TURBOMACHINERY AERODYNAMICS

Lect- 13

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In this lecture...

- Inlet distortion and its effect on compressor stability
- Control of instabilities

Inlet distortion

- Engine performance significantly depends upon the "quality".
- Air inlets are required to provide the necessary quantity of good quality air to the engine.
- The exit flow may become non-uniform under a variety of circumstances: manoeuvre, geometry of the intake, boundary layer ingestion, wakes/jet plume from freestream, cross-wind etc.

Inlet distortion

- Intakes of civil and military combat aircraft have very different geometries.
- Combat aircraft intakes can have very complex geometries leading to inherent problem of flow non-uniformity.
- Inflow non-uniformity or distortion is detrimental to engine operation.
- Several aircraft in the past, that were operating with engines not designed for distortion have had serious operational issues including several engine failures.
- Some of these are F100 (1954), F101 (1954), Hunter (1955), Britannia (1956), F111 (1966) etc.

Inlet distortion

Transport aircraft intakes

Military aircraft intakes

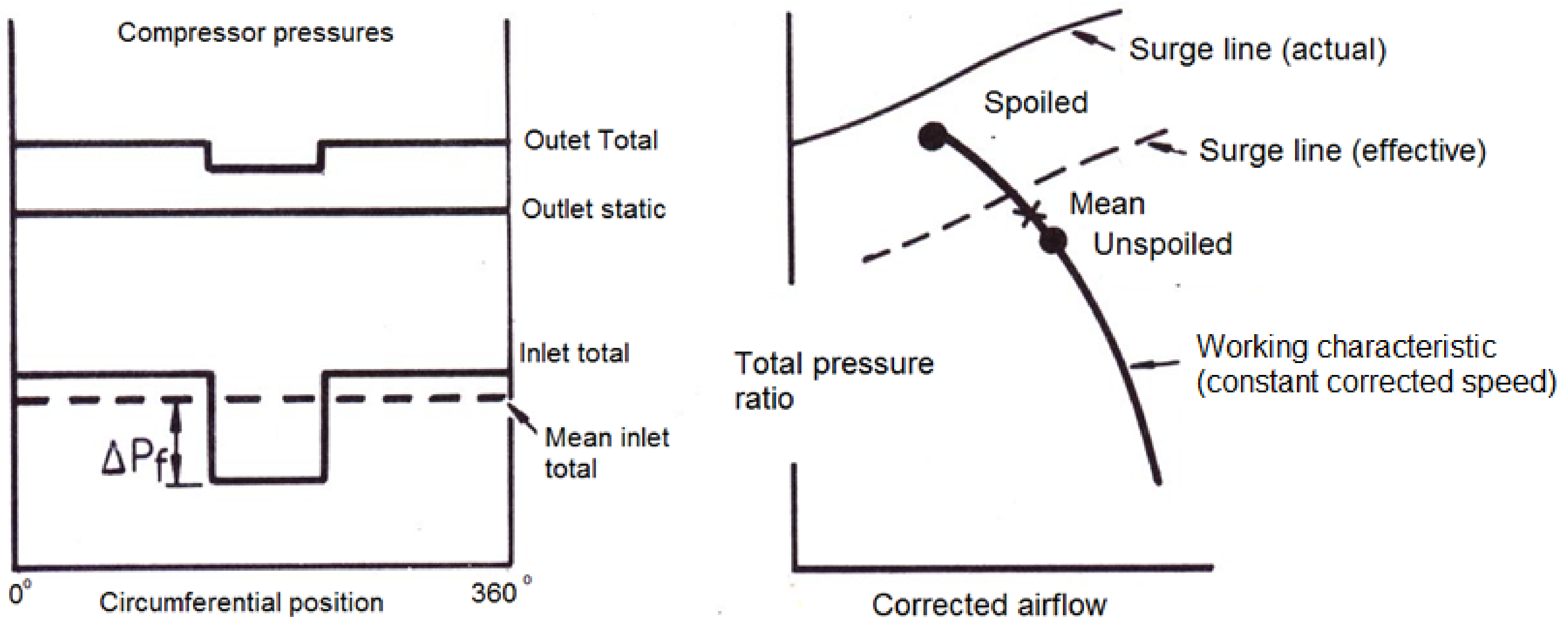
Types of inlet distortion

- Inflow distortion here refers to the non-uniformity in the inlet exit total pressure distribution.
- There are different types of inlet distortion:
  - Static and dynamic distortion
  - Circumferential and radial
  - Combination of the above
- The primary effect of inflow distortion on the engine performance is on the compressor operation.

Inlet distortion

- Inflow distortion can lead to earlier initiation of instabilities: rotating stall and surge.
- Flow distortion causes local change in incidence angles.
- If these angles exceed the critical angles, one or more adjacent blades falling in this zone of distortion, stalls.
- The stall cell(s) propagate if these are able to withstand the system dynamics. Else, they dissipate and the system does not undergo any instabilities.

Inlet distortion



Parallel compressor theory

Distortion coefficient

- Quantification of distortion: total pressure non-uniformity
- Most commonly used measure: distortion coefficient.

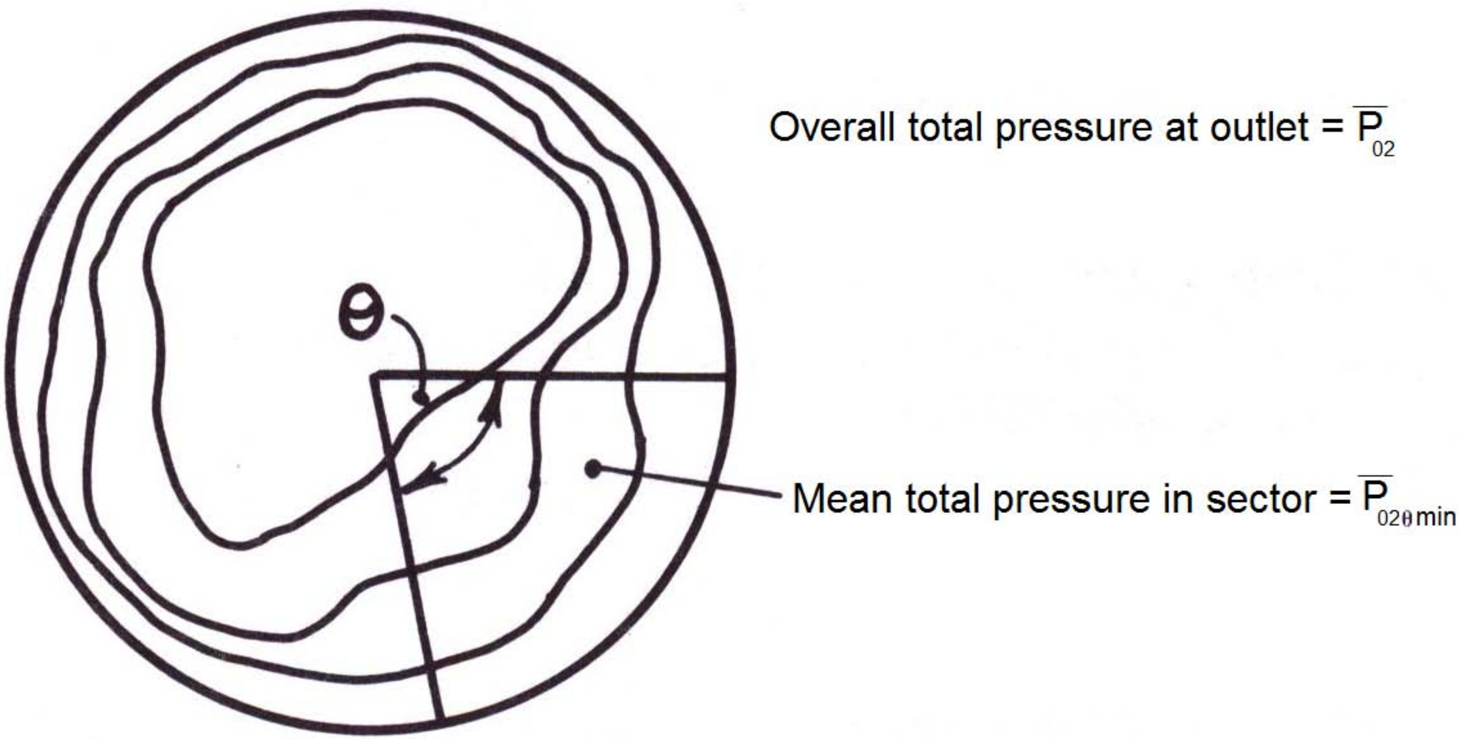
$$DC_\theta = \frac{\overline{P}_{02} - \overline{P}_{02\theta\,min}}{1/2\rho V_\infty^2}$$

$\overline{P}_{o2}$ is the average outlet stagation pressure

$\overline{P}_{02\theta\,min}$ is the average outlet stagnation pressure is sector where stagnation pressure is minimum

$1/2\rho V_\infty^2$ is the inlet dynamic pressure

Inlet distortion



Distortion coefficient definition

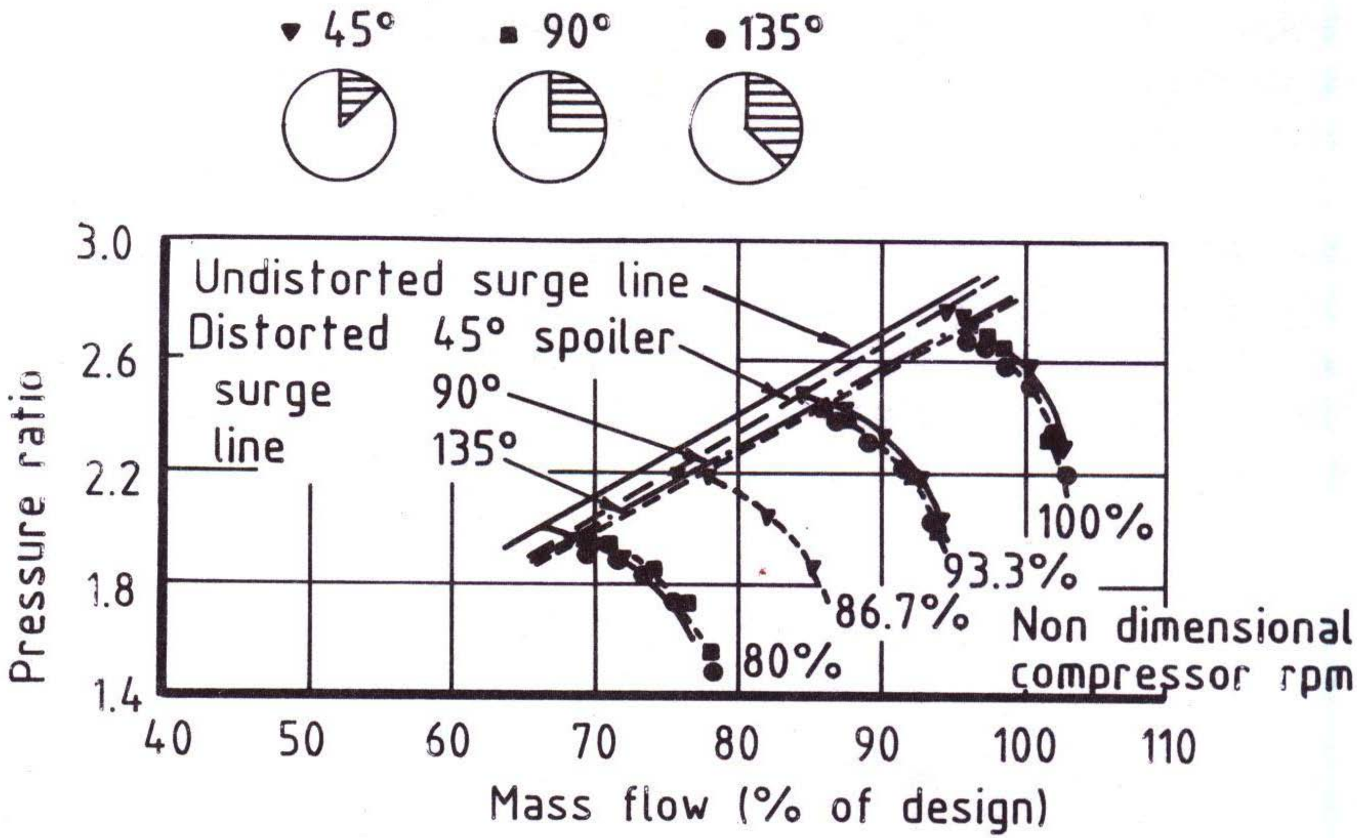
Distortion coefficient

- Based on the sector angle chosen, there are different ways of defining distortion coefficient.
- The sector angle that is most commonly used is 60^o and therefore the distortion coefficient is DC_{60}.
- Other angles like 45^o and 90^o are also sometimes used.

Effect of inlet distortion

- Inflow distortion affects the surge margin significantly.
- The presence of inflow distortion can lead to early initiation of instabilities.
- If the inflow distortion is severe, it may lead to surging of the engine.
- Engine manufacturers attach a certain distortion tolerance with each engine. This indicates the extent of inflow distortion that the particular engine can withstand without the threat of surge.

Effect of inlet distortion



Effect of circumferential distortion on surge line (Hercock and William,1974)

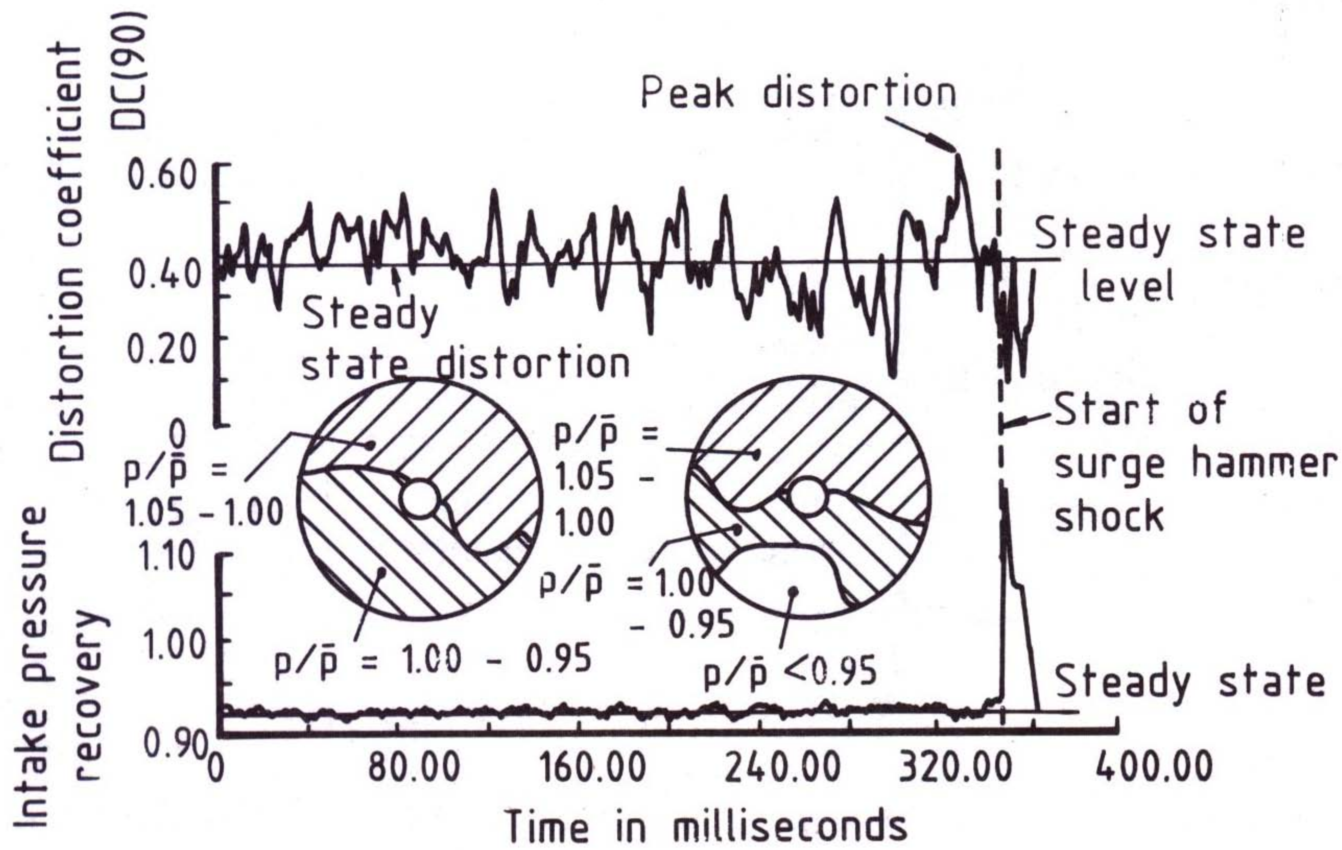
Effect of inlet distortion

- Static/steady inlet distortion is more common form of distortion.
- Considers spatial non-uniformity of time-averaged total pressure.
- Usually circumferential non-uniformity is considered more severe as it significantly affects the incidence angle.
- Radial distortion is likely to occur due to thickening of the boundary layer. A certain amount of radial distortion will be present due to the presence of boundary layer.

Effect of inlet distortion

- Dynamic distortion involves unsteady flow effects.
- Distortion is time-variant and hence its effect on the compressor performance is even more severe.
- Quantification of dynamic distortion is challenging. There are no descriptors as such for dynamic distortion.
- It has been observed that surge is likely to occur if the critical value of distortion coefficient exceeded for a time period of the order of that for one engine revolution-typically about 5 ms.

Effect of inlet distortion



Engine surge caused by dynamic distortion (Hercock and William, 1974)

Swirl

- Many of the military aircraft have engines that are offset from the intake centerline.
- Such intakes referred to as S-type or Y-type intake, inherently suffer from strong secondary flows.
- In the absence of guide vanes, the flow entering the compressor is likely to have some amount of swirl.
- This swirl may get amplified under certain operating conditions, leading to severe inflow distortion.

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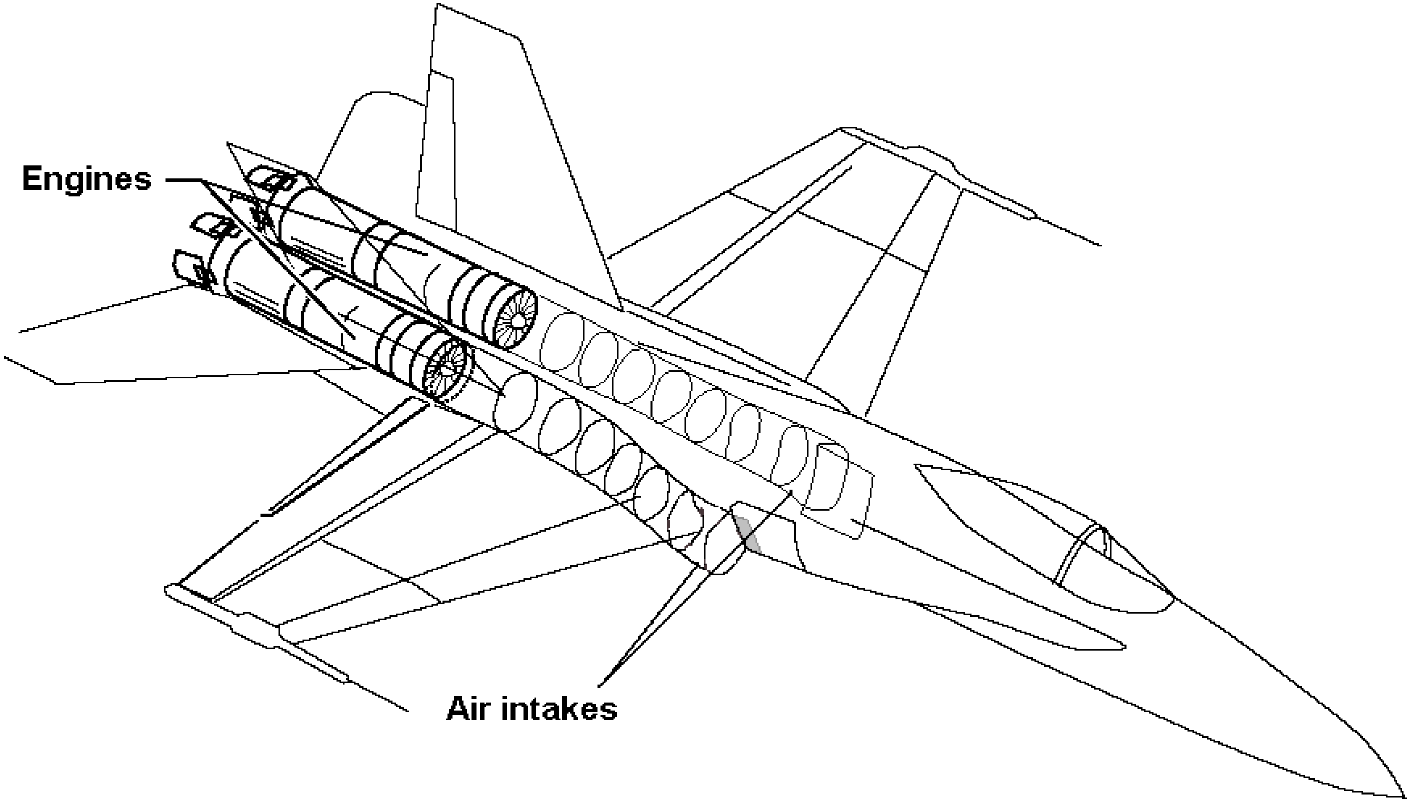
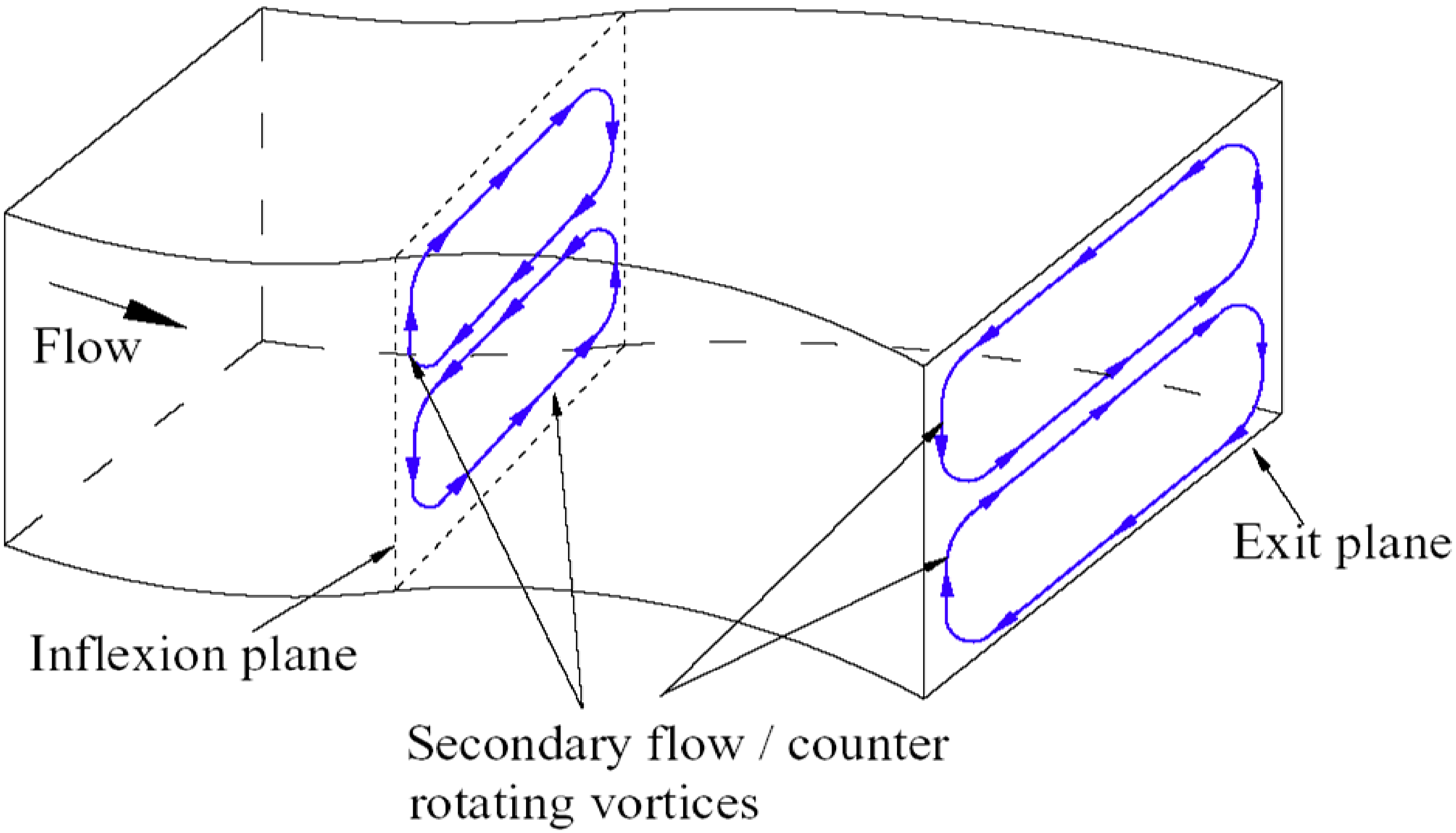
Swirl



Swirl



Structure of secondary flows in S-duct diffusers

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Control of instabilities

- Compressor instabilities limit the operating range of an engine.
- Operating the compressor too much away from the surge line compromises the efficiency.
- Ability to operate the compressor close to high efficiency points (and possibly closer to the surge line) is of immense interest.
- This would require methods of preventing or controlling the occurrence of instabilities.
- The other way of preventing this altogether is to control the inflow from the inlet by flow control methodologies.

Control of instabilities

- There are several methods that have been proposed by researchers over the past 50 years or so.
- These can be broadly classified as Passive and Active control techniques.
- Passive control
  - Does not involve any external energy addition.
  - Control scheme incorporated by design changes on the compressor blade and/or the compressor casing.
  - "Simpler" to design and implement.
  - Disadvantage: cannot be controlled, may lead to performance penalties when the control is not required.

Control of instabilities

- Active control
  - Involves addition of energy external to the system.
  - Separate control scheme and associated components need to be designed and integrated with the compressor system.
  - More complex, difficult to design and implement.
  - Can be controlled, “switched-off” when not required, minimal performance penalties.

Control of instabilities

- Passive control methods
  - Casing treatments
    - Proposed in late 40s
    - Involves making grooves/slots on the casing above the rotor.
    - Affects the tip flow behaviour.
    - Delays stall and therefore offers better stall margin.
    - However reduces the efficiency.
    - Area of active research to develop casing treatments that improve stall margin without efficiency penalty.

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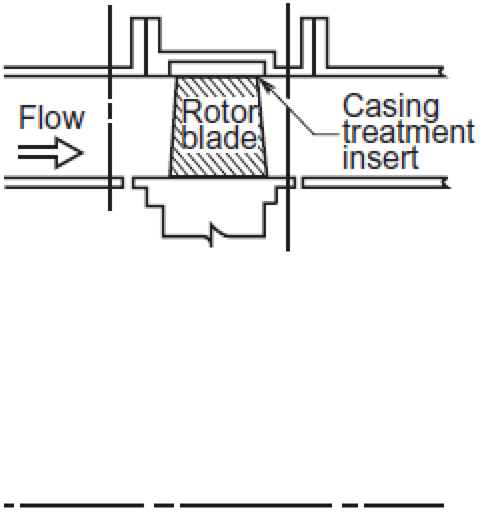
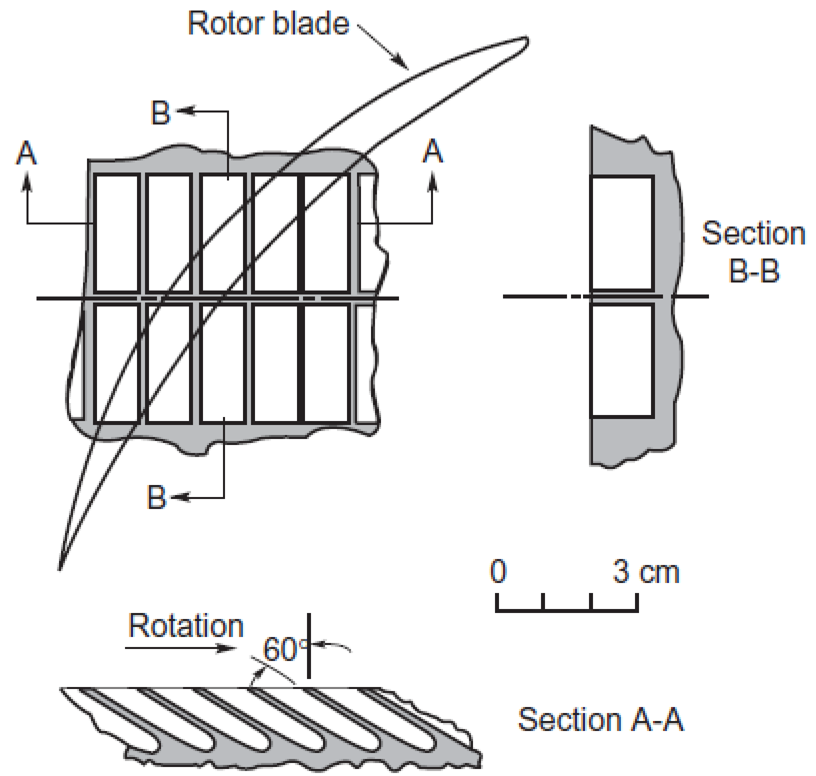
Control of instabilities



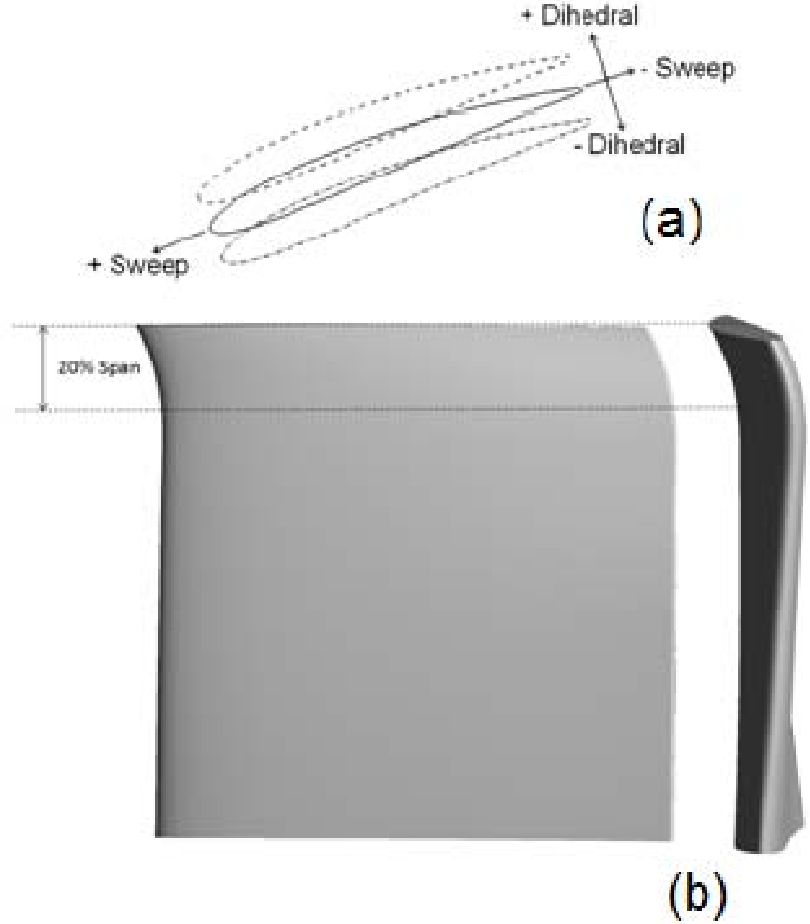


Casing treatment (Grietzer et. al, 1979)

Control of instabilities

- Passive control methods
  - Blade shape modifications
    - Sweep and dihedral
      - Non-radial blade stacking methods.
      - Depending upon the orientation, can significantly alter the rotor tip flow characteristics.
      - Envisaged to improve the stability characteristics as well as the efficiency.
      - Currently under research and development.
    - Other methods: tandem blading, vortex generators, fins etc.

Control of instabilities



Sweep and dihedral

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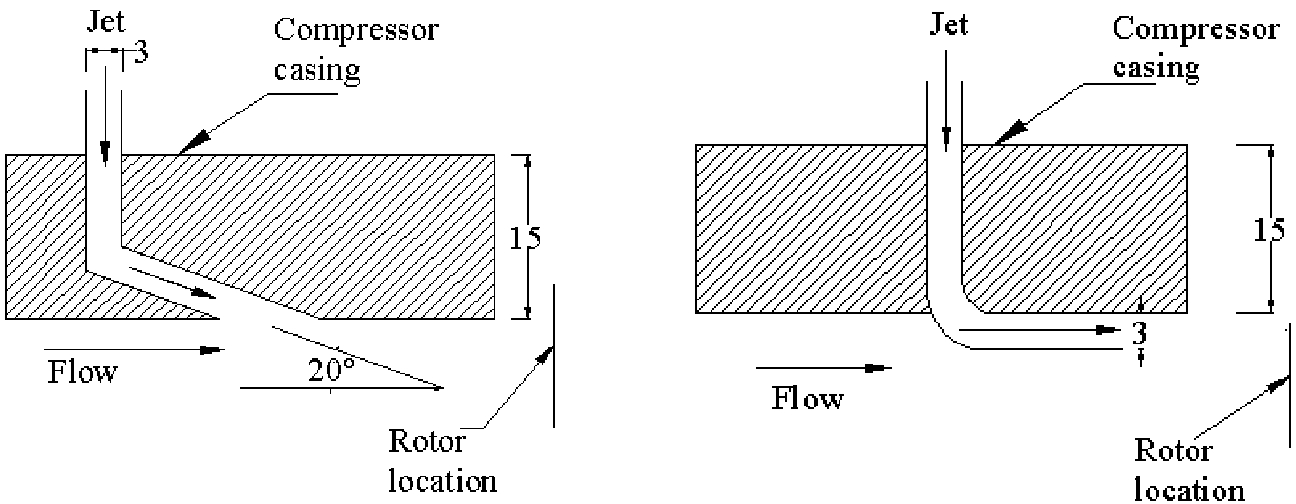
Control of instabilities

- Active control methods
  - Compressed air injection from casing
    - Energises the blade tip region, making the tip flow more resistant to adverse pressure gradients.
    - Use air from later stages of the compressor for injection.
    - Expected to improve the stability margin and possibly efficiency.
    - Variants of tip injection scheme: steady injection, pulsed injection, injection at varying angles (skew and pitch).

Control of instabilities



Tip injection schemes

Control of instabilities

- Other active control methods
  - Variable IGVs
  - Bleed valves
    - Typically used during starting to prevent stall due to front and rear stage mismatch
  - Plasma actuators and synthetic jets
    - Are in premature state of research
    - Seem to show promise under certain operating conditions.

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