example, the GE 90 engine can handle angles of attack up to 17 degrees.
  - A very basic means of accomplishing this requirement is to simple cant the inlet downward a few degrees relative to the engine centerline.
    -

Introduction

- Inlets can be classified as to the way that they decelerate and compress the free-stream fluid.
    - In ______________________ compression, all of the fluid compression takes place prior to entry into the inlet, itself.

Supersonic **Subsonic**

Introduction

- In ___________________ compression, all fluid deceleration takes place within the inlet cowl, itself.

Supersonic **Subsonic**

- _______________________ compression is a combination of the two, with some compression upstream and the remainder occurring inside of the device.

Supersonic **Subsonic**

Subsonic Inlets

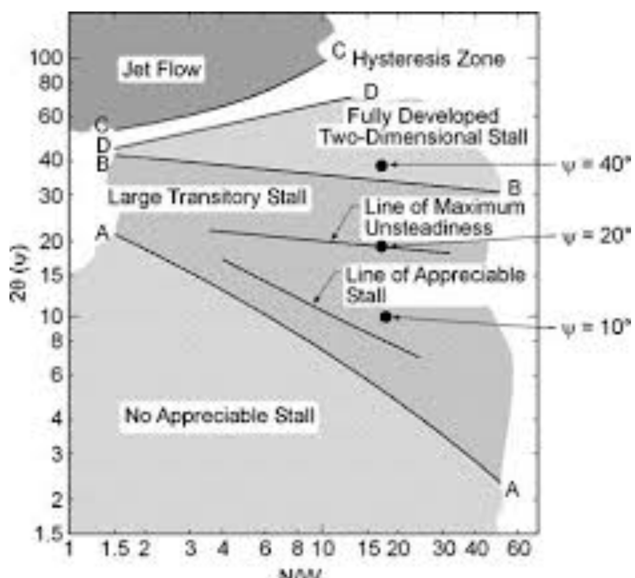
- Most subsonic inlets are ____________________ compression type devices under cruise conditions.
  - However, the same inlet will be of ______________________ compression type at very low speeds or at very high mass flow conditions.
- If we consider the flow to the inlet lip to be incompressible, the reduction in the stream-tube area will generate an ______________________________ and decrease in pressure per the Bernoulli equation.
  - Drag forces on the nacelle during these periods are high, but this is not typically a problem since inevitably this occurs at very low speeds.
- Since inlets act as diffusers, they operate with an _______________________________.
  - They are subject to boundary layer separation, or _____________________.

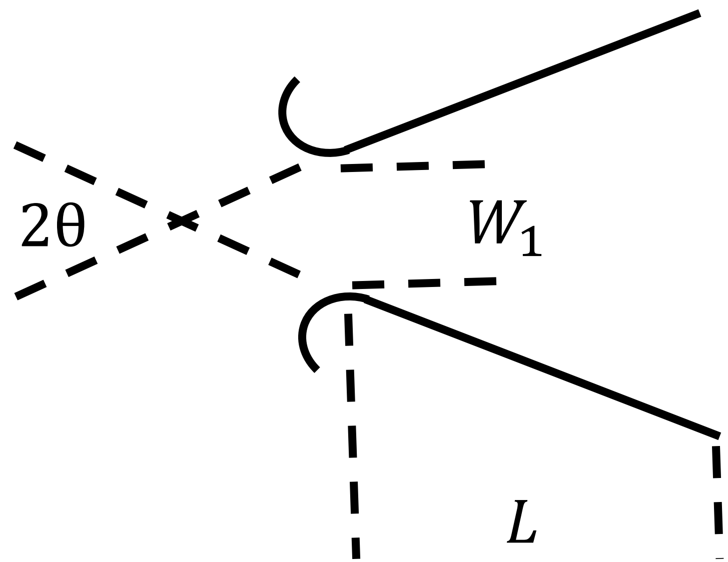
(Apparently) Well-Behaved Flow **Steady Stall**

Subsonic Inlets

Jet Flow **Transient Stall w/ Unsteady Flow Zone**

- Inlet wall divergence angles must be small enough to avoid these conditions.
  - Well-characterized empirically, and can be captured with CFD.



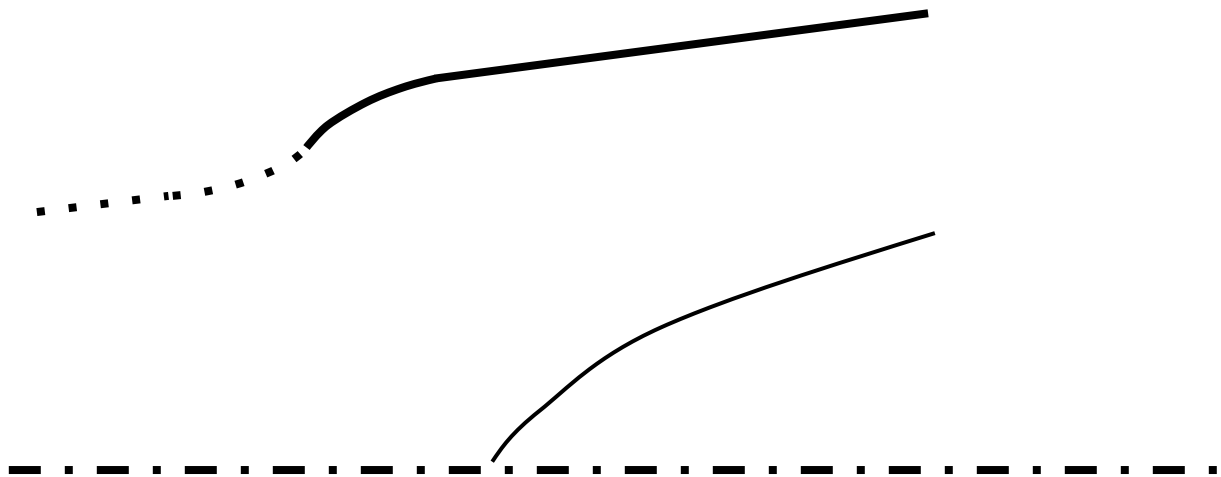


Subsonic Inlets

- Inlet areas may be determined reasonably well by assuming one-dimensional, isentropic flow behavior throughout.

- In general, we are given the requirement that the Mach number entering the compressor, M_2, must be restricted to some value (__________________________).
  - This is to avoid losses due to shock formation on the blades.

- If we define our control volume as below,



Subsonic Inlets

- We can write the continuity equation as

  Where we assume that either the capture area (A_c) or the inlet mass flow rate is known. Substituting for the speed of sound and using the perfect gas relation, this equation becomes

- Making use of the fact that both the stagnation pressure and temperature are constant for this process, we can write the pressure and temperature ratios in terms of the Mach numbers to give:

Subsonic Inlets

- Note that:
  - Either the hub diameter or the hub-tip radius ratio must be known to give the actual dimensions of this annular region.
  - The inlet length, L, must be large enough to keep reasonable divergence angles in the duct to achieve the desired area. Of course, weight is the trade-off against this deign value.
  - The area is chosen to give the minimum nacelle drag for the cruise condition
  - Correlations have been developed to relate A_1/A_c through Mach number and other interference drag parameters.

- Recalling that we defined the diffuser efficiency for a real turbojet as:

Subsonic Inlets

- As we eluded to in our previous analysis, the diffuser efficiency of a real engine design can be evaluated relative to the _______________________________________.
  - This parameter can be easily measured with impact probes at the fan or the compressor face (the inlet…exit)

$$r_d = \frac{p_{o,2}}{p_{o,0}}$$

Where we have assumed that $p_{o,2}$ is a suitable average of several measurements. Combining these two relations, we can show that

Subsonic Inlets

Typical Subsonic Diffuser Performance

Introduction

Turbomachinery Fundamentals

- Turbomachinery is a device that adds energy to a fluid, or subtracts energy from it.
  - The prefix *turbo*- in Latin means to 'spin' or 'whirl'.

- Turbomachinery can take many forms through aerospace and other industrial applications
  - Turbine: extracts energy from a fluid.
  - Pump: adds energy to a liquid.
  - Fans, Blowers, Compressors: Add energy to gases
    - $\Delta P_{fan} \approx$
    - $\Delta P_{blower} \approx$
    - $\Delta P_{compressor} \geq$

- Operating ranges vary with application
  - Machine speed for $60\ Hz$ power generation:
  - Machine speed from ABP:

Introduction

Turbomachinery Fundamentals

- There are several classes of turbomachinery, even in airbreathing propulsion applications
  -
- The controlling physics of each machine-class can be very different
  - Most notably:
  -
- Machine design can vary significantly depending on design goals (both technical and otherwise)
  - Axial flow, radial/centrifugal flow, mixed-flow machines
  - Impulse, reaction, and mixed work transfer mechanisms
  - Single-stage and multi-stage, single-shaft and multi-shaft, geared, …
- Design tradeoffs:

Introduction

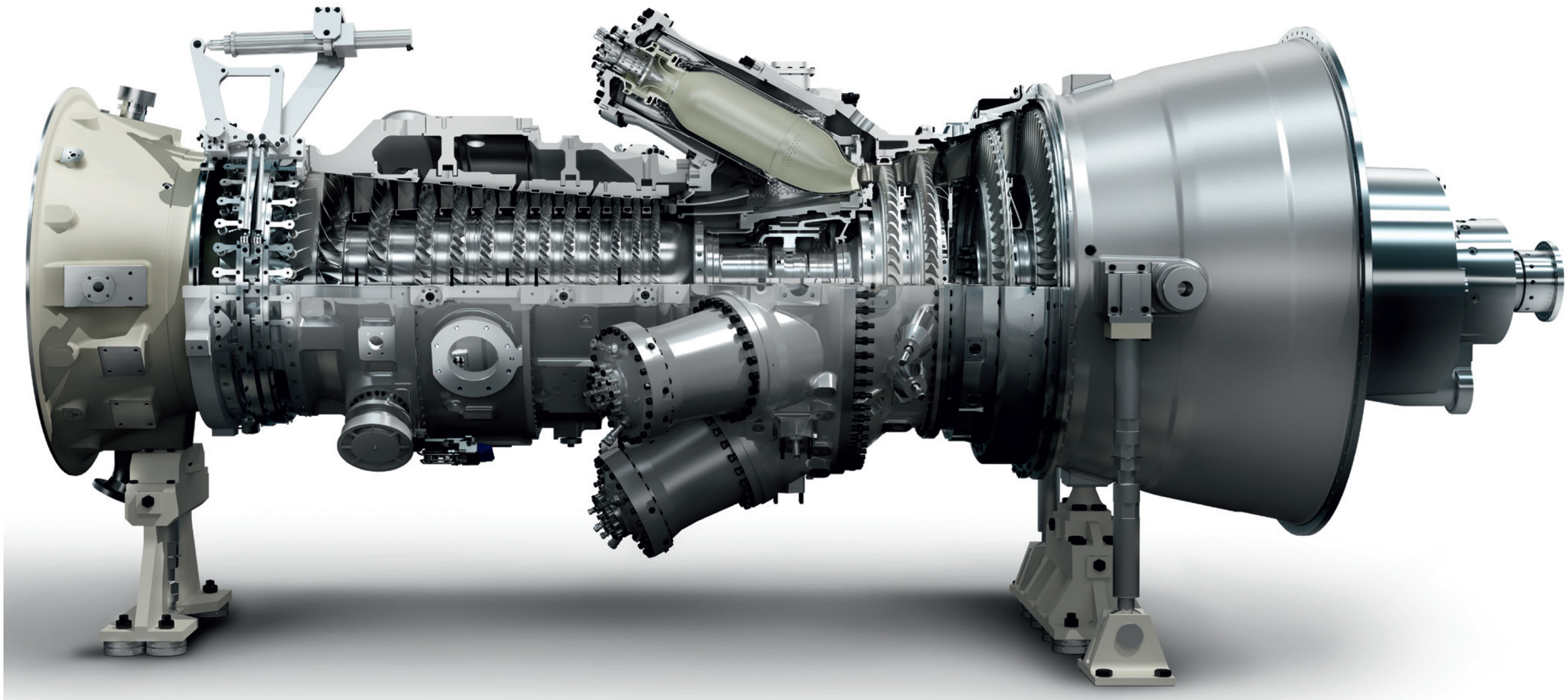
Turbomachinery Design Methodology

- Establish Design Requirements with Qualified Processes, Methods, and Tools
  - Determine ____________________ tradeoffs to establish turbomachinery requirements.
- Conceptual and Preliminary Design Process
  - 1D methods and (sometimes) 2D methods using analytical any basic (fast) numerical tools:
- Detailed Design Process
  - 3D Analysis
    -
    -
- Verification and Validation with Component and Engine Data
  - __________________________ determines if the models utilized appropriate capture the physics they represent
  - __________________________ determines the accuracy of the model for predictive design use.

Basic Concepts

Turbomachinery Components

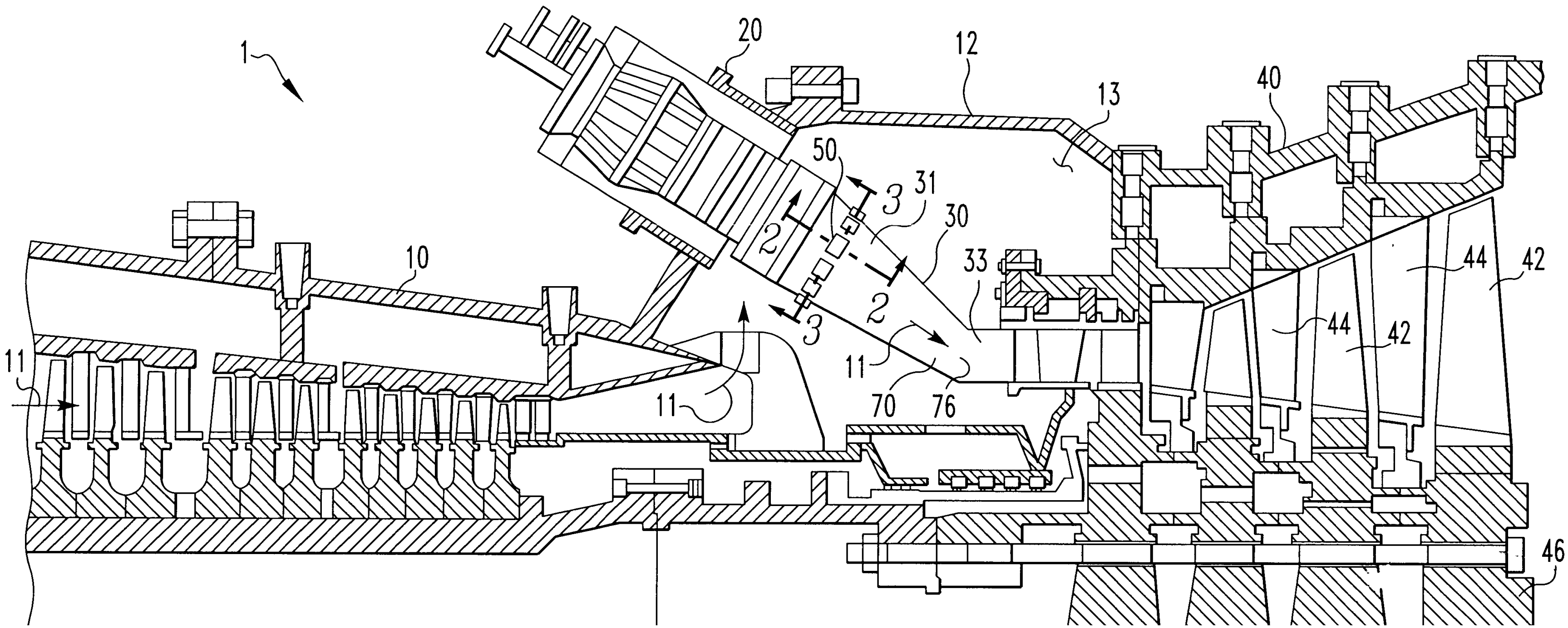
- As stated earlier in the class, both compressors and turbines are made up of stages.
    - Each 'stage' contains one row of ______________________ (a rotor) and one row of ________________________ (stators).



Shroud/Casing, Inlet Guide Vanes, Secondary Passage Bleeds, Shrouded vs. Unshrouded Rotors

Basic Concepts

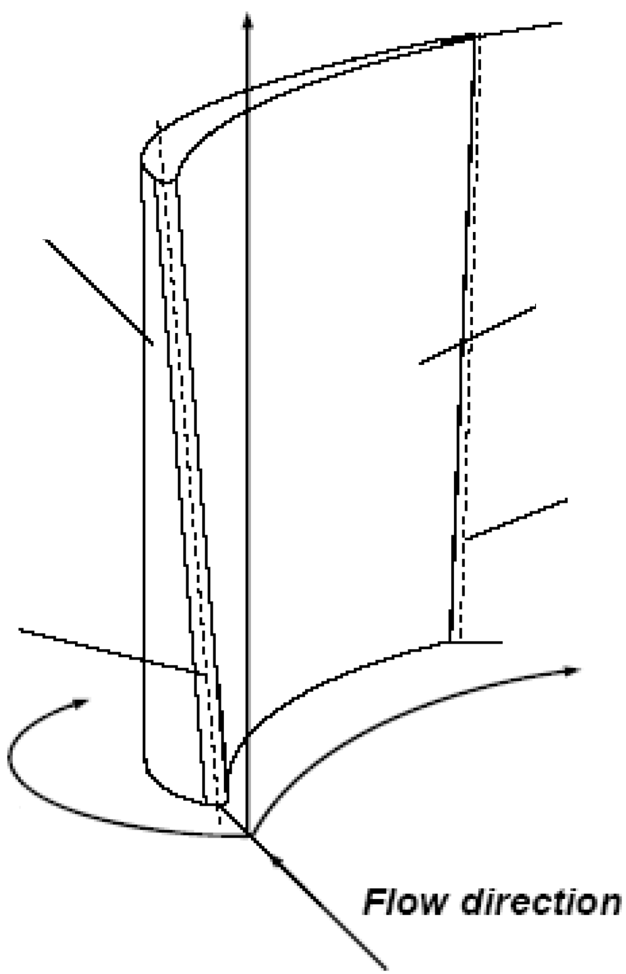
Turbomachinery Components



- Shown more clearly in this schematic:
  - Flow passage becomes smaller through compressor
    -
  - Flow passage is larger in the turbine than in the compressor
    -

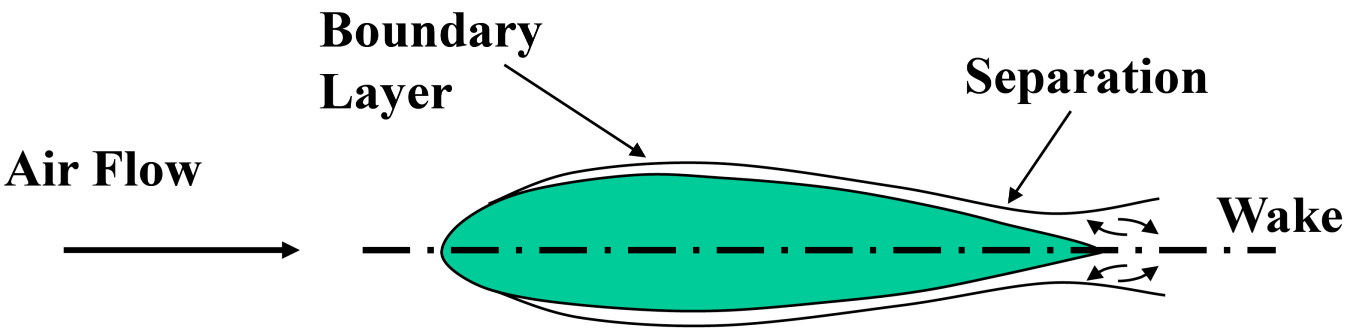
Basic Concepts

Airfoil Terminology



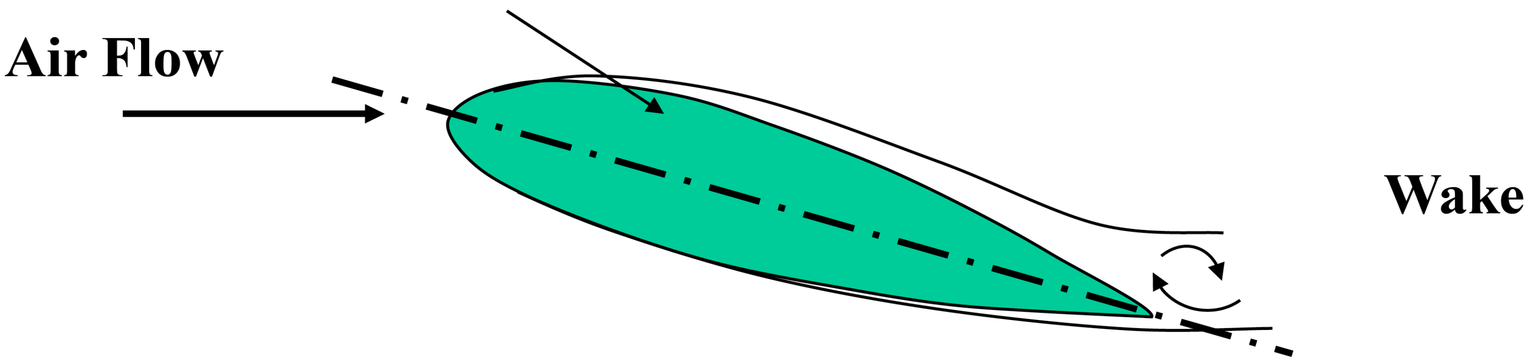
Basic Concepts

Symmetric Airfoil



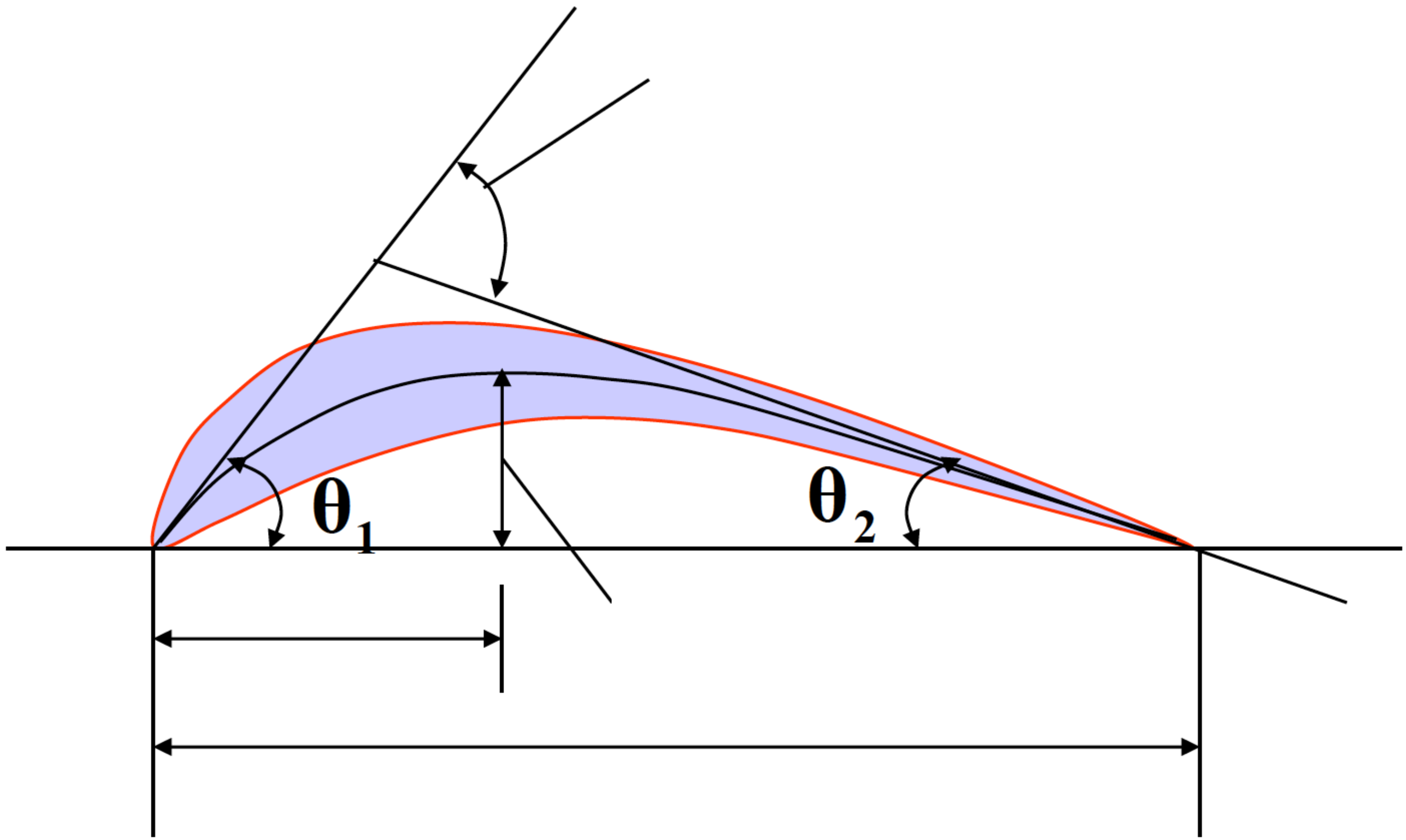
Basic Concepts

Symmetric Airfoil with Angle of Attack



Basic Concepts

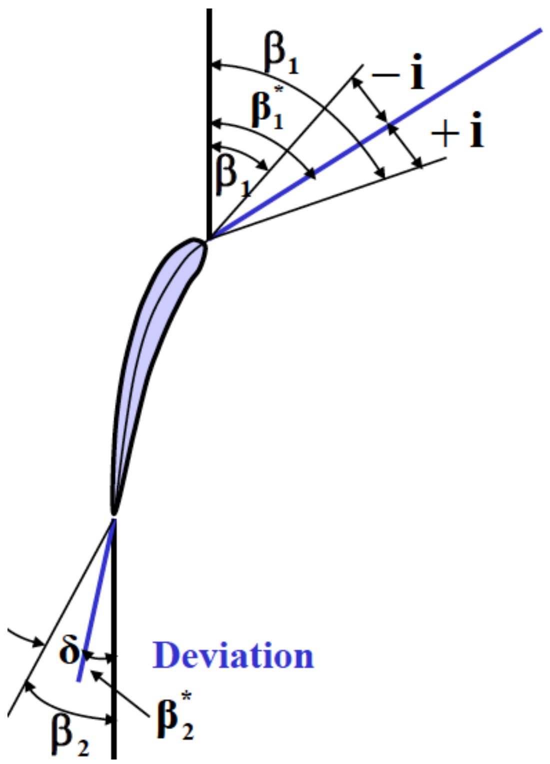
Airfoil with Camber



Basic Concepts

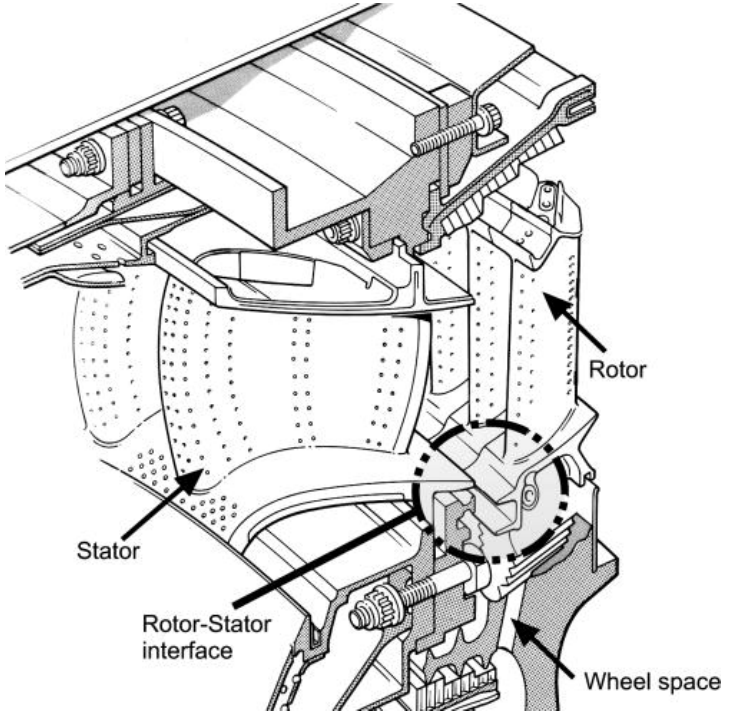
Incidence and Deviation Angles for a Blade (Rotor)

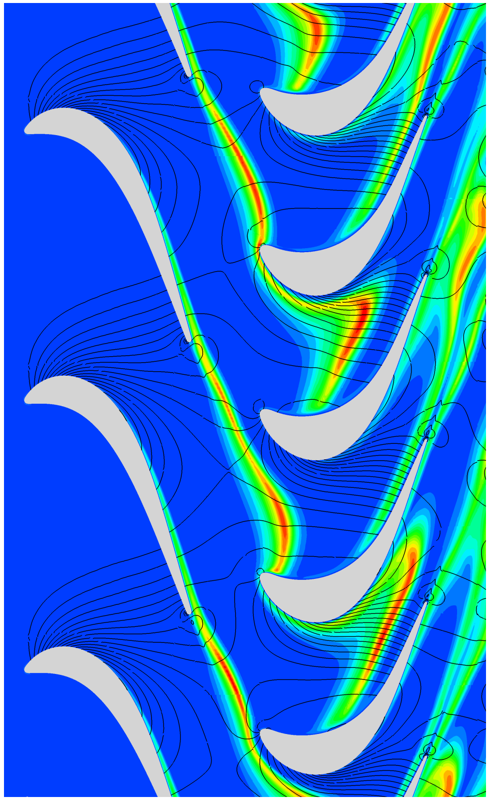
- The inlet and exit flow angles determine the amount of flow turning that is caused by the blade.



Basic Concepts

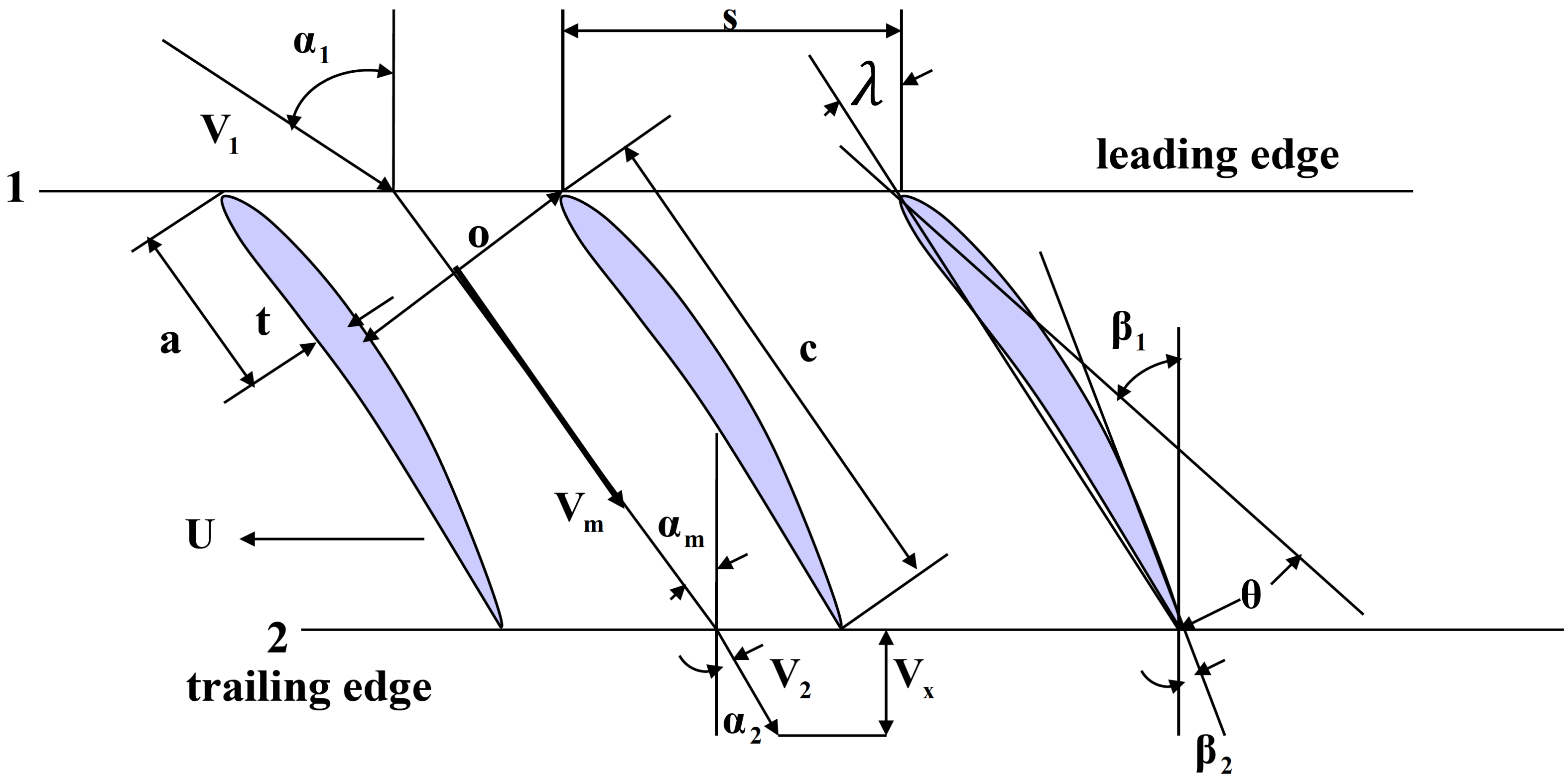
- Imagining a circumferentially _______________ compressor or turbine annulus, we obtain a 2D repeating series of blades (vanes)
    - Typically referred to as a _______________.
    - Often considered as an analysis simplification





Basic Concepts

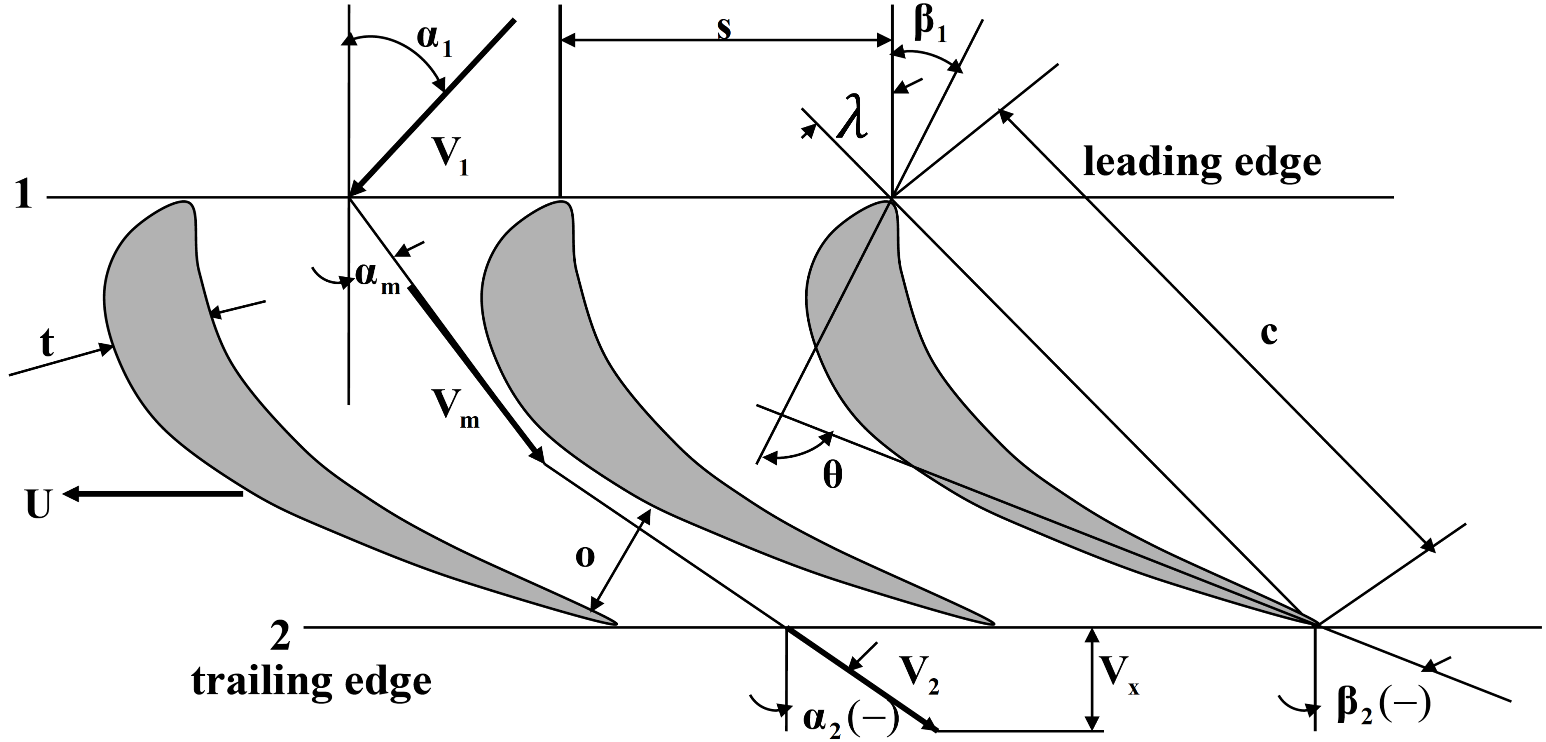
Cascade Terminology



$s = pitch$	$\alpha = fluid\ flow\ angle$	$i = incidence\ angle\ (\alpha_1 - \beta_1)$
$c = chord$	$\beta = blade\ camber\ line\ angles$	$\delta = deviation\ angle\ (\alpha_2 - \beta_2)$
$a = chord\ to\ maximum\ camber$	$\lambda = stagger\ angle$	$\epsilon = deflection\ angle\ (\alpha_1 - \alpha_2)$
$t = maxium\ thickness$	$o = throat\ opening$	$\theta = camber\ angle\ (\beta_1 - \beta_2)$

Basic Concepts

Cascade Terminology



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