TURBOMACHINERY FLOWS FROM A DYNAMICAL SYSTEMS PERSPECTIVE: PRINCIPLES AND APPLICATIONS

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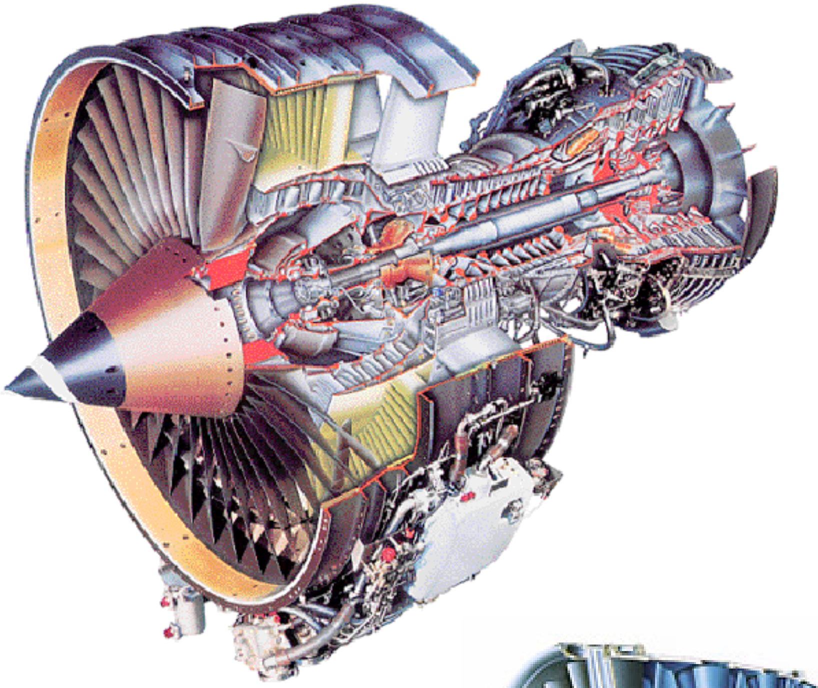
MESSAGE

- Well-defined modeling goals enhance the ability to attack complex physical problems
  - In terms of “success literature” -- Begin with the end in mind [Steven Covey]
- A number of important turbomachinery problems are usefully tackled using a dynamical system framework
  - Technological problems cut across disciplines

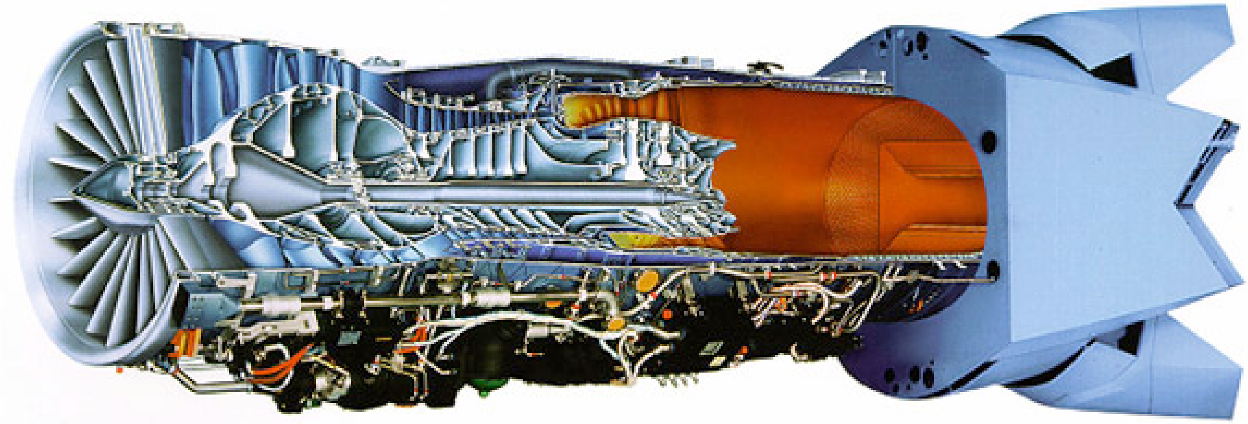
GAS TURBINE ENGINE

- Enormously complicated device
- Development time has been longer than aircraft development times
- A broad spectrum of length and time scales
- A rich array of physical phenomena
  - Fluid
  - Structure
  - Materials
  - Control
  - All of the above
- **Any** of the above can be the basis of a career

GAS TURBINE ENGINES



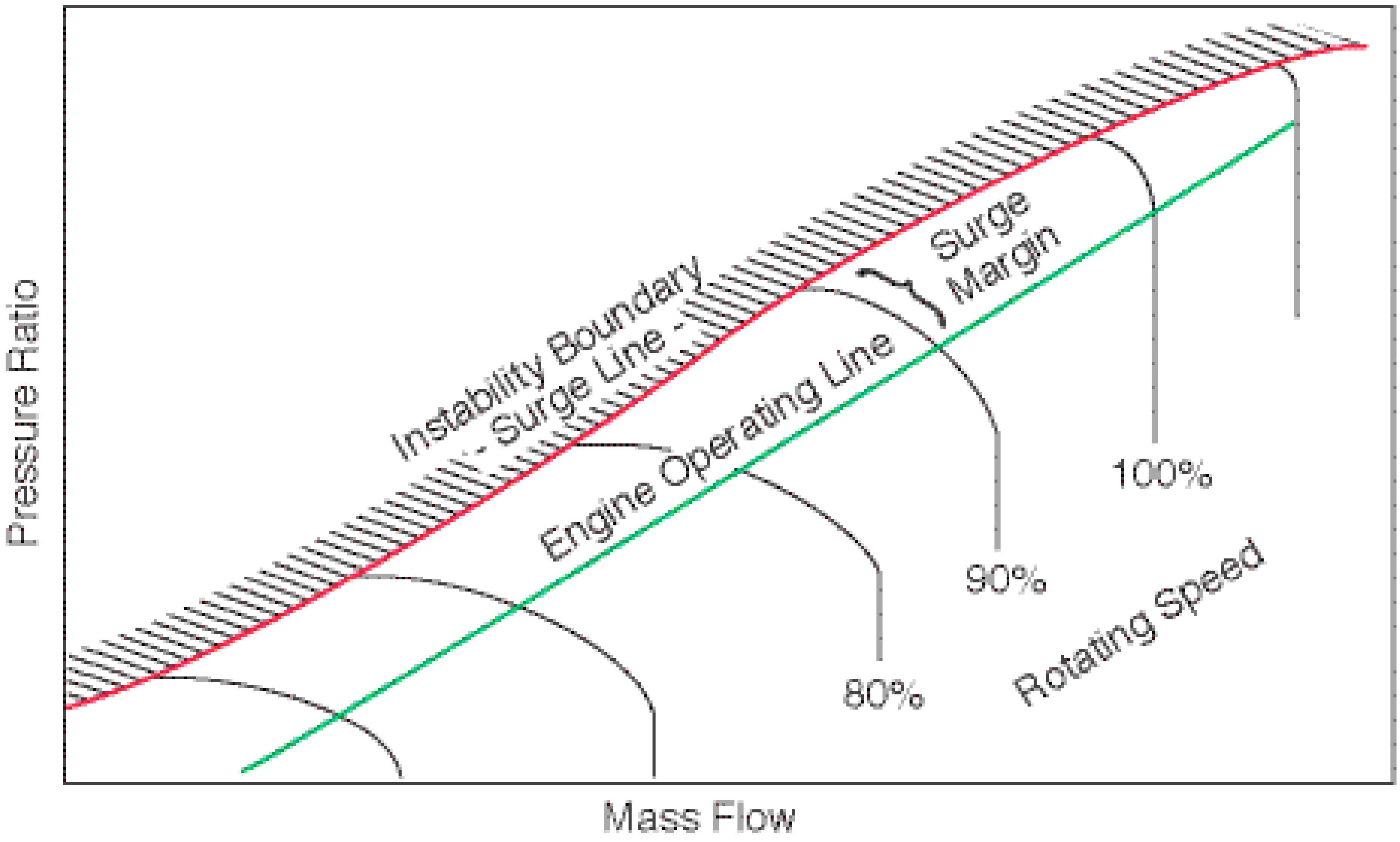
GE CFM56 for Boeing 737



P&W 119 for F-22

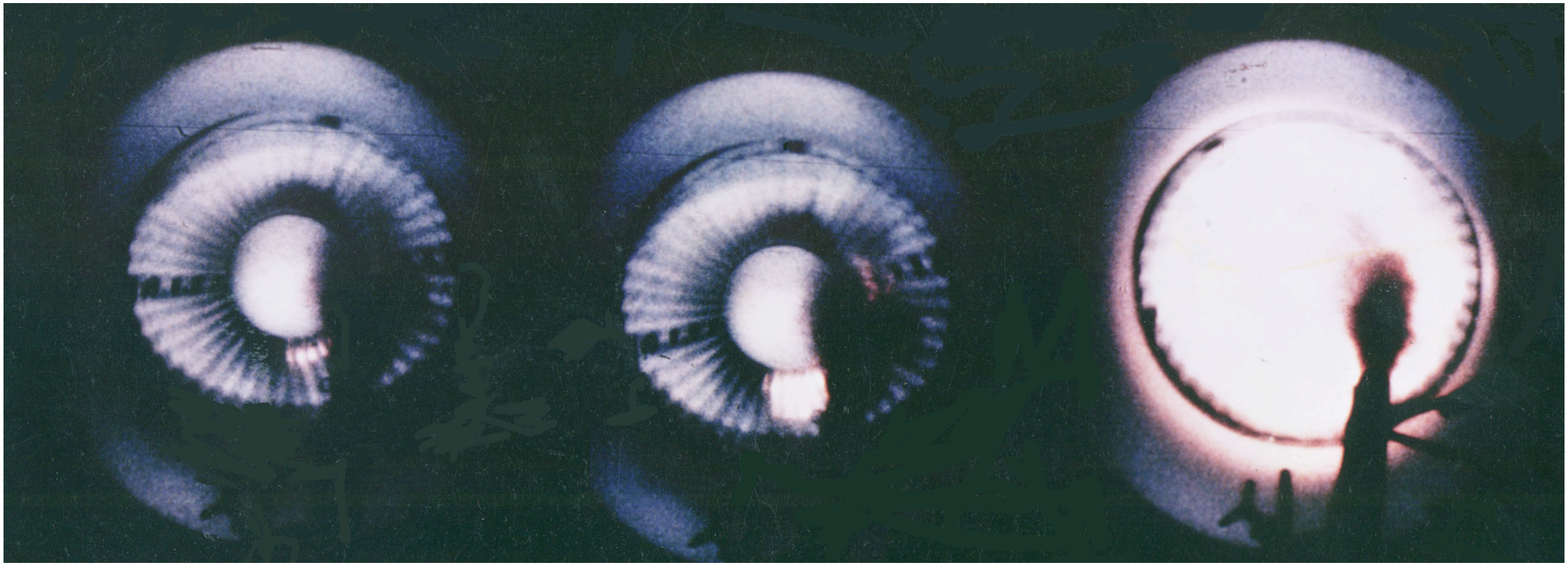
[GE and Pratt&Whitney]

COMPRESSOR OPERATING CHARACTERISTICS



A FRONTAL VIEW: LOCAL AND GLOBAL GAS TURBINE ENGINE INSTABILITY

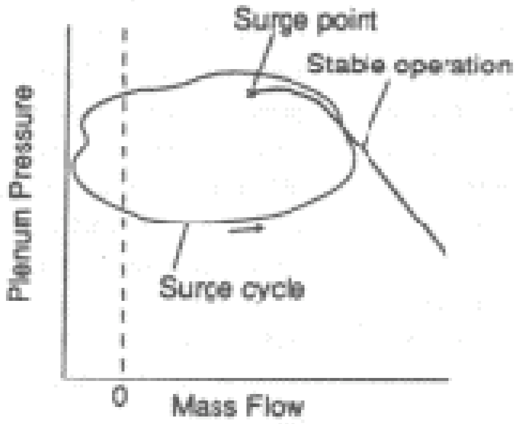
(The mature form of a small perturbation)

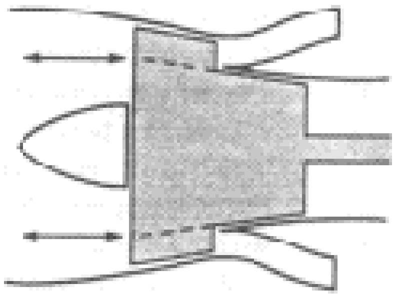


[Mazzawy]

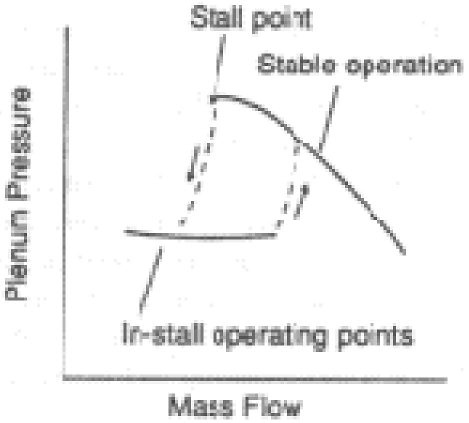
Dynamic Compressor Instabilities – Surge and Rotating Stall

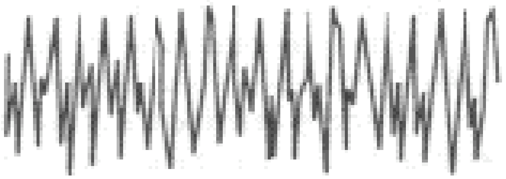
“Surge”



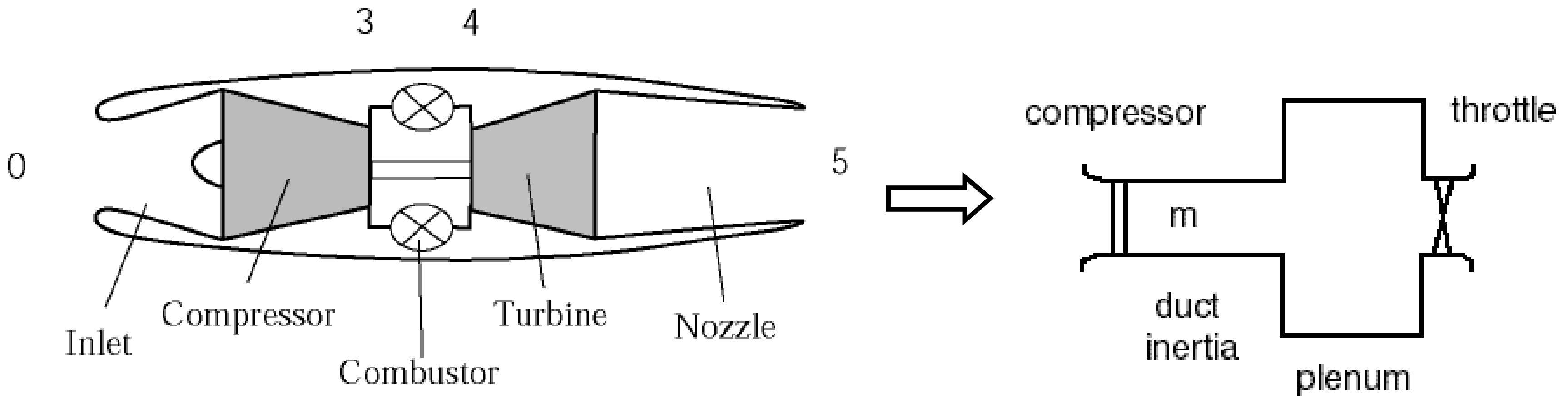


“Rotating Stall”

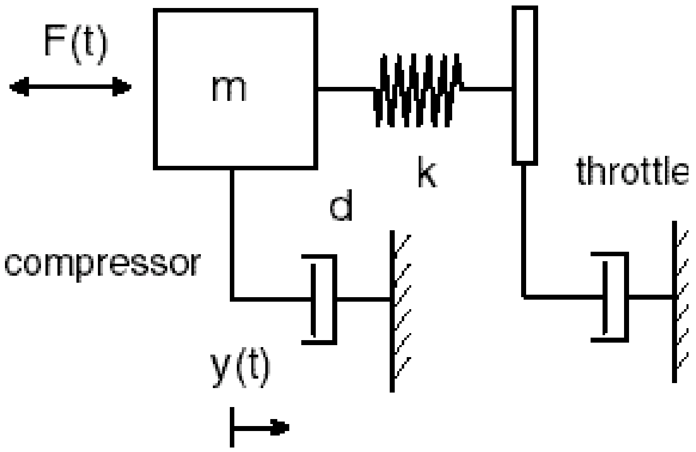




SIMPLEST ENGINE SURGE MODEL



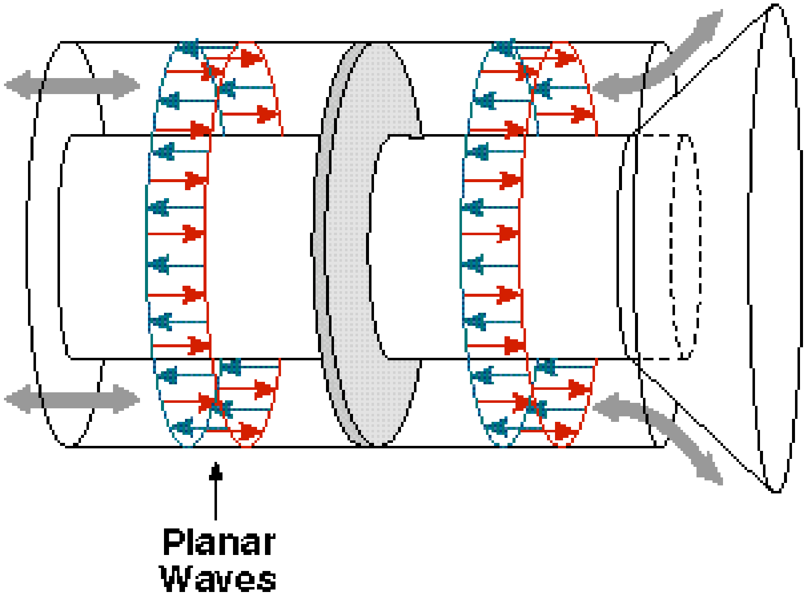
- System rather than component view
- Reduced order lumped parameter basis
- Dynamic stability analysis
- Mechanical analogue very instructive



NATURAL OSCILLATORY MODES OF COMPRESSORS

Global

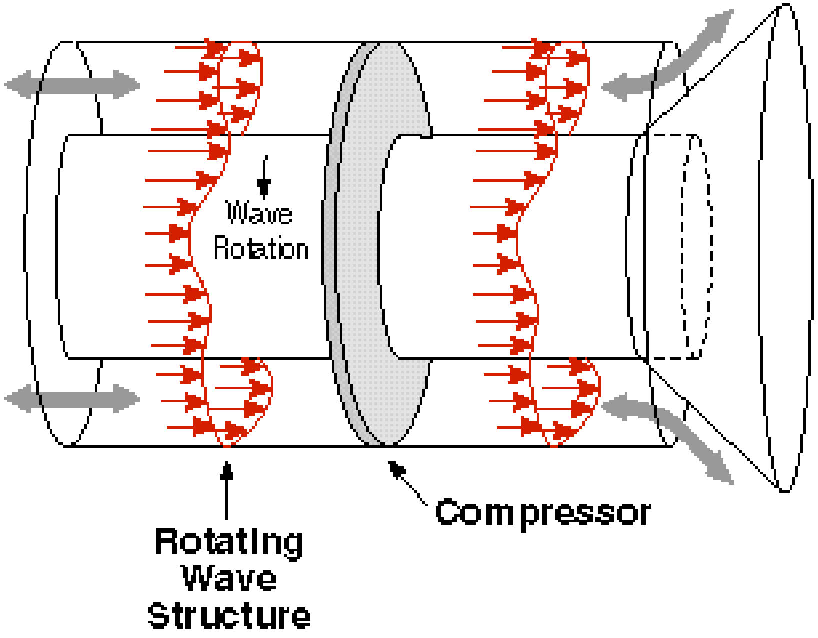
(Lowest Order)



Surge

Local

(Higher Order)

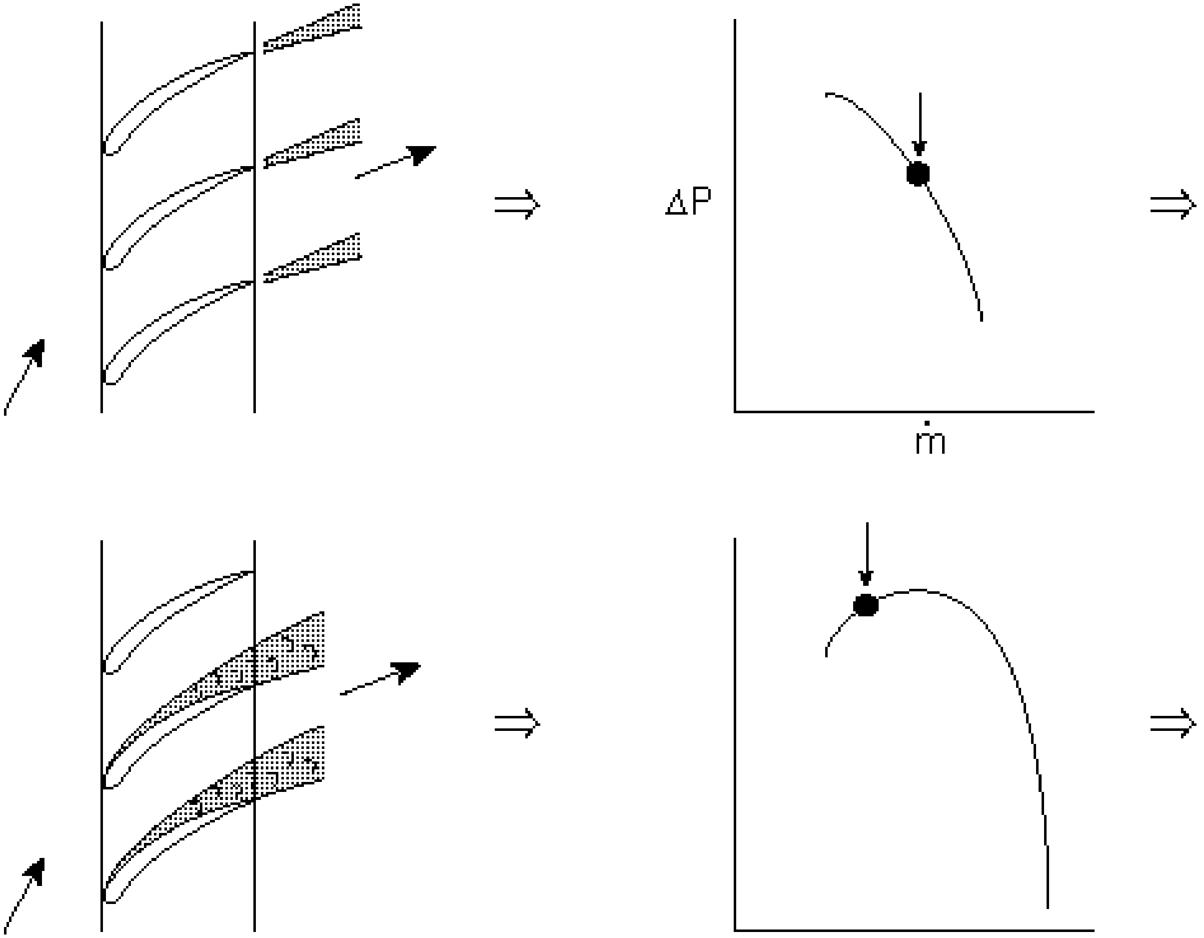


Rotating Stall

PHYSICAL FEATURES AND RELATED CONCEPTS

Physical Feature	**Concept**
• Growth of small disturbance waves with **length scale large compared to blade spacing**	• Description of upstream and downstream, unsteady, vortical flow fields that support waves
• "Smeared out" effect of blades	• Description of unsteady turbomachinery response
• Unsteady motion linear in initial stages, evolution to non-linear limit cycle in mature stages	• Energy input process
• Non-conservative system – energy fed in over part of cycle, dissipated over rest	• System description to dynamically couple components – Compressor, combustor (plenum), throttle

CONNECTION BETWEEN BLADE PASSAGE SCALE FLUID DYNAMICS AND SYSTEM INSTABILITY



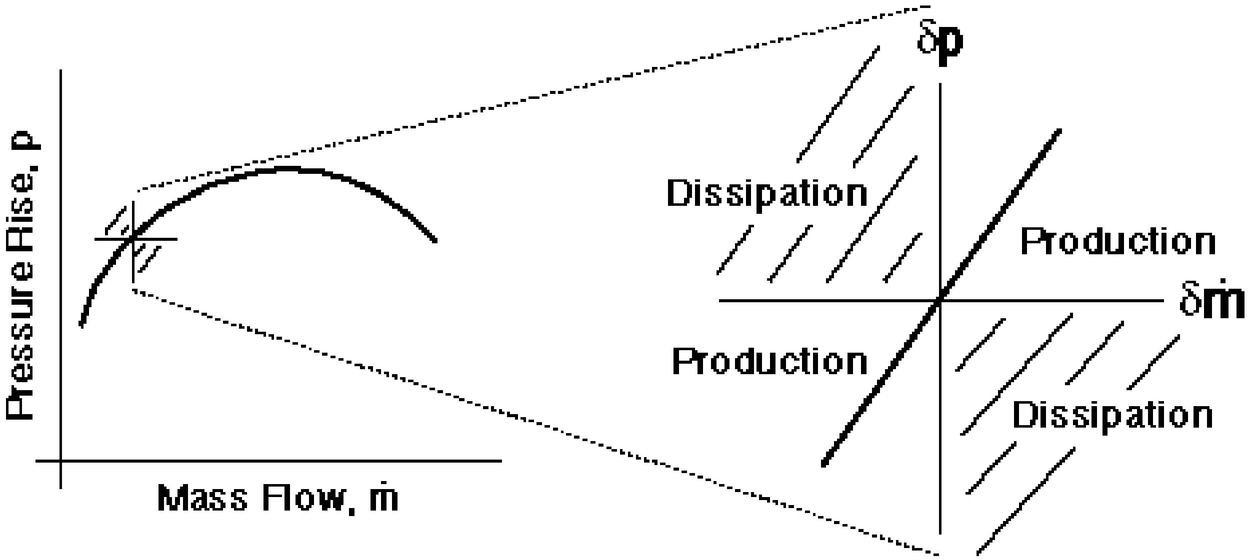
Environment
in which
disturbances
are damped out

Environment
in which
disturbances
are amplified

- Don’t need detailed description of flow to see whether disturbances grow
  - Key requirement is ability to define “environment”

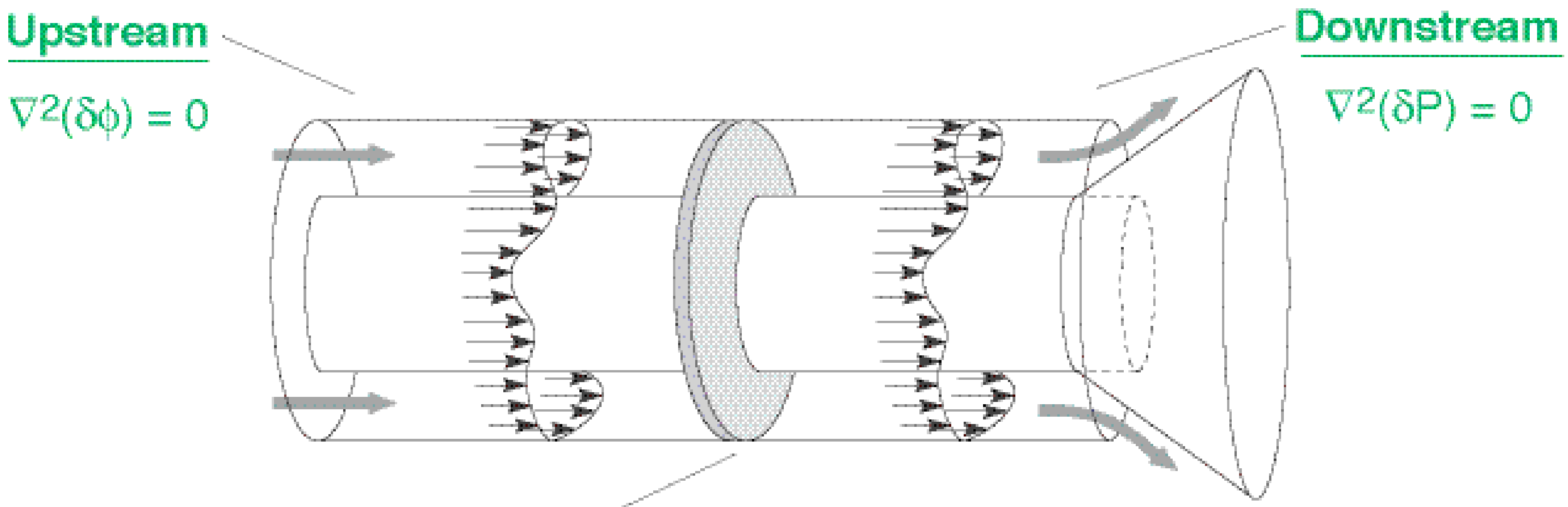
COMPRESSOR UNSTEADY POWER DRIVES INSTABILITY

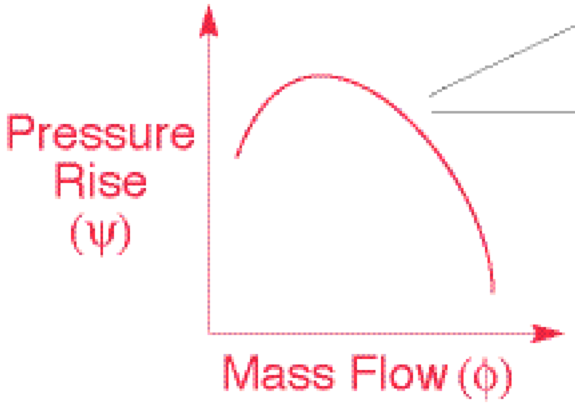
- Unsteady power production $\propto \delta\dot{m} \cdot \delta p$



- Compressor slope important
  - Sign determines production or dissipation
  - Magnitude sets unsteady power
- In this problem, only dissipative element is throttle

COMPRESSOR SYSTEM STABILITY MODEL





$$\Delta P = \left(\frac{\partial \psi}{\partial \phi}\right)\delta\phi - \delta L - (\mu)\,\frac{\partial(\delta\phi)}{\partial \tau} - (\lambda\,\omega_{\text{rotor}})\,\frac{\partial(\delta\phi)}{\partial \theta}$$

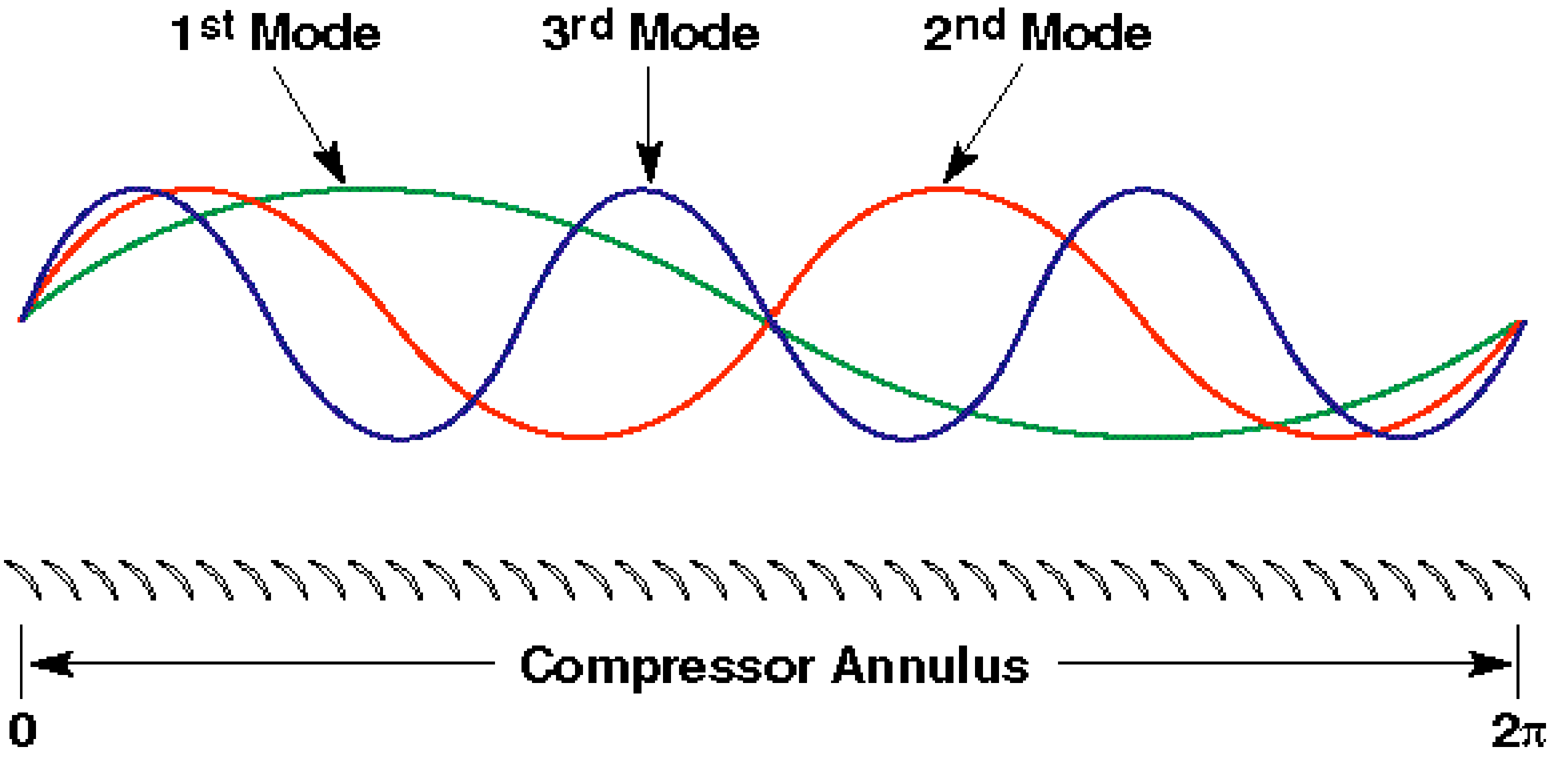
$\mu, \lambda \equiv$ Fluid inertia (from geometry)

$\delta L \equiv$ Blade row losses

WHAT NONLINEAR ASPECTS ARE IMPORTANT?

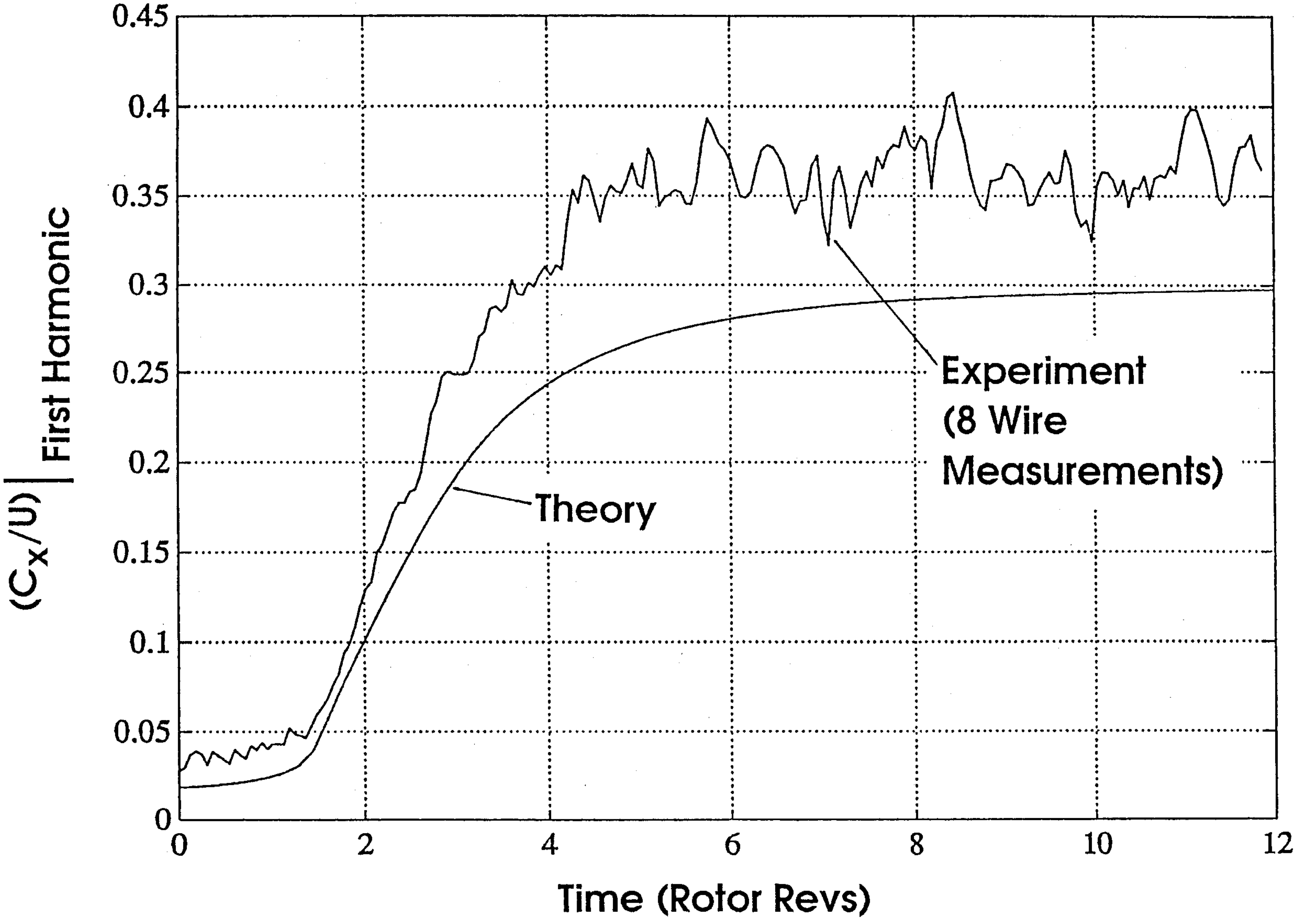
- Compressor is a mechanical energy source
- Energy put into flow field depends on impedance (upstream, downstream)
  - What is important is relation between velocity and pressure perturbations at inlet and exit of compressor
- Linear flow field description is appropriate approximation
- Linear description not appropriate for compressor behavior
  - Sign of input changes for small changes in flow rate
  - Positive and negative damping in different parts of cycle

ONSET OF ROTATING STALL



- Rotating waves
- Decompose into “components” or <u>modes</u>
- Modes are state variables for system

TIME EVOLUTION OF FIRST MODE DURING STALL INCEPTION



CONCEPTS AND FINDINGS SO FAR

- Existence of wave structure (or oscillation form) in compression system
  - Natural spatial modes simple sinusoids
- Length scale for disturbances much larger than blade-to-blade spacing
  - Don’t need to describe blading (and flow) in detail to extract behavior of interest
- Unsteady flow perturbations in compressor feed energy into eigenmodes
- Rotating stall and surge coupled in nonlinear stages
  - Phenomenology of observed coupling captured
  - Onset of local instability can drive global instability
- Lowest order (“Galerkin”) models give high-level understanding
  - Define relationships, trajectories
  - Bifurcation analysis yields possible concepts for control

LINEARIZED SURGE AND ROTATING STALL

– Decoupled 2-State Oscillators –

SURGE:

Equations already appear in state space:

$$\begin{bmatrix} \ell_{tot}\dot{\bar{\phi}} \\ 4B^2\ell_{tot}\dot{\psi}_p \end{bmatrix} = \begin{bmatrix} d\psi_c/d\phi & -1 \\ 1 & -d\phi_T/d\psi_p \end{bmatrix} \begin{bmatrix} \delta\bar{\phi} \\ \delta\psi_p \end{bmatrix}$$

ROTATING STALL:

Two states required to describe wave position and amplitude:

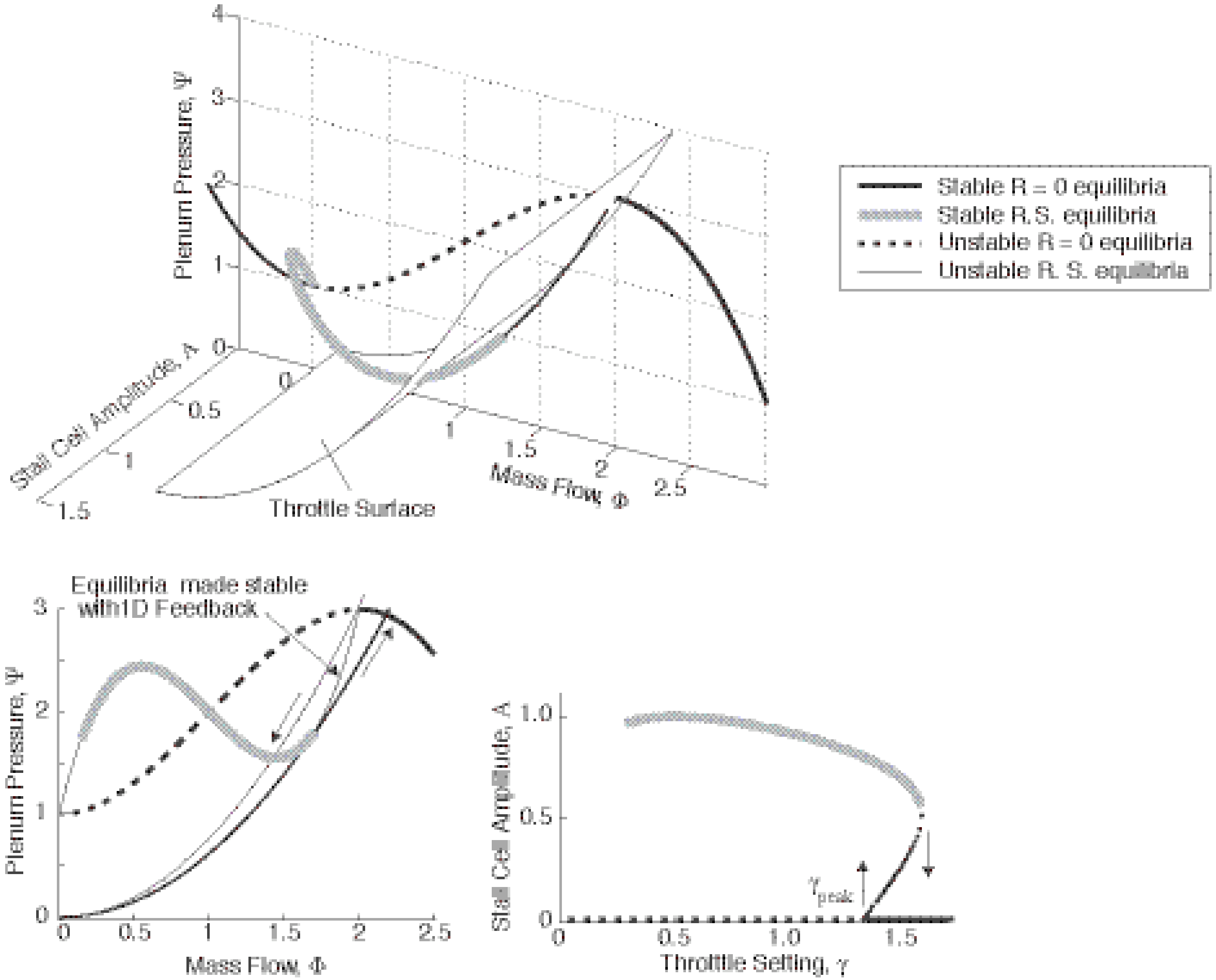
$$\tilde{a}_{-n}e^{-in\theta} + \tilde{a}_n e^{in\theta} \Rightarrow c_n \cos\theta + s_n \sin\theta$$

These two states form an oscillator!

$$\begin{bmatrix} \dot{c}_n \\ \dot{s}_n \end{bmatrix} = \frac{1}{(2/|n| + \mu)} \begin{bmatrix} d\psi_c/d\phi & -n\lambda \\ n\lambda & d\psi_c/d\phi \end{bmatrix} \begin{bmatrix} c_n \\ s_n \end{bmatrix}$$

oscillation frequency = rotation rate of wave

EQUILIBRIA OF A 3-STATE SYSTEM MODEL



[Paduano et al.]

CASTING A WIDER NET

- The concepts described should apply (perhaps with extensions) to many other situations in turbomachinery
- Different geometries
  - Centrifugal machines
- Different sources of operational difficulty
  - Inlet distortion (forcing)
  - Non-uniform (asymmetric) tip clearance
  - Coupled fluid-structure interaction
- Different flow regimes
  - Linear vs. nonlinear
  - Effects of compressibility and new classes of disturbances
- Different goals
  - Control (changing the dynamic system)

DYNAMIC FEATURES OF PHYSICAL SITUATIONS

Dynamic Feature	**Situation**
Negative damping (self-excited instability)	Surge onset Rotating stall onset (forward & backward travelling waves)
Mode coupling	Rotor whirl Evolution of instability waveform
Mode localization	Instability onset with inlet distortion Instability onset with non-uniform tip clearance
Limit cycles	Surge (periodic in time) Mature form of rotating stall (periodic in □)
Resonance	Response to propagating inlet distortion Response to tip clearance non-uniformity
Feedback control	Suppression of surge Active suppression of rotating stall Passive suppression of rotating stall\
Tuned absorber damping	Suppression of surge
System Identification	Eigenmode diagnosis

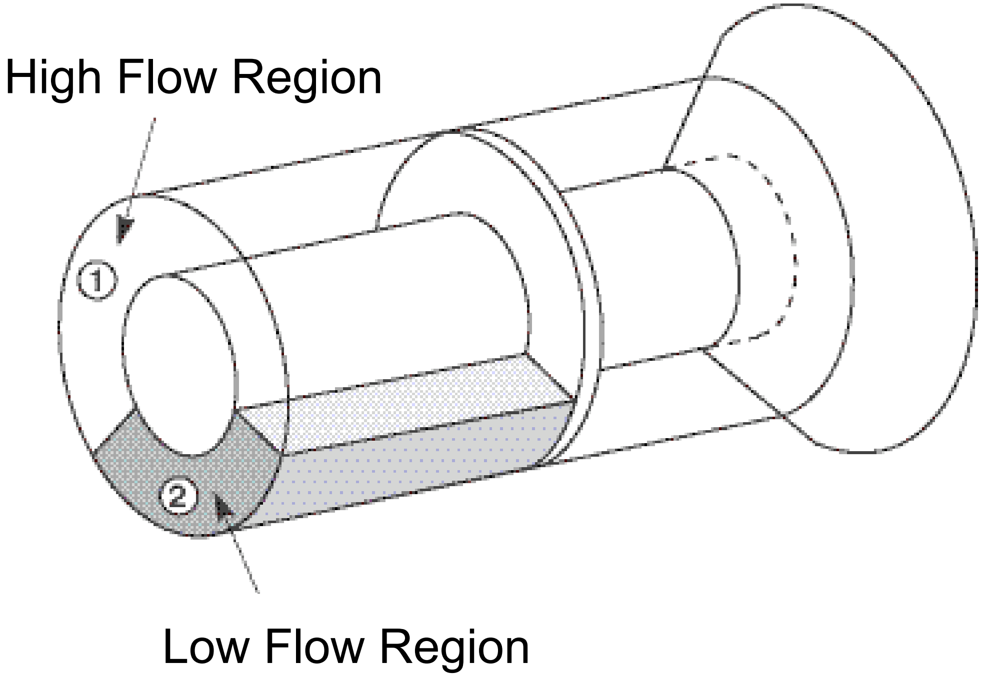
PROBLEMS ADDRESSED

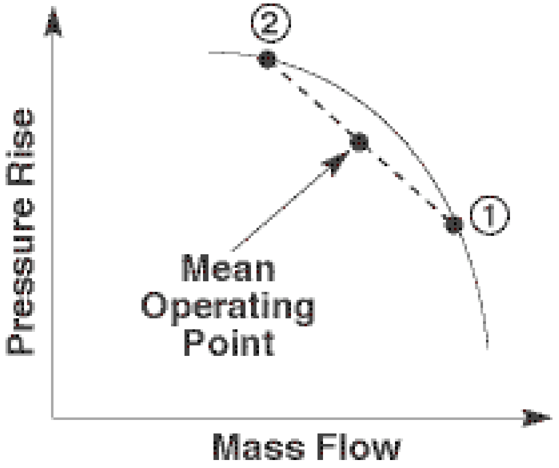
- Initiation and evolution of instability (rotating stall and surge) in axial compressors
- Inlet distortion effects (non-uniform background flow)
- Instability onset in centrifugal compressors
- Active control (suppression) of surge
- Active control of rotating stall
  - Linear
  - Non-linear
- Structural control of surge (fluid-structure interaction)
- Structural control of rotating stall
- Instability onset due to tip clearance non-uniformity
- Rotor whirl onset (rotor dynamic instability)
- Instability onset in compressible flow machines
  - New class of modal disturbances, new behavior
- Control of instability in compressible flow machines

EFFECTS OF INLET DISTORTION

- Non-uniform flow (*distortion*) degrades compressor aerodynamic stability
  - Stationary distortion due to crosswinds, maneuver, tip clearance asymmetry
  - Rotating distortion due to upstream rotating stall in two-spool engine
  - Upstream vortical disturbance
- Disturbance waves propagate through non-uniform “background” flow
  - Modes non-sinusoidal
  - Rich harmonic content
- Basic ideas of smearing out blades, non-linear and linear elements, thinking in terms of dynamical systems still apply

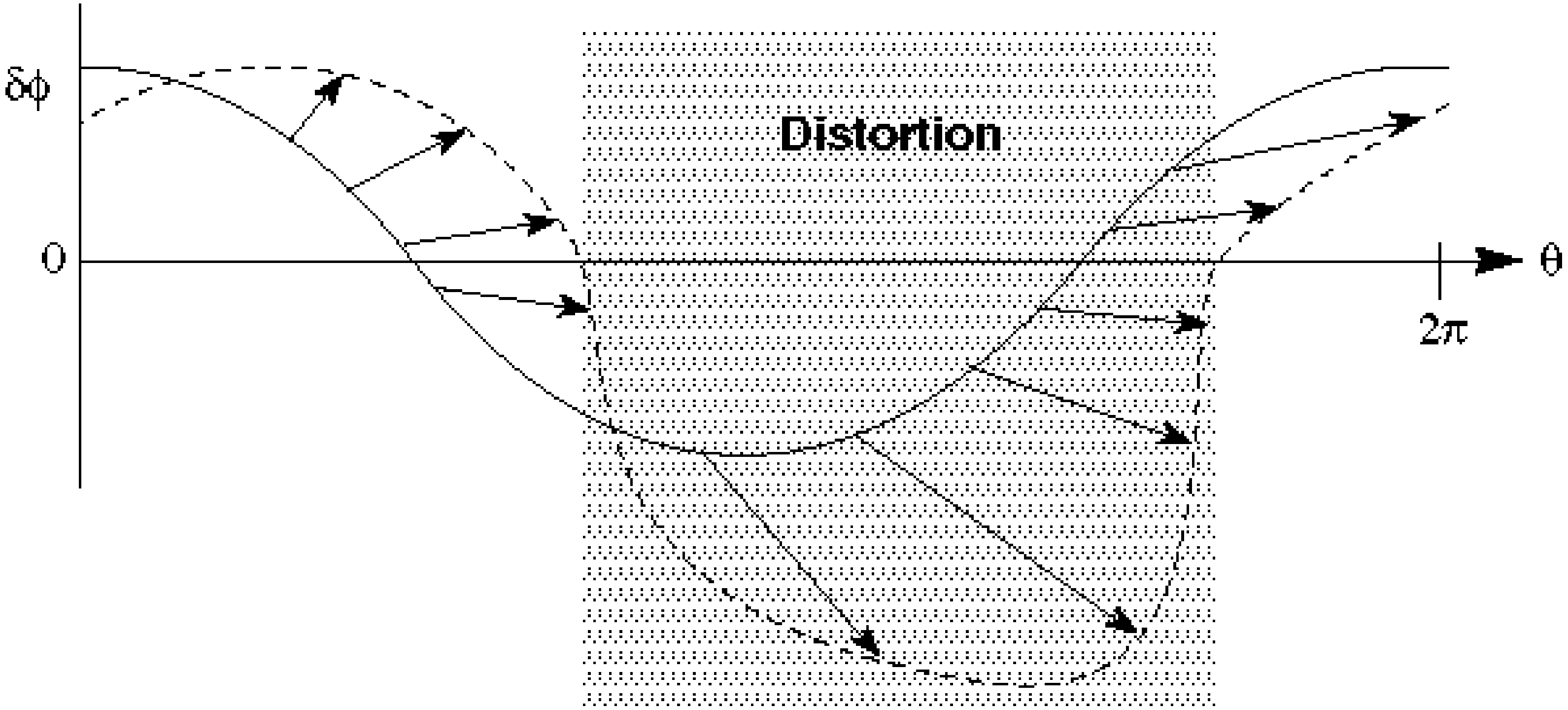
COMPRESSOR BEHAVIOR WITH INLET DISTORTION





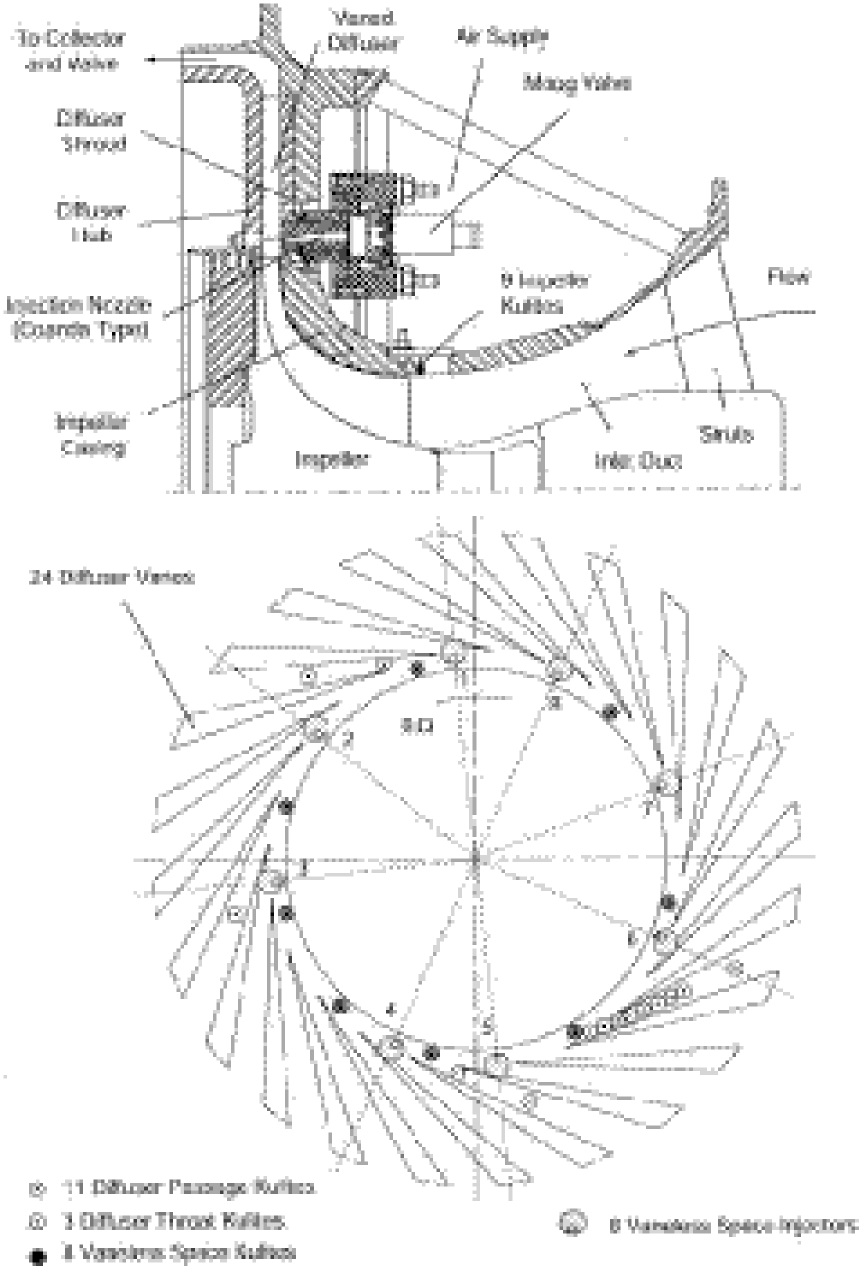
- System flow, stalling pressure rise reduced

EFFECT OF DISTORTION ON WAVE STRUCTURE



- Medium through which waves travel is nonuniform
- Size of nonuniformity ~ Wavelength of disturbances

CENTRIFUGAL COMPRESSOR GEOMETRY



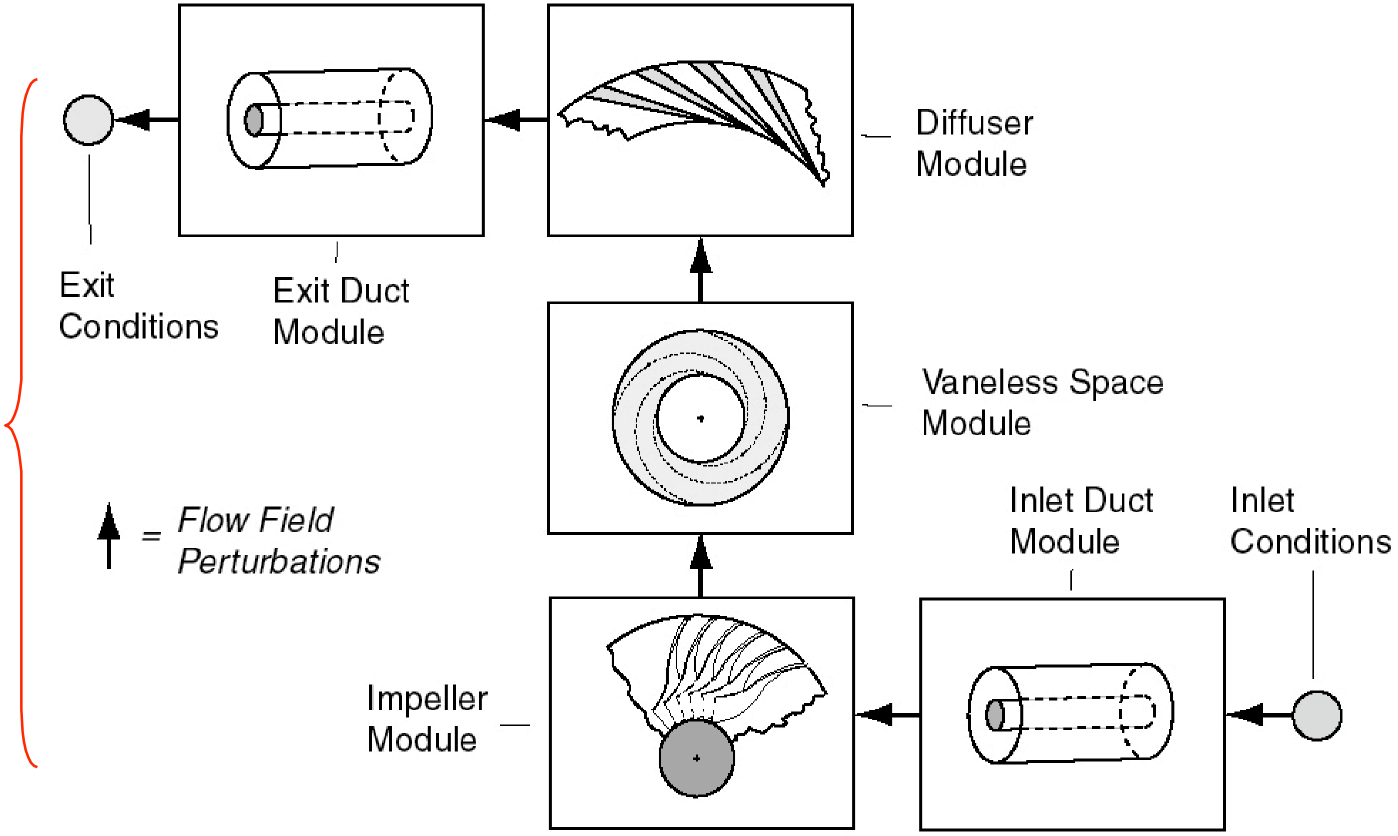
MODULES FOR CENTRIFUGAL COMPRESSOR SYSTEM MODEL

Objective:

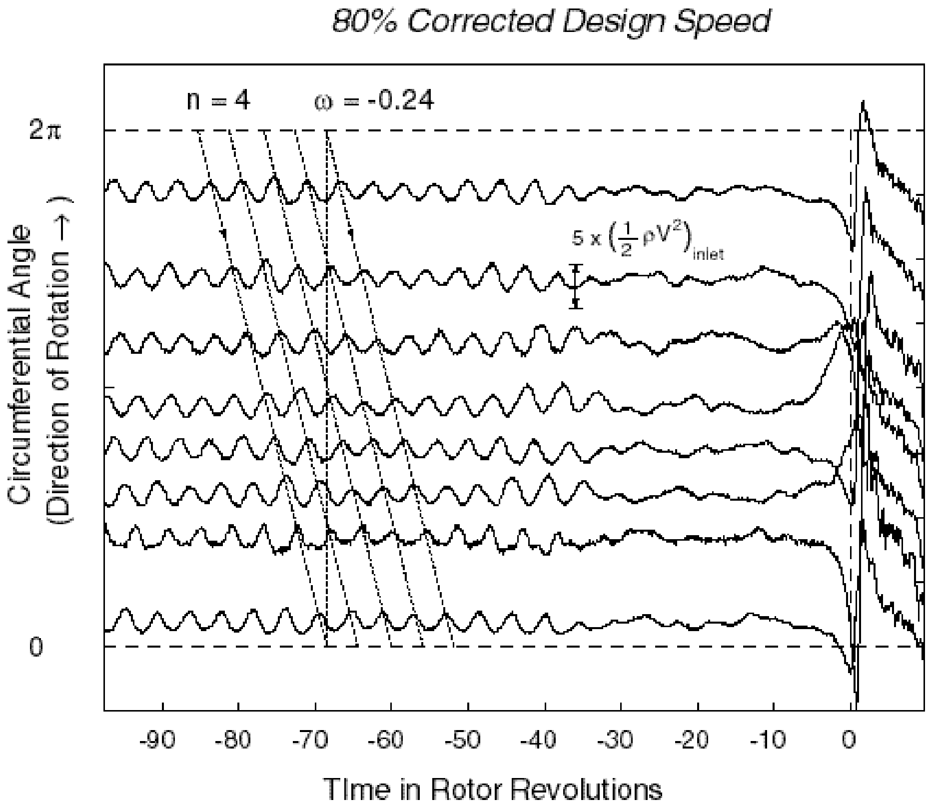
Determine flow resonances

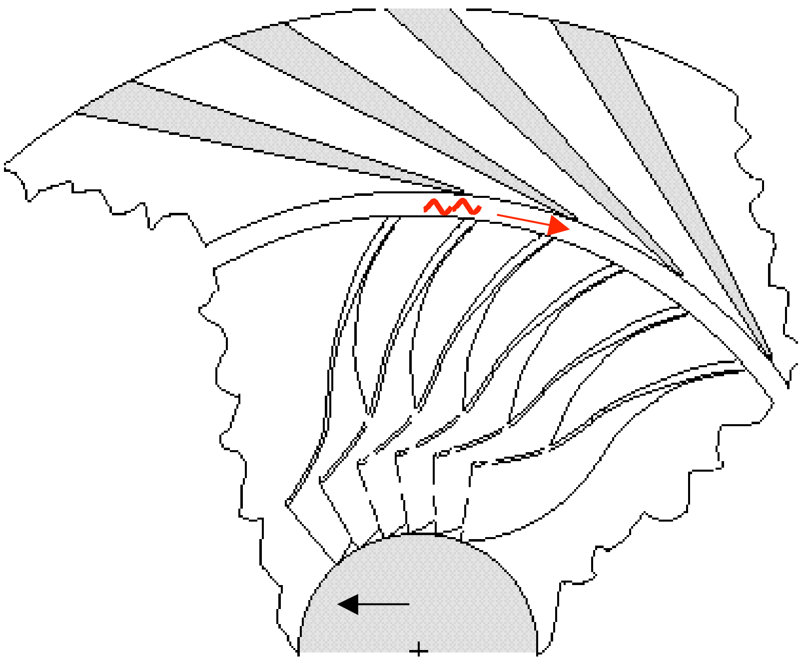
⬇

Eigenvalue Problem



ROTATING (TRAVELING) WAVE STRUCTURES IN CENTRIFUGAL COMPRESSORS





Backward traveling waves ➡

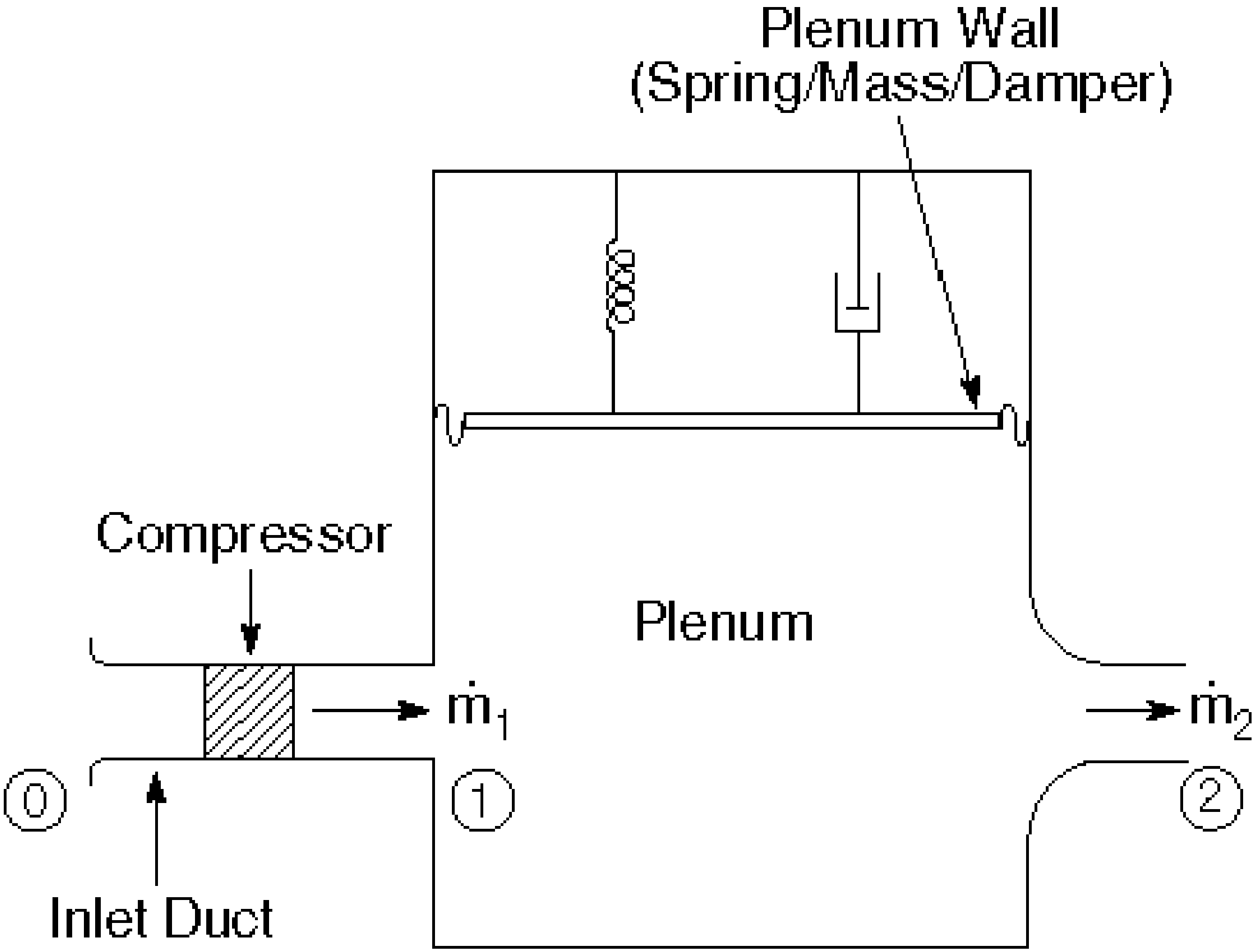
	model prediction	compressor experiment
wave harmonic	4	4
rotation rate	-0.18	-0.24

[Spakovszky]

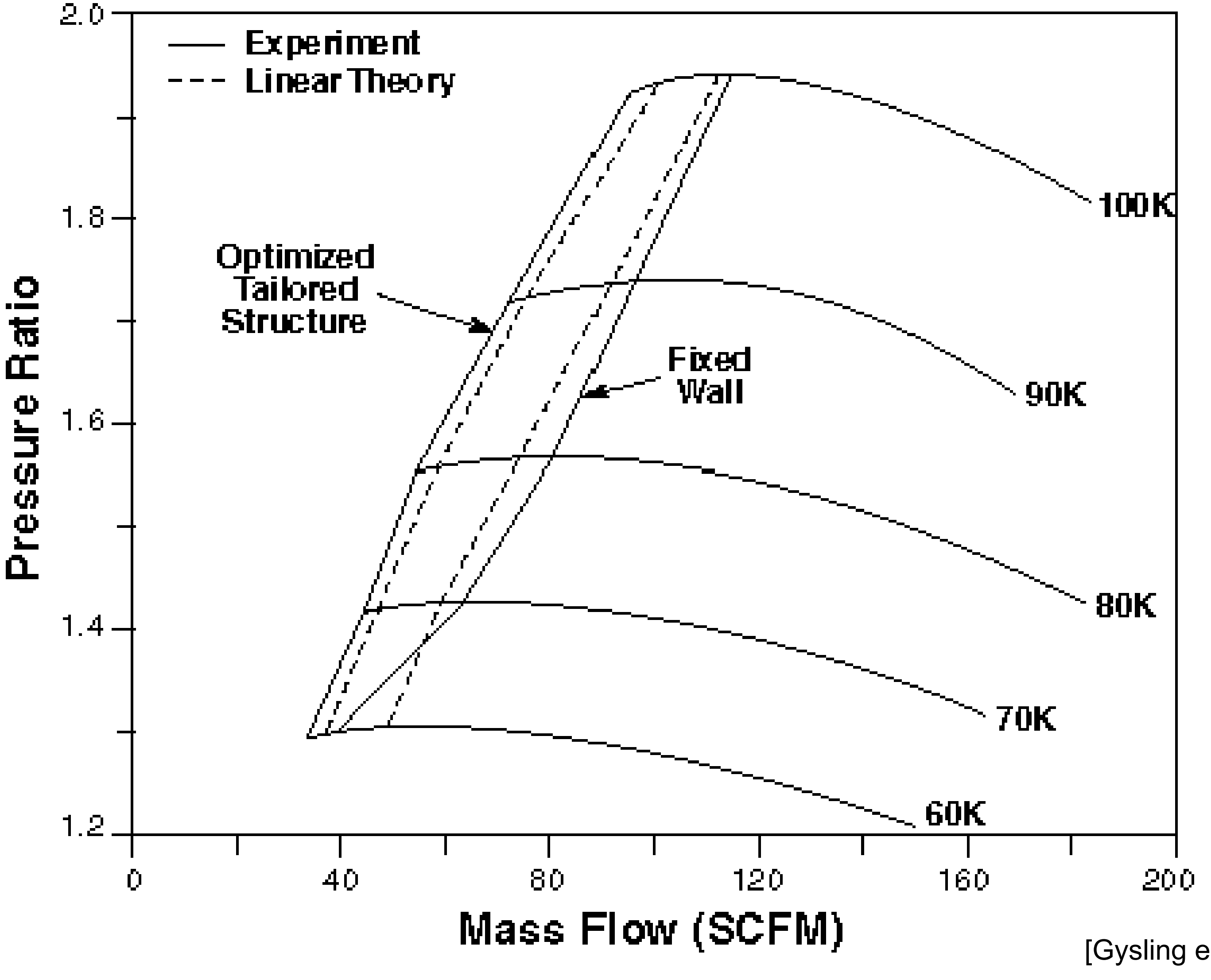
COMPRESSION SYSTEM WITH TAILORED STRUCTURE
(Plenum Wall)

- Surge = pulsations due to energy addition by compressor
- Absorb unsteady energy using tailored structure
- Damp oscillations, increase useful flow range
- Many approaches possible, model enables:
    - Design of structure
    - Definition of mechanism
    - Clarification of perturbation energy paths
- Examination of phase relationships shows link between passive and active control

COMPRESSION SYSTEM WITH TAILORED STRUCTURE
(Plenum Wall)



PREDICTED AND EXPERIMENTAL SURGE BOUNDARIES



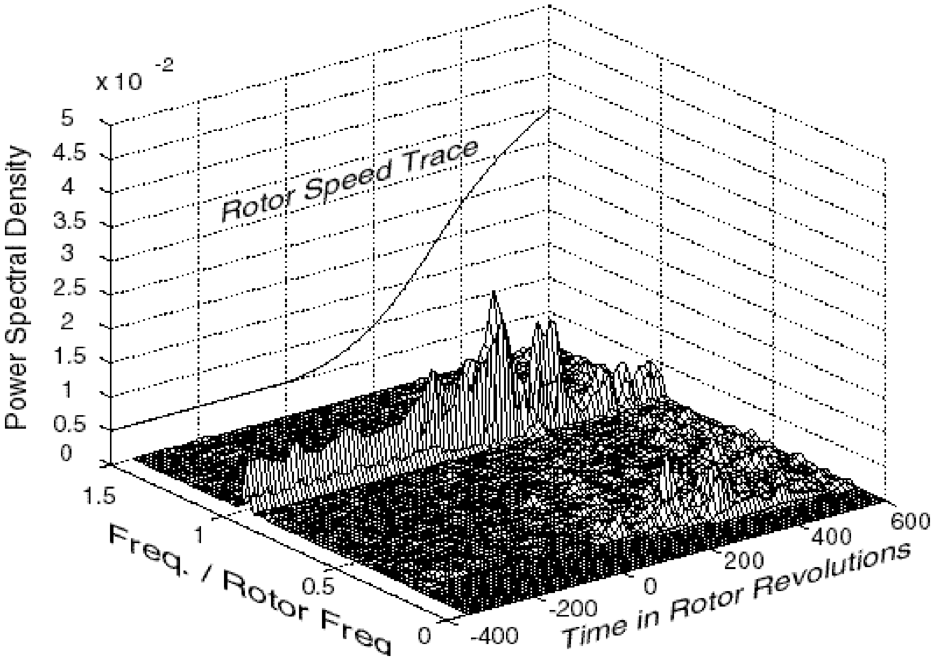
[Gysling et al.]

UNSTEADY TURBOMACHINERY FLOW IN THE COMPRESSIBLE REGIME (M □ UNITY)

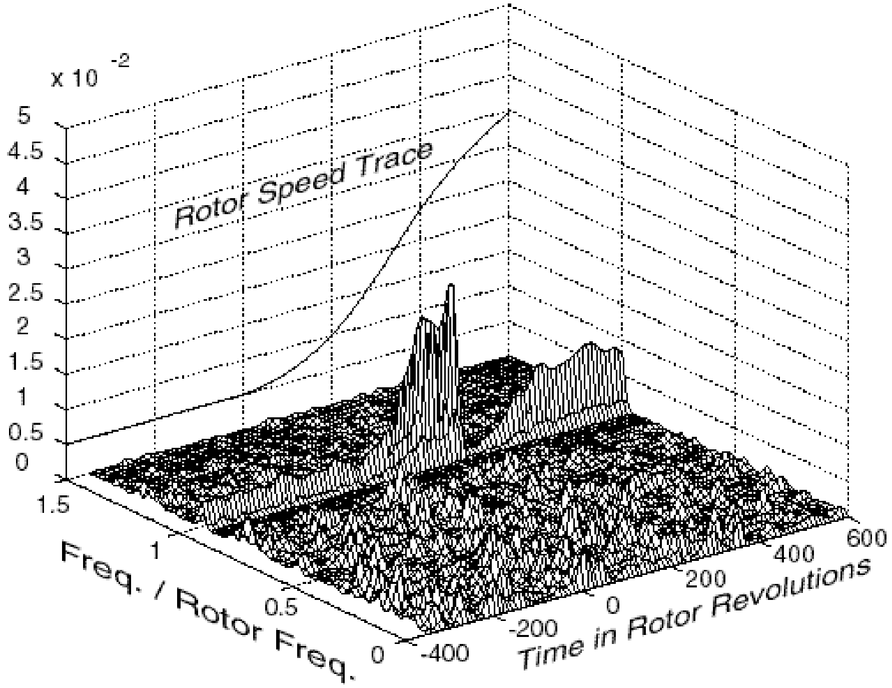
- Compressible flow supports additional classes of waves (compared to incompressible flow)
- Analogous to longitudinal acoustic waves *but* possessing structure in □.
- These disturbances can be “forced” by asymmetry in the rotor (which rotates at engine RPM)
- In a linear system with uniform background flow, forcing and instability do not interact
- In compressors the forced wave amplitude can increase until non-uniform flow becomes unstable
- Non-linear alteration of the background flow to an unstable condition
- Very different mechanism than for incompressible flow

DISTURBANCE BEHAVIOR IN ACTUAL ENGINES

Aircraft Engine Experiment



Modeling Result

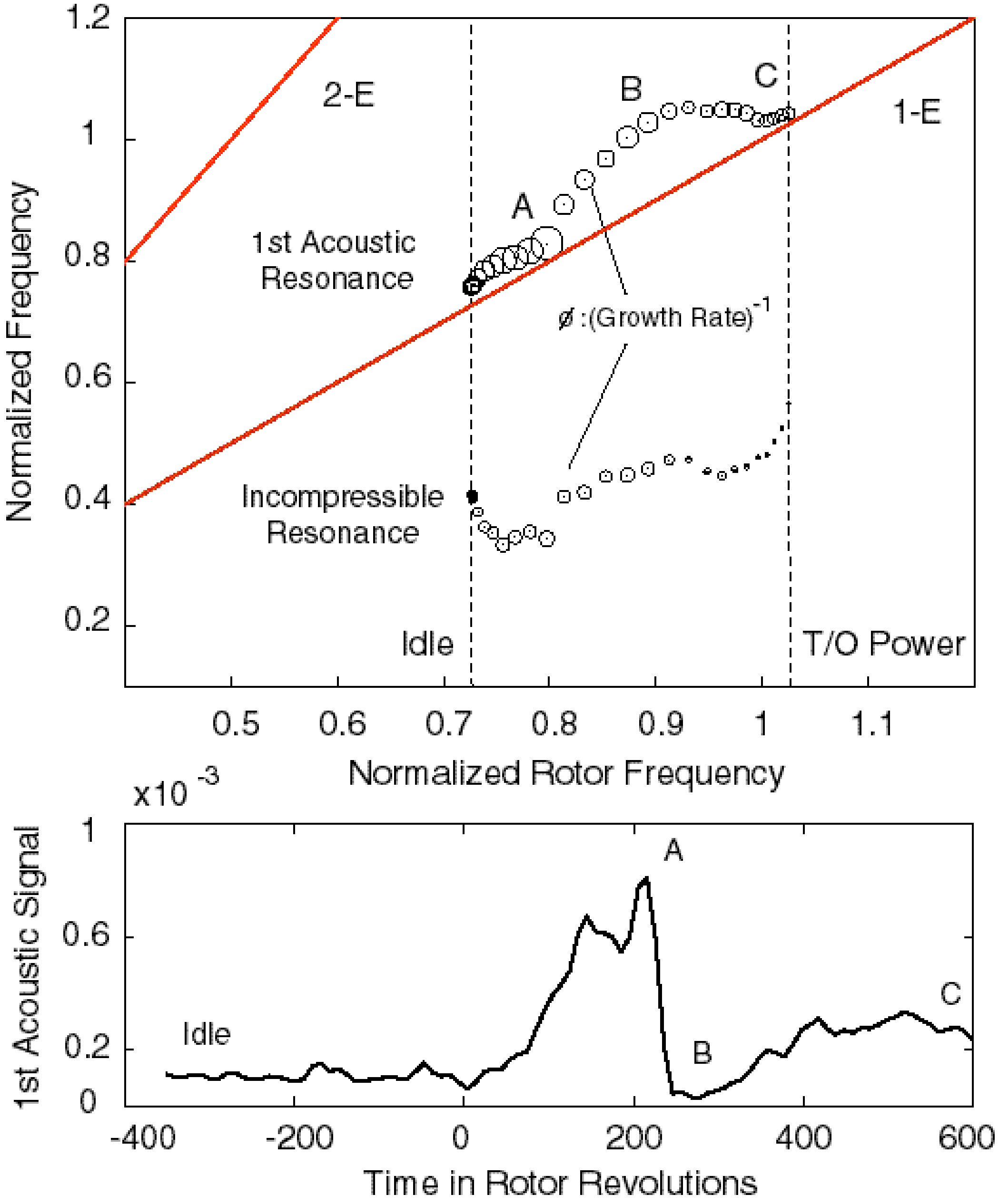


- Unsteady pressure measurement in compressor of a large commercial aircraft engine
- Growth of acoustic mode at rotor frequency is root cause of compressor instability

[Spakovszky et al.]

Mechanism for observed dynamics:

- 1st acoustic resonance coincides with rotor noise forcing (1-E)
- Damping varies along operating line
- Energy fed into 1st mode during compressor transient
- Result is large amplitude oscillation in time domain



[Spakovszky et al.]

SUMMARY AND BACK TO MESSAGE

- Ideas (concepts) for a broad class of dynamic behavior in gas turbine engines have been presented
- Though developed for a specific problem these relatively simple ideas carry over to a number of different phenomena
- One emphasis has been on determining mechanisms
  - "Very often….a simplified model throws more light on the real workings of of nature than….calculations of individual situations which even where correct contain so much detail as to conceal rather than reveal reality" [Anderson, Nobel lectures 1977]
- The approach to understanding the type of flows described is not monolithic
  - You can make an impact on important problems without waiting until the tools exist to resolve every length and time scale