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Detection and Control of Instabilities and Blowoff for Low Emissions Combustors

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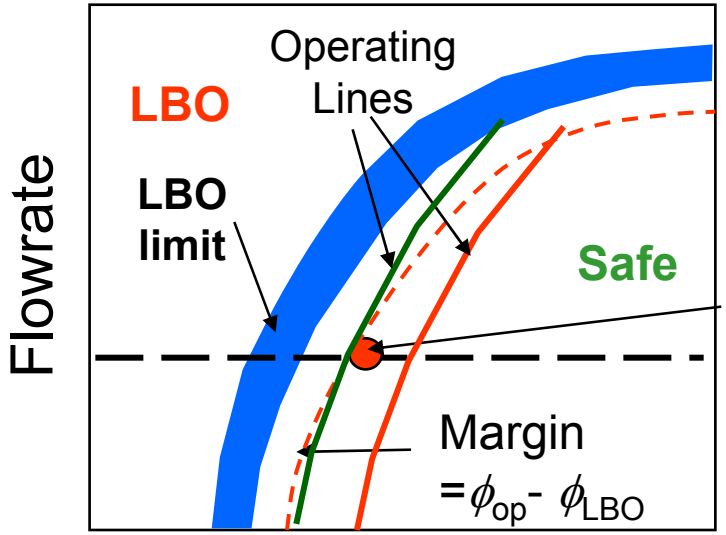
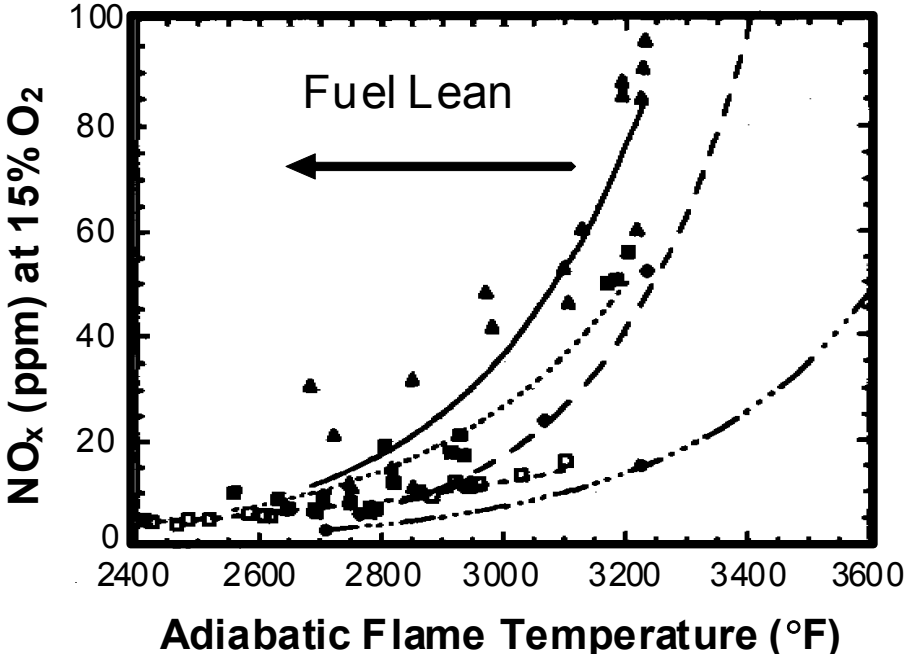
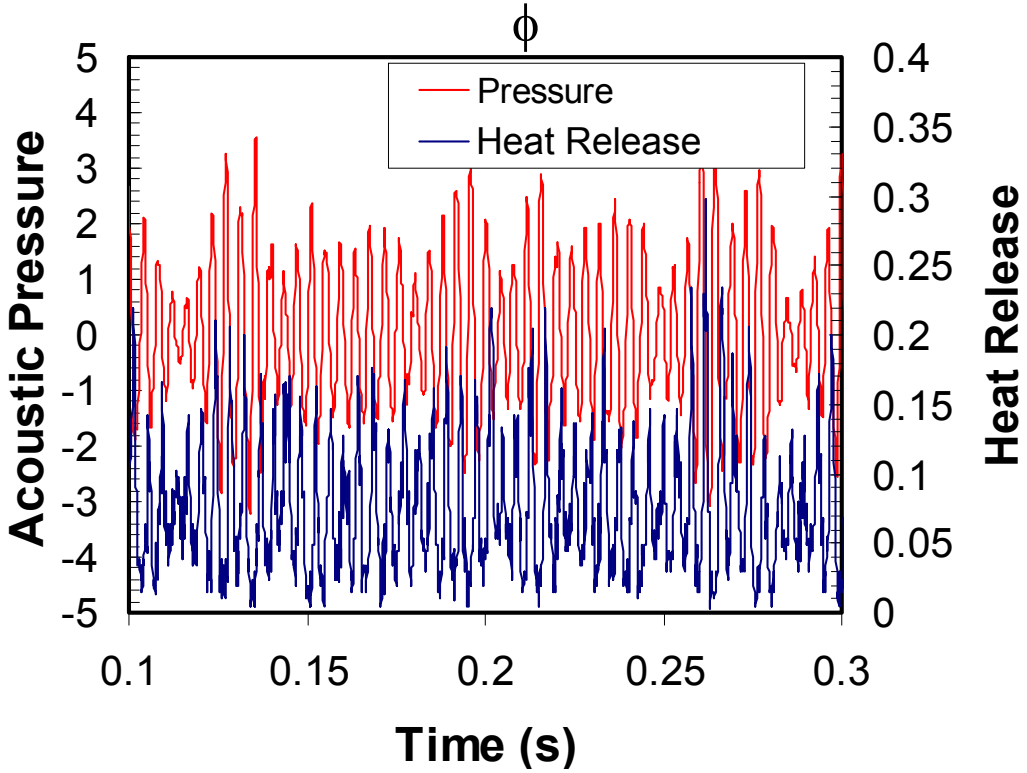
Motivation

- Combustor control can provide optimal tradeoff between low emissions and engine reliability/ operability
  - static and dynamic instability (blowout and oscillations)



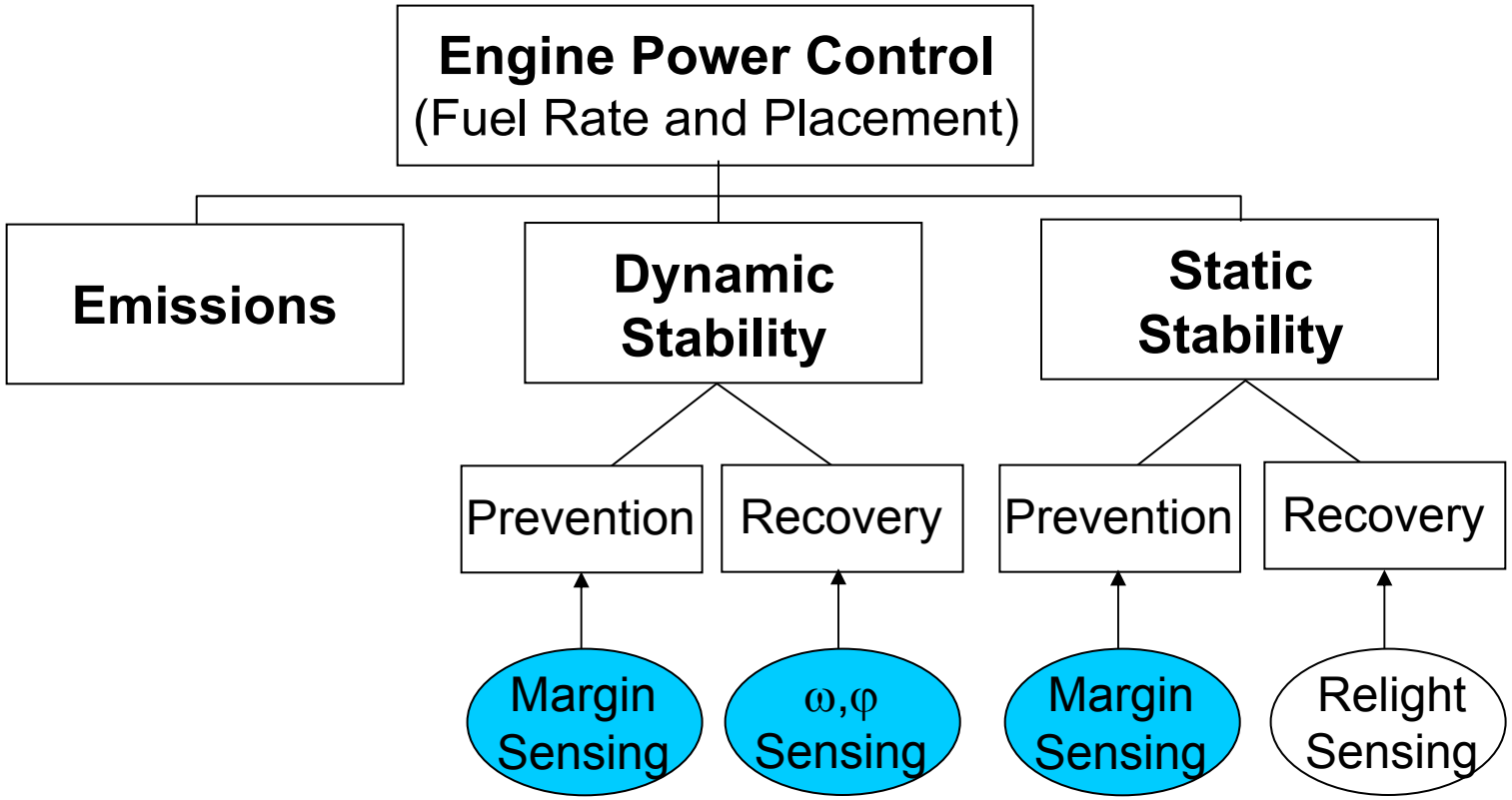


McVey et al., ASME 92-GT-133



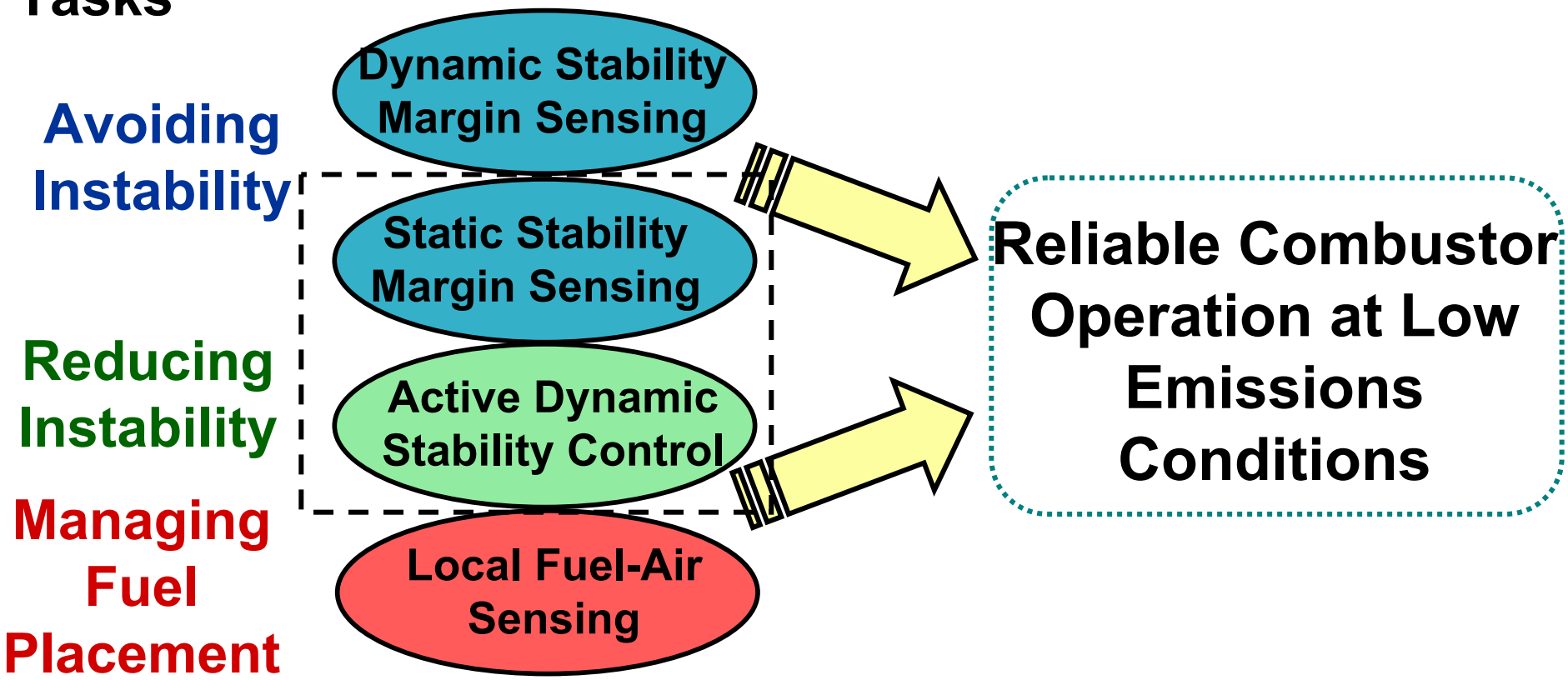
Combustion Control

- **Control Needs:** Control systems that can 1) provide low emissions (lean operation) and 2) prevent or recover from loss of dynamic stability and 3) prevent loss of static stability



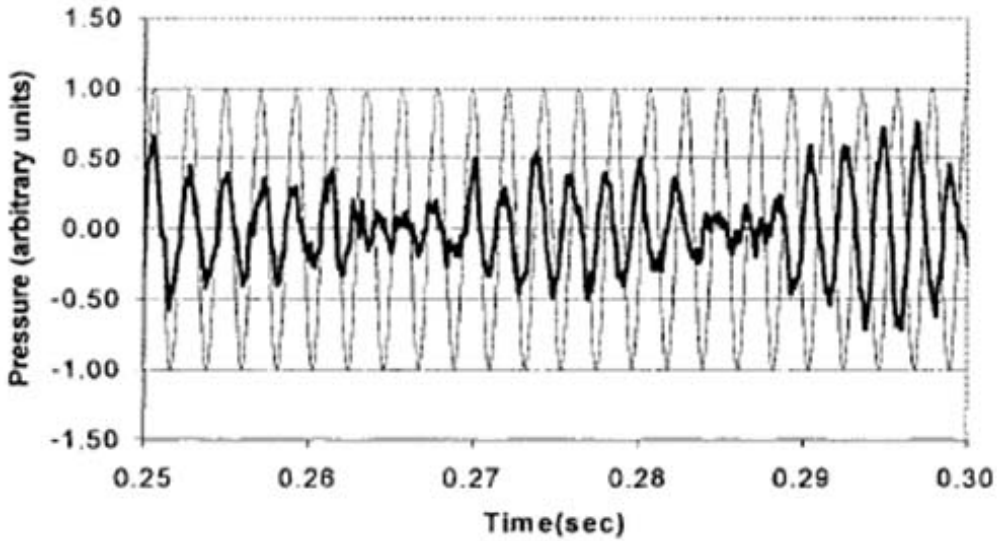
Needs

- **Goal**: fundamental understanding needed to convert signals from simple sensors to stability margin estimates and active control inputs
- **Tasks**



Active Control of Combustion Dynamics

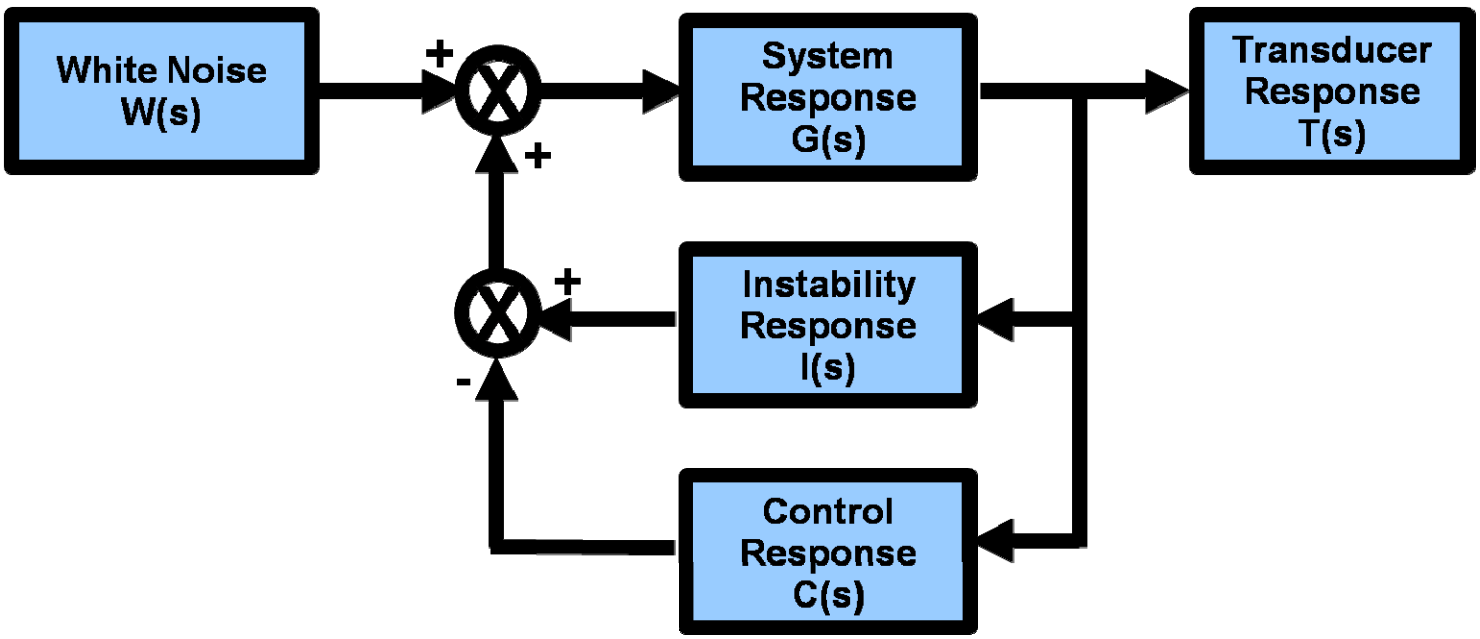
- **State of the art**
  - widely demonstrated that active control can reduce instability amplitude
  - poorly understood variability in effectiveness
    - SPL reductions range from 3 to 40 dB
  - controlled combustors can exhibit significant amplitude modulation



- **Goal**
  - *model factors that limit control effectiveness*

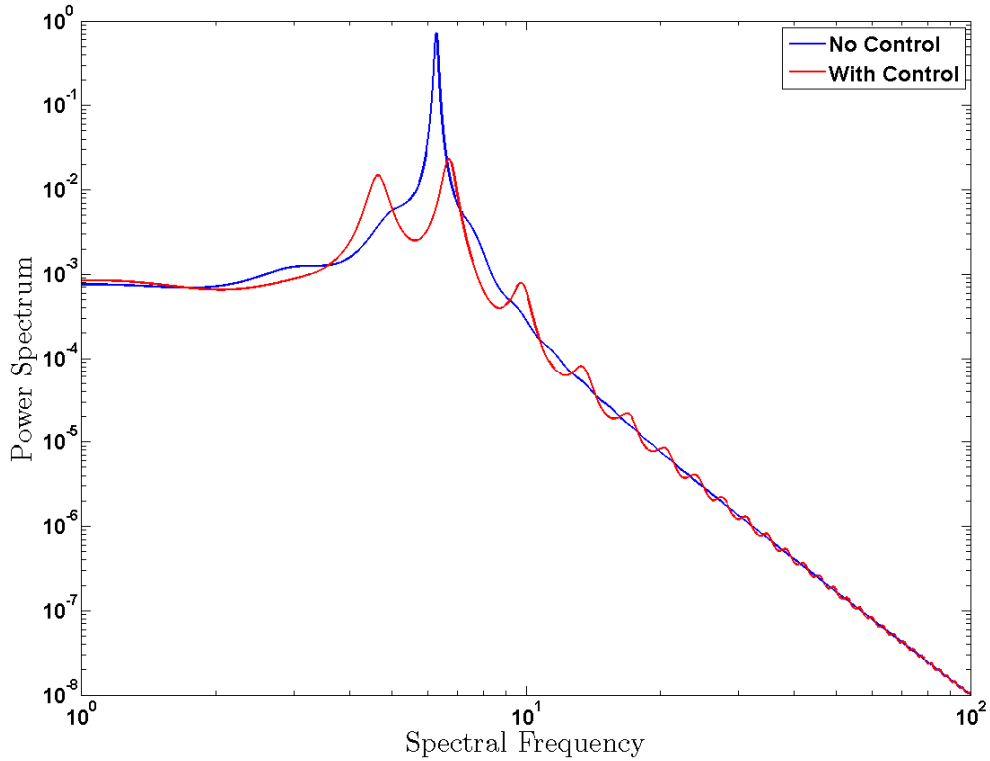
Modeling Approach

$$p''(t)+2\zeta\omega p'(t)+\omega^2 p(t)=\varepsilon_v p(t-\tau_v)+\varepsilon_c p'(t-\tau_c)+\sigma\xi(t)$$



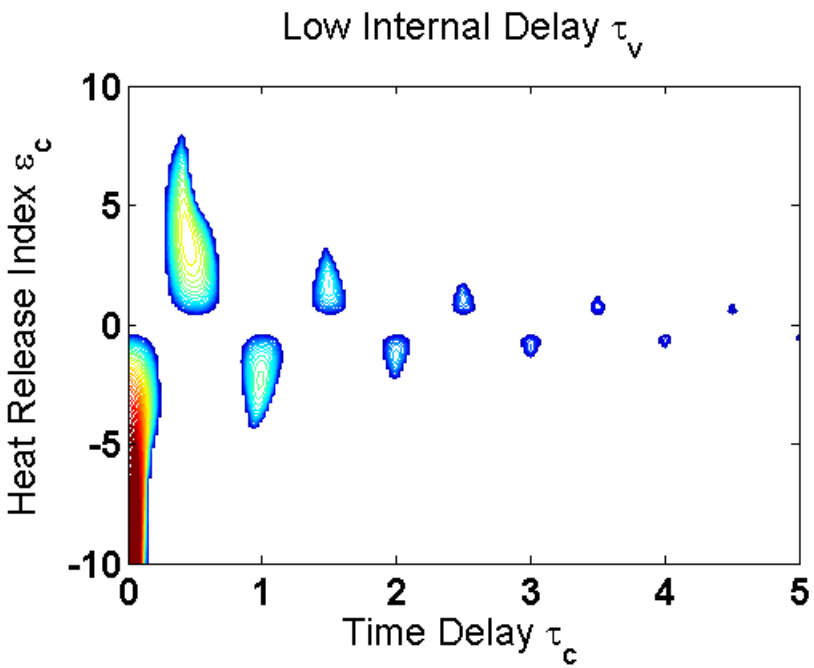
- Use Culick's formulation to describe time evolution of combustor modes with time delays and noise
  - include both "internal" and control induced delays
- Solve for statistical and spectral characteristics of pressure as function of control time delays and gain

Accomplishments



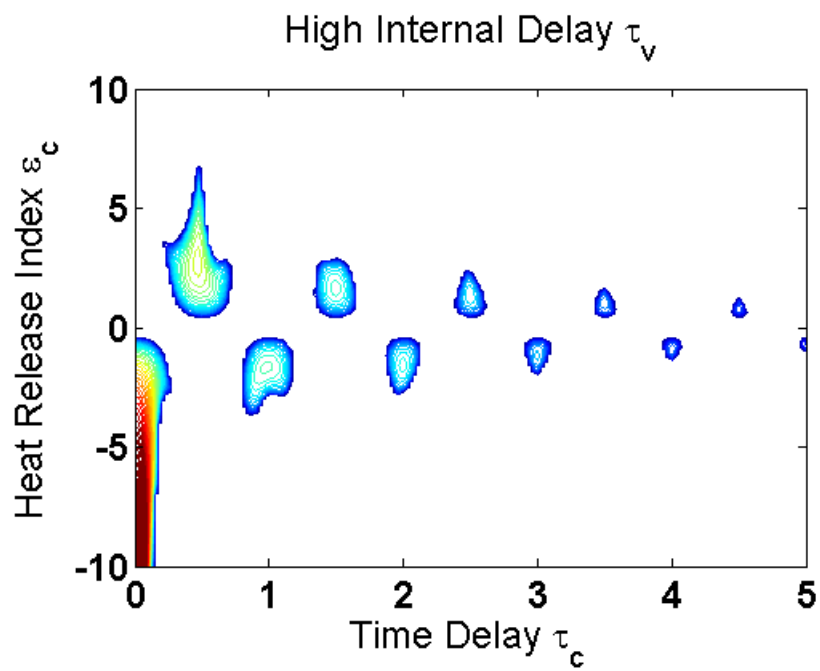
- Developed statistical theory of controlled combustion dynamics including time delays and noise
  - closed form solutions for statistics and spectra of combustor pressure
- Reproduced common experimental observations of controlled combustor dynamics
  - e.g., one controller can have significantly different influences on instability, depending upon “nominal” combustor dynamics

Interplay between "Nominal" Combustor Dynamics and Control



- Increasing control time delays decreases control effectiveness and window of controllability
- Controller impact varies with internal time delays

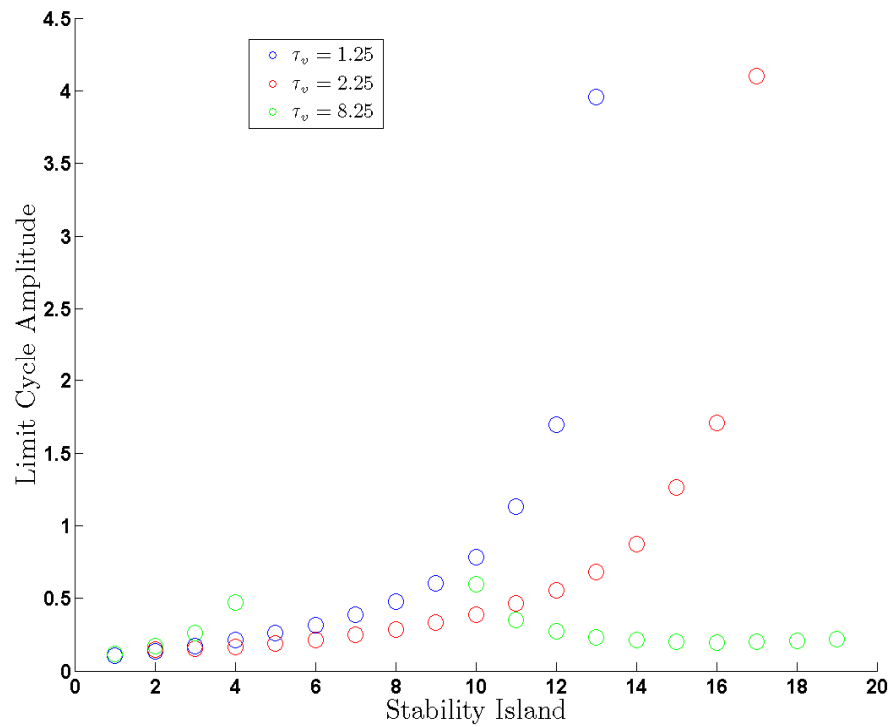
•Plots show inverse limit cycle amplitude of controlled combustor



Quantifying Controller Performance

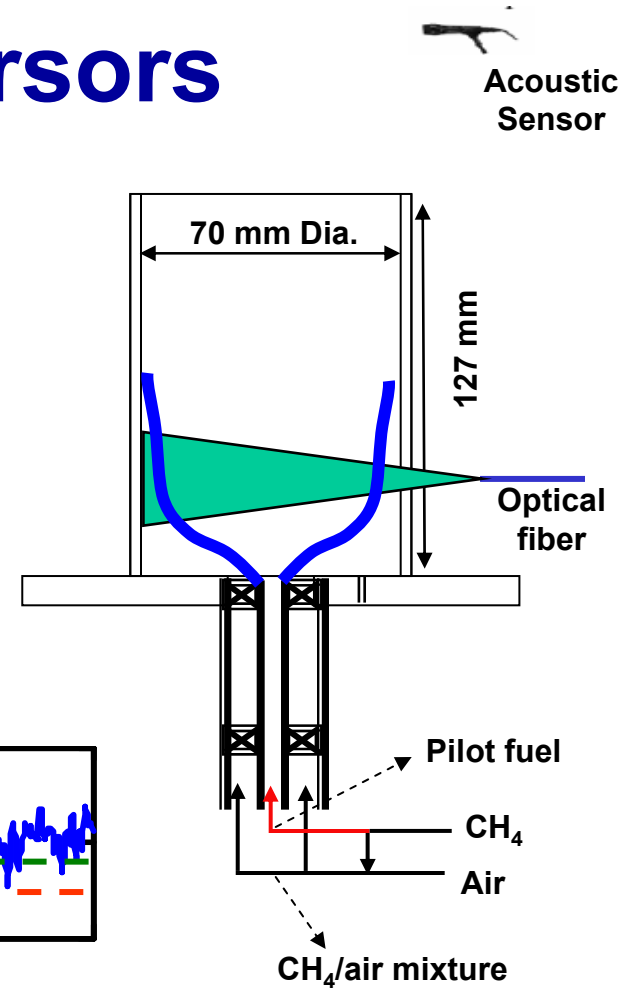
- Model captures experimentally observed
  - increase of minimum limit cycle amplitude with controller time delay
  - variation of controller performance with internal delays

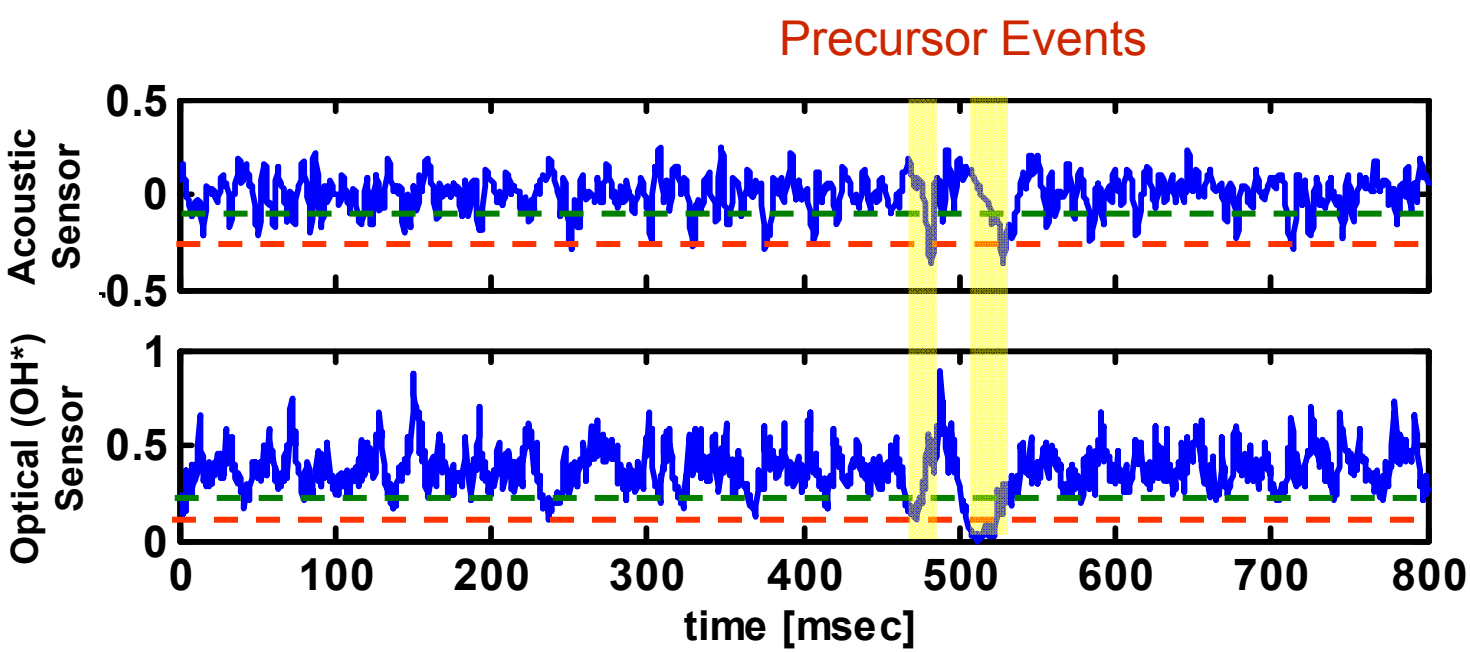
- Future work - add physics
  - model predicts much smaller amplitude modulation than experimentally observed
  - currently working on incorporating observer dynamics



Static Stability : LBO Precursors

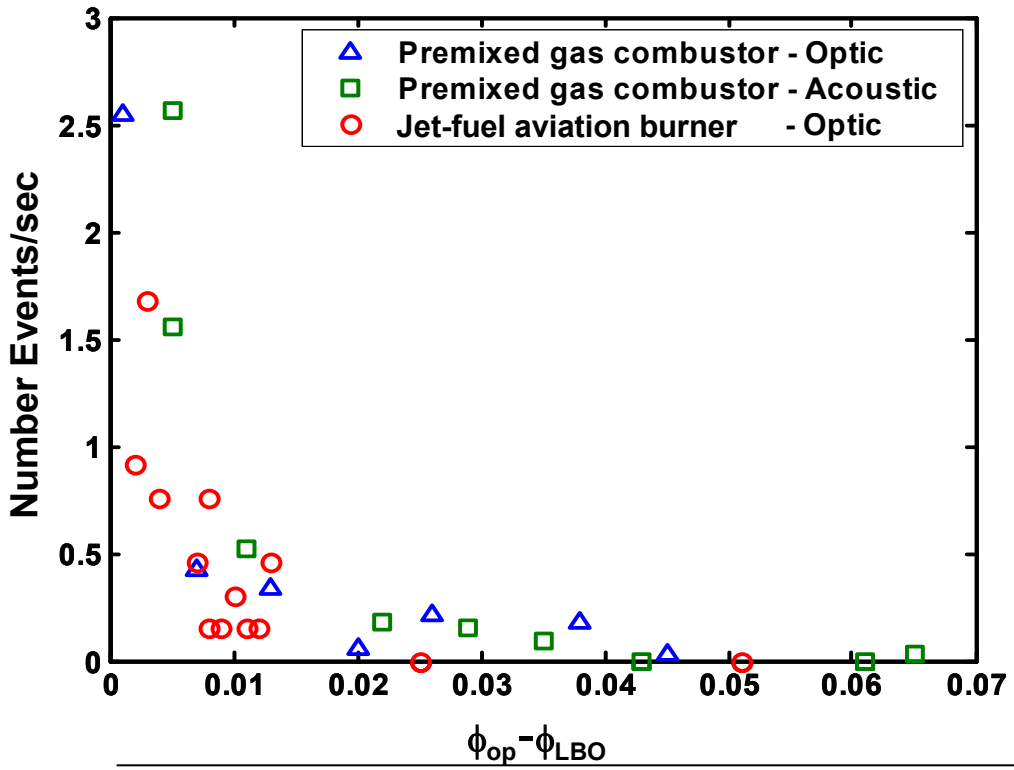
- Goal: Estimate LBO margin in-situ
- Approach: Occurrence of local extinction/re-ignition events = LBO precursors
  - optical/acoustic detection
  - e.g., double thresholding of signals

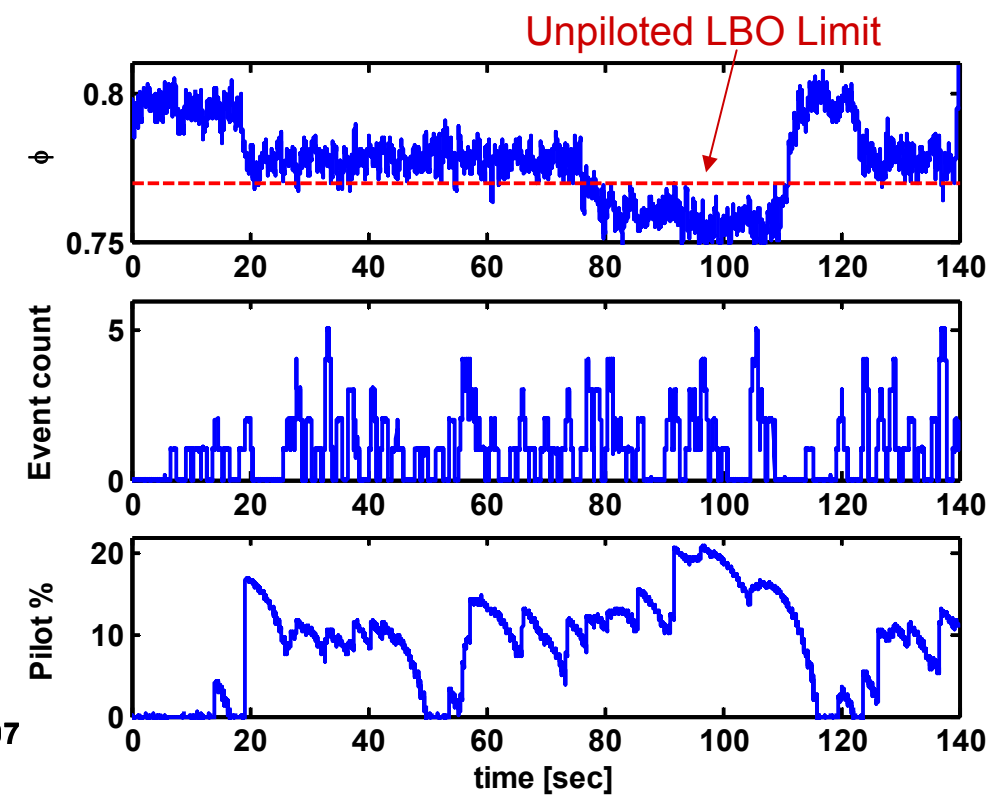




LBO Control

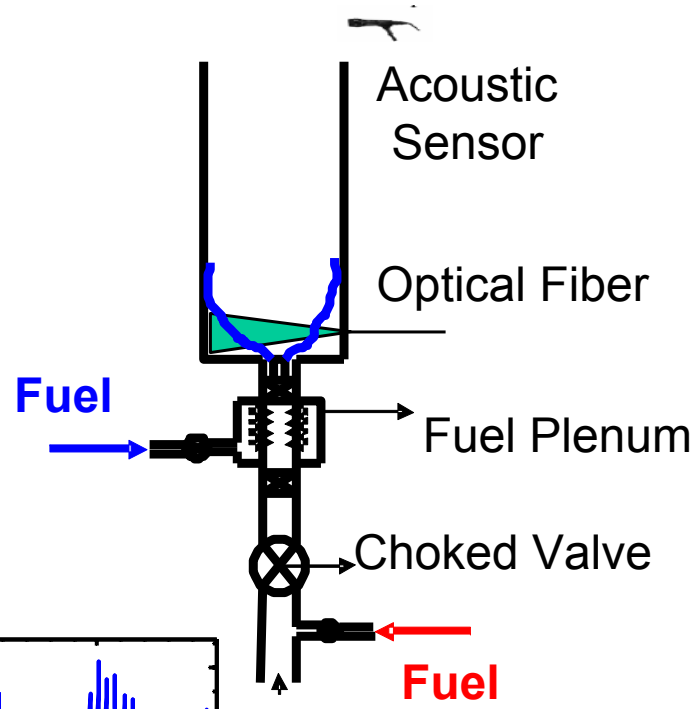
- LBO proximity parameter : event rate (avg number of events/sec)
  - more frequent events as LBO is approached
- Can use as input to LBO avoidance controller
  - e.g., fuel distribution control
- Static stability can be linked to dynamic instability
  - ➢ LBO margin sensing in the presence of combustion dynamics?

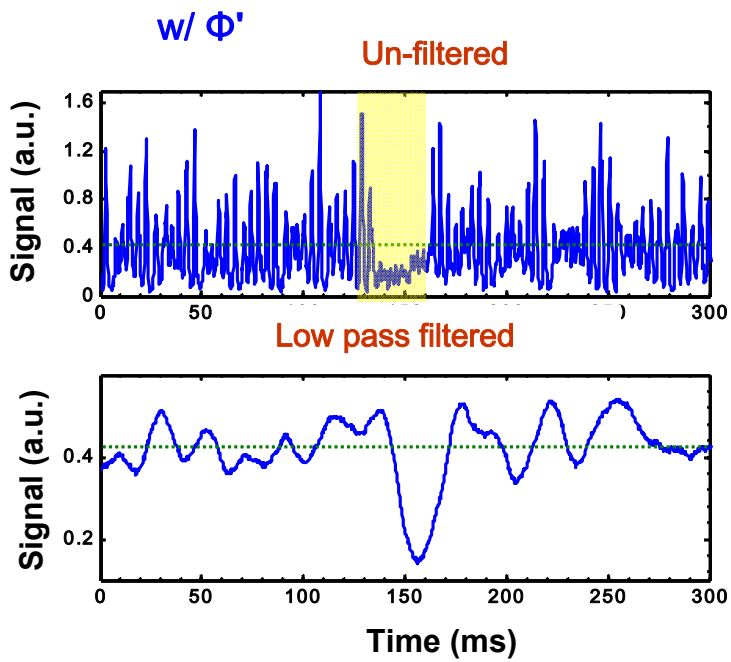


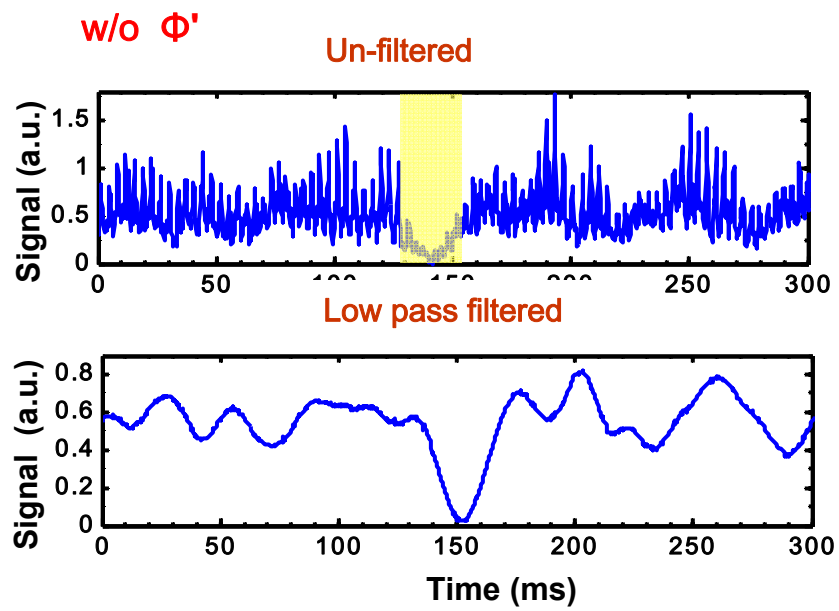


Precursor Events: Combustion Dynamics

- Two kinds of instability mechanisms
  - Equivalence ratio oscillations (w/ Φ')
  - Flame-acoustic interactions (w/o Φ')
- Low pass filtering (~50Hz) for improved precursor detection
- Same event signatures as dynamically stable conditions



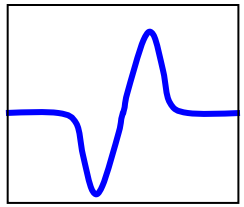


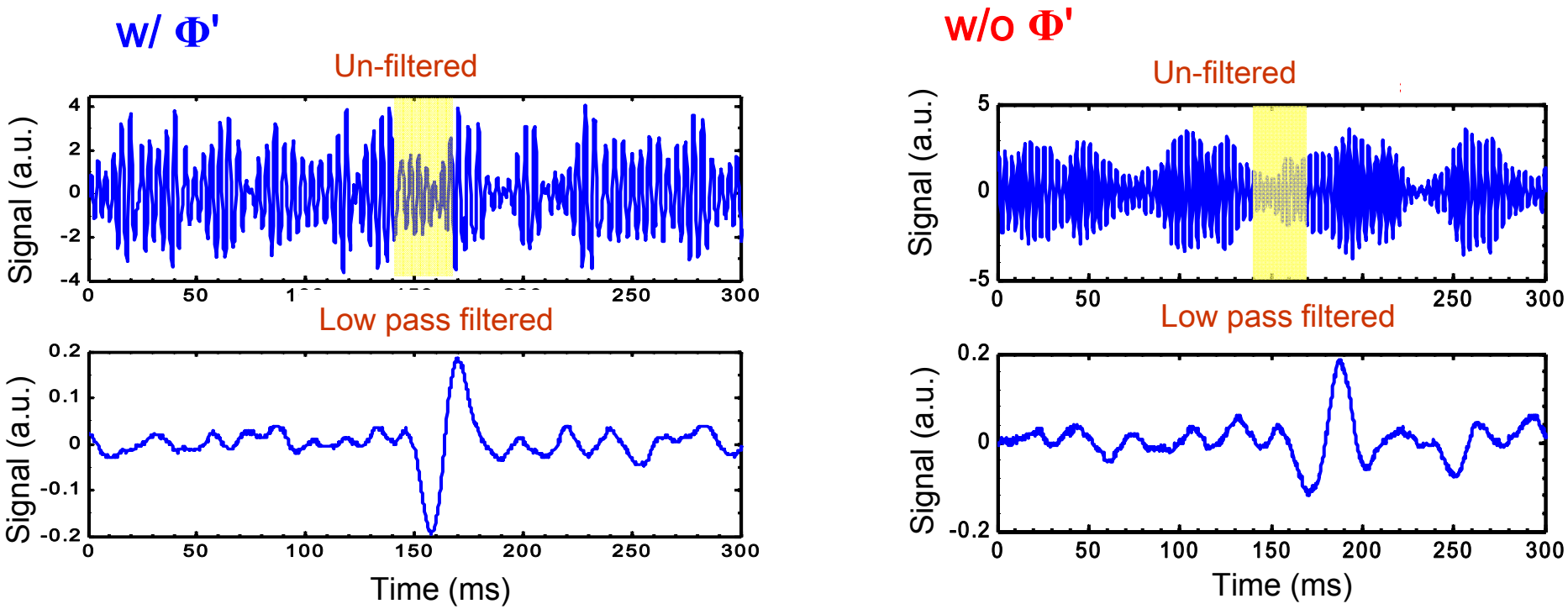


Precursor Events: Acoustic Signal

- Precursors not evident in raw acoustic signal
- LP filtering reveals precursor event signature
- Same event characteristic shape as dynamically stable conditions
  - can use same event sensing algorithm (e.g., identification with wavelet filter)

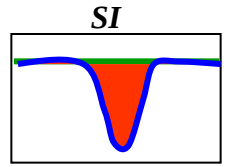
Wavelet

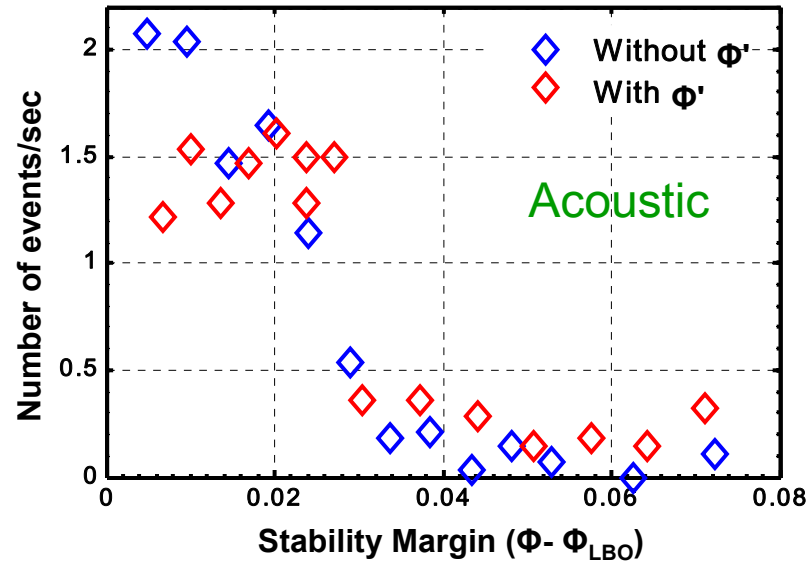


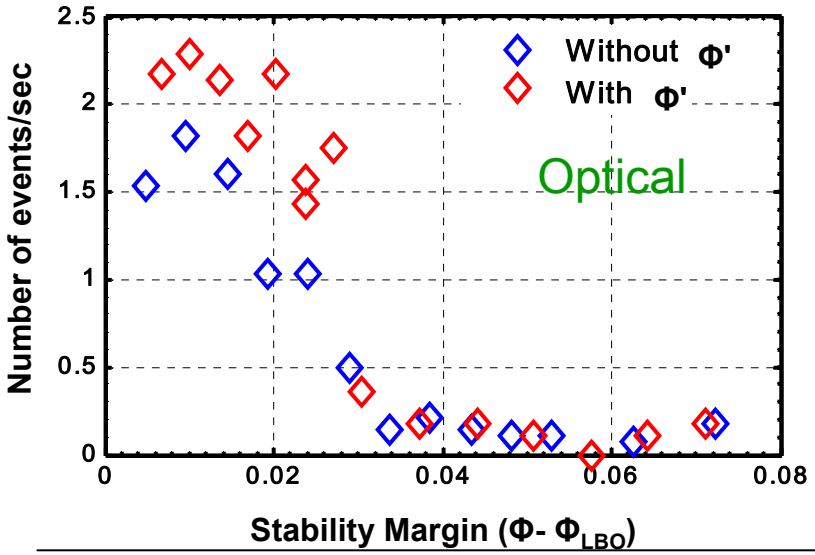


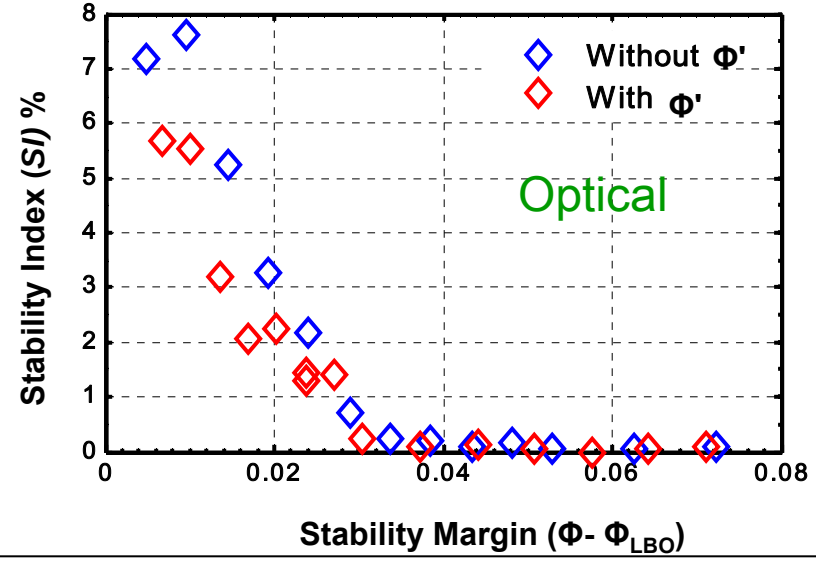
LBO Sensing

- Robust optical signal stability parameter : Stability Index (*SI*)

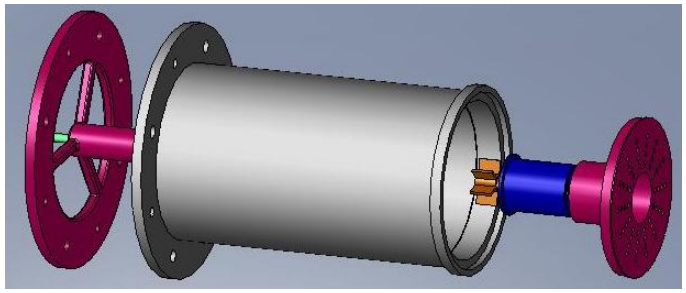




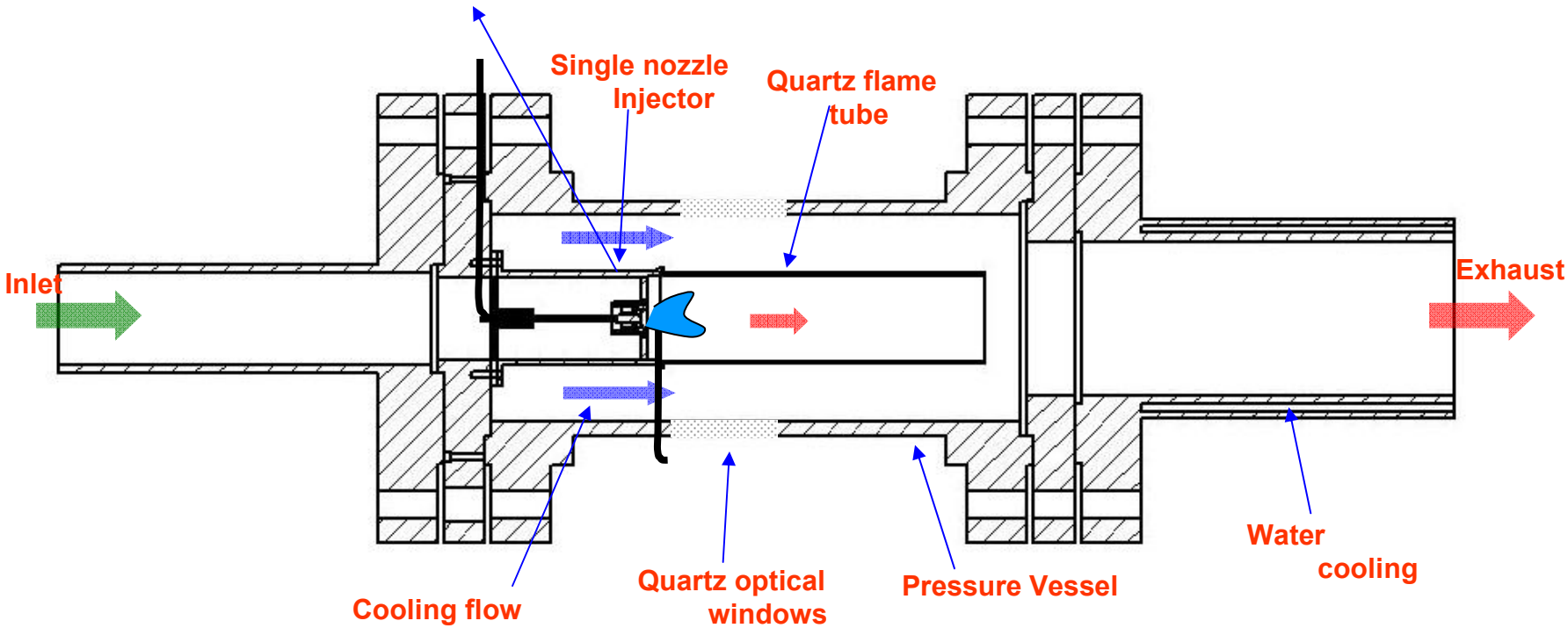




Single Nozzle LDI System



- Objective: Examine LBO margin sensing in advanced, low NOx, elevated pressure combustor



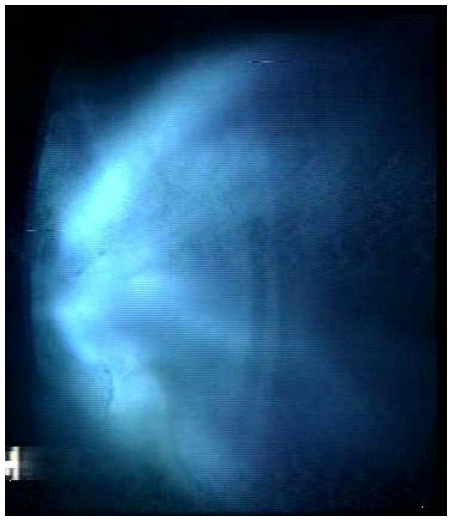
LDI Tests – Jet A

- Initial shakedown at atmospheric pressure
- Flame zone has lean signature (blue flame)

Movie

T_3=740 F, V_{ref} = 46 ft/s, Φ=0.51-0.37

T_3=740 F (667K), Φ=0.46, V_{ref} = 46 ft/s (14 m/s)



T_3=751 F (672K), Φ=0.7, V_{ref}=28 ft/s (8.5 m/s)

Summary

- Developed statistical theory of controlled combustion dynamics including time delays and noise
  - closed form solutions for statistics and spectra of combustor pressure
- Reproduced common experimental observations of controlled combustor dynamics
  - can use to study limits of control effectiveness and improve controller design
- Demonstrated robust LBO precursor sensing
  - robust event sensing algorithms: multiple combustors, with and without dynamics instability
- Currently extending work to NASA single-element LDI combustor