SMART JET ENGINES:
CASE HISTORY OF A MULTIDISCIPLINARY RESEARCH PROJECT

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MESSAGE

- Step improvements are possible in mature devices given new approaches

- Interdisciplinary teaming enables new approaches

OUTLINE

- Themes
- Background and historical context
- Technical challenges
- Current status
- Lessons learned
  - Technology
  - Process

THEMES: SMART JET ENGINES

- Many engineering problems involve more than one discipline*
  - System rather than component view

- Team approach is essential for attacking such problems
  - Marriage of different disciplinary cultures

- Strong interplay between modelling and experiment aimed at overall goal

- Involvement with customer shapes overall goal

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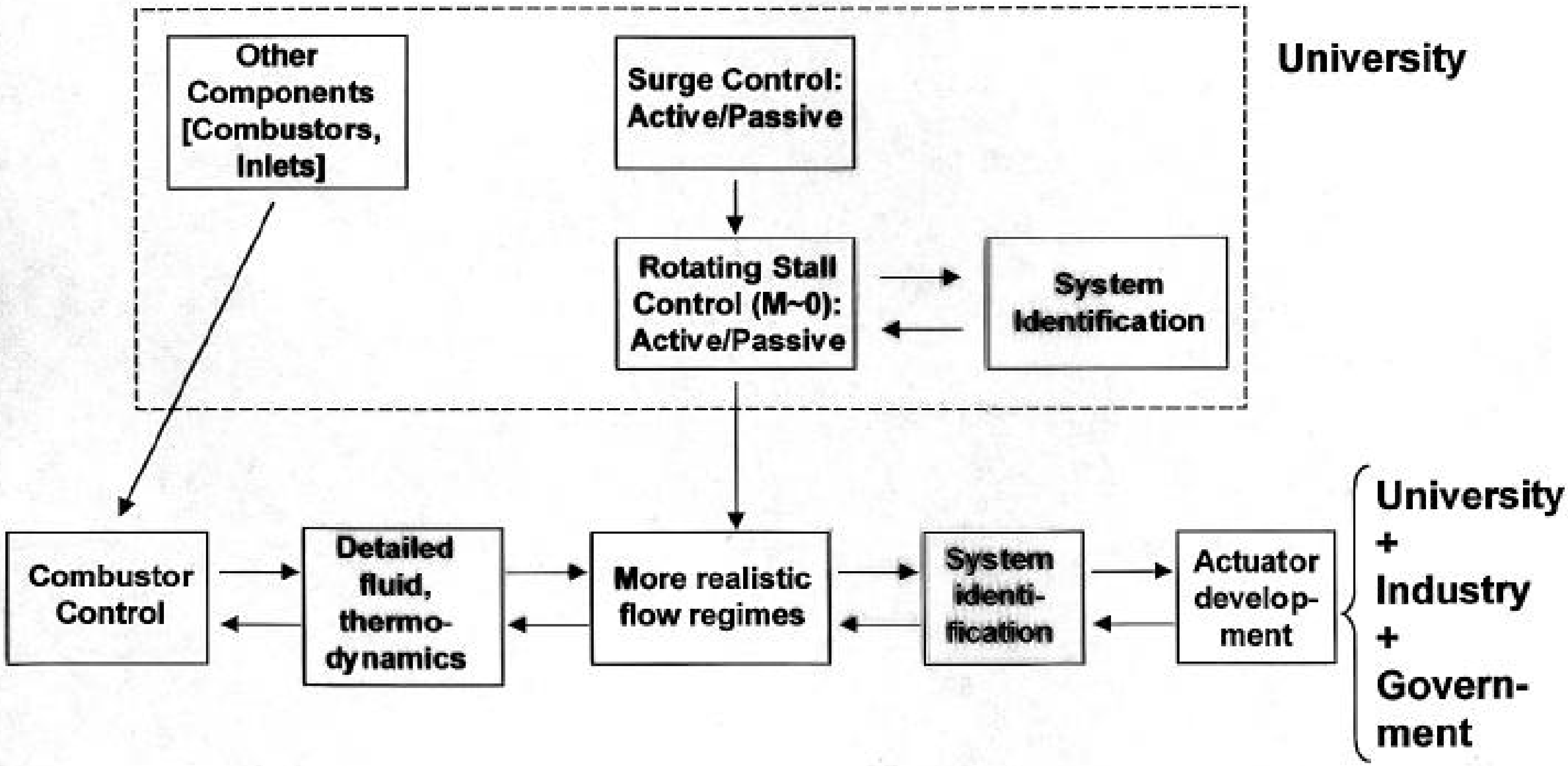
* "God did not make the natural world according to the departmental structure of research universities" - L.A. Armstrong

DYNAMIC CONTROL OF TURBINE ENGINE SYSTEMS



[Product needs spark research issues]

BACKGROUND: GAS TURBINE TECHNOLOGY
(Circa Mid 1980's)

- Components open-loop
- Few control inputs
- Few controlled variables (fuel flow, nozzle, stators)
- Constraints
  - Processing power
  - Sensor, actuator capability
  - Complexity
  - "Experience"

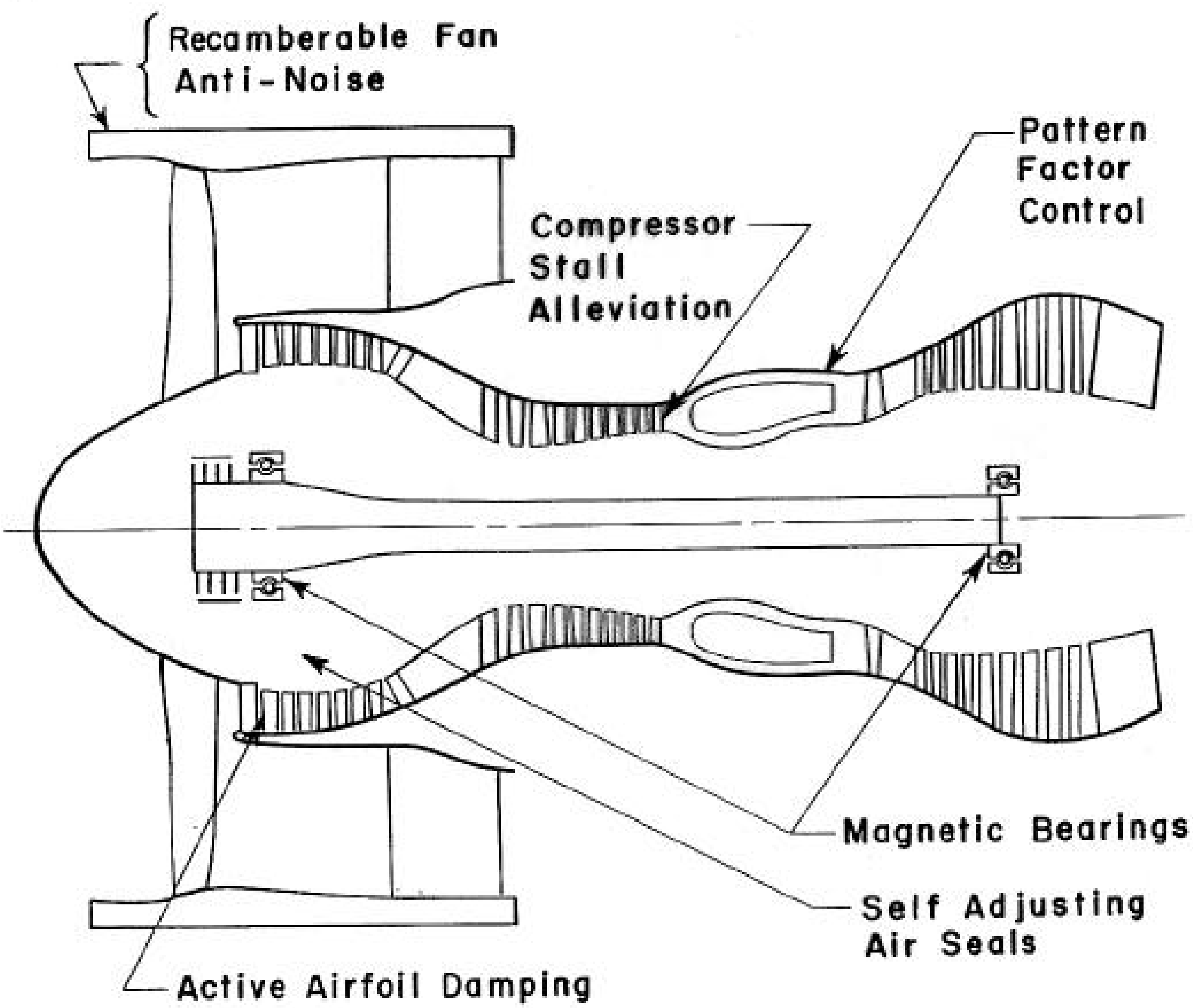
OBSERVATIONS

- Computational power increasing rapidly
- This power can alter the basic nature of gas turbine components from open to closed loop operation
- Components adapt to local conditions to improve performance, life, cost

INITIAL REACTIONS OF INDUSTRY AND UNIVERSITY EXPERTS

- Extreme skepticism - Reactions included
  - Polite silence
  - "We don't have those problems in our products"
  - "All you're going to do is prove linear theory"
  - "That is physically impossible"
- Non-experts were biggest supporters
  - Basic research people
  - Controls people

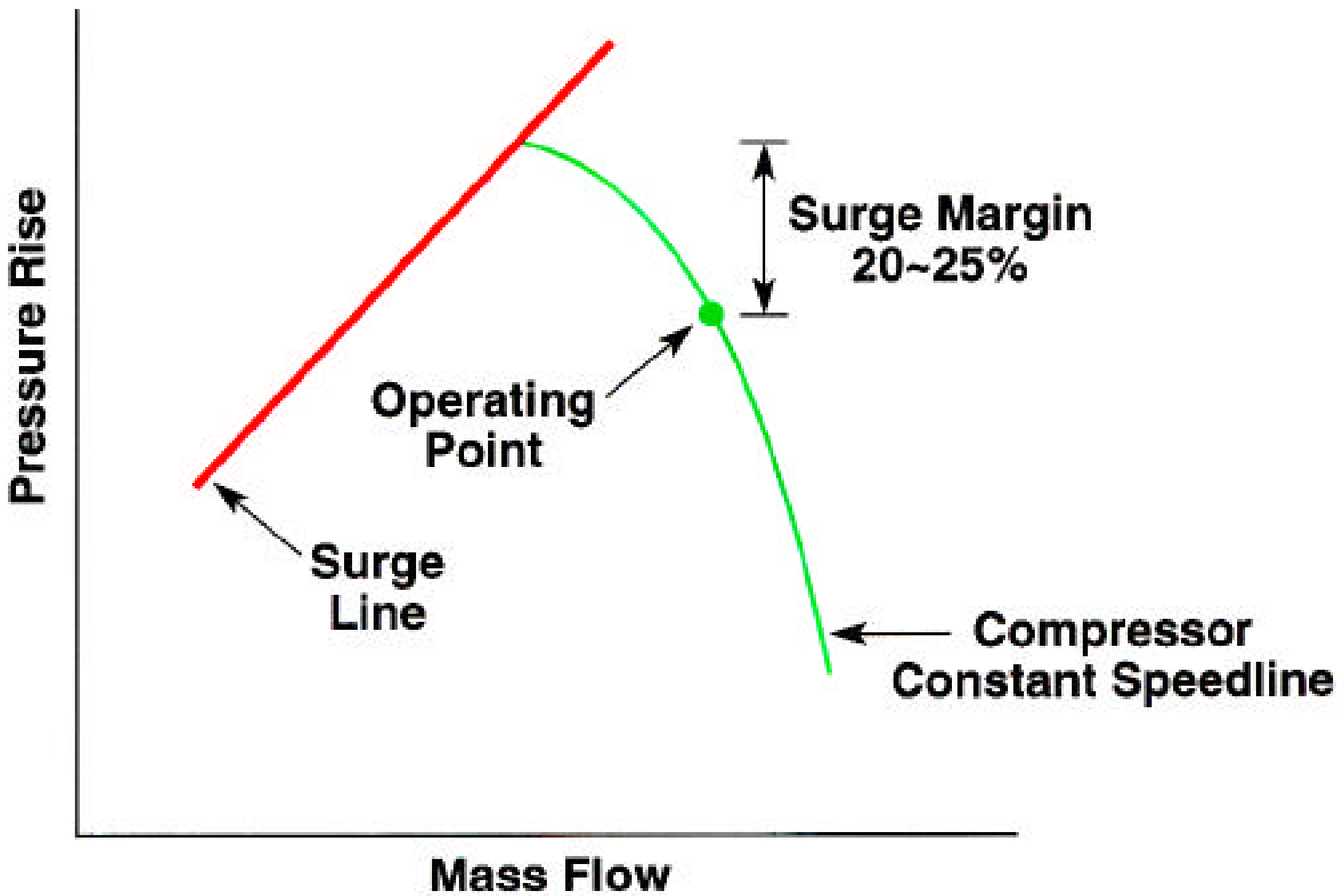
SMART ENGINE APPLICATIONS



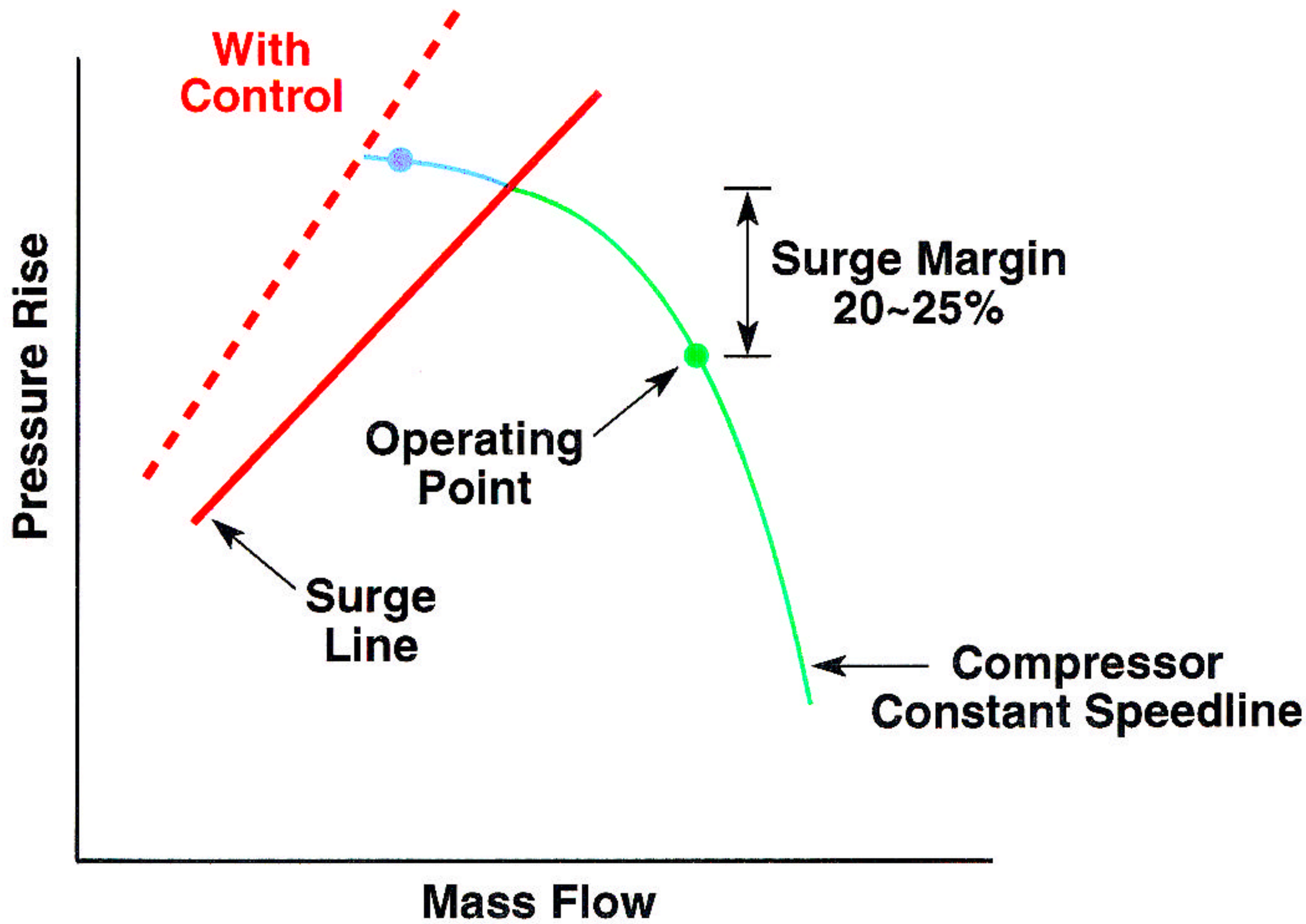
SMART ENGINES AND ACTIVE CONTROL

- Concept - Explore the use of large amounts of feedback control in jet engines
- Potential applications
  - Compressor stabilization
  - Magnetic bearings
  - Combustor control
  - Noise control
- Initial objective - Active compressor stabilization
  - Largest return for system
  - Best theoretical base
  - Matched MIT capabilities

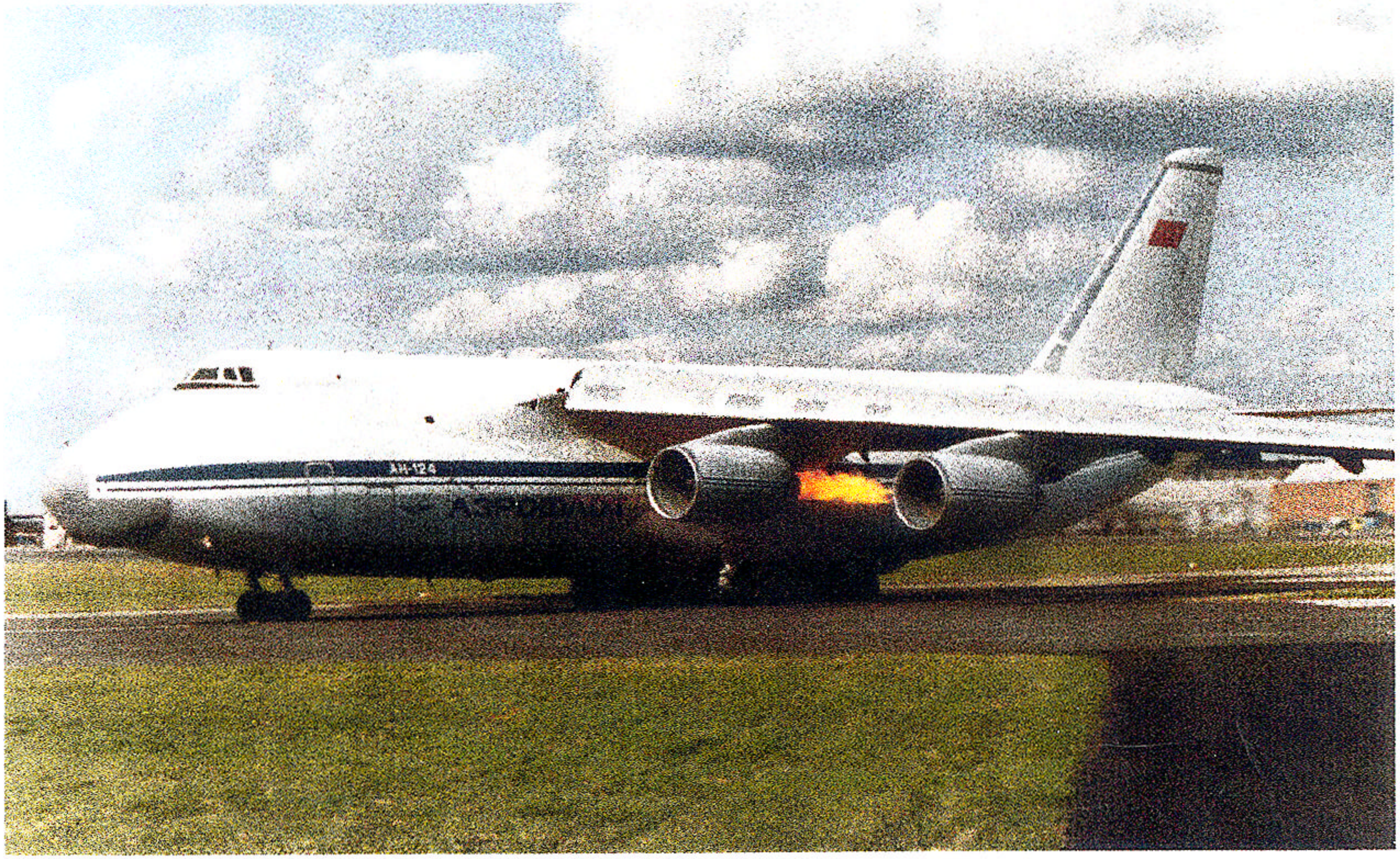
COMPRESSOR OPERATING CHARACTERISTIC



COMPRESSOR OPERATING CHARACTERISTIC



CONSEQUENCES OF "SMALL PERTURBATION" INSTABILITY



WHY ARE COMPRESSOR INSTABILITIES IMPORTANT?

- Surge margin costs pressure ratio
- Surge is a limiting load for compressor mechanical design
- Surge and stall limit design space
- Instability limits difficult to predict
  - Can lead to expensive surprises during development
- Stability deteriorates with age

TECHNOLOGY DEVELOPMENT STRATEGY

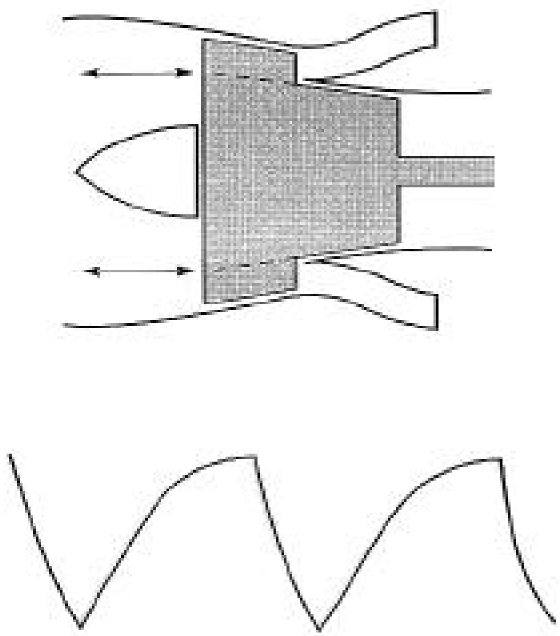
- Only data is convincing
  - Demo early and often
  - Build on many small successes
  - Use customers' hardware whenever possible
- Talk to people frequently
  - Enlist allies at companies
  - Build consensus and enthusiasm
- System studies to identify impact
  - Not all gains and costs are obvious
  - Good vehicle for talking with customers
- Stay focused on compressor control, not science

EARLY MULTIDISCIPLINARY VIEWPOINT

- Basic assumption
  - My job is challenging, theirs is straightforward
- Questions
  - Why do we really need those guys?
  - How much do I have to pay them?
- Initial answers
  - To get support (from an interdisciplinary pot)
  - To talk to sponsors in their disciplines
  - To write the software
- People problems
  - Those guys just don't understand (don't speak same language)
  - How to get recognition for cross-disciplinary accomplishments

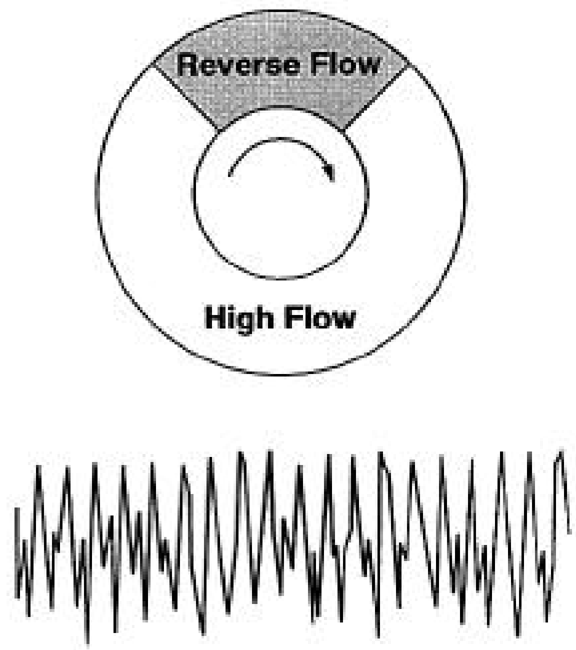
COMPRESSOR FLOW INSTABILITIES

Surge
Axially Oscillating Flow



Frequency ~ 3-10 Hz

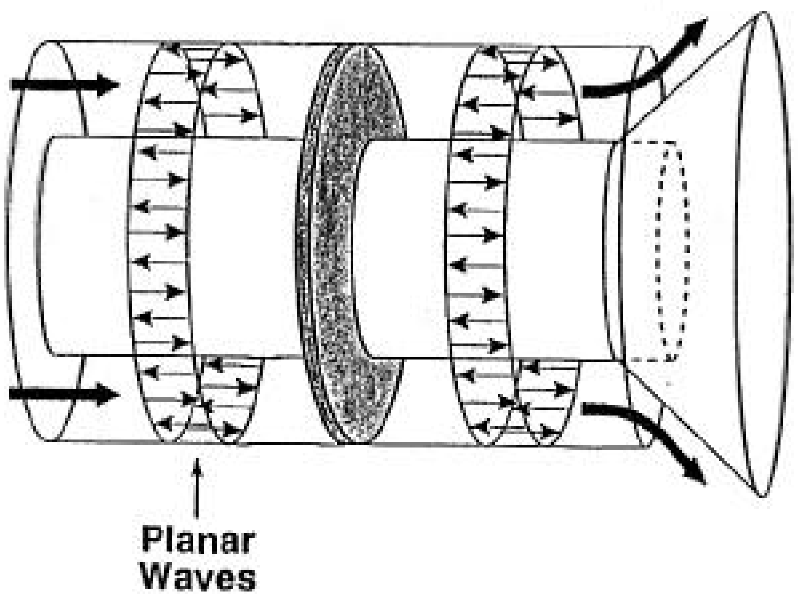
Rotating Stall
Circumferentially Nonuniform Flow



Frequency ~ 50-100 Hz

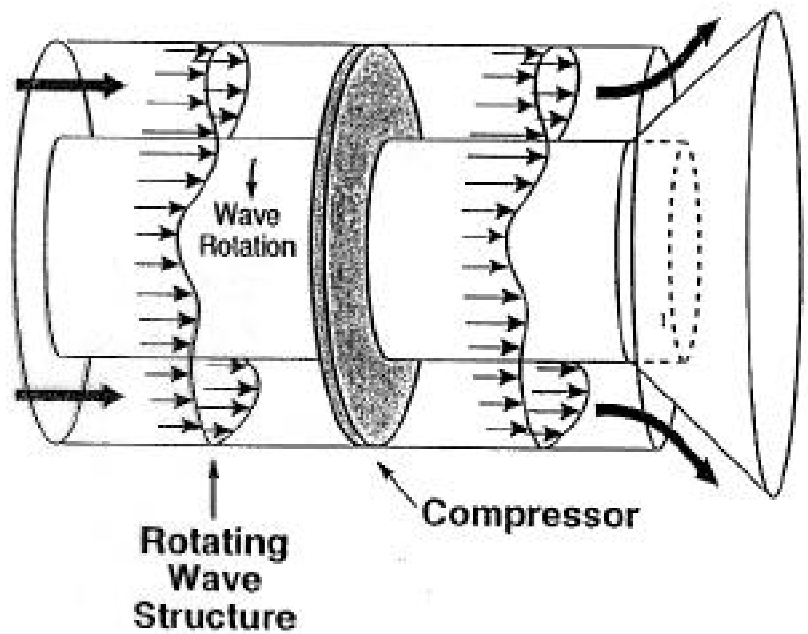
NATURAL OSCILLATORY MODES OF COMPRESSORS

Lowest Order



Surge

Higher Order



Rotating Stall

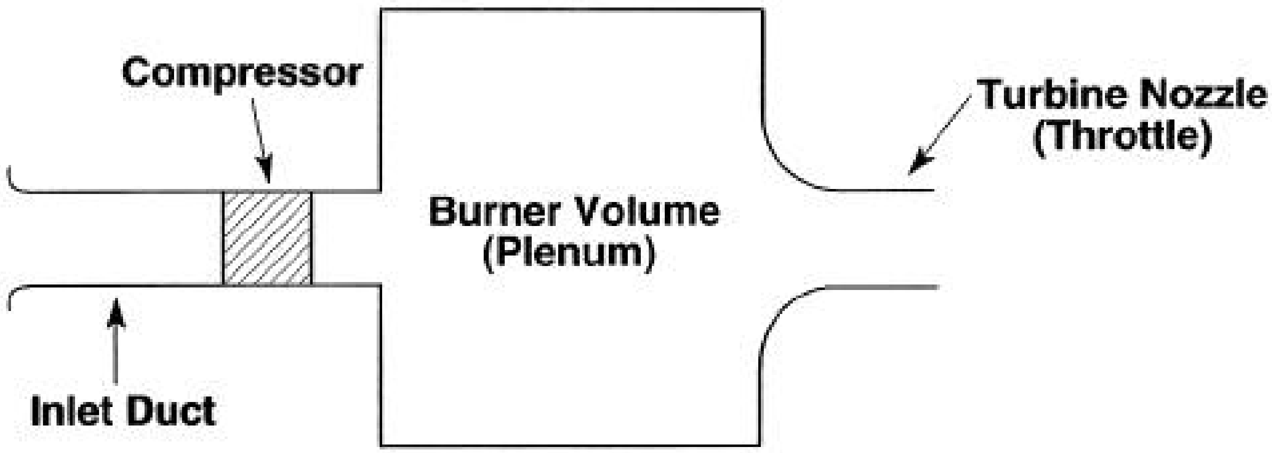
ACTIVE SURGE STABILIZATION

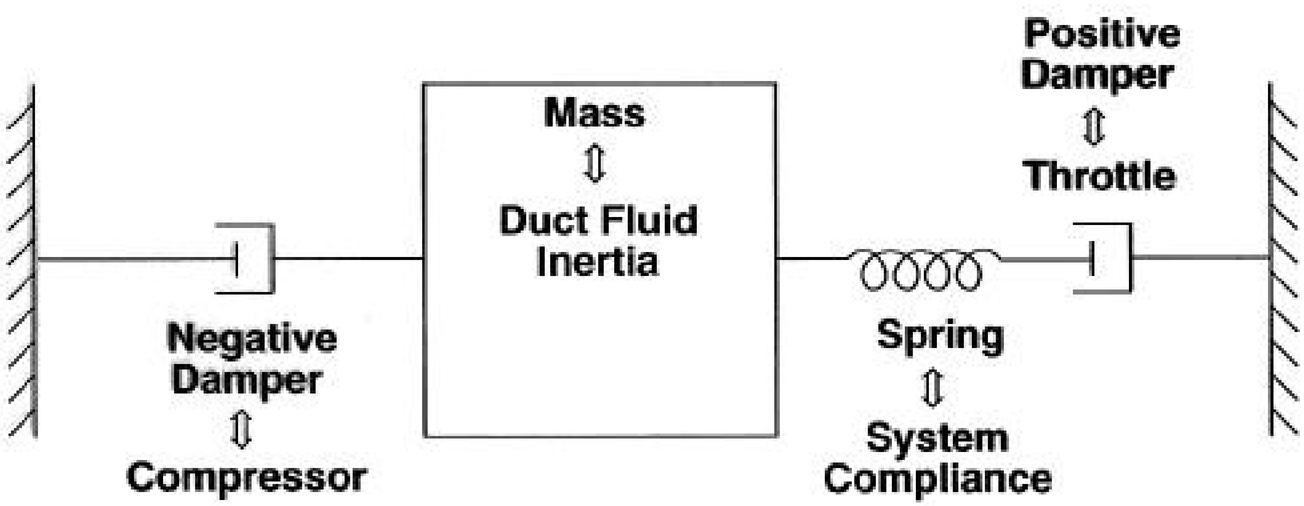
- Surge important for centrifugal and axial compressors
- Surge control alone sufficient for centrifugal compressors
- Use centrifugal compressor as initial test bed
- "Simple" control task
  - Lumped parameter dynamics
  - Single sensor, single actuator
  - Relatively low frequency (10~50 Hz)

COUNTERPOINT: MODELLING

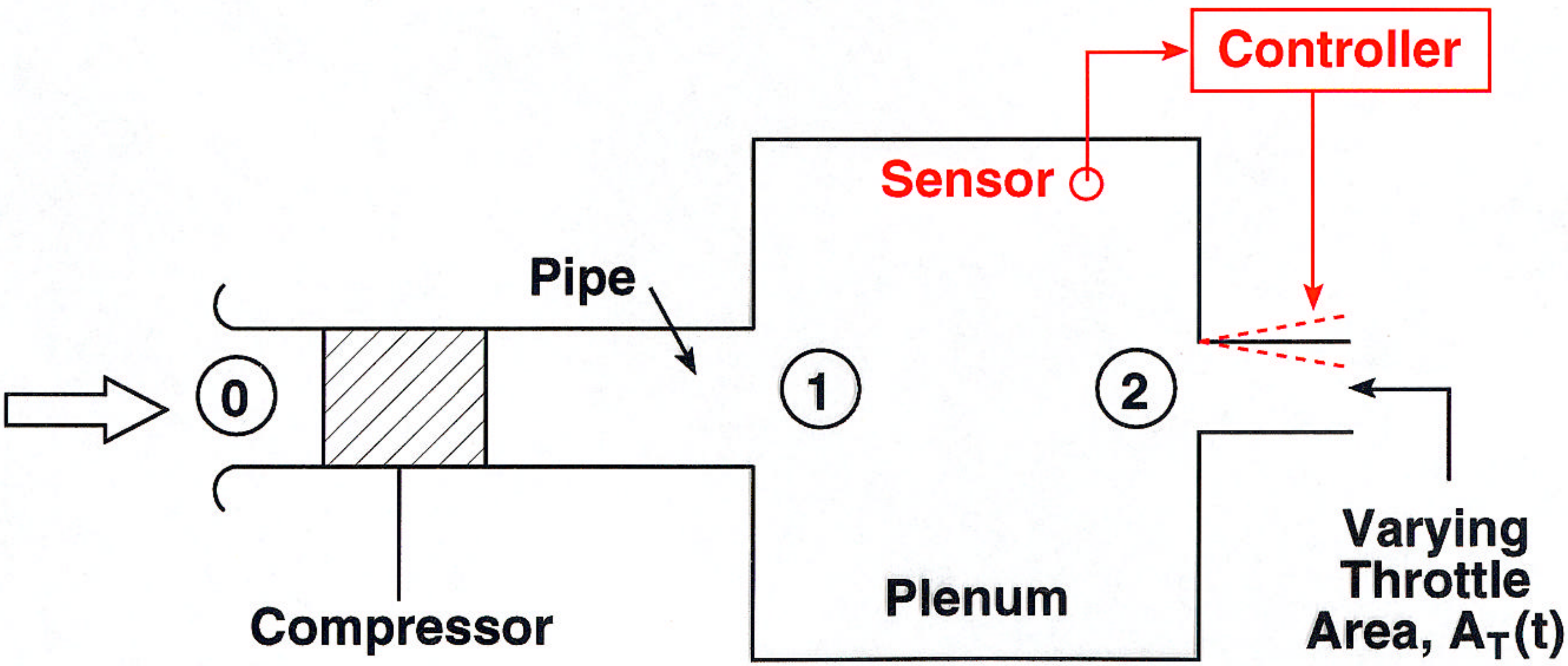
- Problems of high technological interest have many levels of complexity
- Generally want to extract enough (not too much!) information
- Modelling extremely helpful in this process
- Use experiment/modelling together to move up learning curve
- Must have clear idea of information needed - overall goal drives modelling level

SIMPLE MODEL CAPTURES PHYSICS

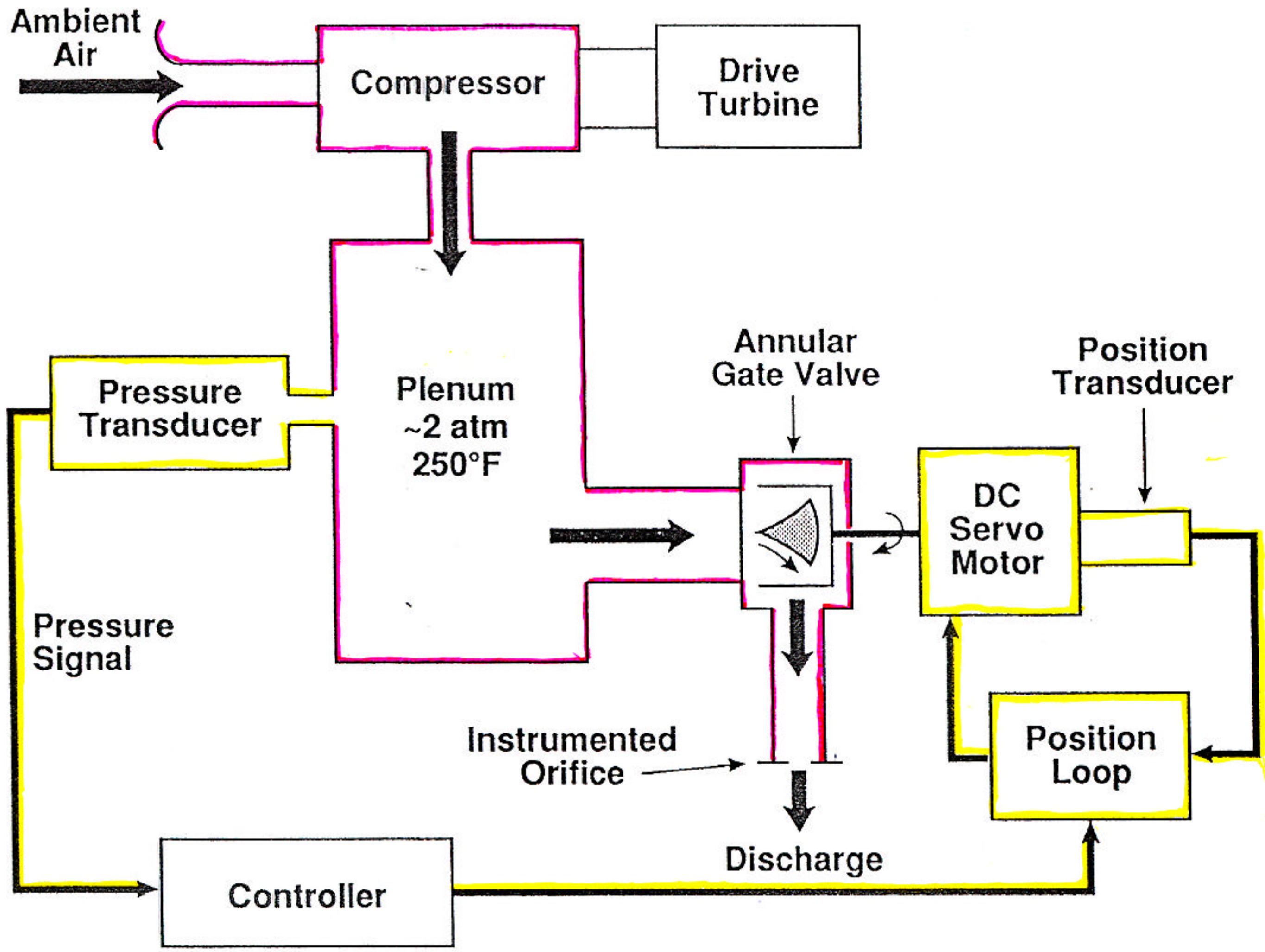




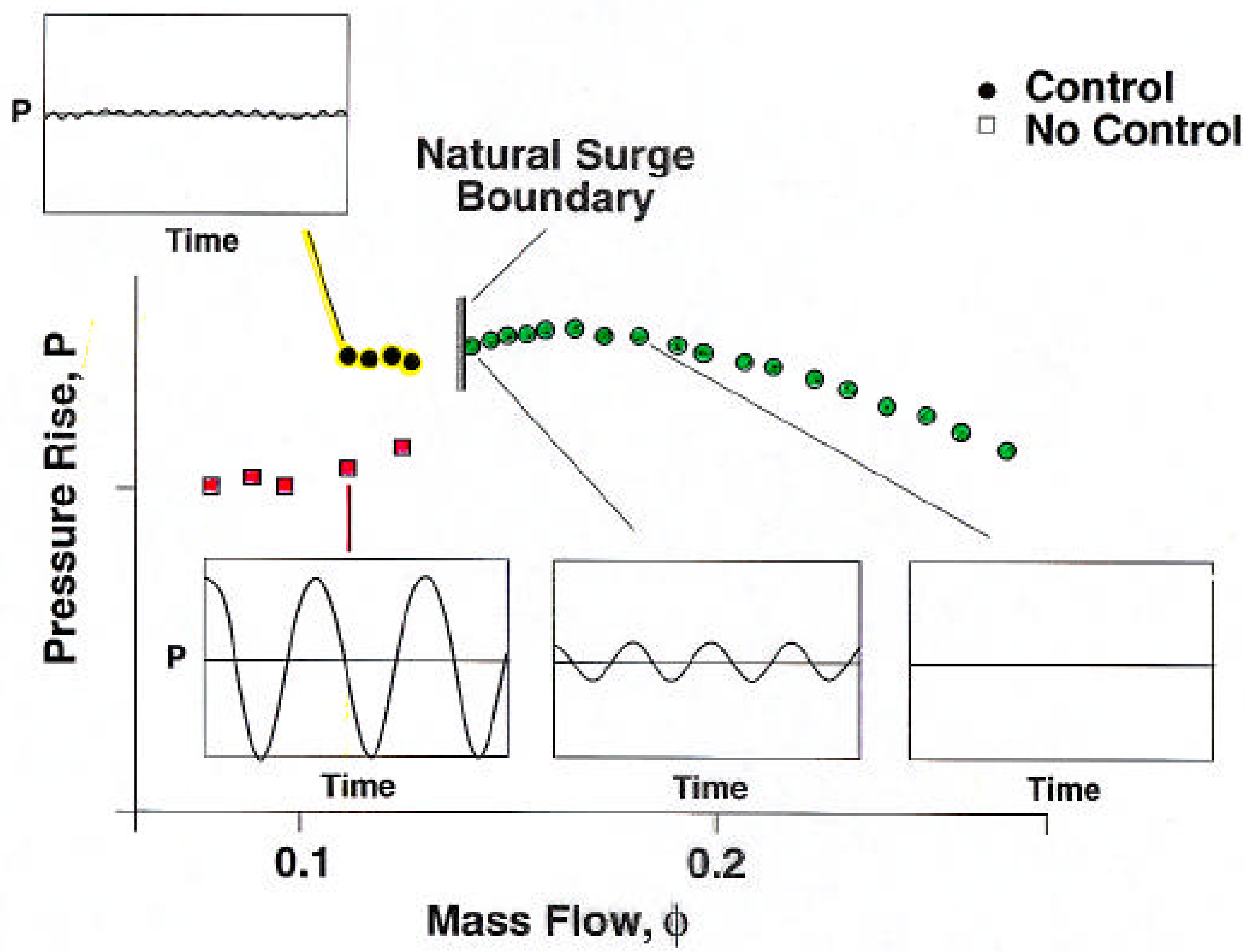
COMPRESSION SYSTEM WITH PLENUM EXIT CONTROL
– Simple Generic Model –



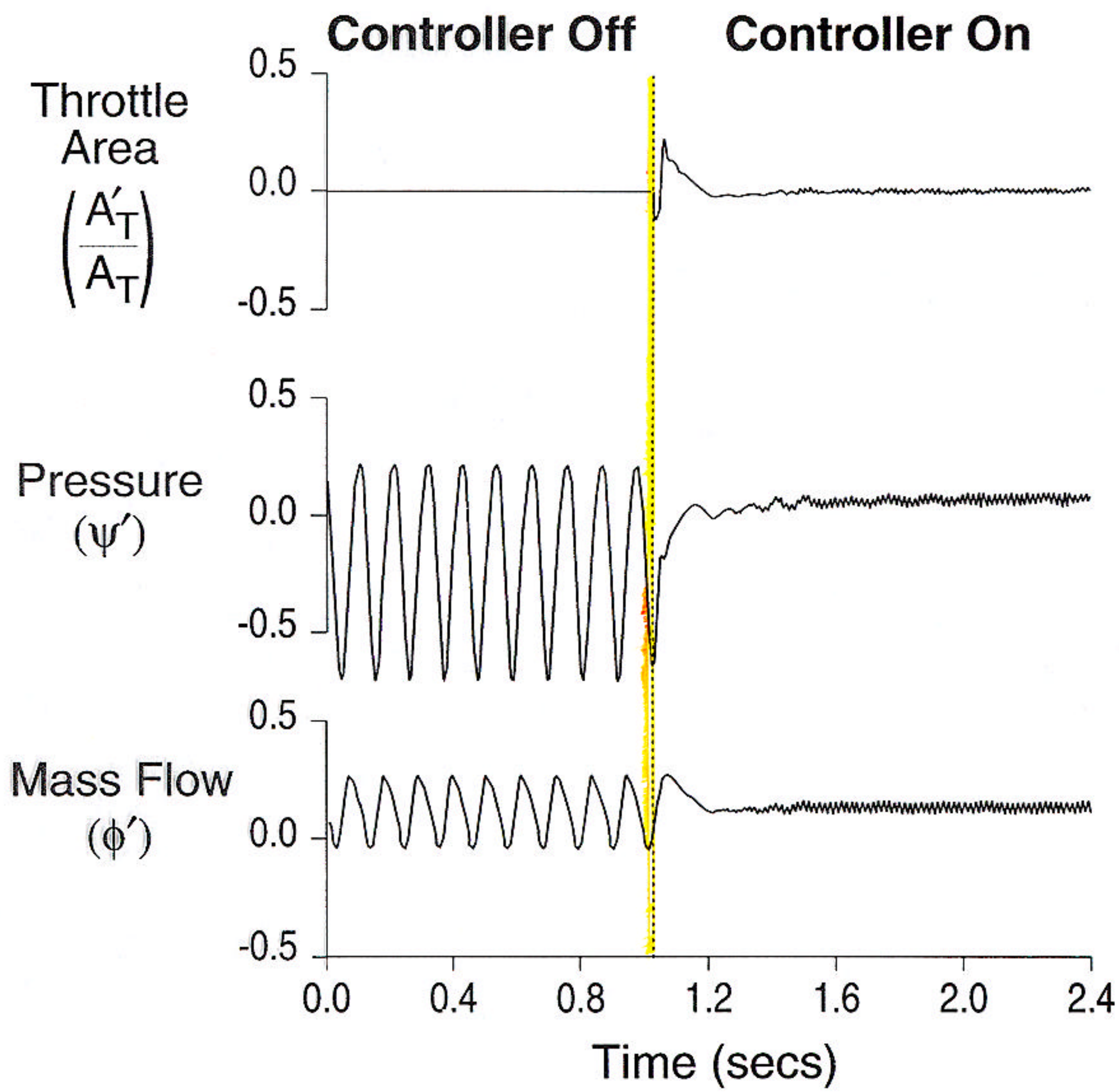
ACTIVELY STABILIZED CENTRIFUGAL COMPRESSOR



TIME RESOLVED SYSTEM BEHAVIOR



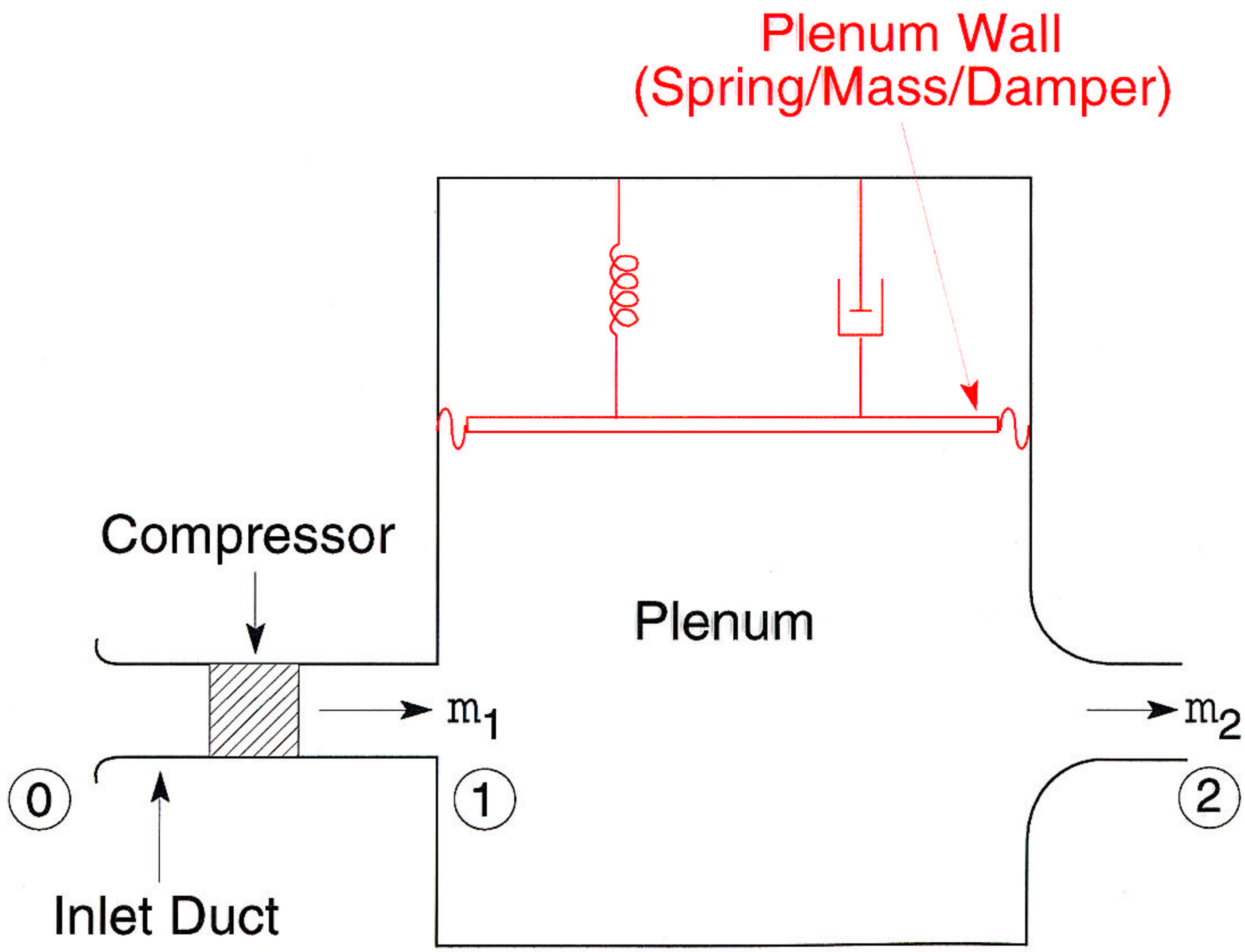
SWITCHING CONTROLLER ON SUPPRESSES SURGE



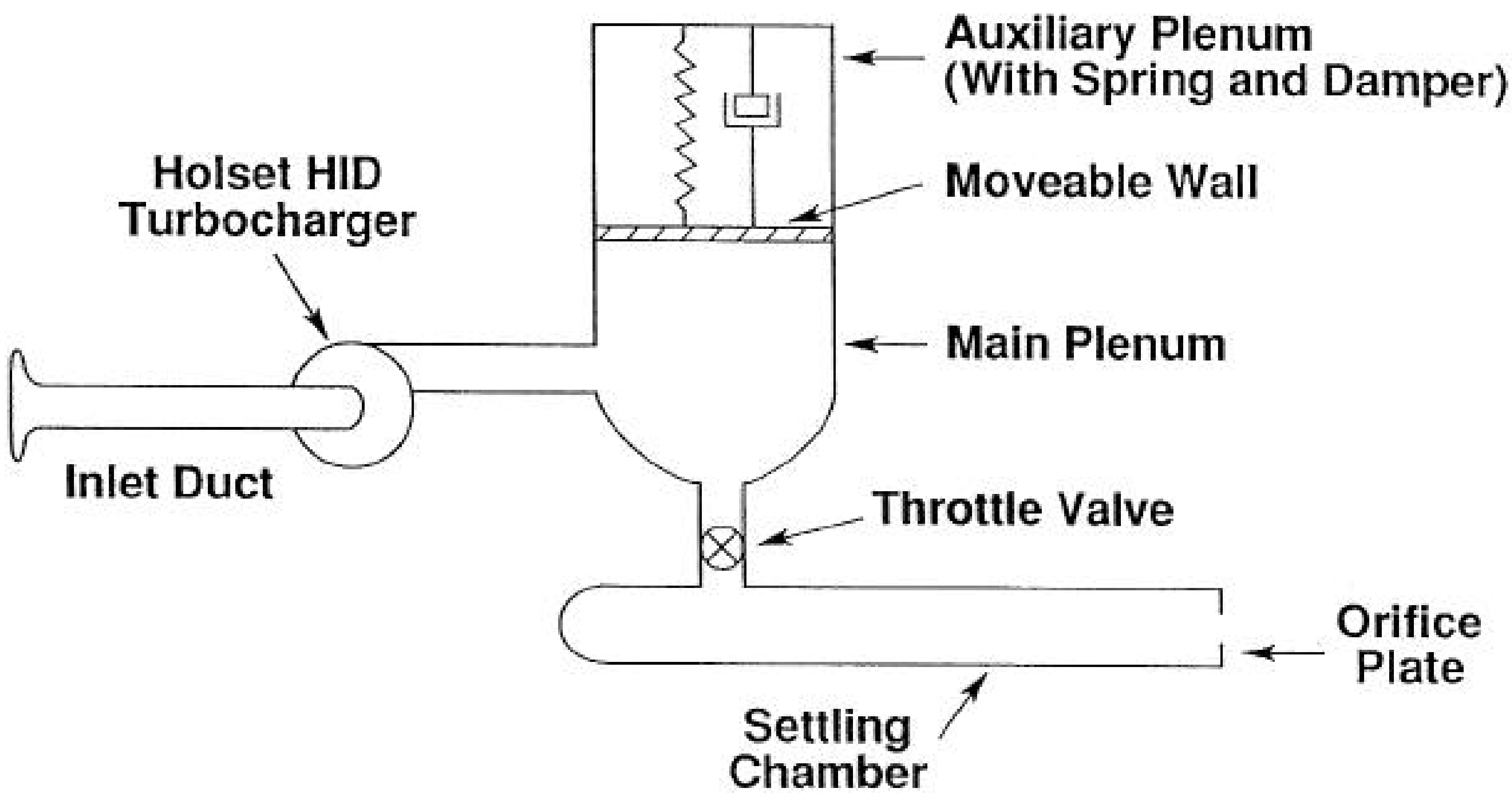
PASSIVE CONTROL OF SURGE

- Active control approach opened new understanding
  - Alternate, simpler approaches became obvious
- Surge = instability (pulsations) due to energy addition by compressor
- Absorb unsteady energy using tailored structure
  - Stabilize system
- Many approaches viable

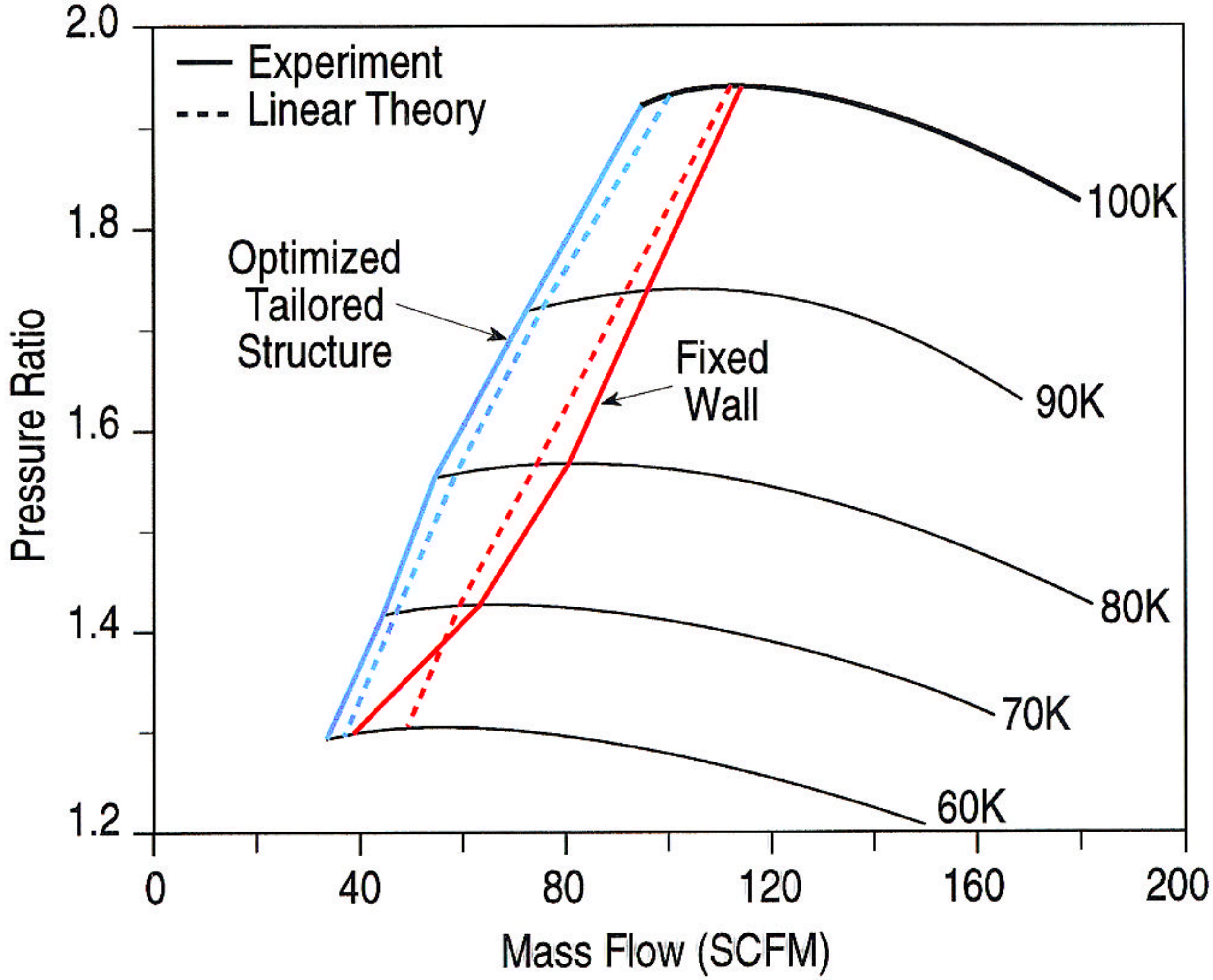
COMPRESSION SYSTEM WITH TAILORED STRUCTURE
(Plenum Wall)



SCHEMATIC OF EXPERIMENTAL FACILITY



PREDICTED AND EXPERIMENTAL SURGE BOUNDARIES



COMPRESSOR SURGE STABILIZATION
- Summary -

- Dynamic control of compressor surge demonstrated
  - Active and passive approaches both successful
- Theory and experiment agree
- Effectiveness strongly dependent on control strategy

ROTATING STALL STABILIZATION

- Must control rotating stall in axial compression system
  - Rotating stall "triggers" surge
- Multi-dimensional control/actuation problem
- Modelling less certain than for surge
- Mainstream problem for aircraft engines

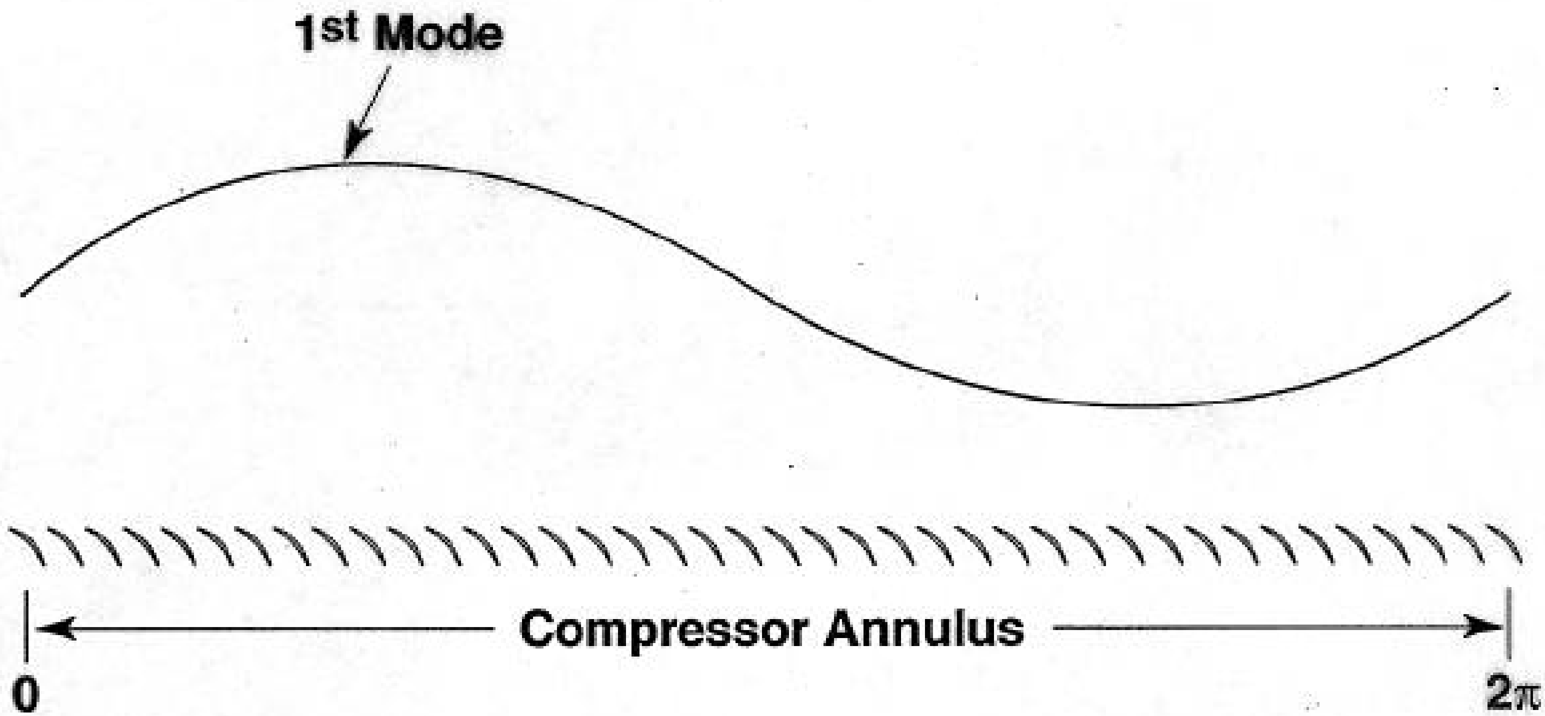
WORKING HYPOTHESIS FOR ROTATING STALL CONTROL

- Observations
  - Travelling waves appear to grow into rotating stall
- Inference
  - Damping the waves will influence (inhibit) stall
- Realization
  - Sense travelling waves in compressor
  - Create appropriate real-time travelling disturbance
  - Damp waves and stabilize compressor flowfield

BARRIER ISSUE TO INNOVATION

- Modeling predicted prestall low amplitude waves
- General disbelief that such waves existed
  - "I haven't seen one in 30 years"
- Industry hadn't suspected these waves, so never seriously looked
  - Sensors in wrong place
  - Only "eyeball" signal processing

ANALYZING AND DETECTING ROTATING STALL

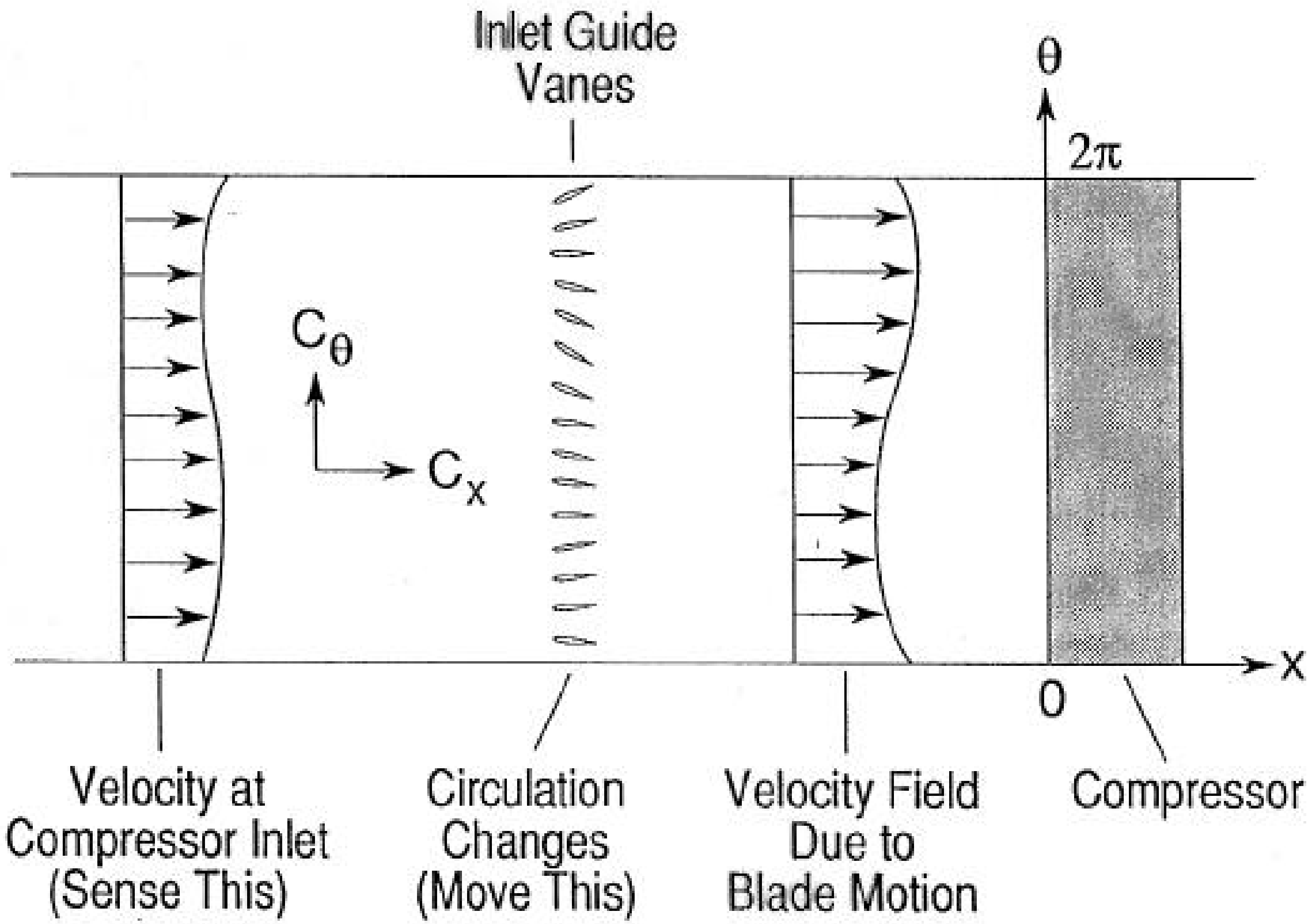


- Look for rotating waves
- Decompose into "components" or modes
- Treat each mode individually
- Level of complexity for fluids arises from control needs

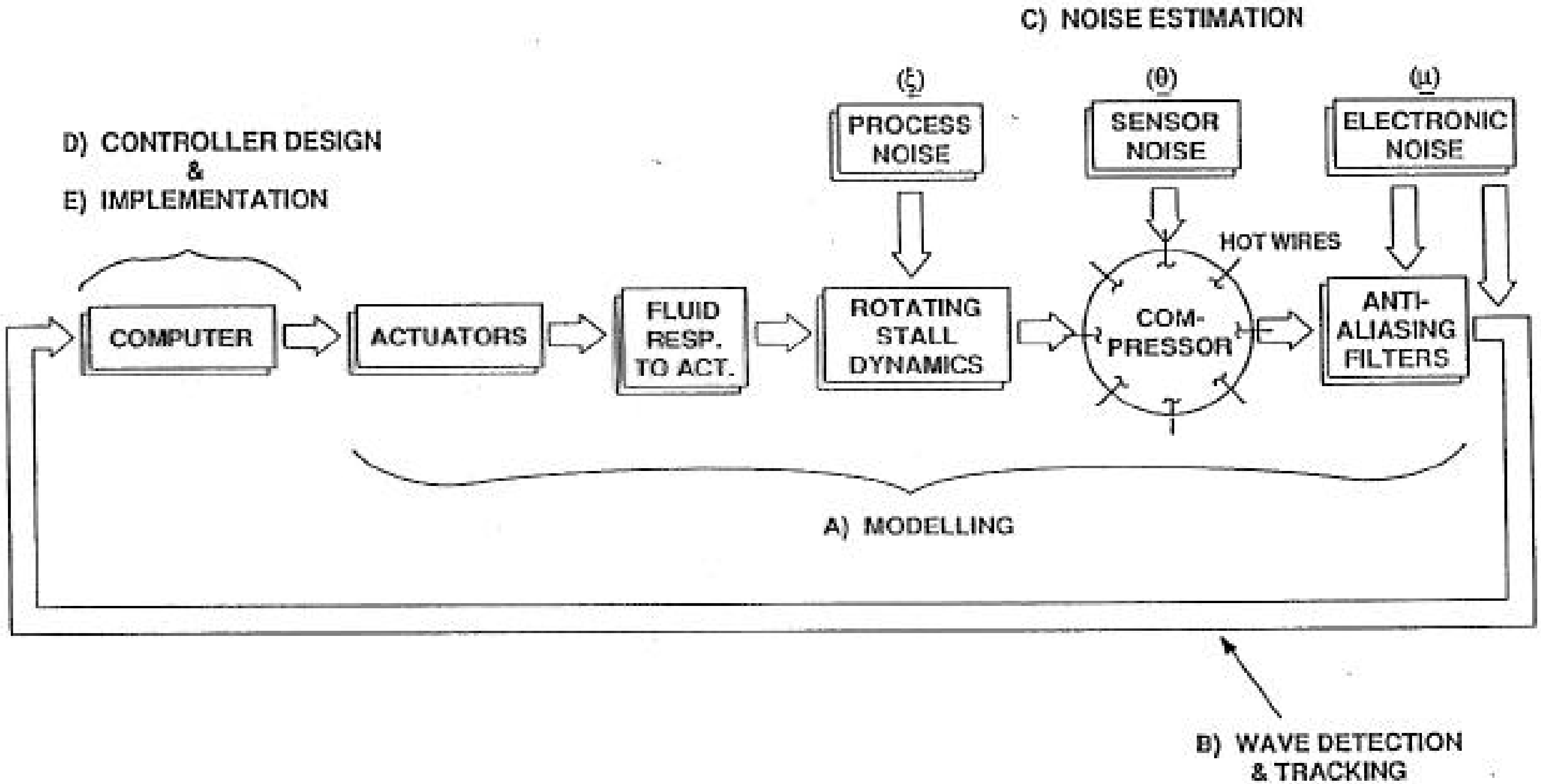
ELEMENTS OF EXPERIMENTAL REALIZATION

- Wave sensing (see if waves are there)
- Wave launching (create "desirable" waves)
- Closing the loop
  - Mathematical design of the controller
- Hardware implementation

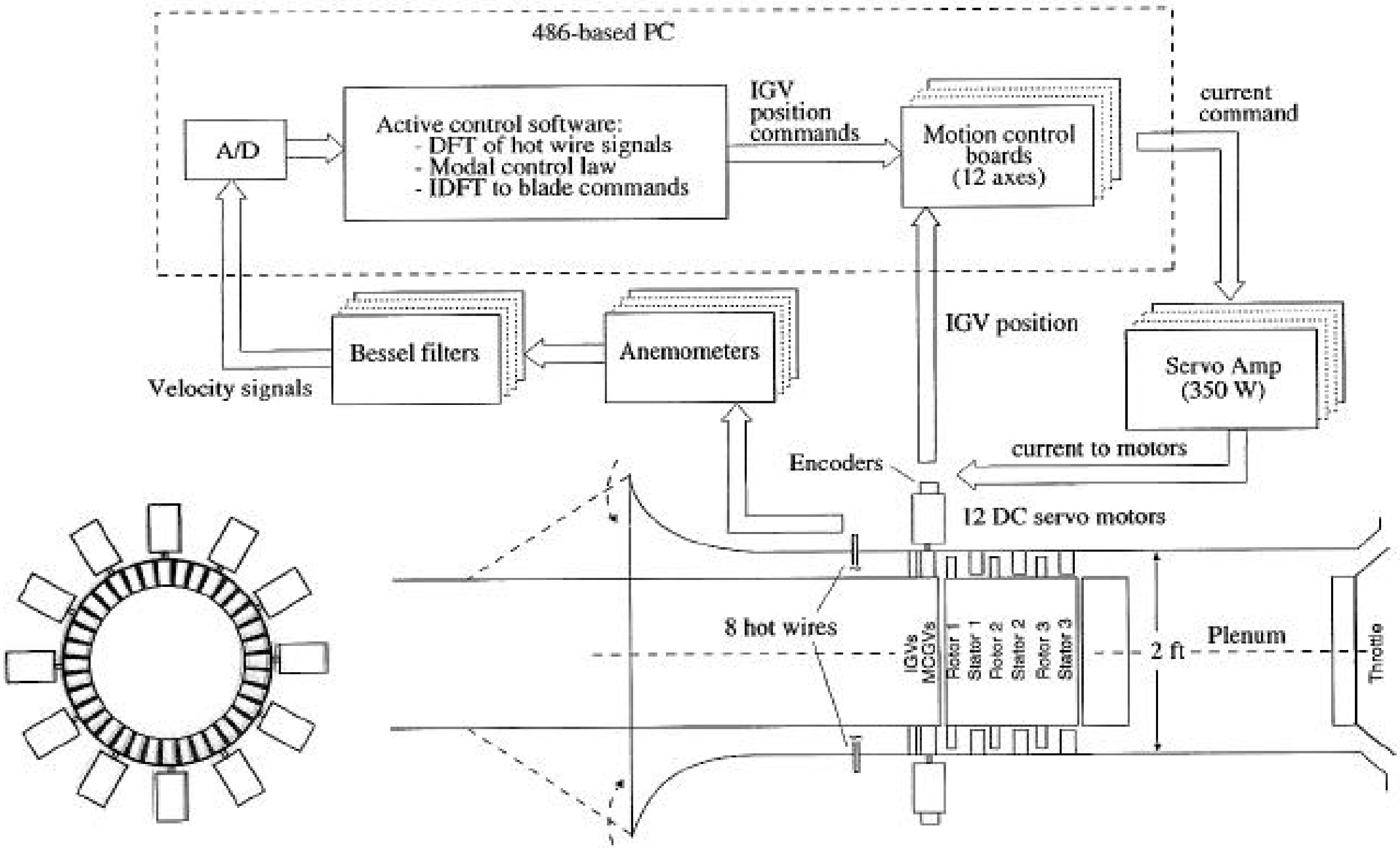
CONCEPTUAL CONTROL SCHEME USING "WIGGLY" INLET GUIDE VANES



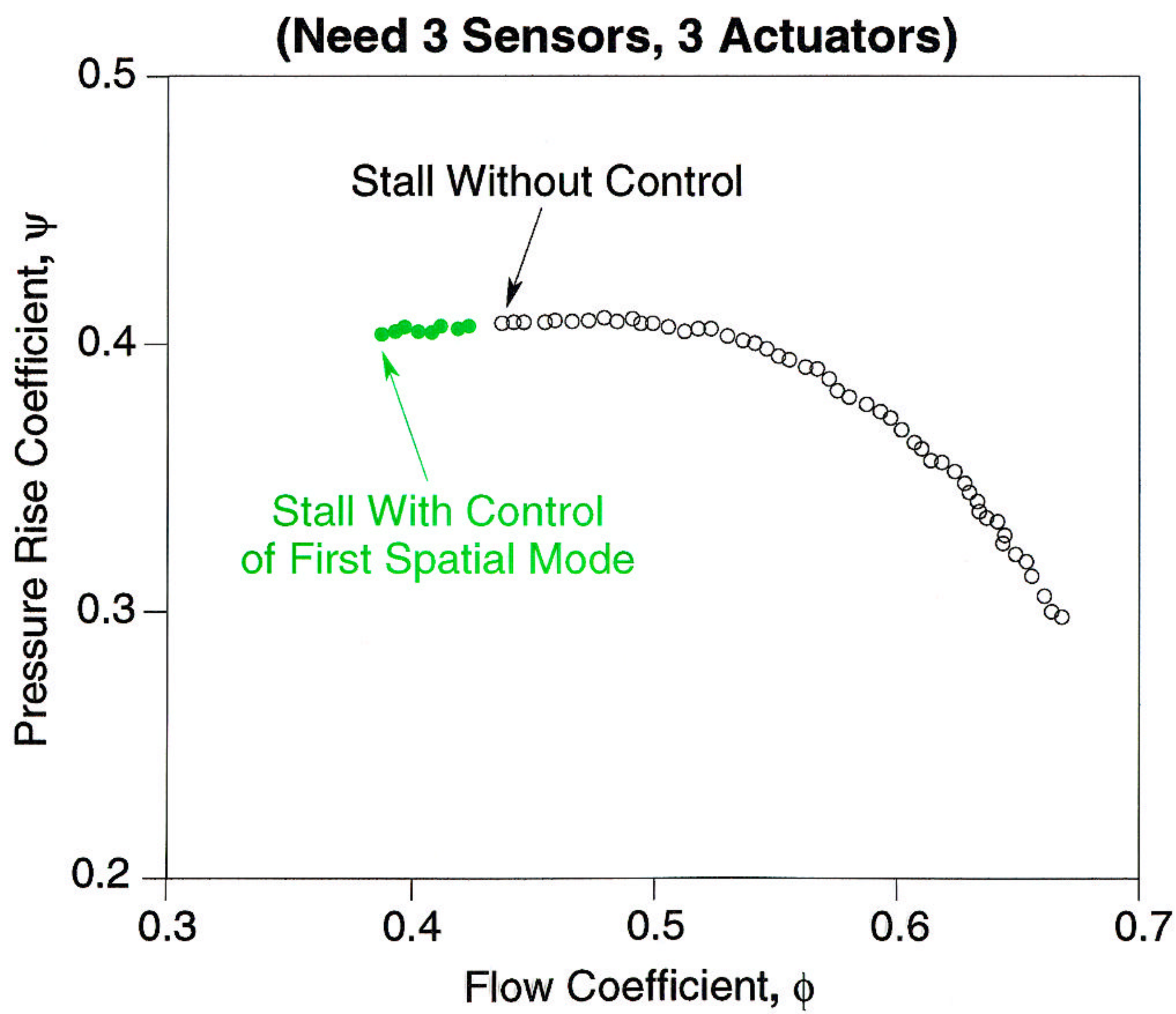
CONTROL LOOP VIEW OF SYSTEM



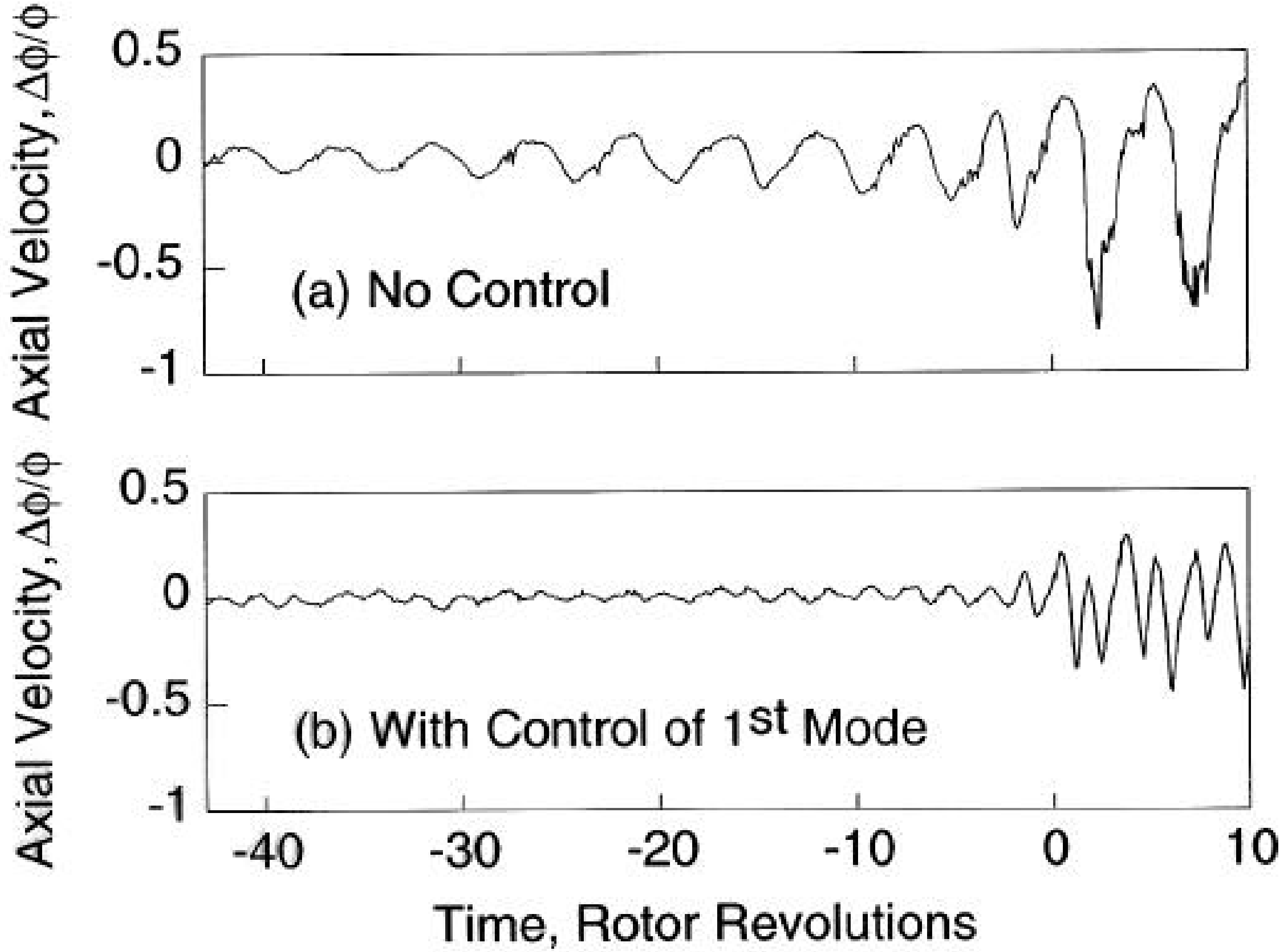
THREE-STAGE ACTIVELY STABILIZED COMPRESSOR RIG



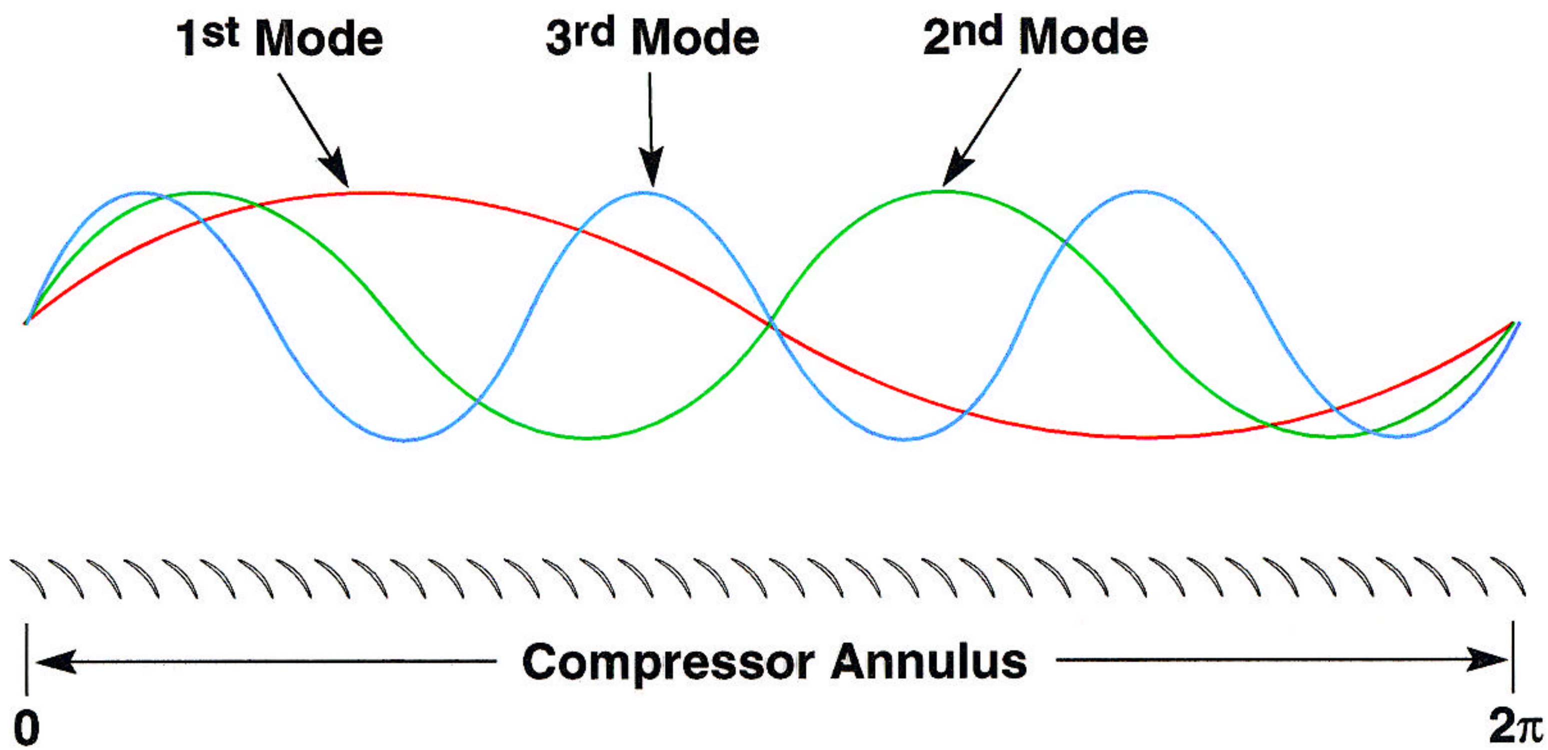
FIRST MODE CONTROL EXTENDS RANGE BY 11%



STALL INCEPTION WITH AND WITHOUT CONTROL



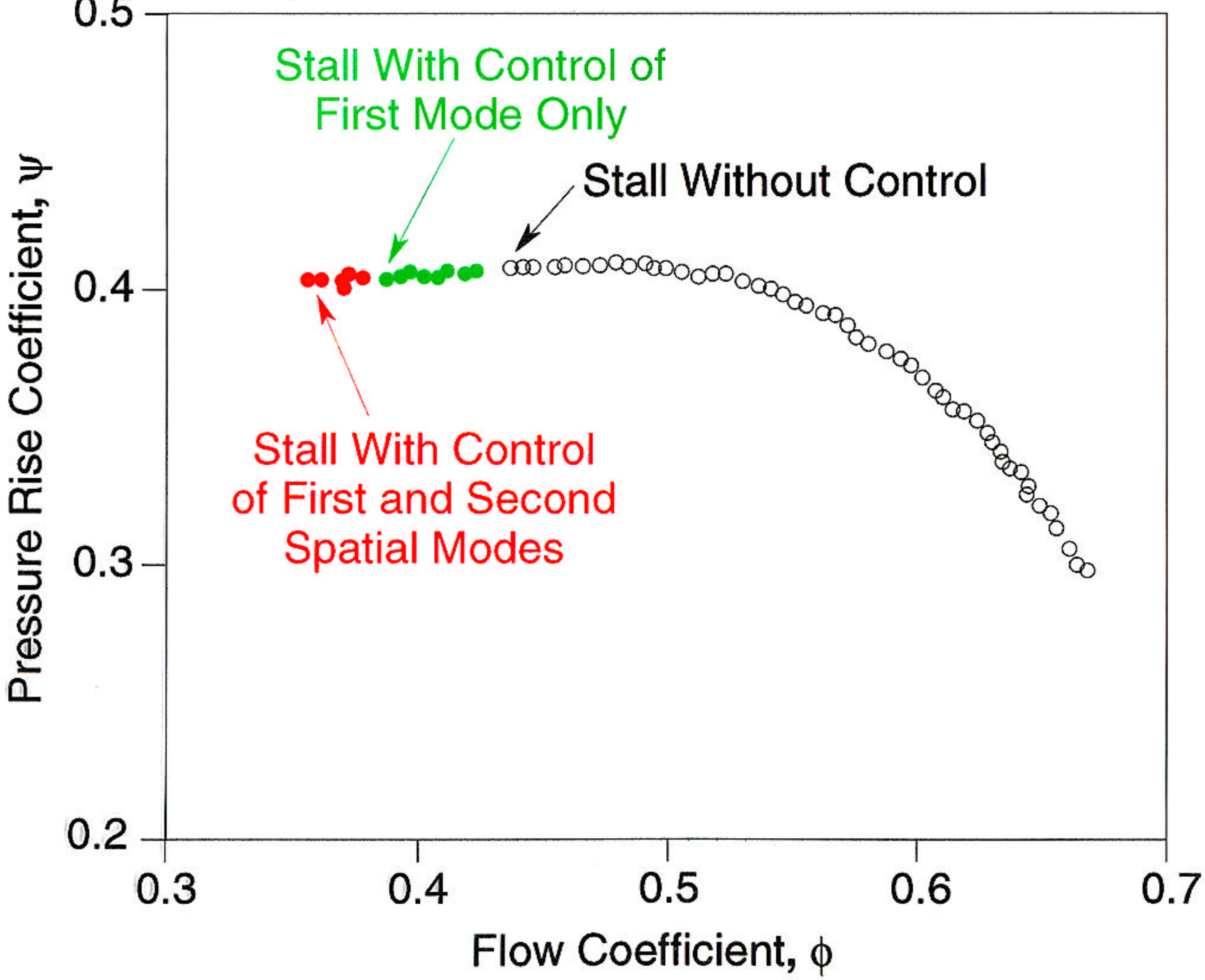
ANALYZING AND DETECTING ROTATING STALL



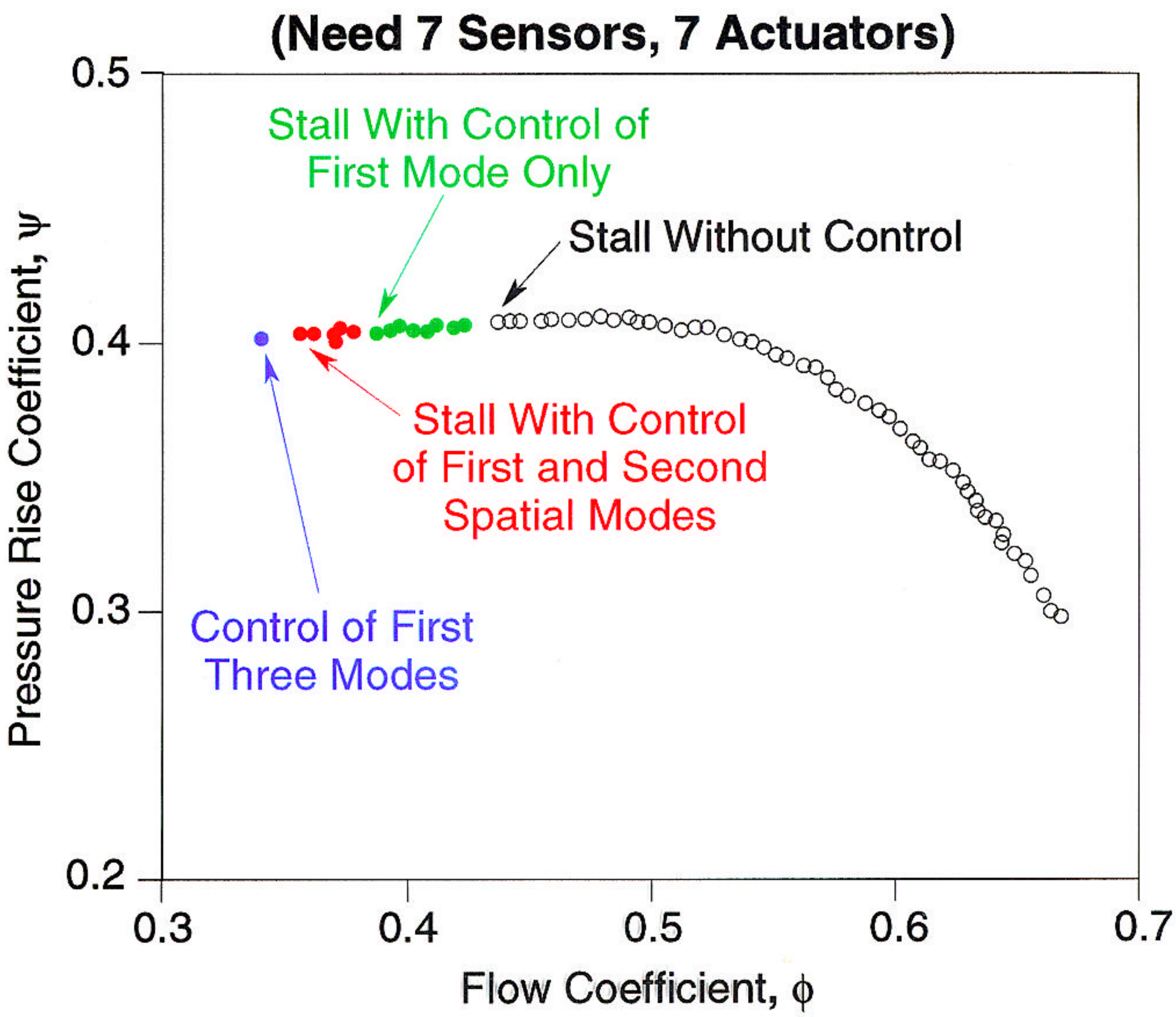
- Look for rotating waves
- Decompose into "components" or <u>modes</u>
- Treat each mode individually

FIRST AND SECOND MODE CONTROL EXTENDS RANGE BY 20%

(Need 5 Sensors, 5 Actuators)



CONTROL OF FIRST THREE MODES EXTENDS RANGE BY 25%



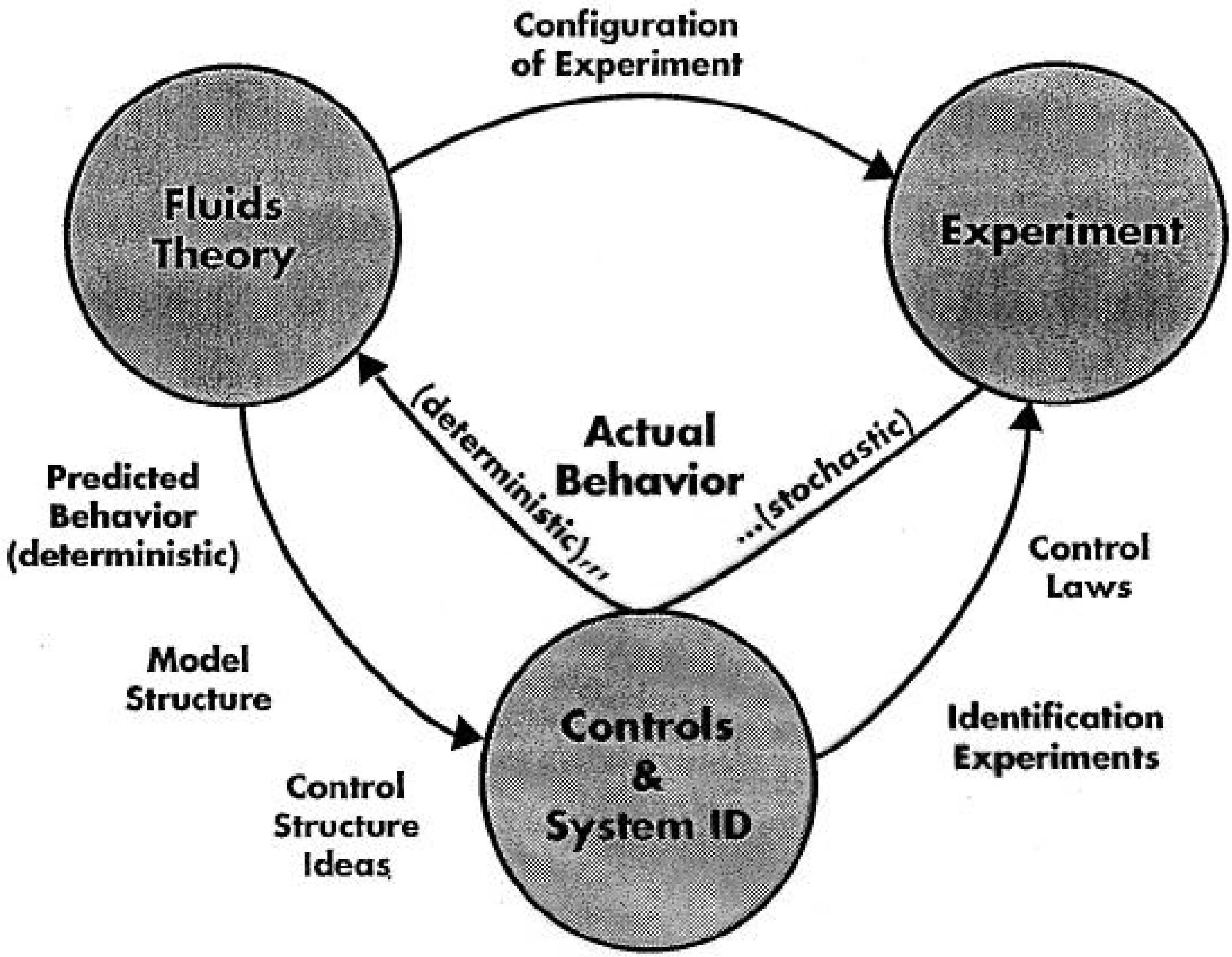
NEW INSIGHTS FROM FLUIDS/CONTROL COUPLING

- Learning process goes in two directions

- Control methodology a new tool for diagnosing fluid mechanic behavior

- Access to increased fluid dynamic understanding
  - Higher fidelity model of unsteady compressor response

Interaction of Theoretical Fluid Dynamics, Experiment, and Control Theory



RECENT PROGRESS/ISSUED FACED

- Active control with "inlet distortion"
  - Eigenmodes rich in harmonics
  - Multi input/output (MIMO) control
- Active control of transonic stage (NASA-LeRC)
  - Actuator bandwidth and authority for high speed turbomachinery
- Structural (local) control of rotating stall
  - Unifying view of control of turbomachine instabilities
- Control experiments give strong motivation for detailed fluid dynamic studies

OVERALL DIRECTIONS OF MIT COMPRESSOR STABILIZATION RESEARCH

- Demonstration of active compressor stabilization technology on gas generator or engine

- Mathematical models and design tools for
  - Accurate compressor stability assessment (basic fluid phenomena)
  - In situ stability margin assessment
  - Control law design

- Work with and transition technology to industry
  - Keep up flow of basic theory and tools
  - Join industry teams

LESSONS LEARNED

- Adding feedback control changes the dynamics
- "Systems" aspects as important as disciplinary concerns
  - Interdisciplinary approach is critical
- Closely examine product for implicit assumptions
- Control "thinking" improved understanding of fluid behavior
  - Opened up new window on an old problem
- Customers have a different perspective

CHANGING THE CULTURE

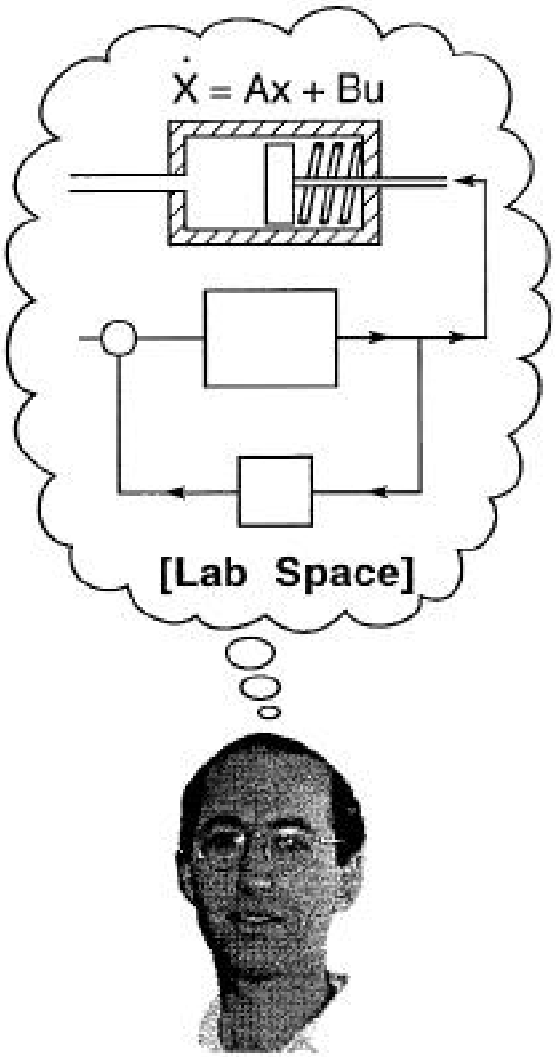
- Focus on system rather than components or disciplines
- Organization often a barrier
  - Reporting structure
  - Rewards and recognition
- Expanding past common assumptions
  - "We understand that"
  - "This is the way we do it here"
  - "I heard that suggestion 20 years ago"

MULTIDISCIPLINARY TEAMS

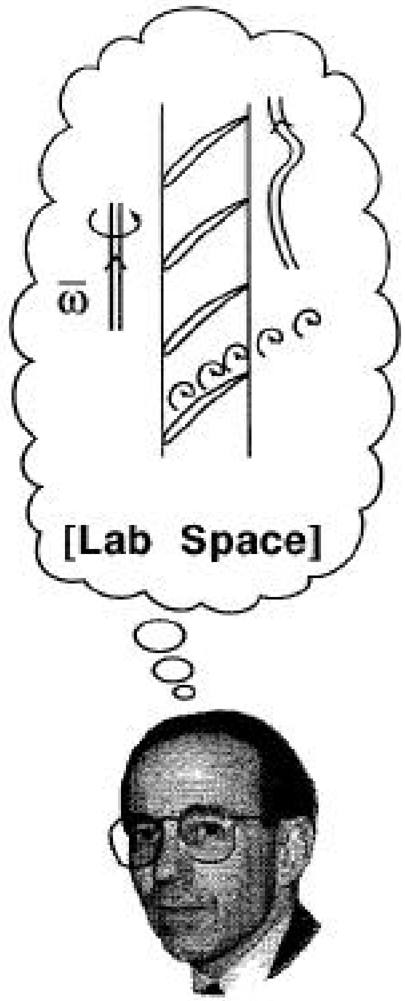
- Focus on product, not disciplines
- Reward structure for interdisciplinary accomplishments
- Large startup time overhead
- Language is a major barrier
  - Common analysis tools needed
  - Appreciation of cross-disciplinary challenges
- Critical mass needed in each discipline

UNIFIED VIEW OF THE AEROENGINE

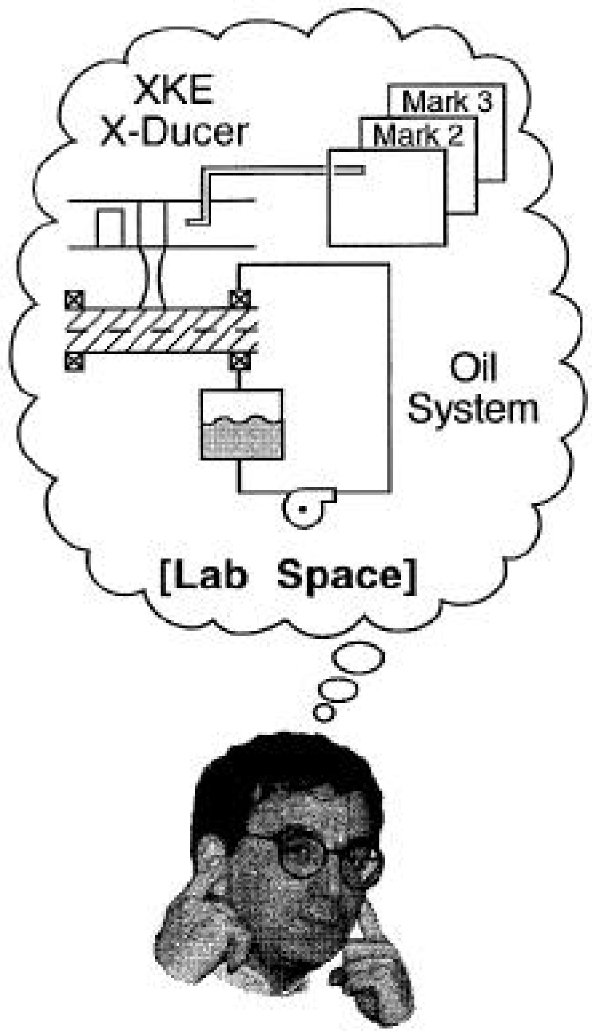
Controls



Fluids



Experiments



SOME COMMENTS ON PROCESS (I)

- Finite time needed to form team
  - You can all sit in the same room, but you are not necessarily a team
- We (universities) have an "advantage"
  - Students are translators
  - Students are multi-disciplinary
- Project goals need to be clear
- Disciplinary research must feed into project goals
  - This is tempered by academic demands

COMMENTS ON PROCESS (II)

- Participants must have commitment to overall vision
  - Not controls people, fluids people but *smart engine people*
- Helps if there is "high level" (Epstein, Greitzer) interest in recognition of other disciplines
- Role of faculty is not always one of "expert"
  (This is not the traditional situation)
- Weekly meeting and student participation encouraged
- Aim is to expunge the we-they syndrome
- Note: Doesn't hurt to have past successes to refer to

SUMMARY

- Zero order mode (surge) actively stabilized
- Structural control of surge shown to be effective*
- Rotating stall actively stabilized*
- Rotating stall suppressed using aeromechanical feedback*
- Stabilization achieved with inlet distortion*
- Stabilization achieved in transonic stage*
- Closing the loop offers substantial benefits
- An actively stabilized machine is a <u>different</u> machine
- Interdisciplinary approach extremely fruitful
- Team effort allows attack on new range of problems

SUMMARY - BIG PICTURE

- Work has progresed rapidly
- Initially
  - Back-of-the-envelope calculation
  - Demonstration powered by vacuum cleaner suction
- Now
  - High speed experiments at NASA, on engines at MIT
- Team approach, subscribed to by participants, is an essential part of this progress
- Active compressor stabilization -- positive results in content and process