Understanding and Control of Combustion Dynamics in Gas Turbine Combustors

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Tom J. George, Program Manager, DOE/NETL
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$452,695 Total Contract Value

Gas Turbine Need

- ***Need:*** **Gas turbine reliability and availability is important factor affecting power plant economics**
  - *Problem:* Combustion driven oscillations severely reduce part life, requiring substantially more frequent outages
    - Ultimately affects consumer through price of electricity

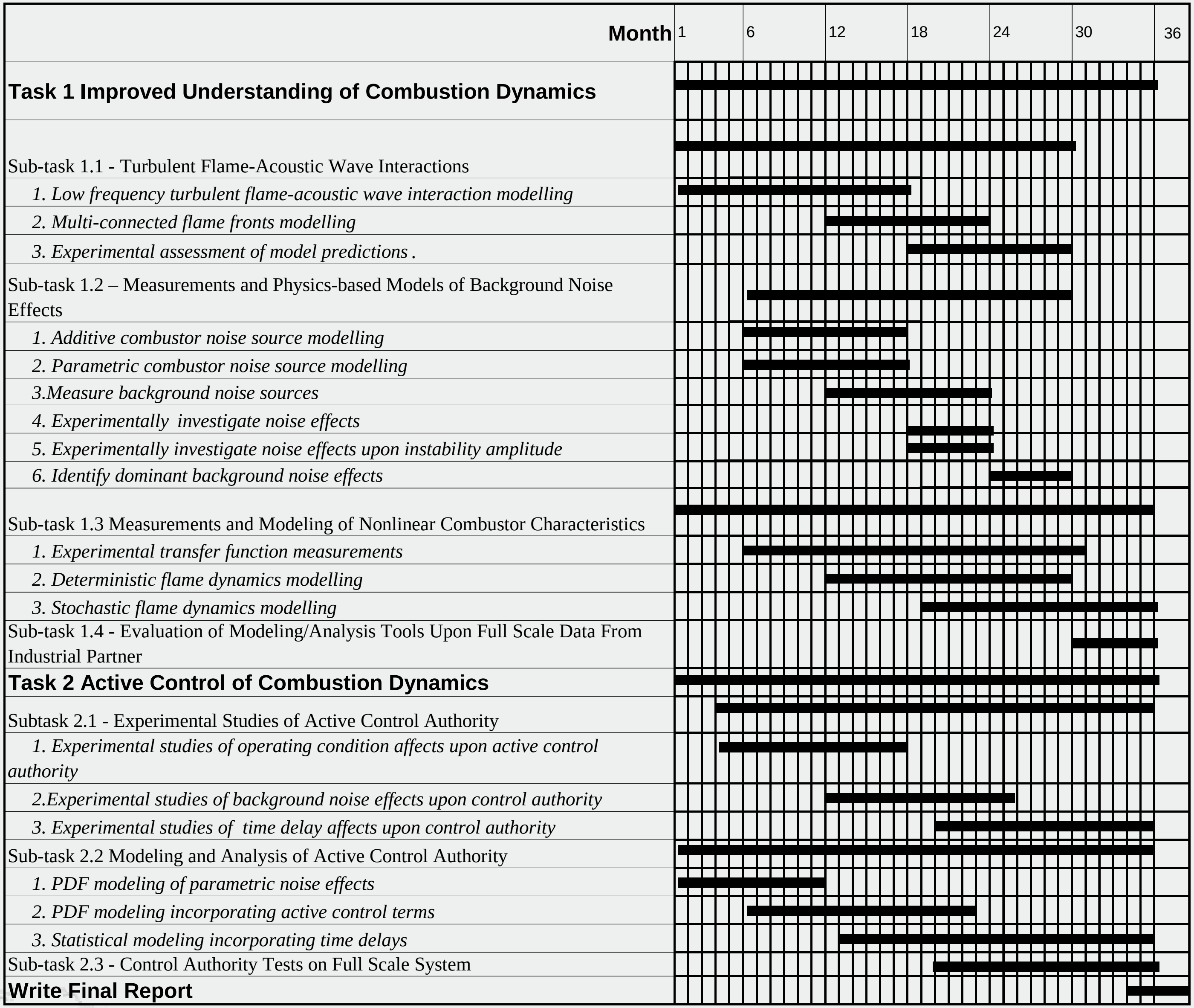
- ***Need:*** **Maximum gas turbine power output is needed in order to meet growing demand**
  - *Problem*: Combustion driven oscillations often necessitate de-rating of turbine power output

Project Objectives

- **Task 1 - Improved understanding of combustion driven oscillations**
  - Will improve capabilities for designing combustors with reduced dynamics problems

- **Task 2 - Active control of combustion driven oscillations**
  - Will improve capabilities for suppressing detrimental dynamics

Project Schedule



Task 1 Improved Understanding of Combustion Dynamics

Sub-task 1.1 - Turbulent Flame-Acoustic Wave Interactions

1. Low frequency turbulent flame-acoustic wave interaction modelling

2. Multi-connected flame fronts modelling

3. Experimental assessment of model predictions .

Sub-task 1.2 – Measurements and Physics-based Models of Background Noise Effects

1. Additive combustor noise source modelling

2. Parametric combustor noise source modelling

3.Measure background noise sources

4. Experimentally investigate noise effects

5. Experimentally investigate noise effects upon instability amplitude

6. Identify dominant background noise effects

Sub-task 1.3 Measurements and Modeling of Nonlinear Combustor Characteristics

1. Experimental transfer function measurements

2. Deterministic flame dynamics modelling

3. Stochastic flame dynamics modelling

Sub-task 1.4 - Evaluation of Modeling/Analysis Tools Upon Full Scale Data From Industrial Partner

Task 2 Active Control of Combustion Dynamics

Subtask 2.1 - Experimental Studies of Active Control Authority

1. Experimental studies of operating condition affects upon active control authority

2.Experimental studies of background noise effects upon control authority

3. Experimental studies of time delay affects upon control authority

Sub-task 2.2 Modeling and Analysis of Active Control Authority

1. PDF modeling of parametric noise effects

2. PDF modeling incorporating active control terms

3. Statistical modeling incorporating time delays

Sub-task 2.3 - Control Authority Tests on Full Scale System

Write Final Report

Accomplishments

- **High impact accomplishments to date:**
  - Improved understanding of factors that affect instability amplitude
    - Experimental characterization of combustion process nonlinearities
    - Developed and validated theoretical analysis for prediction of flame nonlinearities

  - Improved methods for active instability control
    - Demonstrated open loop control of instabilities
    - Improved understanding of factors influencing open loop control effectiveness

  - Developed and validated models of turbulent flame/acoustic wave interactions that occur during screeching instabilities

- **Results are improving understanding of combustion instability physics and methods of suppressing oscillations**

Experimental Characterization of Heat Release Nonlinearities

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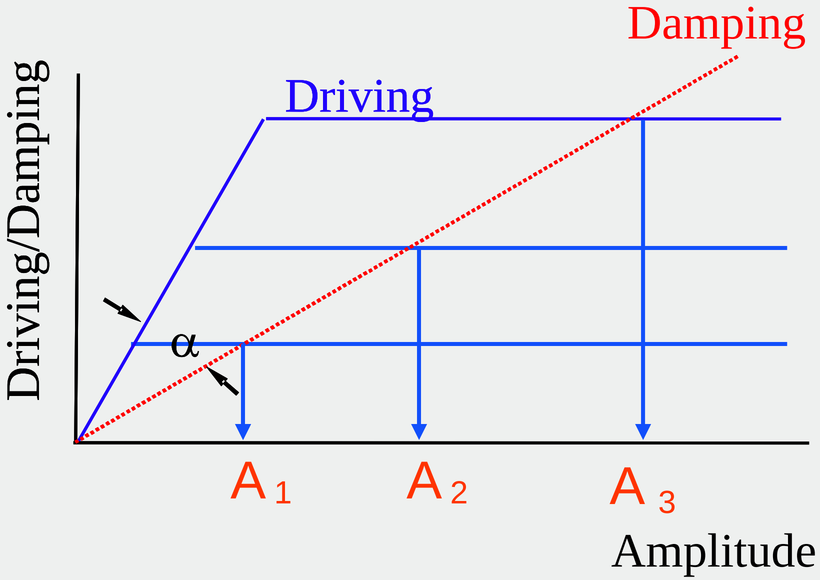
Motivation: Linear and Nonlinear Processes in Unstable Combustors

- **Linear processes**
  - Cause inherent disturbances to become self excited and grow in amplitude exponentially, $A \sim e^{\alpha t}$



- **Nonlinear processes**
  - Saturate amplitude of self-excited oscillations
  - Amplitude prediction capabilities require understanding nonlinearities!

- **Objective of this part of work is to measure shape of “Driving” curve**

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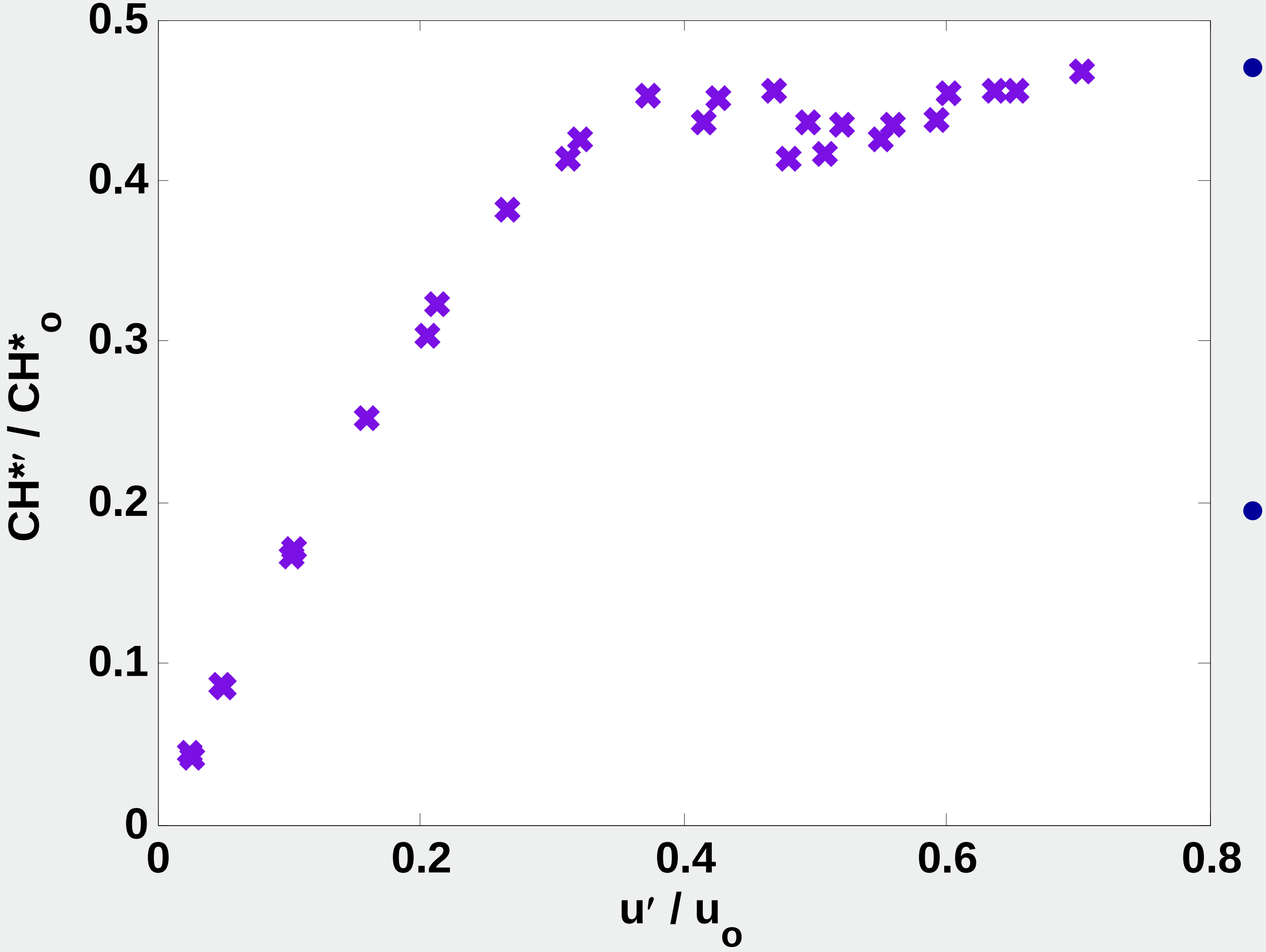
Experimental Approach

- **Determine transfer function between chemiluminescence and flow forcing amplitude**
  - Dependence upon driving frequency, flow rate, equivalence ratio
  - Reactants premixed ahead of choke point to ensure constant fuel/air ratio
  - Reynolds Number based on premixer exit diameter: 21000 – 43000 (mean velocity = 20-45 m/s)
  - Amplitude dependence of transfer function determined at 96 conditions/frequencies

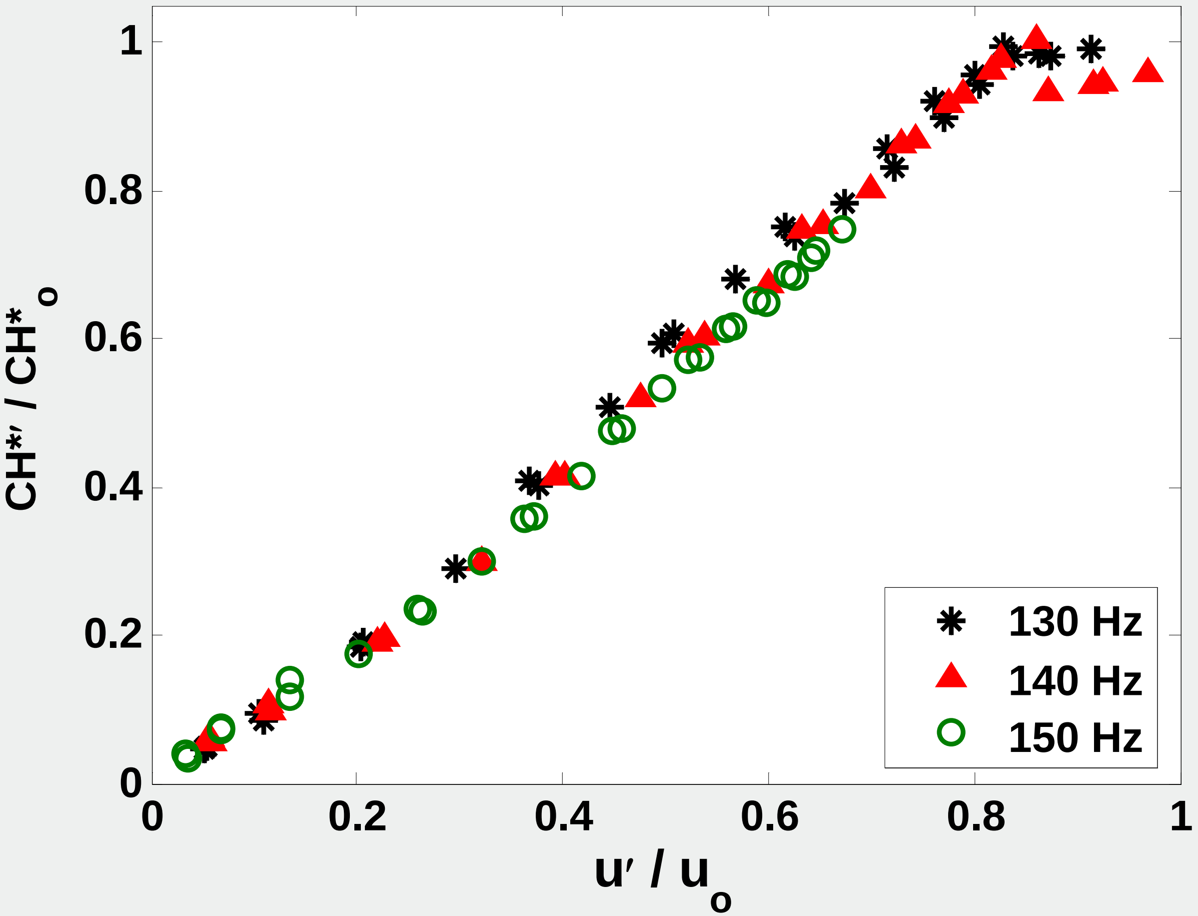
- **Key Findings:**
  - Flame response nonlinearities significantly more complicated and varied than simple saturation
  - Mechanisms identified:
    - Amplitude-dependent flame liftoff
    - Vortex roll-up
    - Excitation of parametric instability

Nonlinear Transfer Function



- **CH*’-u’ relationship remains linear up to ~ 35% of mean velocity**
- **CH*’ response saturates at large amplitudes of driving**

Saturation Amplitude Can Vary Substantially!



- **Similar saturation value as assumed in Dowling nonlinear flame model (temporary global extinction)**
- **Mechanism is not instantaneous heat release equaling zero here, but flame liftoff**

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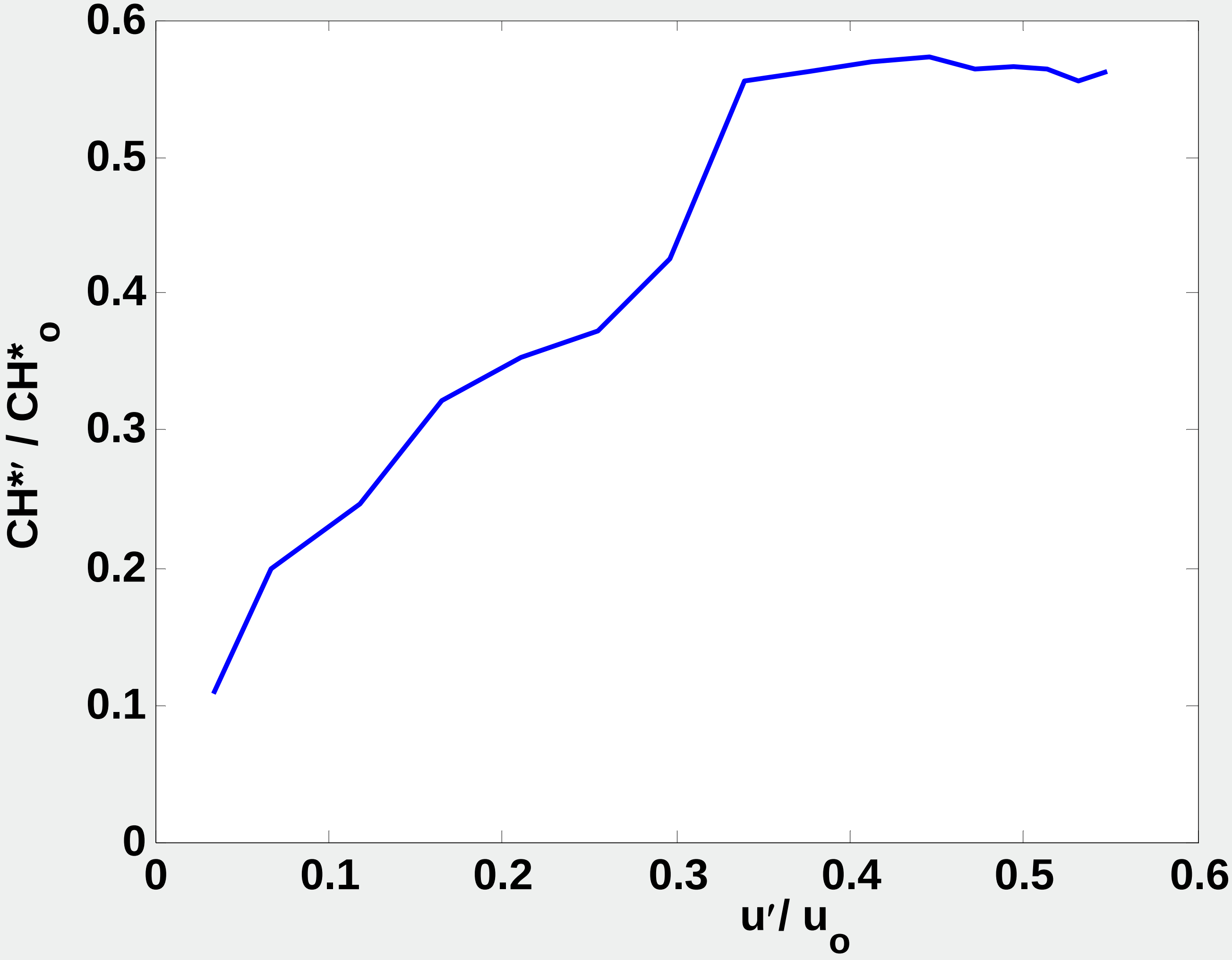
Nonlinear Flame Response More Complicated than Simple Saturation



- **Very similar behavior to recent observations of Balachandran *et al.* (C&F, 2005)**
- **Reynolds number ~21000, f_{drive} = 410 Hz**

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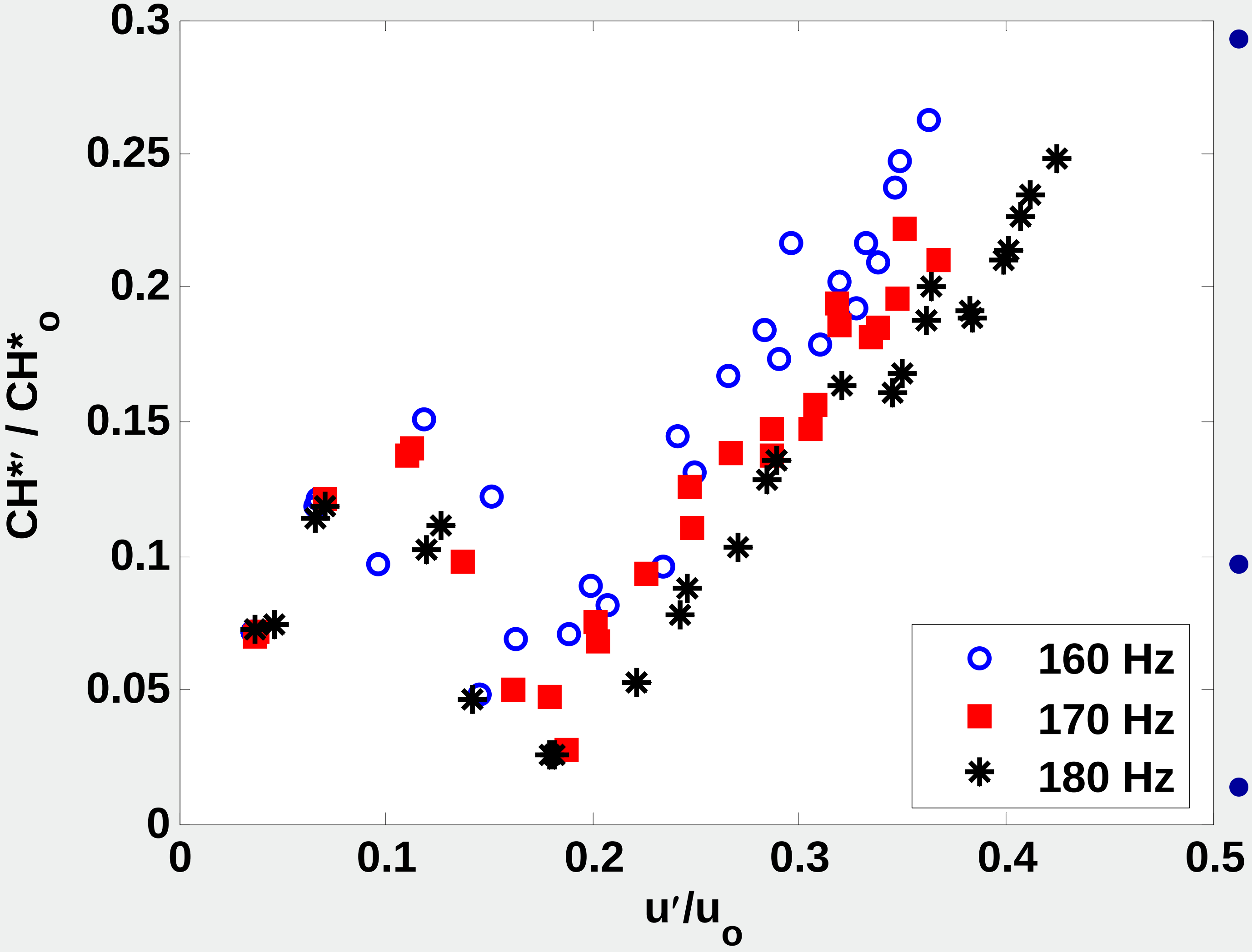
Even More Complicated Nonlinear Flame Response Observed as Well



- **Transfer function shape changes drastically**
  - Chemiluminescence initially increases then sharply decreases followed by further increase
- **Response of flame shifted to 1st harmonic**
- **Reynolds number ~ 30000**

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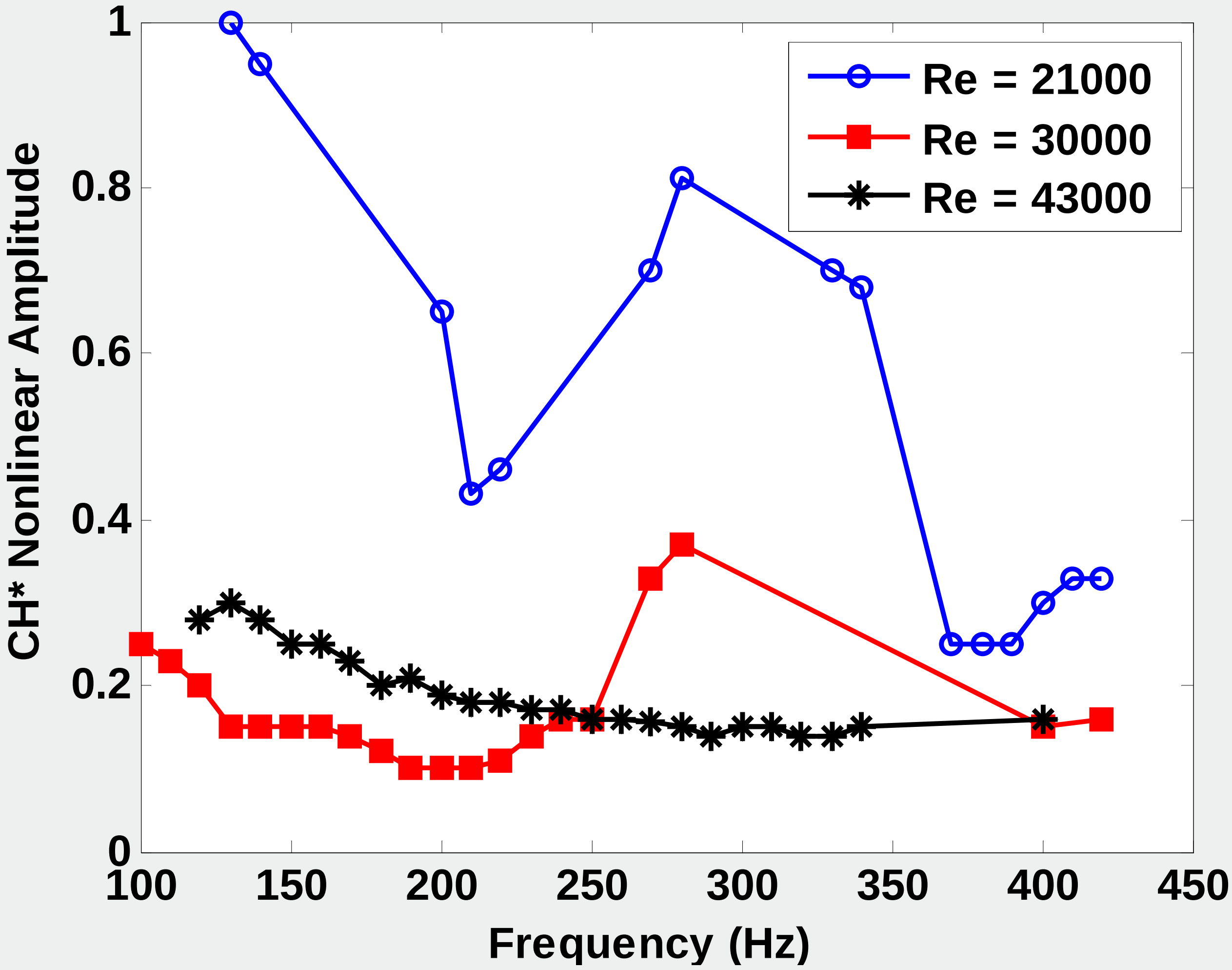
Summary of Nonlinear Flame Characteristics



- **Characterization of flame nonlinearities substantially more complicated than simple saturation amplitude**
- **Here, we plot amplitude at which nonlinearity is first observed.**
- **Results indicate that variety of behaviors (shape, mechanisms) exist in single combustor**

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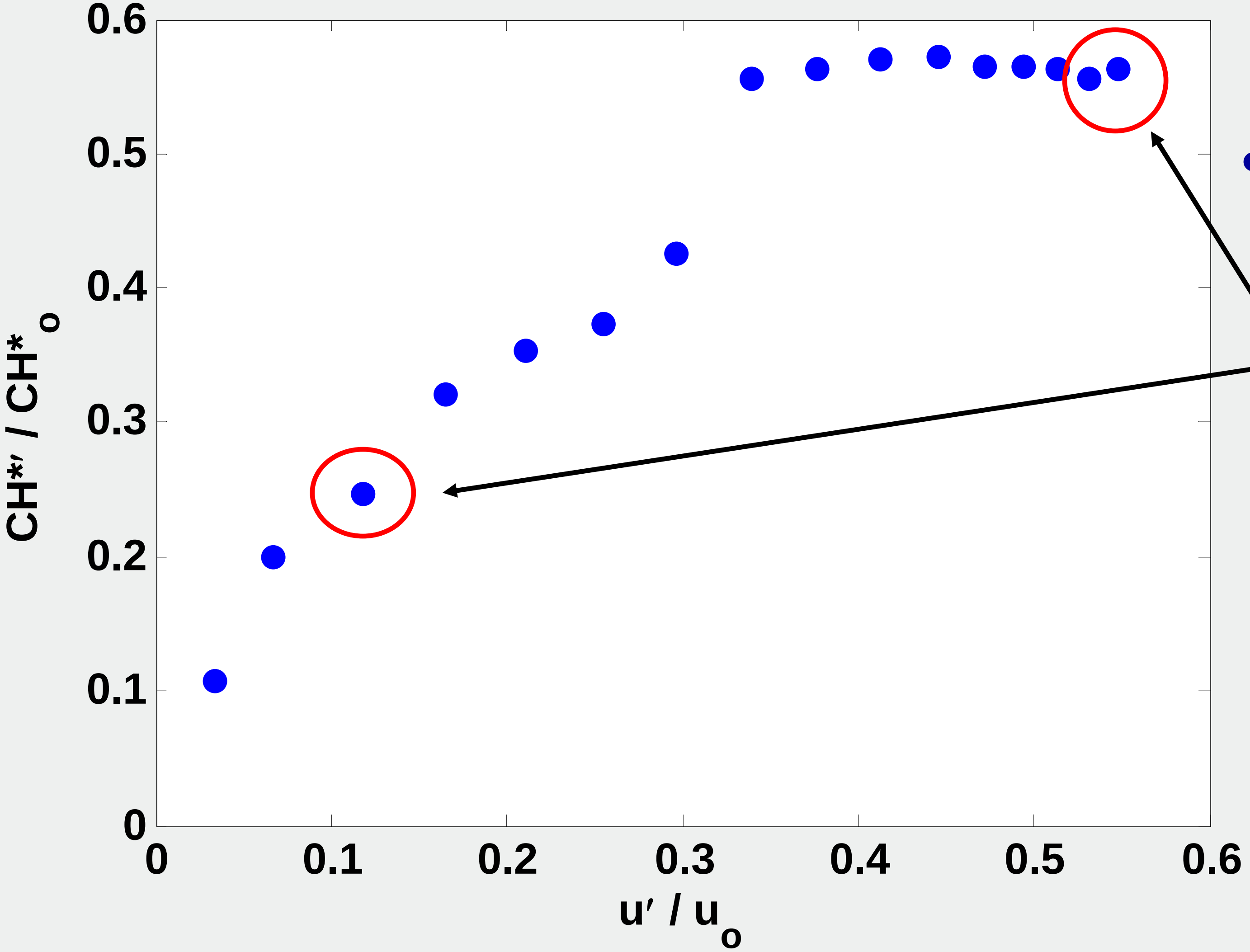
Mechanisms of Nonlinearity

- **Performed Large Number of OH-PLIF Imaging Studies to Elucidate Flame Dynamics at two driving frequencies- 130 and 410 Hz**
  - 5 driving amplitudes
  - 8 phases taken during cycle, for total of 4000 images per data set

- **Many thanks to D. Santavicca and J.G. Lee for their assistance and advice!**

Simultaneous OH-PLIF Imaging to Elucidate Flame Dynamics -410 Hz



- Subsequent images taken at two indicated driving amplitudes

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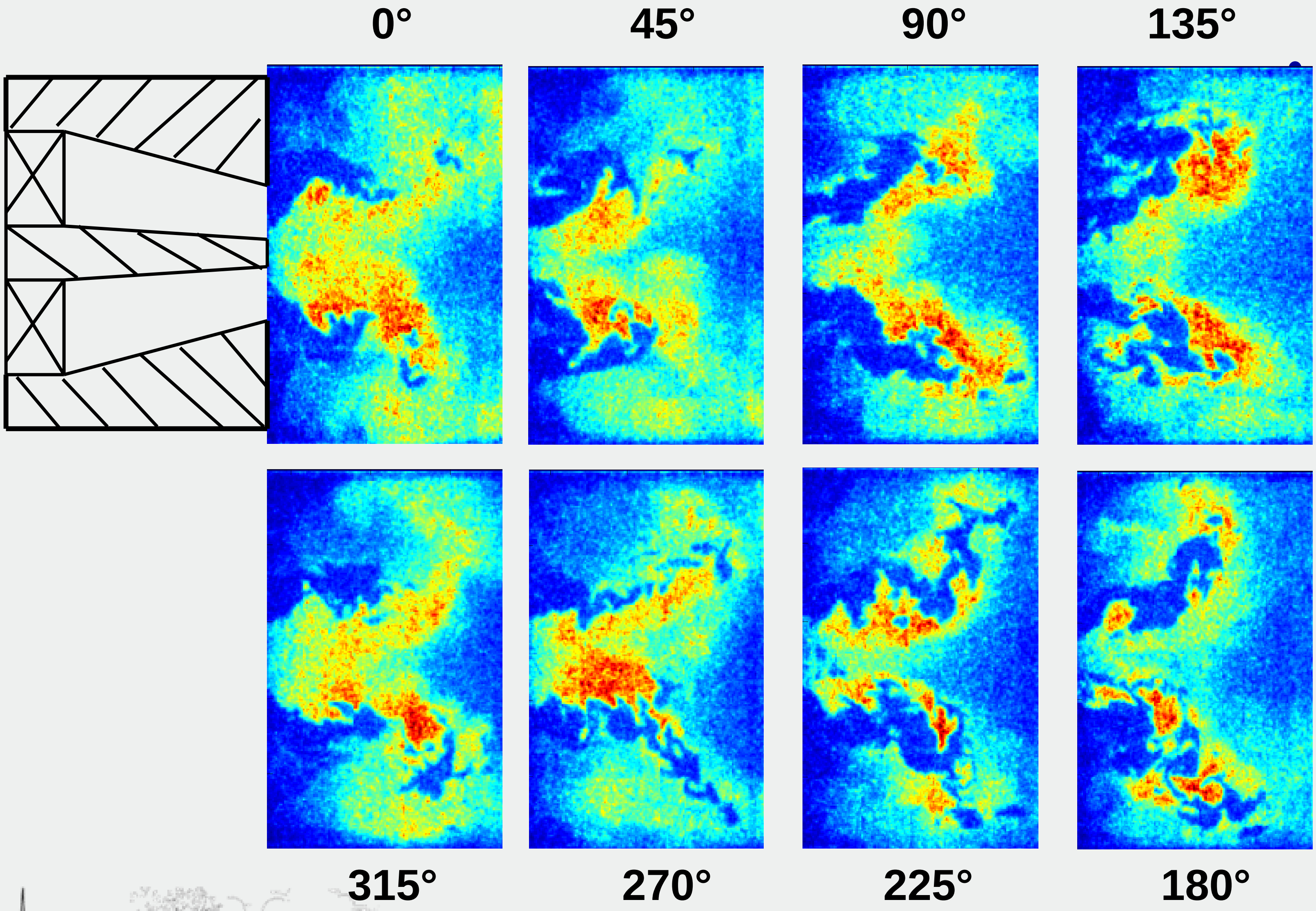
Low Amplitude Forcing

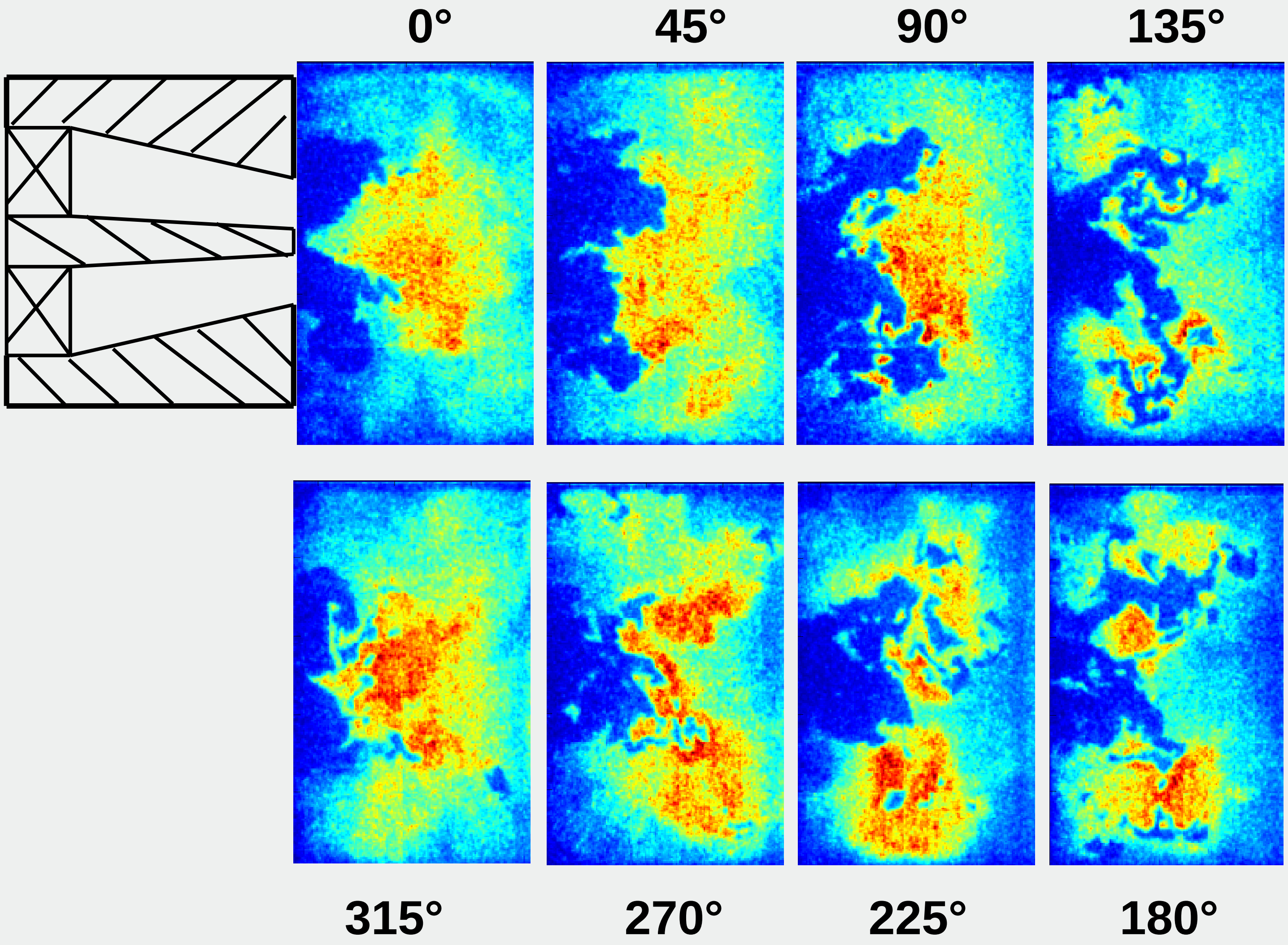


- F_{drive} = 410 Hz

  Convecting structures can be seen in some images

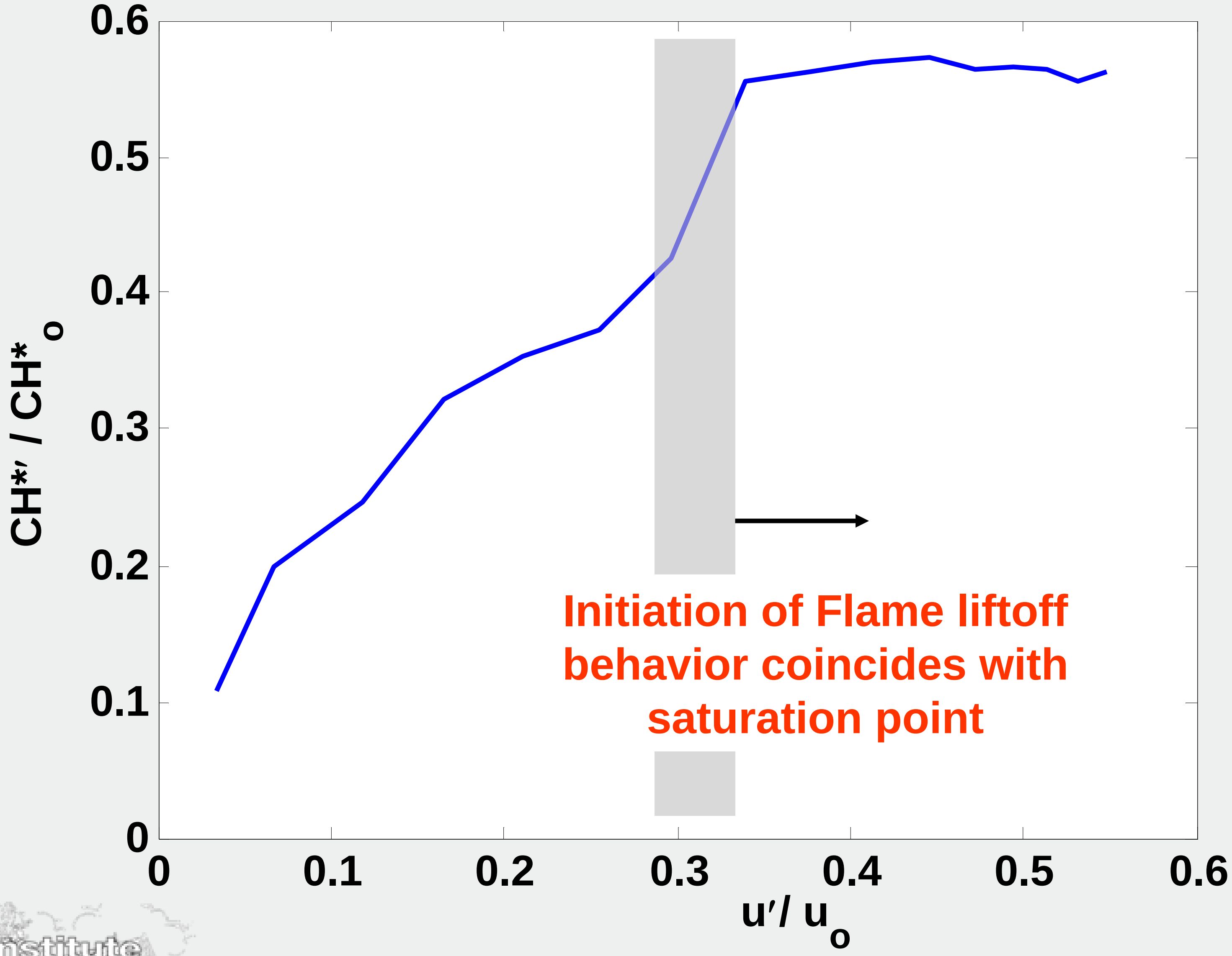
  Any suggestions for good averaging techniques that don't turn images into mush?

Large Amplitude Forcing



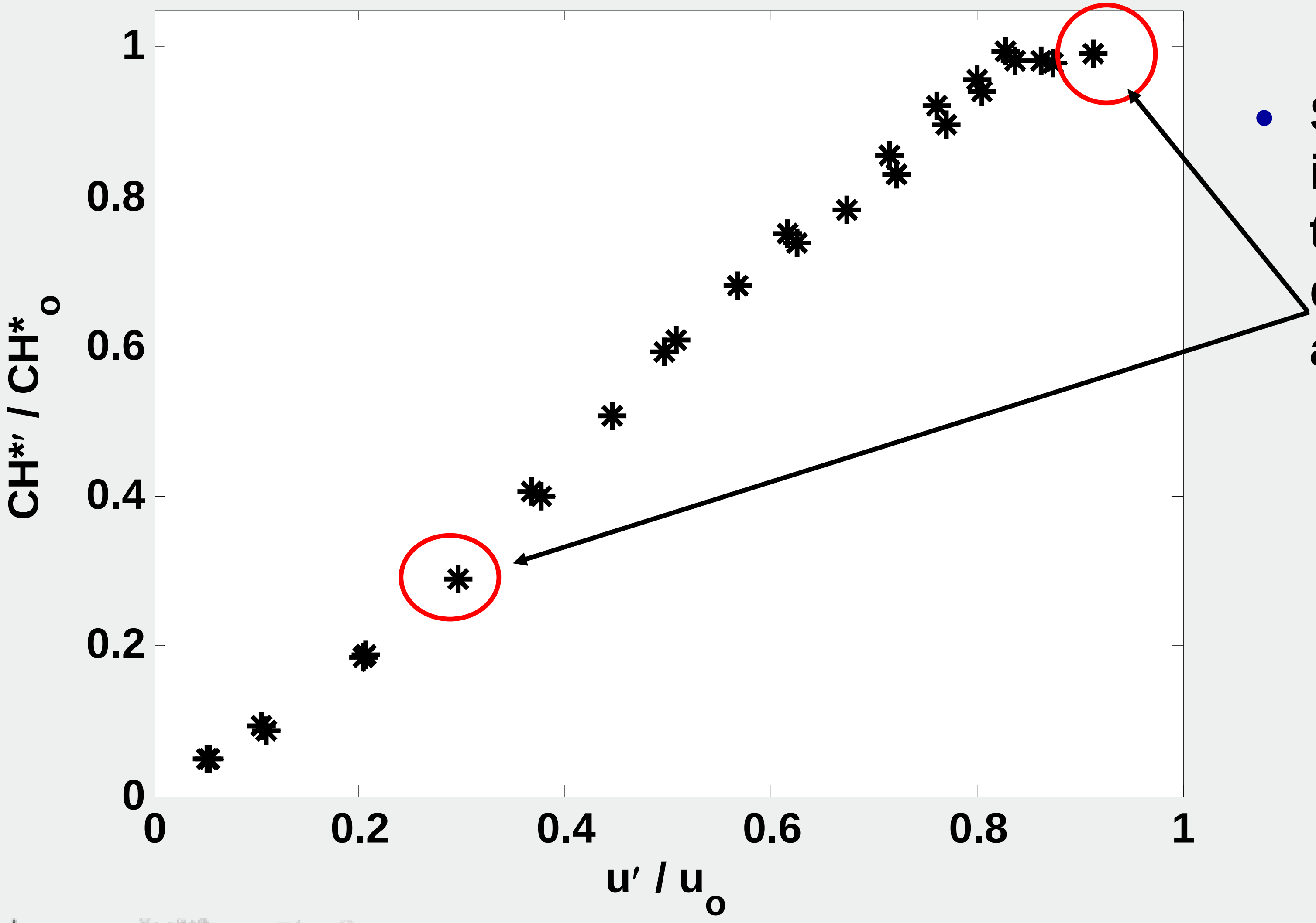
- $F_{drive} = 410$ Hz
- Large amplitude driving
  - Flame liftoff throughout driving cycle
  - Stabilization point of flame moves from centerbody to local low velocity location downstream

Simultaneous OH-PLIF Imaging to Elucidate Flame Dynamics -410 Hz



Initiation of Flame liftoff behavior coincides with saturation point

Simultaneous OH-PLIF Imaging to Elucidate Flame Dynamics -130 Hz



- **Subsequent images taken at two indicated driving amplitudes**

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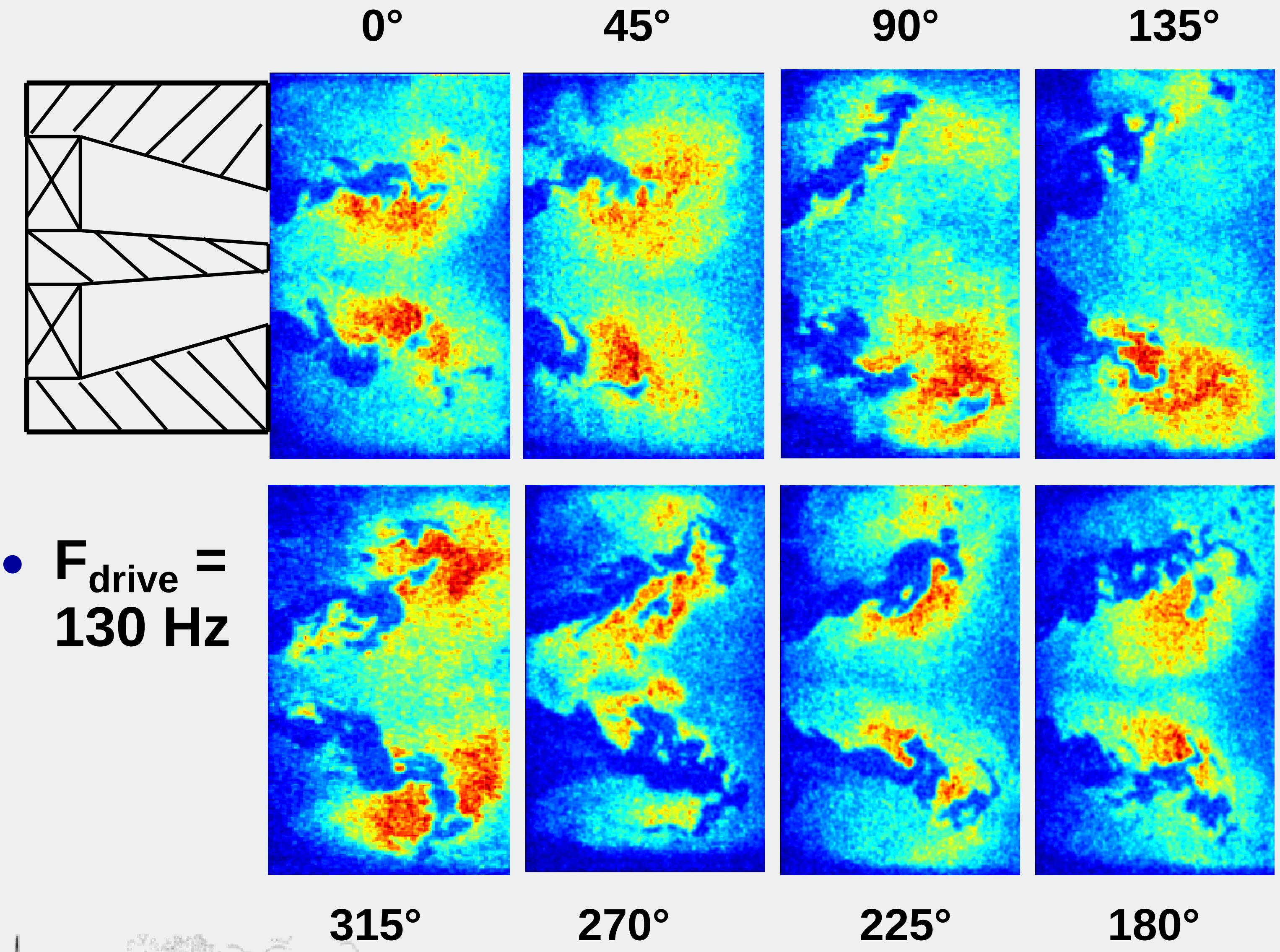
CLEMSONPRES.PPT, 10/28/2003, B.T. ZINN, T. LIEUWEN, Y. NEUMEIER

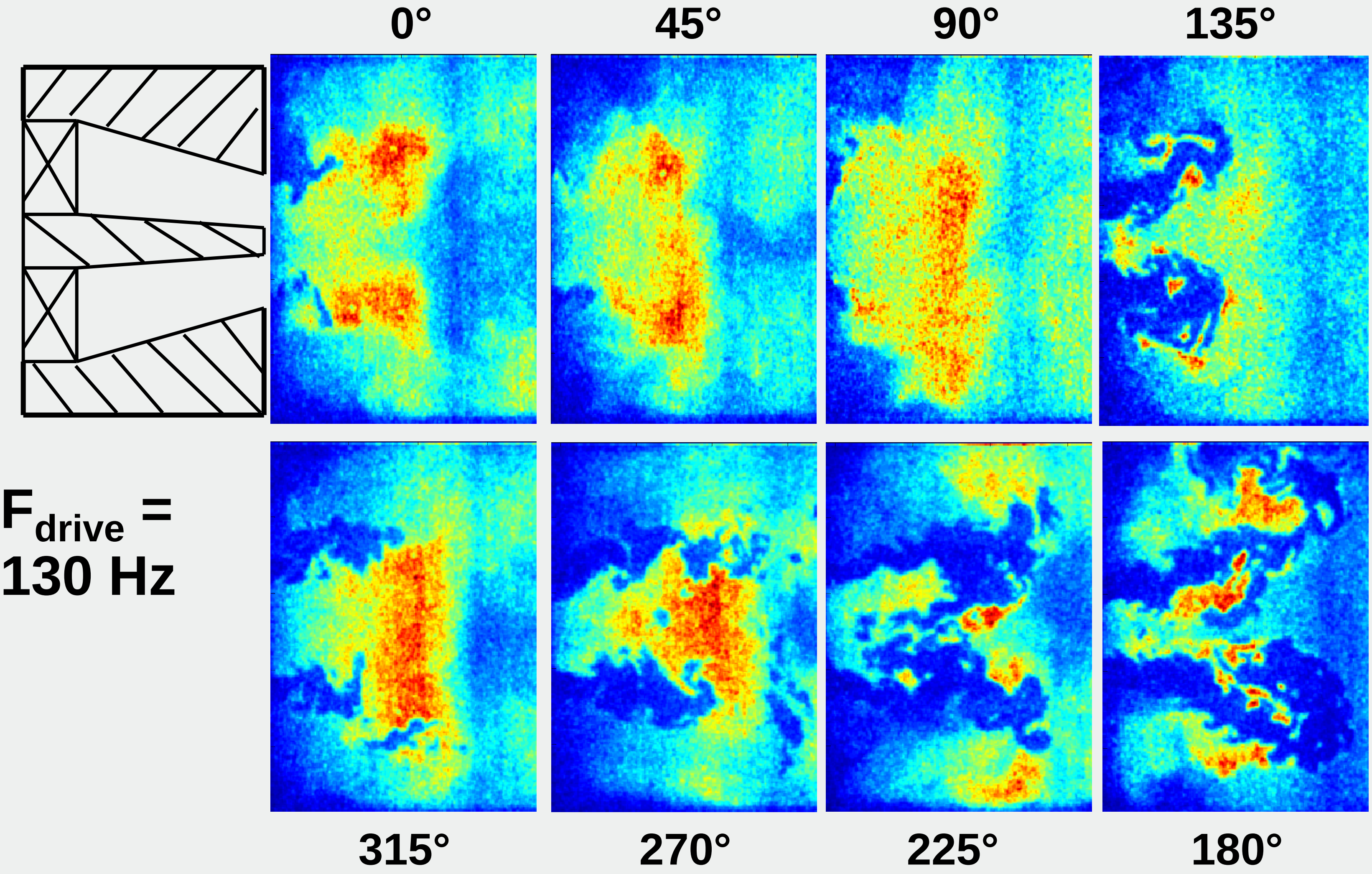
Low Amplitude Forcing



- F_{drive} = 130 Hz

- Well-defined flame position, structure throughout driving cycle

Large Amplitude Forcing



- F_{drive} = 130 Hz

- Turbulent flame speed is apparently modulated – peaks at highest instantaneous velocity
- Vortex rollup with occasional merging (3-D effect)

Frequency Locking and Open Loop Control

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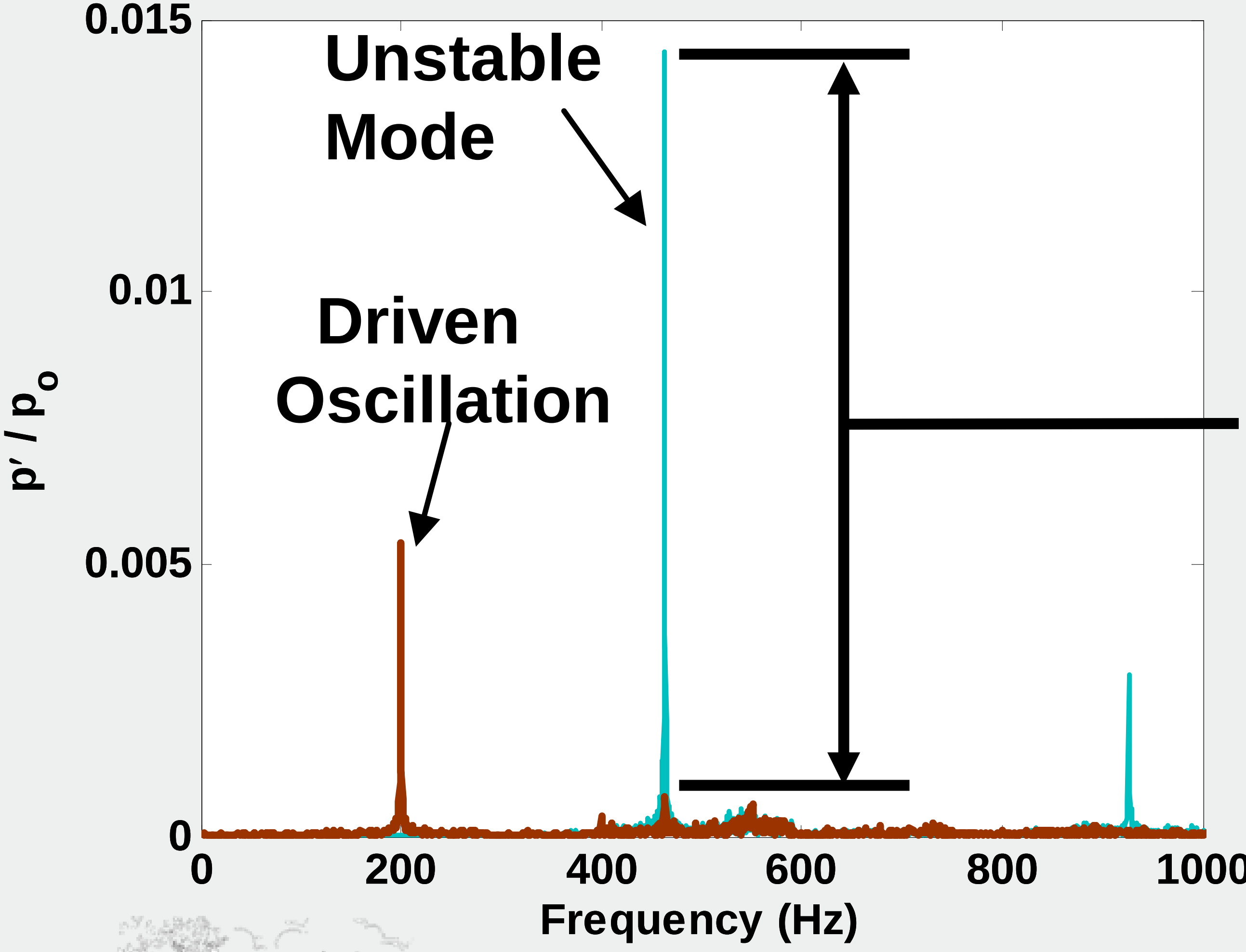
Objective

- Investigate nonlinear interaction between driven acoustic oscillation and natural combustor mode during unstable combustion

- Determine important parameters which are affected by frequency spacing between driven oscillation and combustor mode

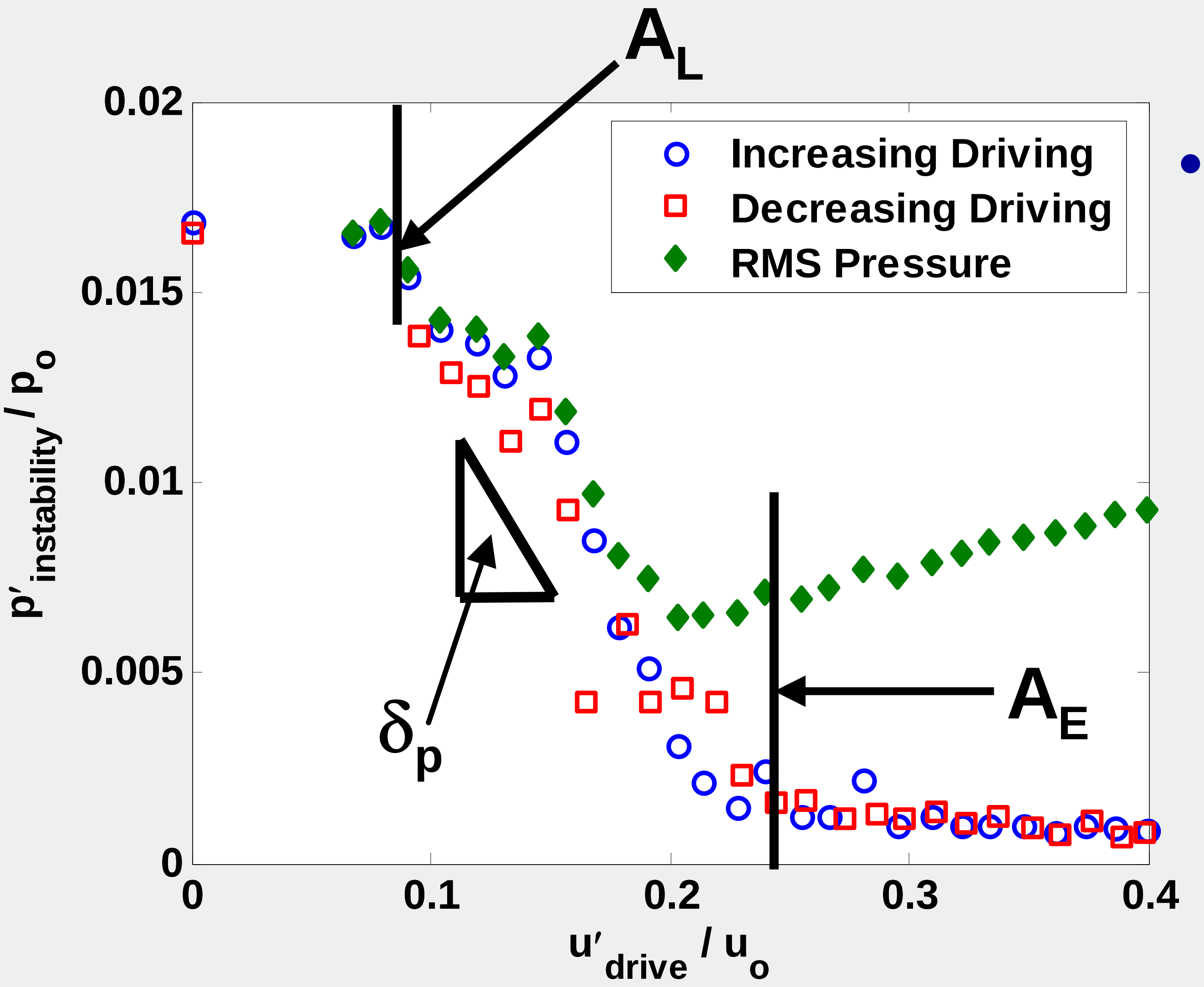
- Investigate the effectiveness of open-loop control on reduction in acoustic power in combustor

Effect of Acoustic Forcing on Instability Amplitude



Reduction in instability amplitude by open-loop forcing

Typical Result



- Investigated parameters in this study
  - Ledge Width, A_L
  - Instability Rolloff, δ_p
  - Entrainment Amplitude, A_E

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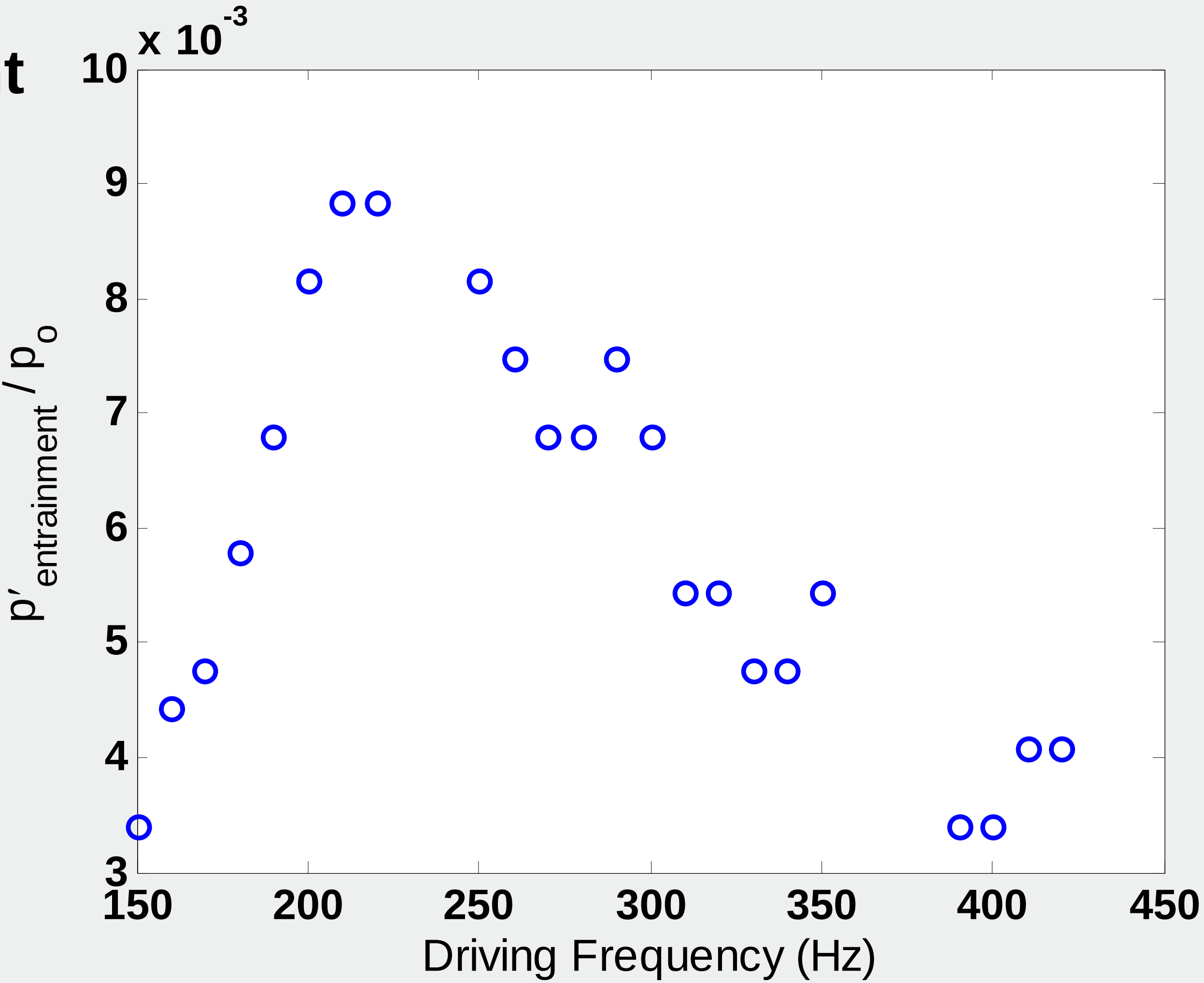
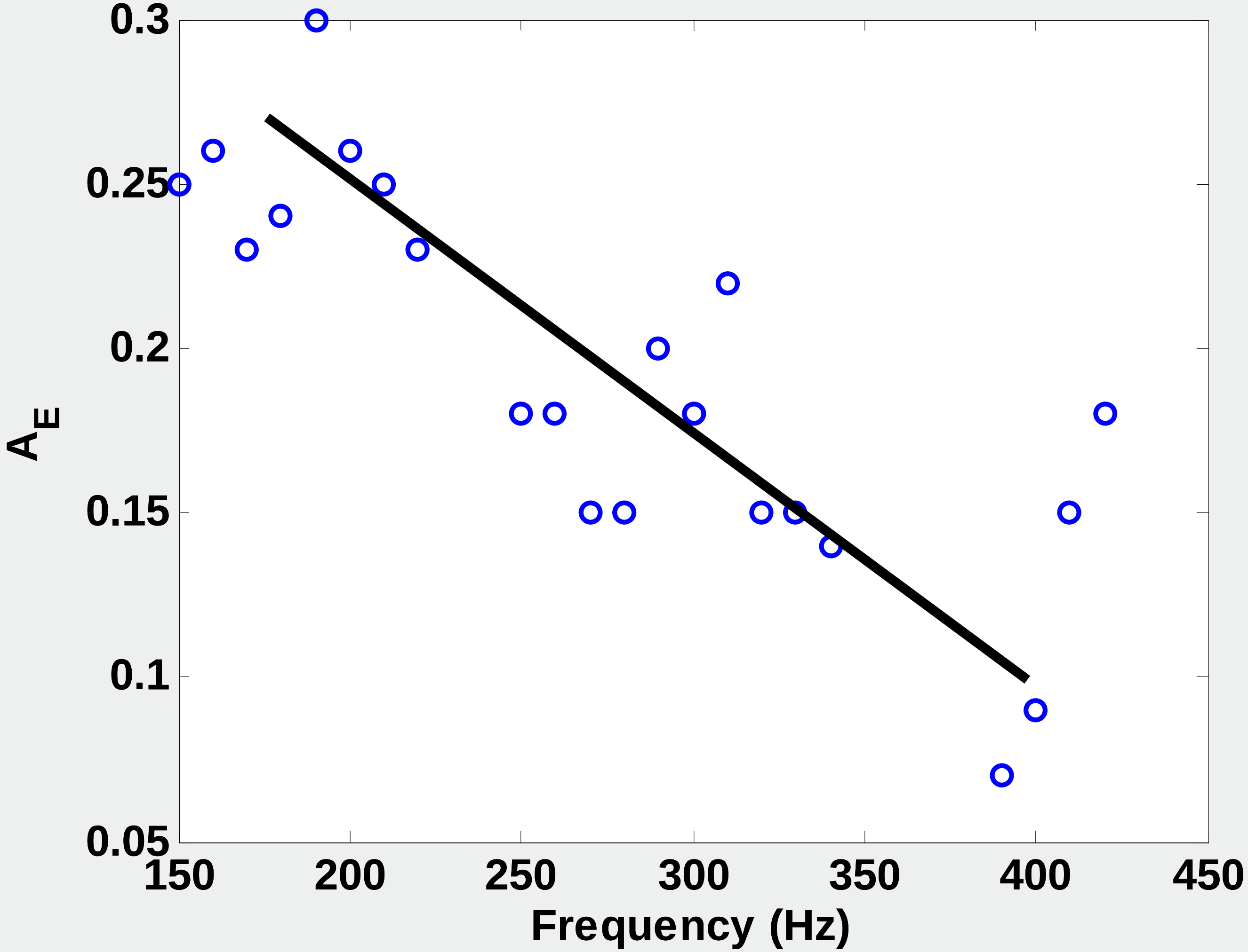
Pressure Entrainment Amplitude Characteristics

- **Pressure Entrainment exhibits nonlinear frequency dependence**
  - **Is velocity a better parameter?**



Entrainment Amplitude Characteristics



- Entrainment amplitude increases with increasing frequency spacing
- More intuitive result compared to pressure dependence

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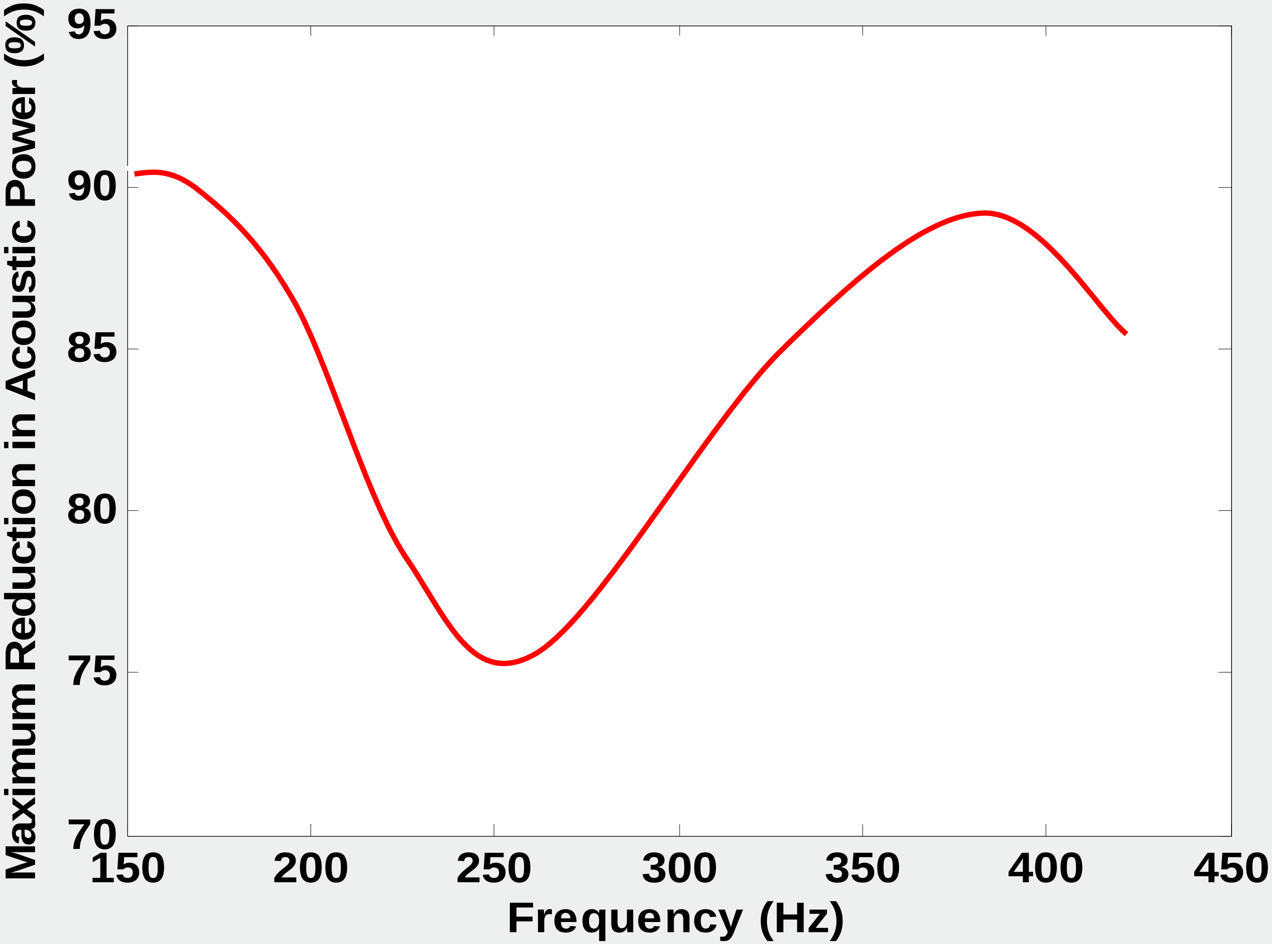
Acoustic Power Reduction



- **Acoustic power reduced by at least 70%. Best results seen where pressure entrainment amplitude is minimized.**

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Concluding Remarks

- **Experimental studies of flame nonlinearity**
  - **Nonlinear flame characteristics significantly more complicated than simple saturation**
  - **Shape of transfer function is a function of frequency, Reynolds number**
    - **Single combustor can exhibit a variety of behaviors**
  - **Mechanisms identified:**
    - Amplitude-dependent flame liftoff
    - Vortex roll-up
    - Excitation of parametric instability

- **Nonlinear Entrainment studies**
  - **Study clarifies nonlinear interactions between driven acoustic oscillations and unstable combustor modes**
    - **Velocity entrainment amplitude seen to decrease with decreasing frequency spacing**

  - **Open loop forcing of combustor at frequencies different from unstable mode shown to be quite effective at studied operating condition.**
    - **Reduction in acoustic power up to 90%. Best results occur at pressure entrainment amplitude minima.**