Control of Compression Systems with Magnitude/Rate Limits

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Caltech Control and Dynamical Systems
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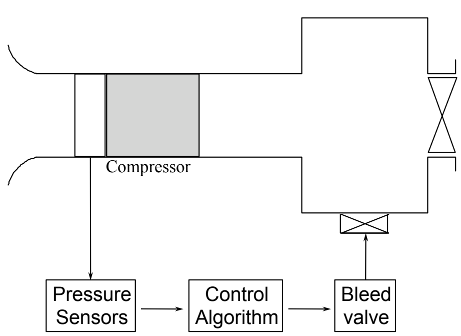
Goals
- Describe how bifurcations & limit cycles arise in engineering applications
- Review some tools for characterizing bifurcations and limit cycles
- Show how feedback can be used for design of (nonlinear) dynamics

Outline
- Lecture 1: Introduction and background
- Lecture 2: Analysis and control of bifurcations
- Lecture 3: Modeling and control of limit cycles
- Lecture 4: Describing function analysis

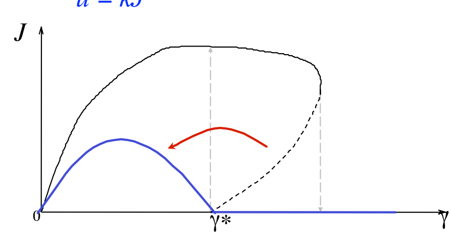
http://www.cds.caltech.edu/~murray/wiki/cds140-bifctrl

Bifurcation Control Using 1D Bleed Valves



$$\dot{\Psi} = \frac{1}{4B^2 l_c}\left(\Phi - (\gamma + u)\sqrt{\Psi}\right)$$

$u = kJ$ **(Liaw and Abed, 1992)**

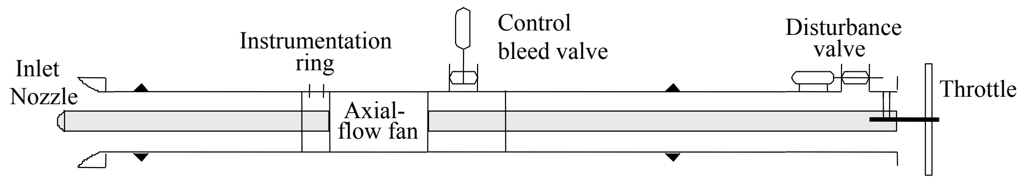


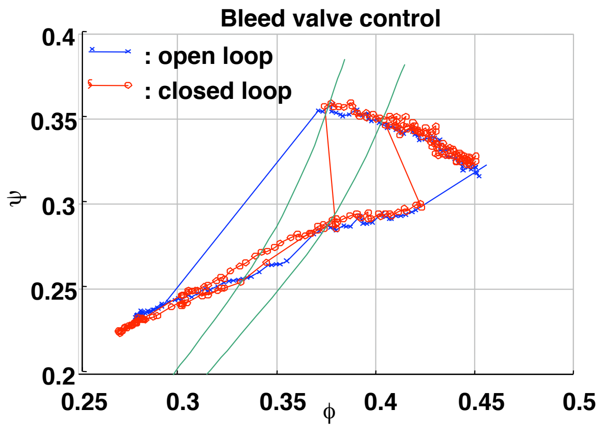
$$k_{\min} = -\frac{\Phi^* \Psi_c'''(\Phi^*)}{8\gamma^* \Psi^* \Psi_c''(\Phi^*)} - \frac{\gamma^* \Psi_c''(\Phi^*)}{8\Psi^*}$$

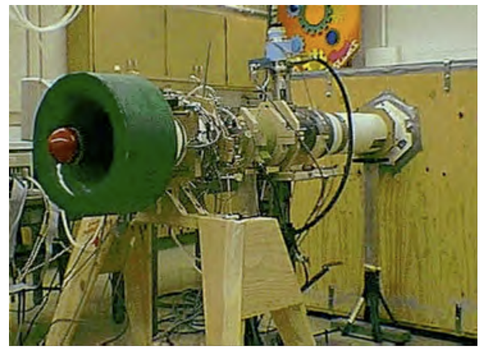
Remarks:
- Can show system is not stabilizable ⇒ can *only* achieve operability enhancement
- Achieve performance benefit by engine redesign; operate closer to peak pressure
- 2D actuation (IGV, BV, or AI) gives stability extension, but more complex (?)

Implementation on Caltech Compressor Rig

Yeung & M, Joint Propulsion Conference, 1997

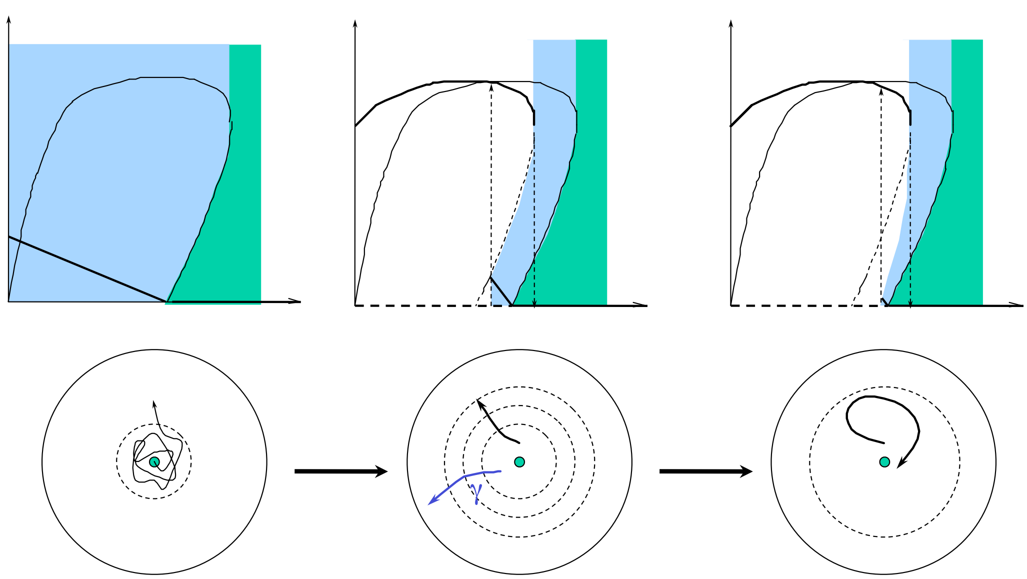






Bifurcation Control w/ Magnitude and Rate Limits

Ideal control **Effect of magnitude limit** **Effect of magn + rate limit**

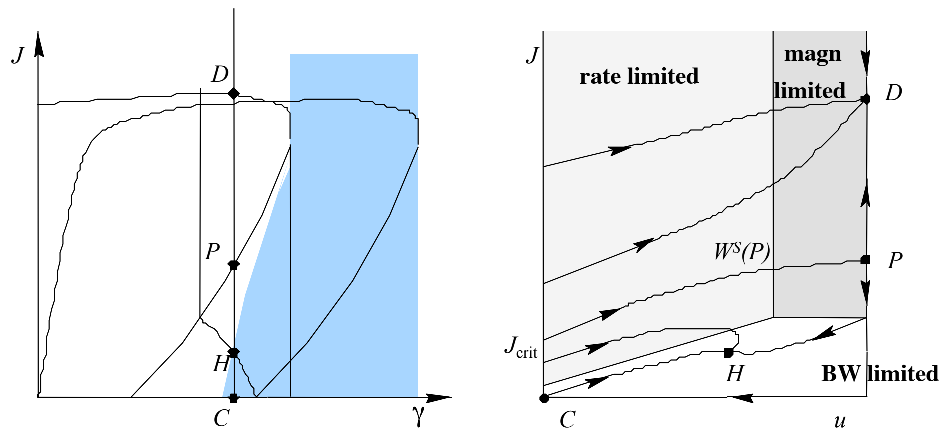


Noise destabilizes system

Control action: increase domain of attraction

Wang & M, Conference on Decision and Control, 1997

Analysis of Effects of Magnitude and Rate Saturations



Approximate MG3 model using center manifold near bifurcation point

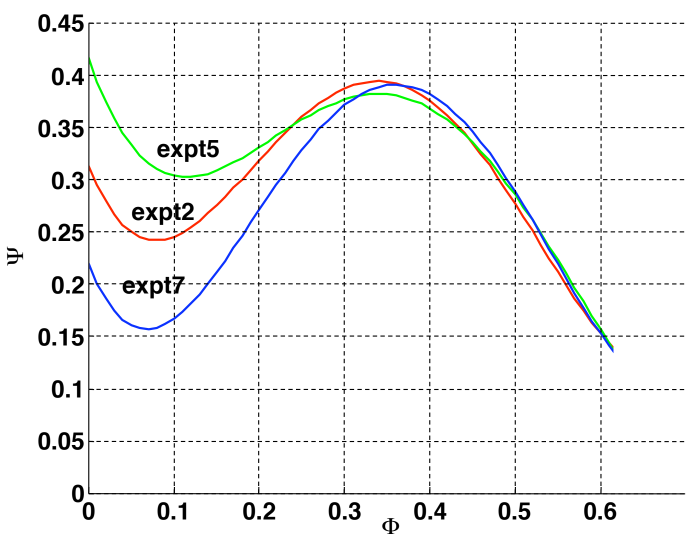
$$\frac{dJ}{d\xi} = \alpha_1(\gamma - \gamma_0 + u)J + \alpha_2 J^2 + \mathcal{O}(\delta J^2, J^3), \qquad \alpha_1 = \frac{2\sqrt{\Psi_0}\psi_c''}{m+\mu}, \quad \alpha_2 = \frac{1}{4(m+\mu)}\left(\psi_c''' + \frac{\gamma_0 \psi_c''^2}{\sqrt{\Psi_0}}\right)$$

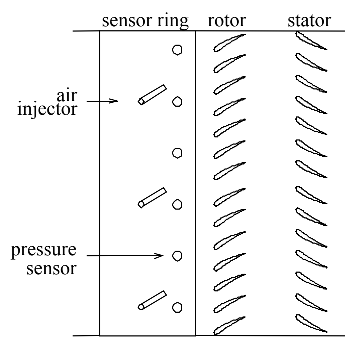
Compute operability enhancement using piecewise linear approximations

$$\Delta = u_{mag} \frac{1 - \frac{2}{\pi}\arctan\left(\frac{\pi}{4}\sigma\eta\right)}{1 - \frac{\sigma}{1+\sigma}\frac{2}{\pi}\arctan\left(\frac{\pi}{4}\sigma\eta\right)} \qquad \sigma = \frac{-\alpha_1 u_{mag}}{\alpha_2 \epsilon}, \quad \eta = \frac{\alpha_2 \epsilon u_{mag}}{u_{rate}},$$

Wang & M, Conference on Decision and Control, 1997

Idea: Change the Compressor Characteristic



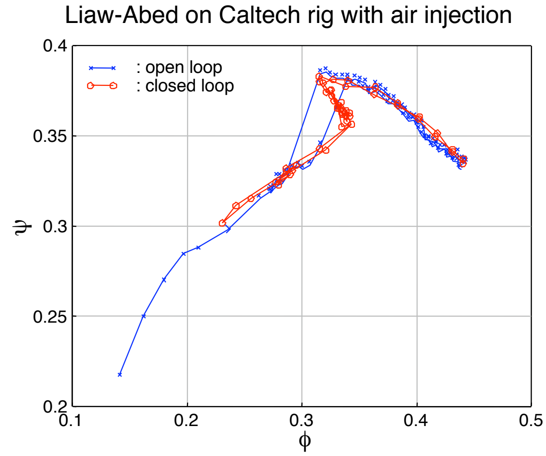


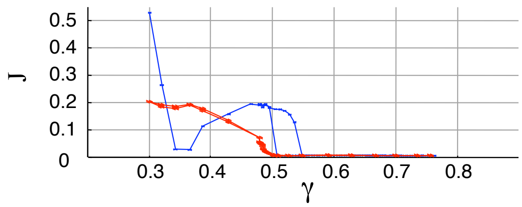
Adjust angles of flow of air injection to move between compressor characteristic curves

- Shape of the compressor characteristic affects Ψ'', Ψ''', etc

Experimental Results Using Modified Ψ_c

Yeung & Murray, JPC 97





Use steady air injection to shift Ψ_c

- Changes shape of Ψ_c to give lower rate requirements
- Implication: actuator requirements strongly affected by system design

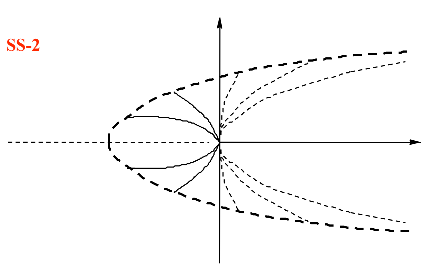
Other mechanisms possible

- Blade redesign
- Casing treatments

Control-Configured Design required to minimize actuation requirements

Bifurcation Control in the Presence of Magnitude Limits

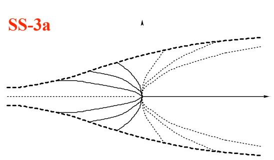
SS-2



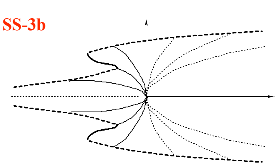
Analytical study of effects of magn limits

- Rely on normal forms around center mfd
- Different actuation mechanisms possible
- Gives qualitative information, insight
- SS-2: magn constraints don't limit operability
- SS-5: can't make equil pt arbitrarily small

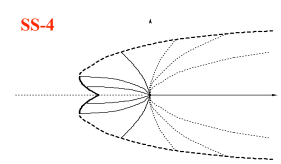
SS-3a



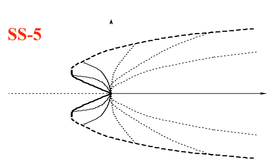
SS-3b



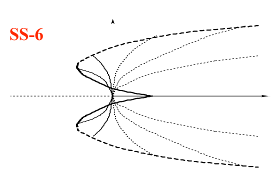
SS-4



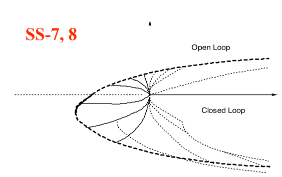
SS-5



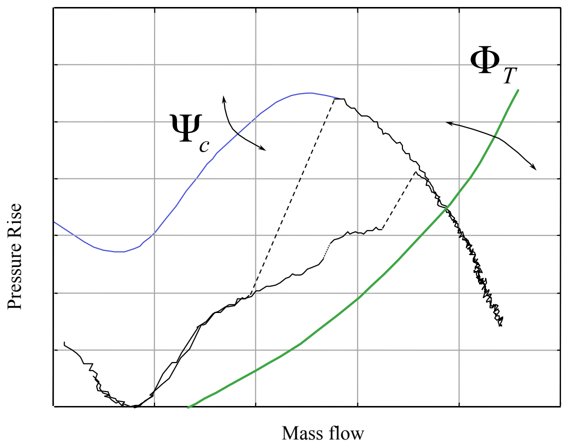
SS-6



SS-7, 8



Control of Rotating Stall Using Air Injection

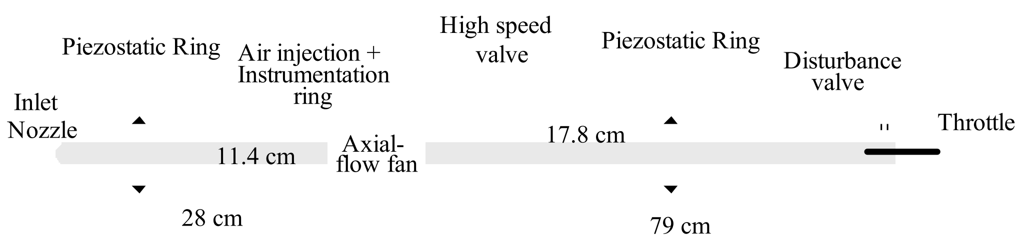


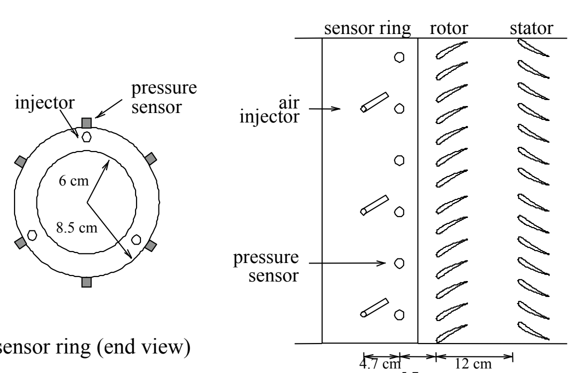
Use air injection (AI) to modulate compressor characteristic

- Air injectors modify local angle of attack ⇒ affect Ψ_c
- MG3 model indicates operability enhancement should be possible

$$\Psi_c = \Psi_{c,\mathrm{nom}} + \Psi_{c,\mathrm{ai}} u$$

Caltech Low Speed, Axial Flow Compressor Experiment



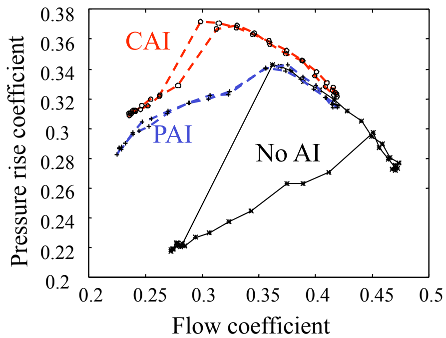


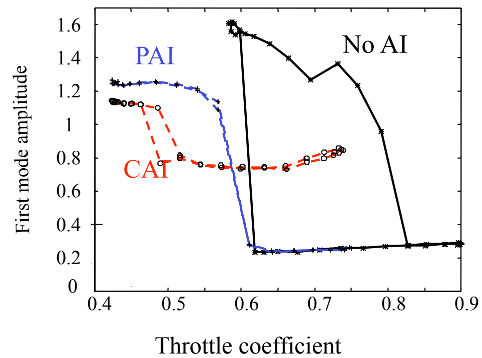
sensor ring (end view)

Rig parameters

- Operating point: 6,000 rpm (100 Hz)
- Stall frequency: 3925 rpm (65.4 Hz)
- Jet flow: 0.1% to 1% of mean flow
- On/off actuators, approx 200 Hz BW

Control using Axisymmetric Air Injection: No Overlap (Proportional feedback with 1D actuation)





Results are similar to control with bleed valves

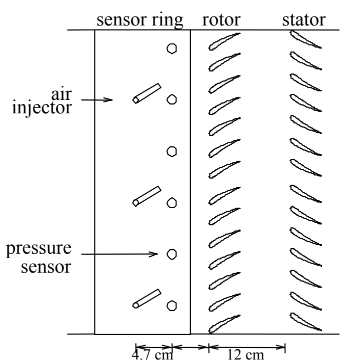
- Change the bifurcation behavior of the system through active feedback
- Specifically: subcritical → supercritical bifurcation

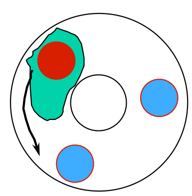
Pros/cons versus bleed valves

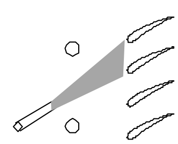
- Pro: bandwidth requirements appear less severe (based on experience)
- Con: requires *new* actuators ⇒ increased weight, cost, complexity

Control Using *Non-Axisymmetric* Air Injection

Basic idea: inject air only where we need it:







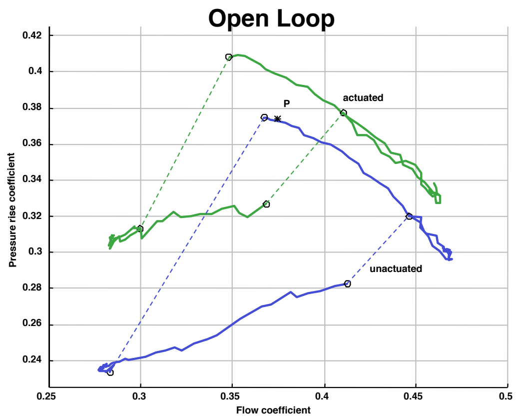
Turn on injector when “stall cell” passes through region affected by specific actuator

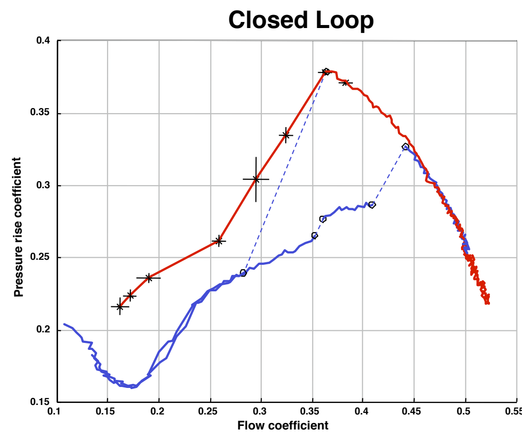
Many parameters to adjust for optimal operation

- Actuation: magnitude, angle, and span of the injected flow
- Control: length of pulse, timing of pulse

Experimental Results

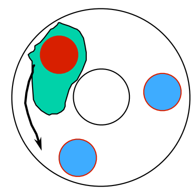
D'Andrea, Behnken, Murray, JTM 98

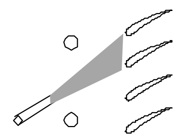




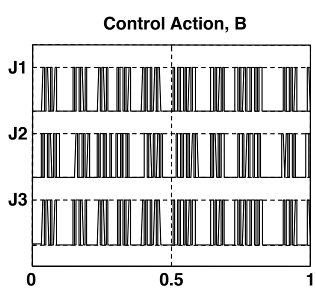
Control algorithm:

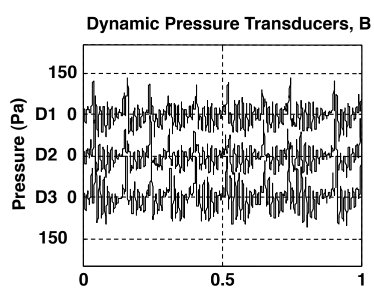
- Detect magnitude, phase of stall cell
- Turn on injector when cell is in window
- Leave injector on for fixed time

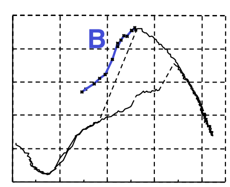


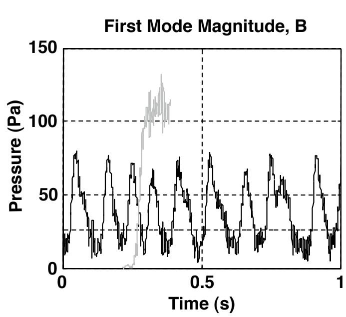


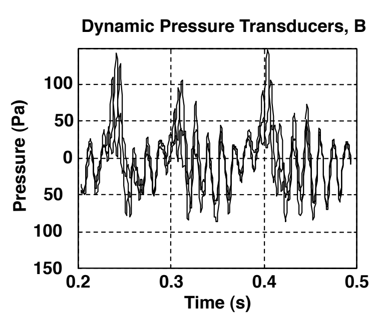
Detailed View of Control Action (B)





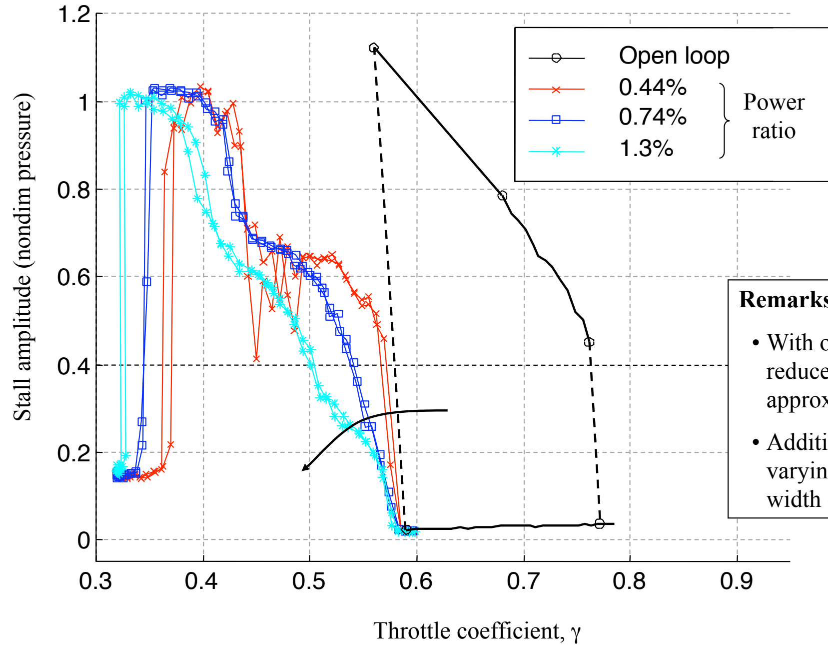






Actuator Authority Tradeoff

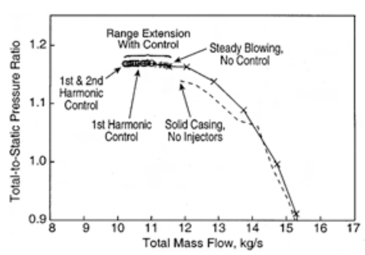
Yeung, PhD 1998



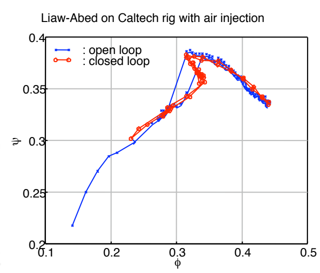
Remarks:

- With optimization, can reduce power flux to approx 0.15%
- Additional tradeoffs by varying number and width of injectors

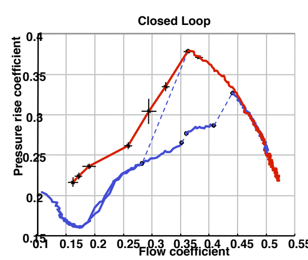
Summary: Active Control of Rotating Stall



Modal Control (AI)



Bifurcation Control (BV)



Bifurcation Control (AI)

Multiple Mechanisms for Active Control of Compressor Stall/Surge

- Modal control using 2D (spatial) actuation
- Bifurcation control using 1D and 2D actuation
- Experimental evaluation + extensions to realistic situations (compressible, multi-stage, etc)

System Level Trades Indicate Areas for Improvement

- Key issue is spatio-temporal bandwidth versus cost/weight/complexity
- Normal operation does not require control $\Rightarrow$ operational cost is potentially high