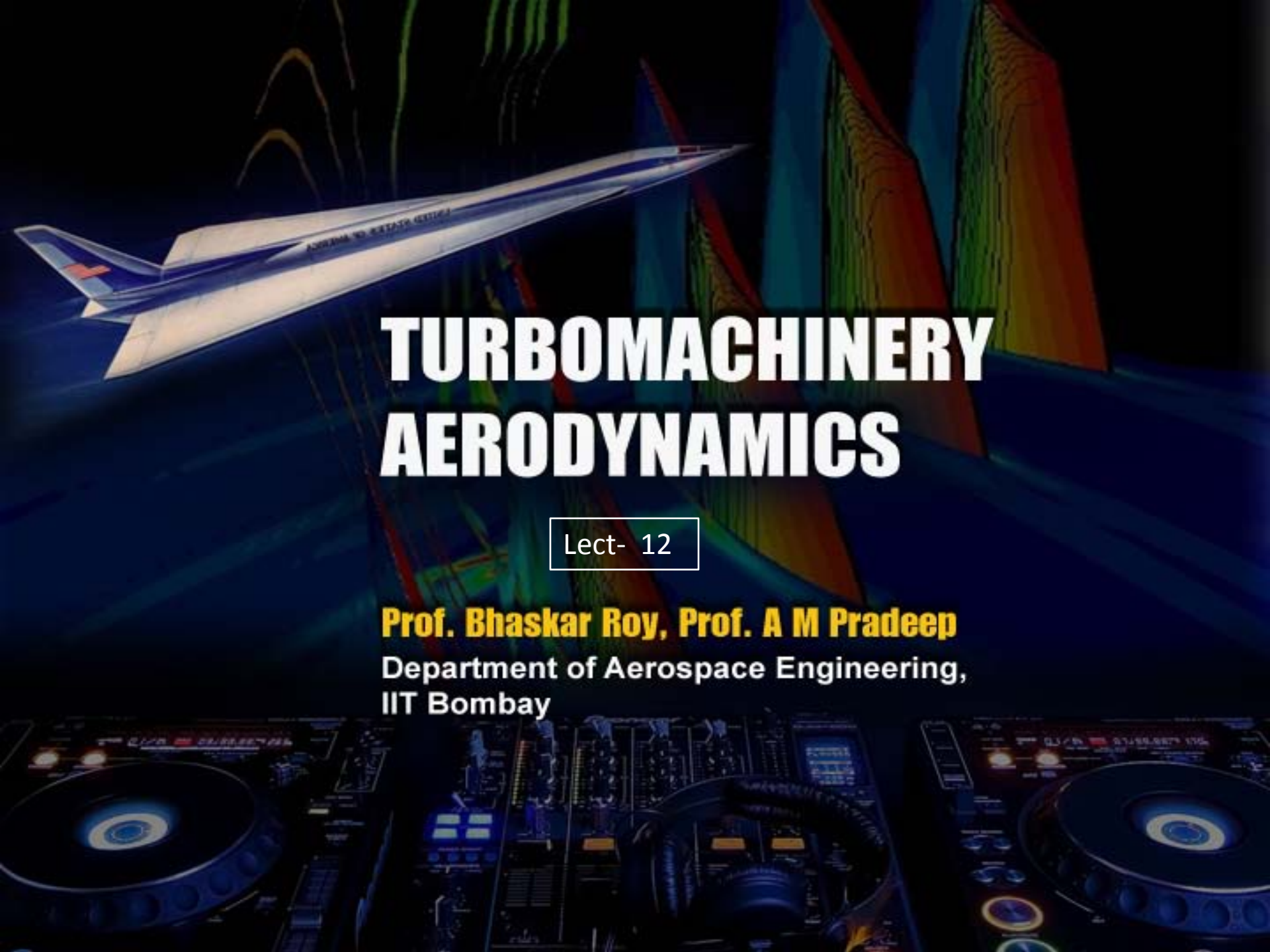

TURBOMACHINERY AERODYNAMICS

Lect- 12

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In this lecture...

- Instability in axial compressors
  - Rotating stall
  - Surge

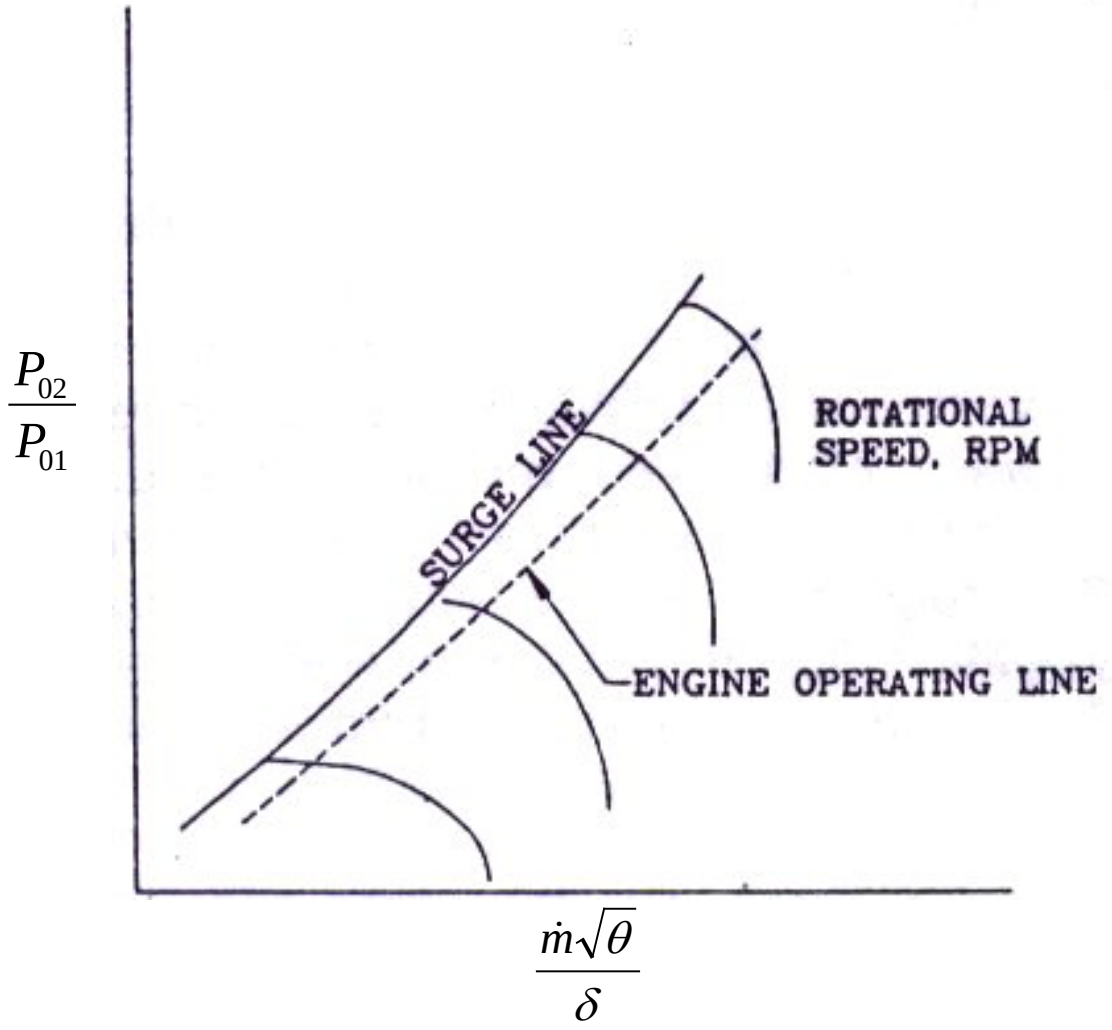
Instability in axial compressors

- Compressor performance is a key factor in the overall engine performance.
- At a given rotational speed, the maximum mass flow is determined by choking of the compressor.
- As mass flow is reduced/throttled, an eventual breakdown of stable flow conditions occur.
- The requirement for a stable range of flow is dictated by the performance characteristics of downstream components such as turbine or nozzle.

Instability in axial compressors

- The importance of this range lies in the fact that engine operation at off-design speeds may occur closer to surge or choke depending upon its operating condition.
- The ability to efficiently operate an engine at all operating conditions depends upon the matching of all components of an engine within the confines of the stable operating range.

Instability in axial compressors



Definition of Instability

- Stability is related to the response of a compressor to a disturbance which perturbs compressor operation from a steady operating point.
- If the disturbance is transient, the performance is considered stable if the system returns to the original point of equilibrium.
- If the response is to drive the operation away from the original point, the performance is unstable.

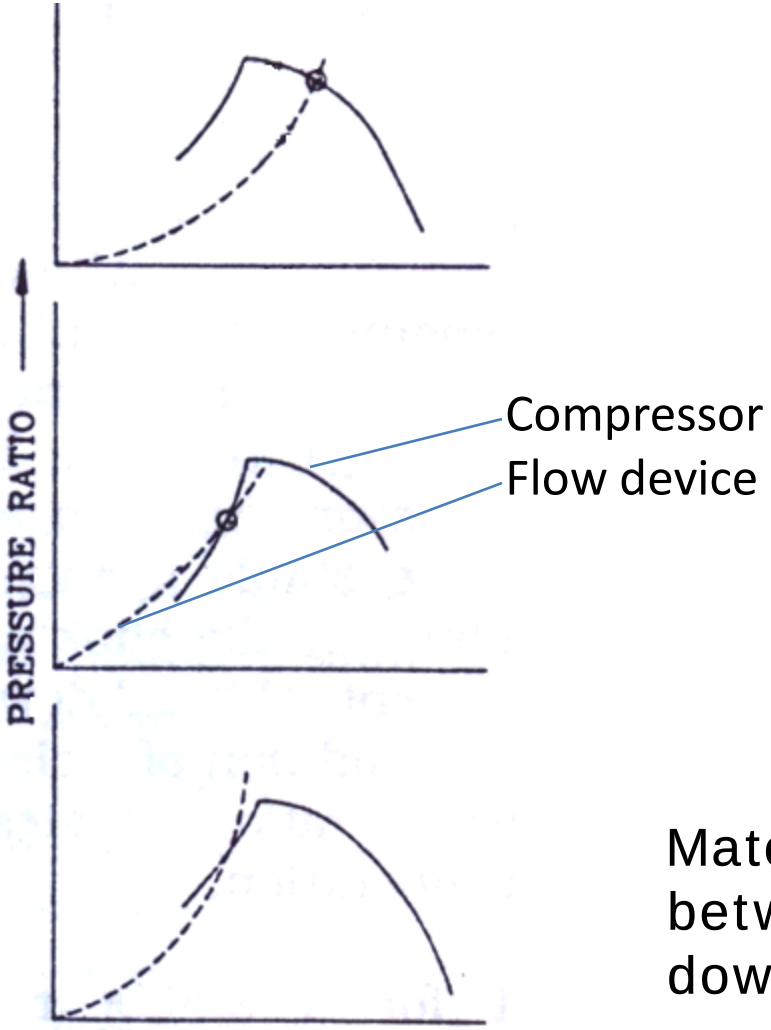
Definition of Instability

- There are two areas of compressor performance that relate to stability:
  - Operational stability
  - Aerodynamic stability
- Operational stability: matching of performance characteristics of the compressor with downstream components.
- Aerodynamic stability: limitation of steady state operation due to stall and surge.

Operational Stability

- In this form of stability analysis, the complete compressor system including inlet ducting, guide vanes, rotors, stators and any pressure recovery exhaust system are considered.
- The operational stability depends upon the rate of change of pressure rise or pressure drop as mass flow rate varies.
- System stability is established when the rate of change of compressor pressure rise with mass flow is algebraically less than the rate of change of throttle pressure drop with mass flow.

Operational Stability

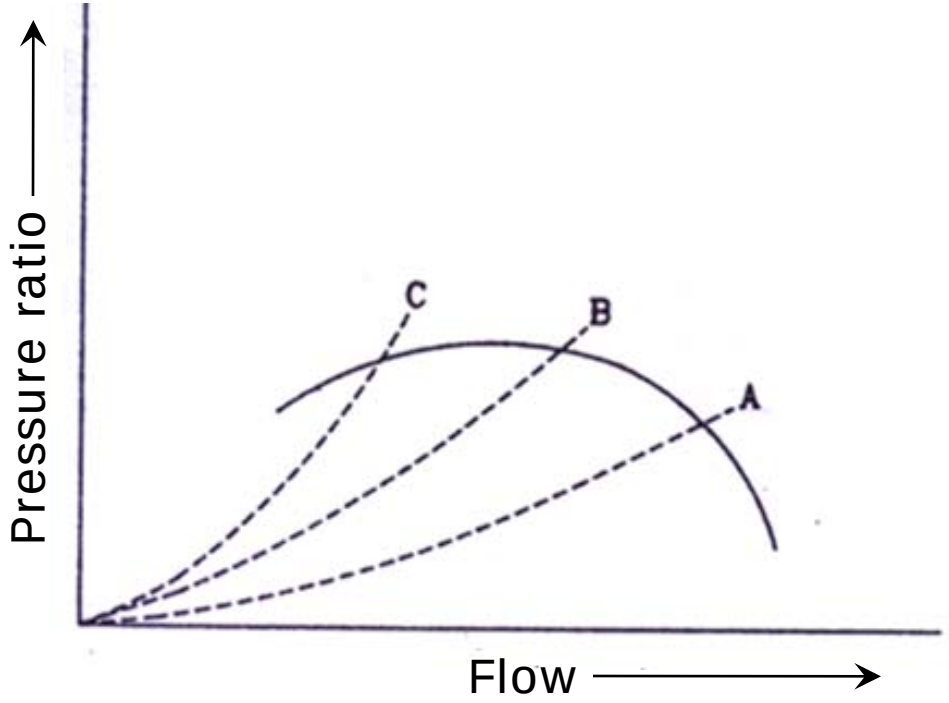


Matching characteristics between the compressor and a downstream flow device

Aerodynamic Stability

- Aerodynamic stability is the ability of the entire compressor system to maintain or increase the delivery pressure when the compressor operation has been perturbed to a lower flow.
- The part of the compressor characteristic with a positive slope is a region containing subsystem stall or complete instability resulting in surge.
- In this region, operational stability may be theoretically possible, but not aerodynamic stability.

Aerodynamic Stability



Progressive throttling characteristics

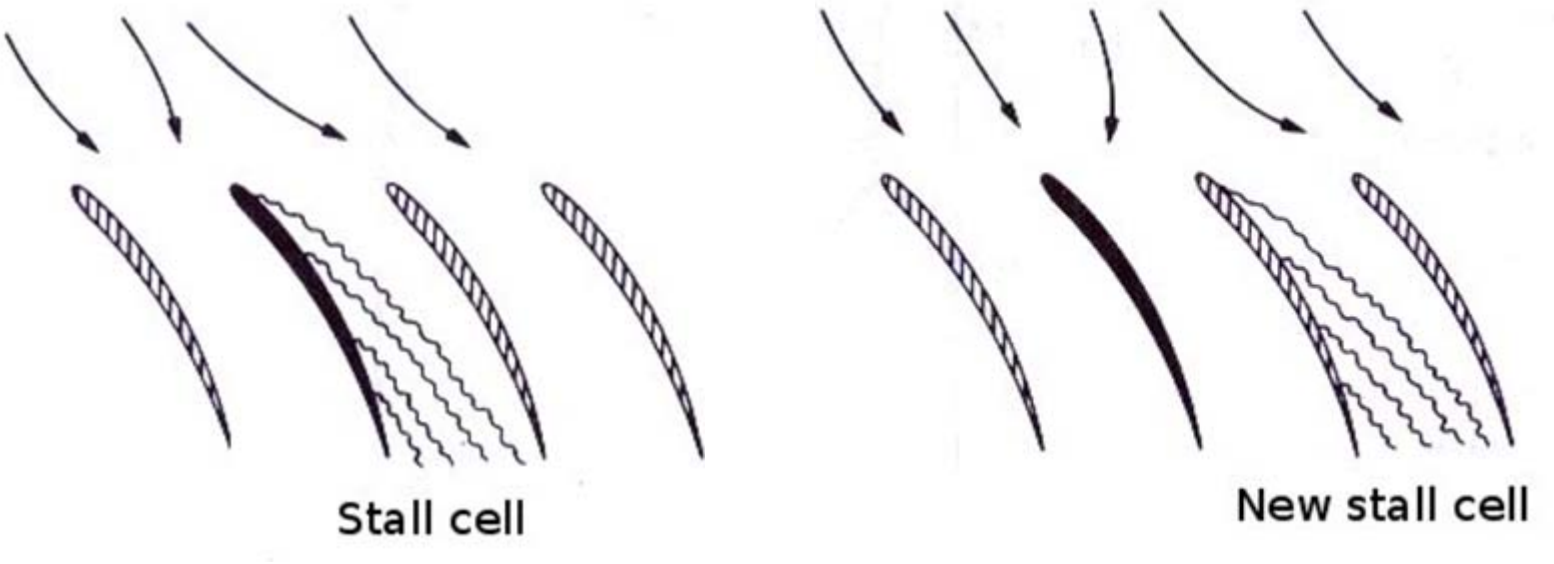
Stall

- There are two types of stall that have been experimentally identified.
  - Individual blade stall
  - Rotating stall
- Individual blade stall occurs when the entire blade row stall at once. This type of stall would be expected in airfoil or cascade data.
- If all the airfoils are identical, all the blades would experience the stall incidence angle and hence the complete row of blades stall.

Rotating Stall

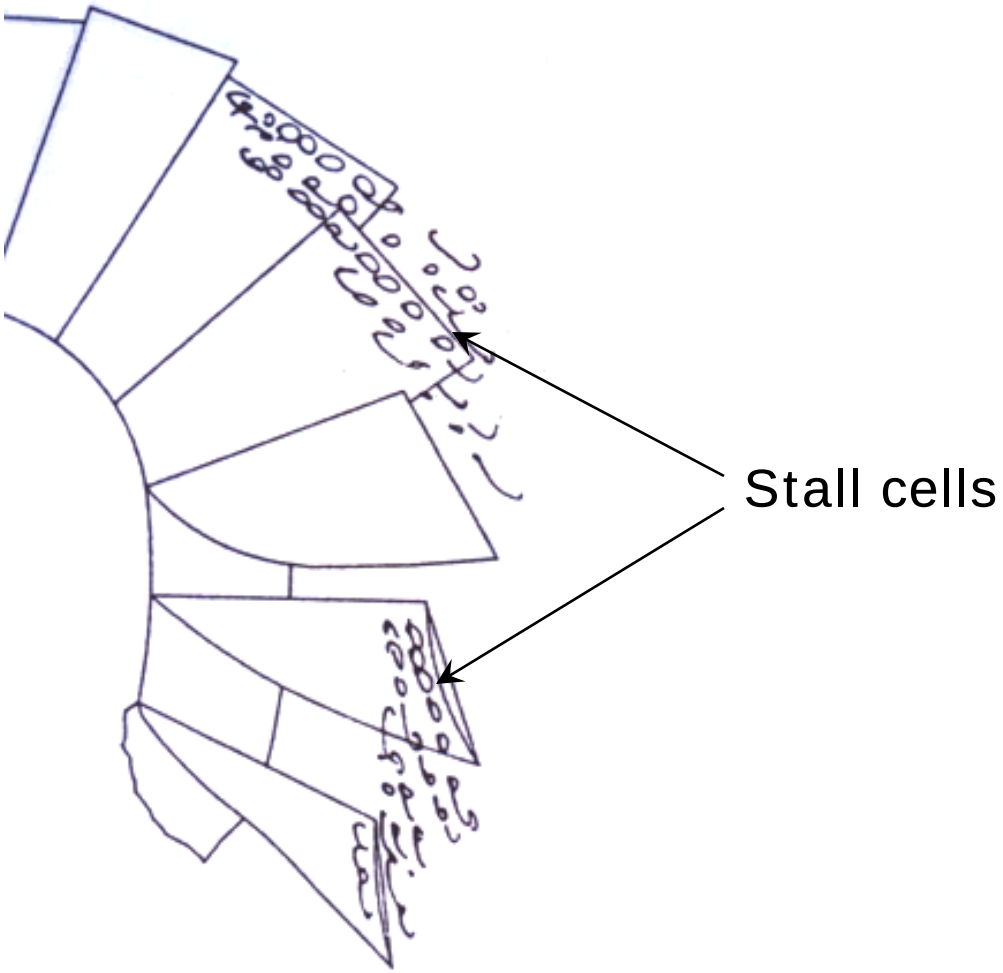
- Rotating stall is the most common type of stall.
- Rotating stall: progression around the blade annulus of a stall pattern, in which one or more adjacent blade passages are instantaneously stalled, then are cleared for unstalled flow as the stall cell progresses.
- Rotating stall causes alternate loading and unloading of the blades: fatigue failure.

Rotating Stall



Propagation of rotating stall

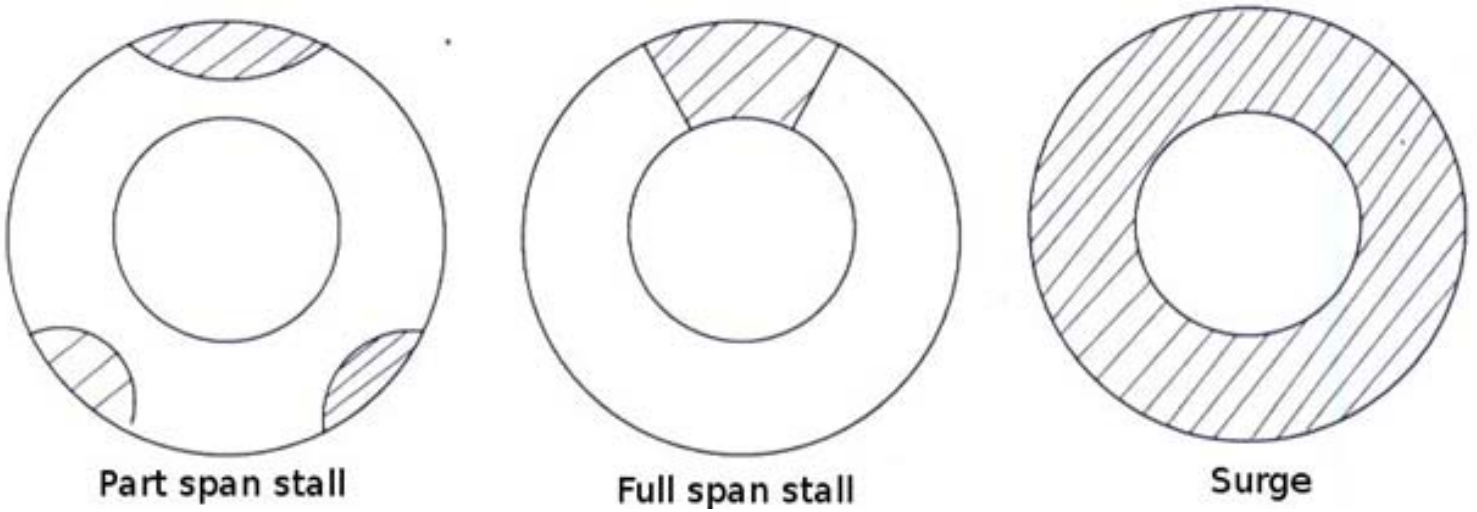
Rotating Stall



Propagation of rotating stall cells

Rotating Stall

- Rotating stall often precedes surge.
- The stall patterns move in a direction opposite to that of the rotor revolution.
- The stall frequency can be as high as 50% of the rotor frequency.



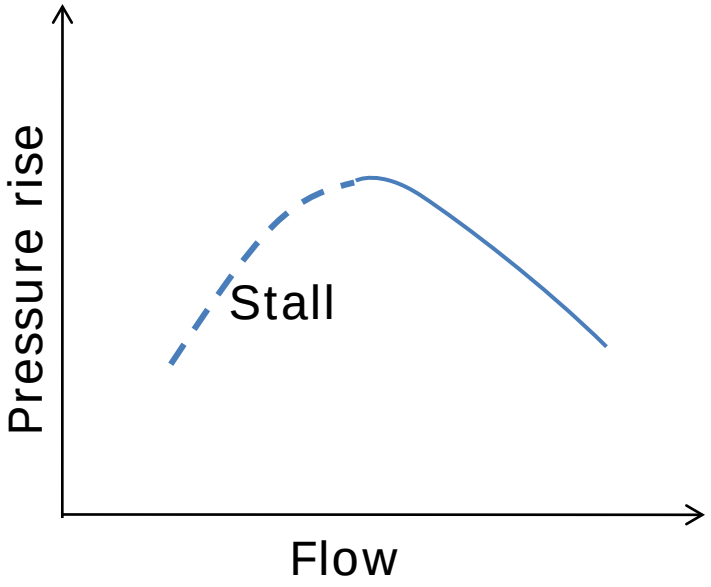
Rotating Stall

- Rotating stall may be initiated due to a variety of reasons: off-design operation, inflow distortion, blade stagger/profile mismatch etc.
- If allowed to propagate, rotating stall may lead to surge of the compressor.
- The number of stall cells can be as high as 9 or more or as low as one.
- The number of stall cells is associated with the type of stall.

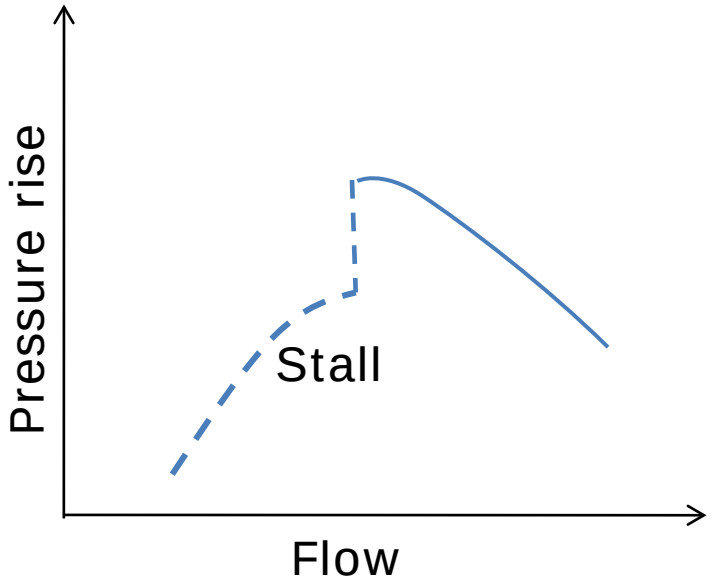
Rotating Stall

- There are two types of stall: progressive and abrupt.
- Progressive stall has a gradual reduction in total pressure ratio after initiation of stall.
- Abrupt stall has a sharp discontinuity in the pressure ratio characteristic.
- Progressive stall usually has multiple stall cell, whereas abrupt stall seems to always occur with a single cell.
- Some of the recent researchers have termed progressive and abrupt stall as *modal* and *spike* type of stall.

Rotating Stall

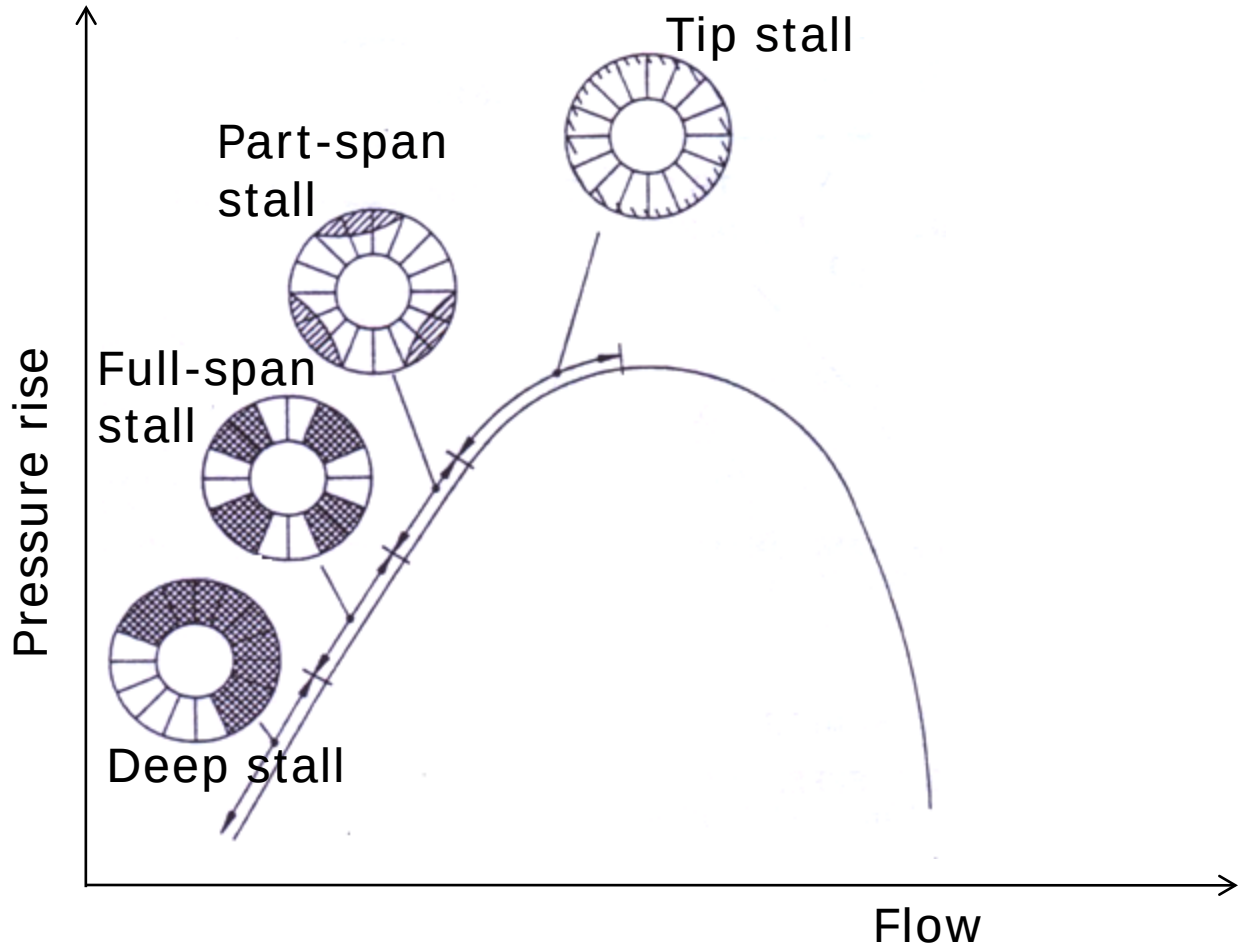


Progressive or modal stall



Abrupt or spike stall

Rotating Stall



Variation of stall pattern during progressive stall

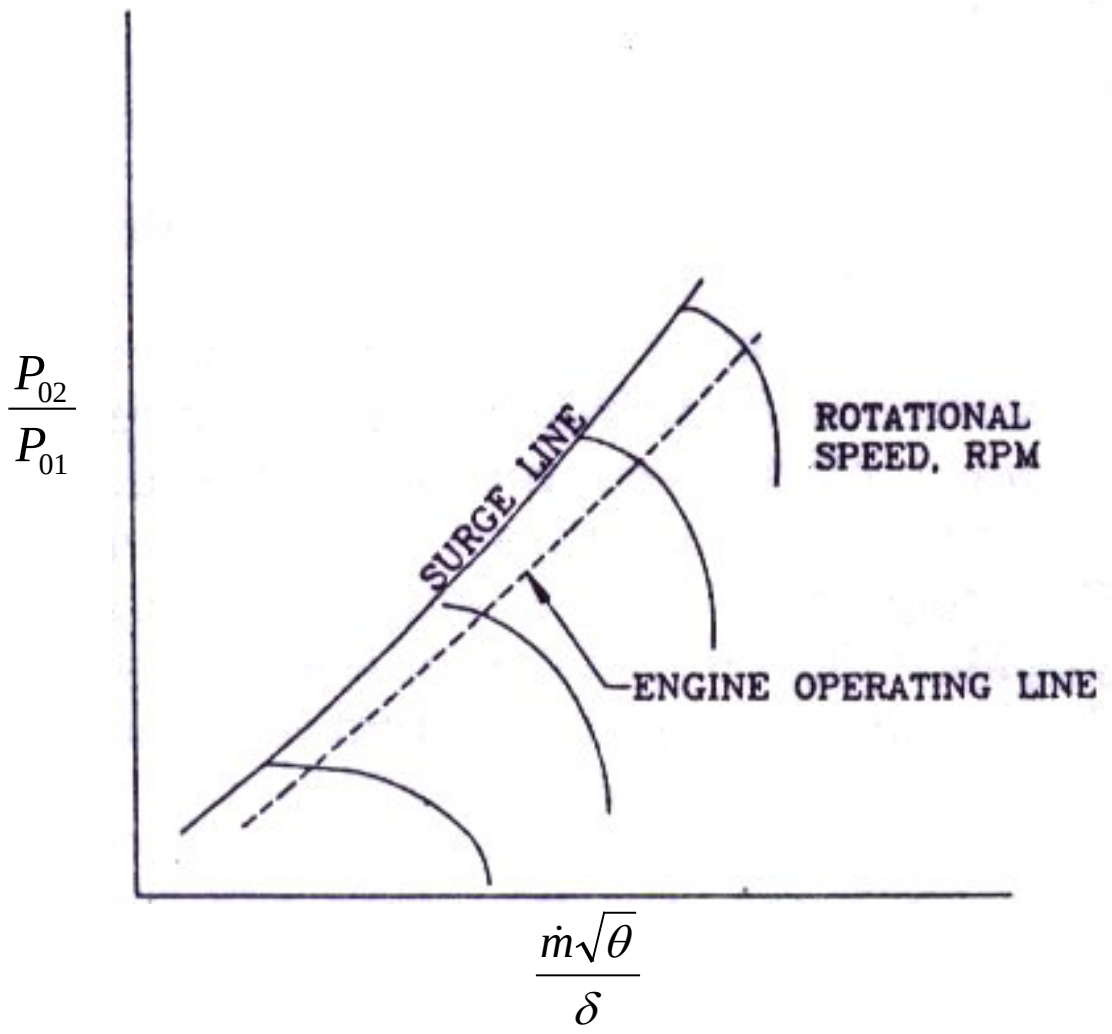
Surge

- Surge is a state of operation during which the complete compression system is unstable.
- Surge is characterised by fluctuations in the average flow throughout the compressor.
- The net flow through the compressor can be positive or negative in this highly transient state.
- This differs from rotating stall wherein the average flow through the compressor system is constant with time.
- During surge, the system is unable to attain a stable match with a throttle.

Surge

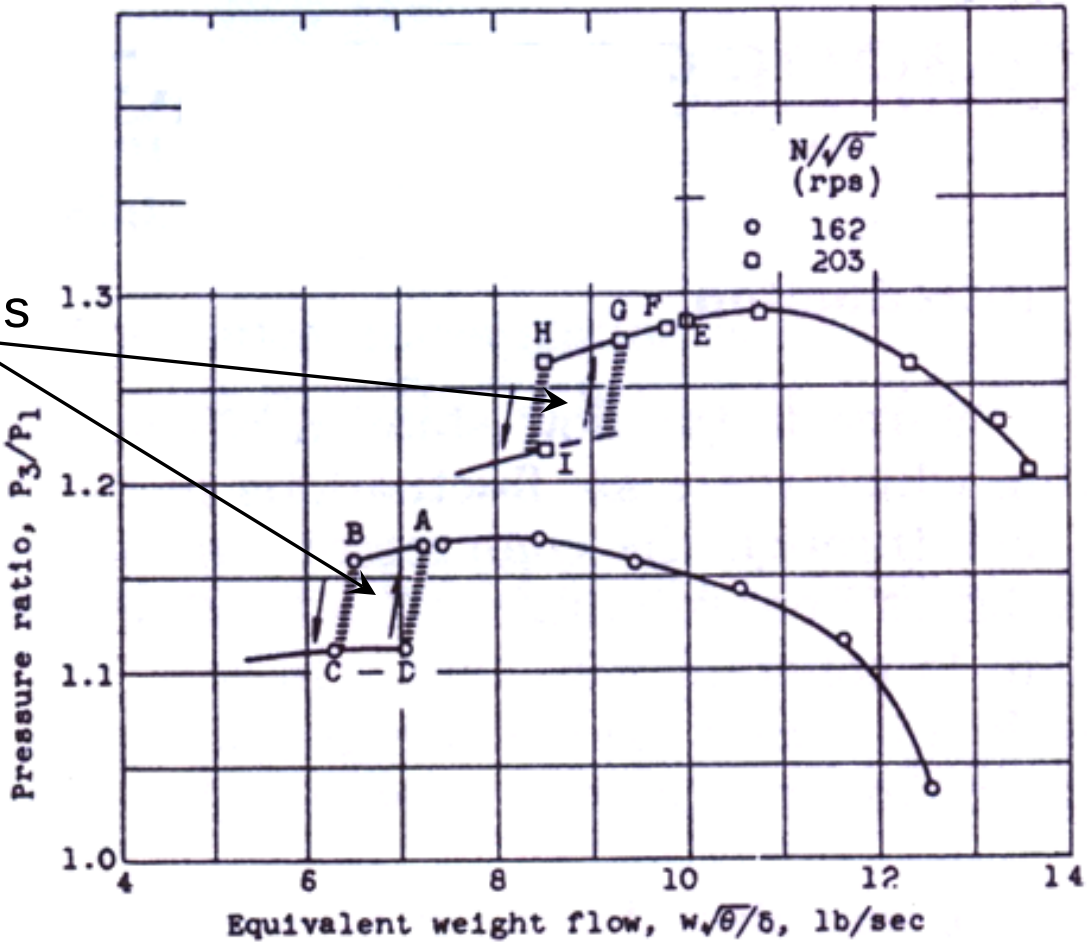
- Surge line denotes the locus of unstable operation of the compressor.
- Surge is characterised by violent, periodic oscillations in the flow.
- Surge might lead to flame blow-out in the combustion chamber.
- Surge can lead to substantial damage to compressors and must be avoided.
- The operating line of the compressor is therefore kept slightly away from the surge line: surge margin.

Surge


$\frac{P_{02}}{P_{01}}$
SURGE LINE
ROTATIONAL SPEED, RPM
ENGINE OPERATING LINE
$\frac{\dot{m}\sqrt{\theta}}{\delta}$

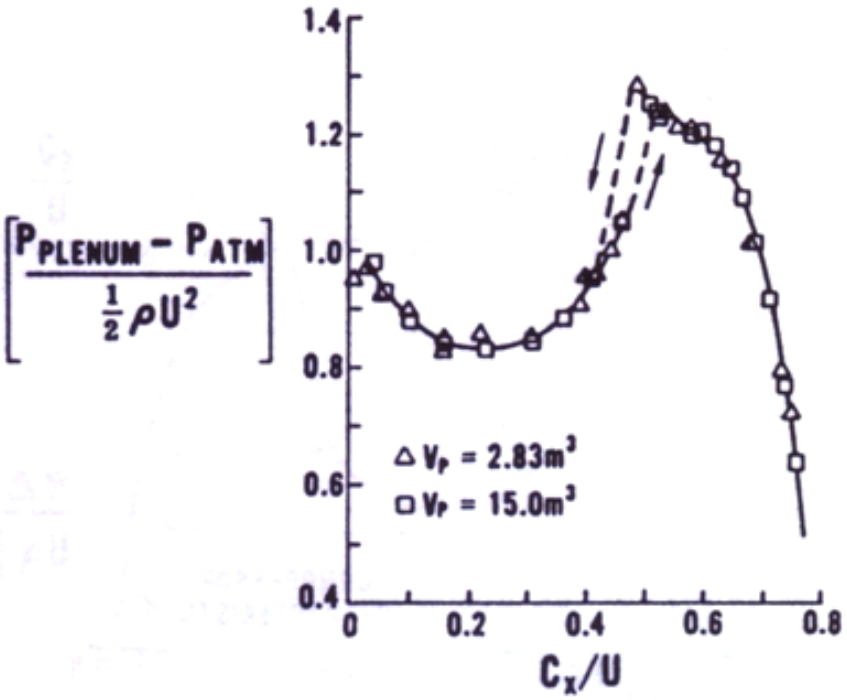
Surge

Hysteresis

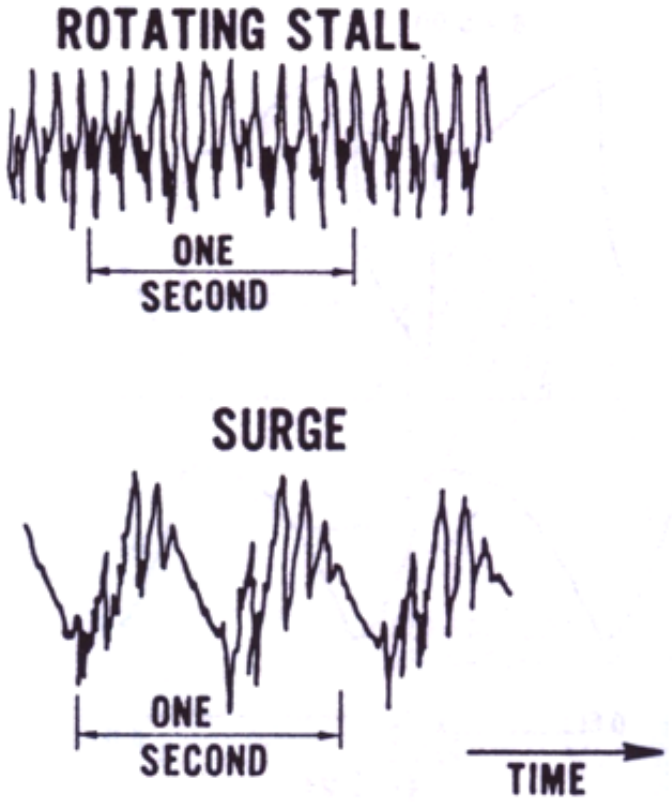


Overall performance of a single stage axial compressor (Huppert, 1952)

Surge



Steady state compressor characteristics (Grietzer, 1976)



Instantaneous velocity variation (Grietzer, 1976)

In this lecture...

- Instability in axial compressors
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In the next lecture...

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