

Understanding and Control of Combustion Dynamics in Gas Turbine Combustors

Georgia Institute of Technology



**Ben T. Zinn, Tim Lieuwen, Yedidia Neumeier, and
Ben Bellows**

SCIES Project 02-01-SR095

DOE COOPERATIVE AGREEMENT DE-FC26-02NT41431

Tom J. George, Program Manager, DOE/NETL

Richard Wenglarz, Manager of Research, SCIES

Project Awarded (05/01/2002, 36 Month Duration)

\$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

	Month	1	6	12	18	24	30	36	
Task 1 Improved Understanding of Combustion Dynamics		[Gantt bar from 0 to 36]							
Sub-task 1.1 - Turbulent Flame-Acoustic Wave Interactions		[Gantt bar from 0 to 30]							
1. Low frequency turbulent flame-acoustic wave interaction modelling		[Gantt bar from 0 to 18]							
2. Multi-connected flame fronts modelling		[Gantt bar from 12 to 24]							
3. Experimental assessment of model predictions .		[Gantt bar from 18 to 30]							
Sub-task 1.2 – Measurements and Physics-based Models of Background Noise Effects		[Gantt bar from 6 to 30]							
1. Additive combustor noise source modelling		[Gantt bar from 6 to 18]							
2. Parametric combustor noise source modelling		[Gantt bar from 6 to 24]							
3. Measure background noise sources		[Gantt bar from 12 to 24]							
4. Experimentally investigate noise effects		[Gantt bar from 18 to 24]							
5. Experimentally investigate noise effects upon instability amplitude		[Gantt bar from 18 to 24]							
6. Identify dominant background noise effects		[Gantt bar from 24 to 30]							
Sub-task 1.3 Measurements and Modeling of Nonlinear Combustor Characteristics		[Gantt bar from 0 to 36]							
1. Experimental transfer function measurements		[Gantt bar from 6 to 30]							
2. Deterministic flame dynamics modelling		[Gantt bar from 12 to 24]							
3. Stochastic flame dynamics modelling		[Gantt bar from 18 to 36]							
Sub-task 1.4 - Evaluation of Modeling/Analysis Tools Upon Full Scale Data From Industrial Partner		[Gantt bar from 30 to 36]							
Task 2 Active Control of Combustion Dynamics		[Gantt bar from 0 to 36]							
Subtask 2.1 - Experimental Studies of Active Control Authority		[Gantt bar from 6 to 36]							
1. Experimental studies of operating condition affects upon active control authority		[Gantt bar from 6 to 18]							
2. Experimental studies of background noise effects upon control authority		[Gantt bar from 12 to 24]							
3. Experimental studies of time delay affects upon control authority		[Gantt bar from 18 to 36]							
Sub-task 2.2 Modeling and Analysis of Active Control Authority		[Gantt bar from 0 to 36]							
1. PDF modeling of parametric noise effects		[Gantt bar from 0 to 6]							
2. PDF modeling incorporating active control terms		[Gantt bar from 6 to 24]							
3. Statistical modeling incorporating time delays		[Gantt bar from 12 to 36]							
Sub-task 2.3 - Control Authority Tests on Full Scale System		[Gantt bar from 18 to 36]							
Write Final Report		[Gantt bar from 30 to 36]							

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



Motivation: Linear and Nonlinear Processes in Unstable Combustors

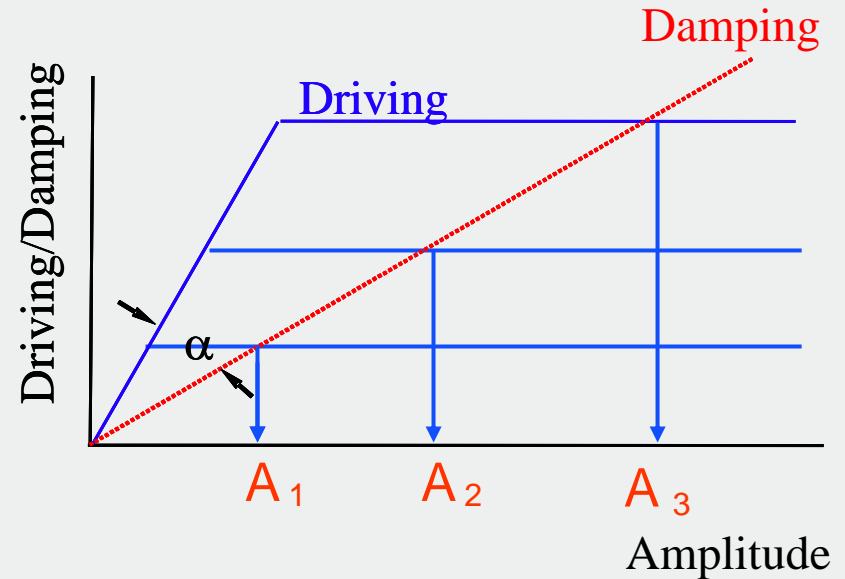
- **Linear processes**

- 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!

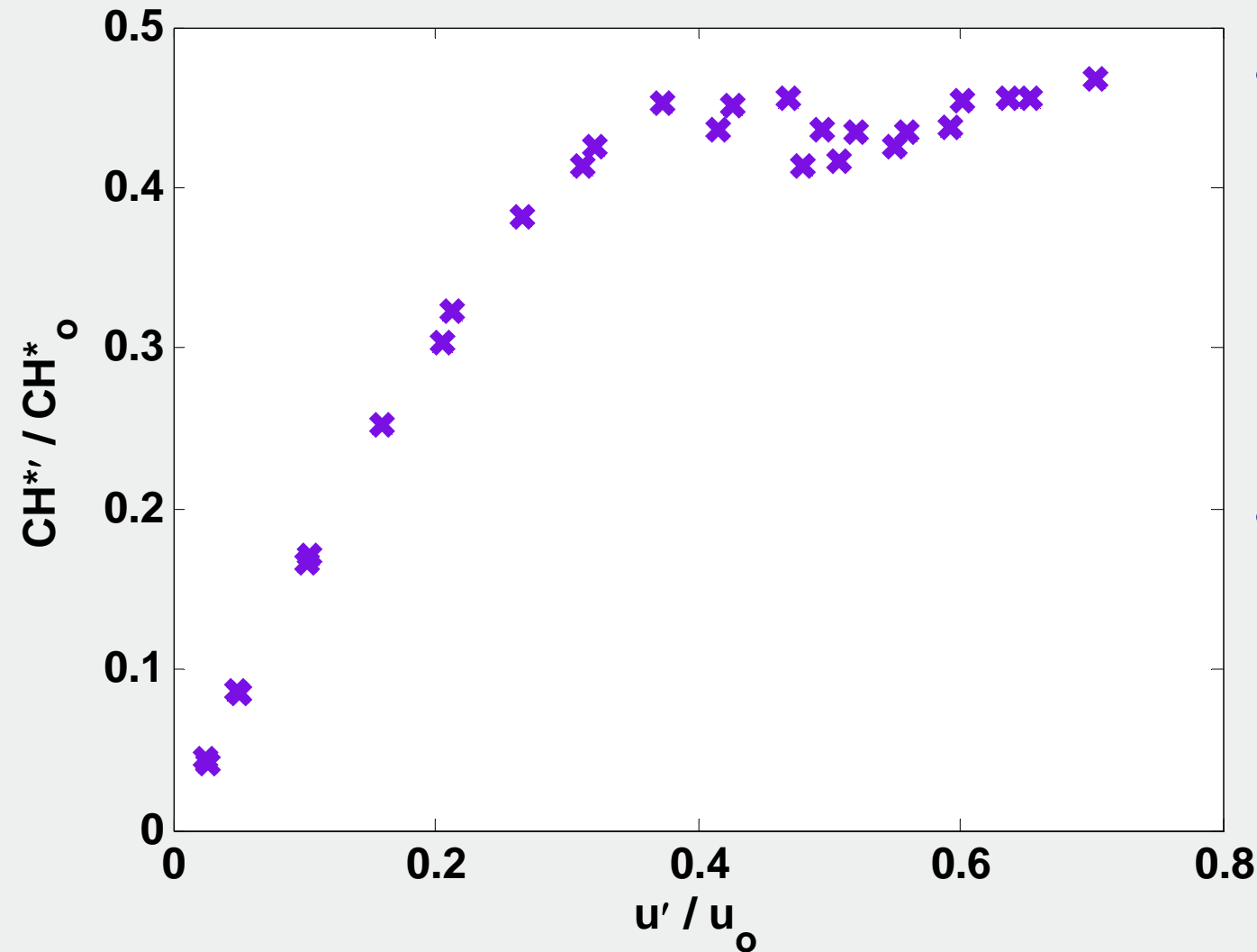
- **Objective of this part of work is to measure shape of “Driving” curve**



Experimental Approach

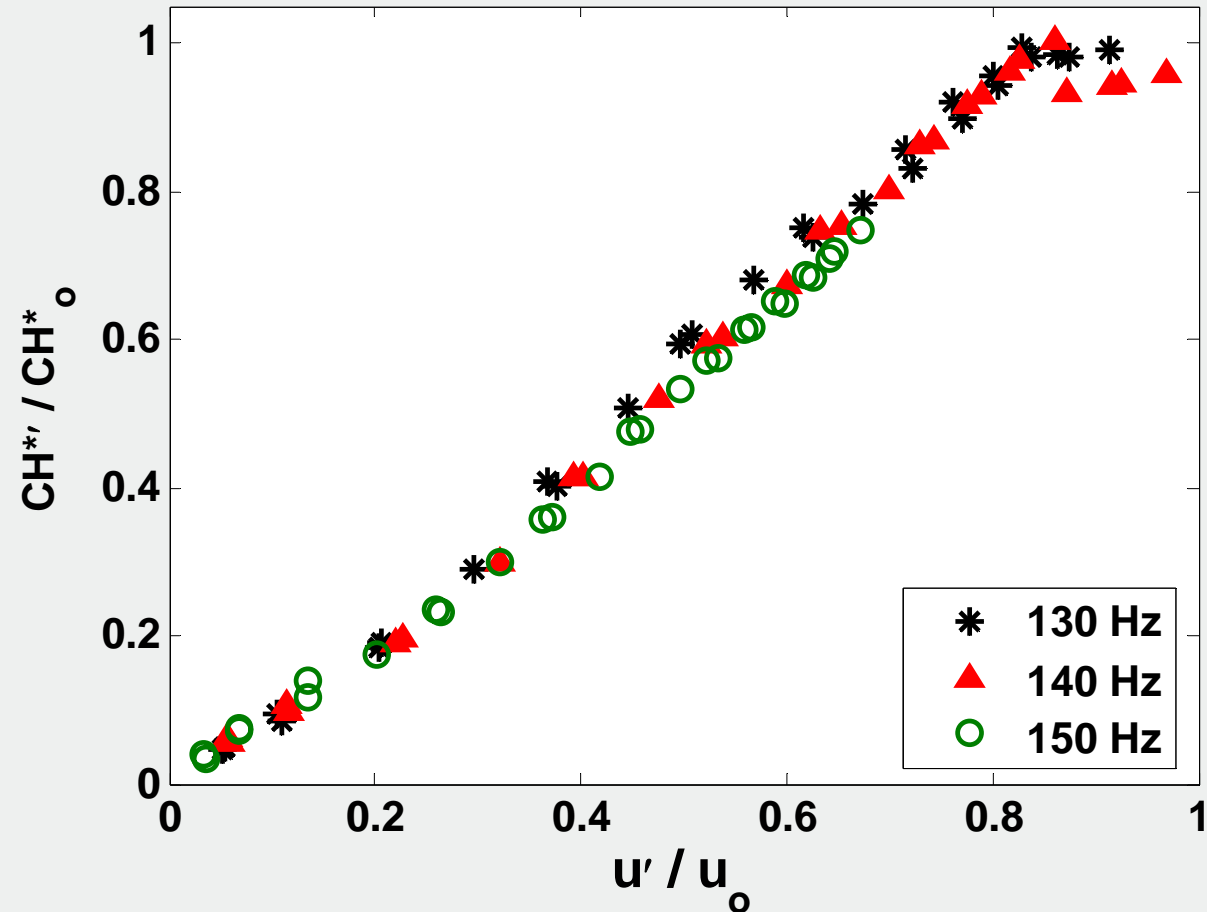
- **Determine transfer function between chemiluminescence and flow forcing amplitude**
 - Dependence upon driving frequency, flow rate, equivalence ratio
 - Reactants premixed ahead of choke point to ensure constant fuel/air ratio
 - Reynolds Number based on premixer exit diameter: 21000 – 43000 (mean 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



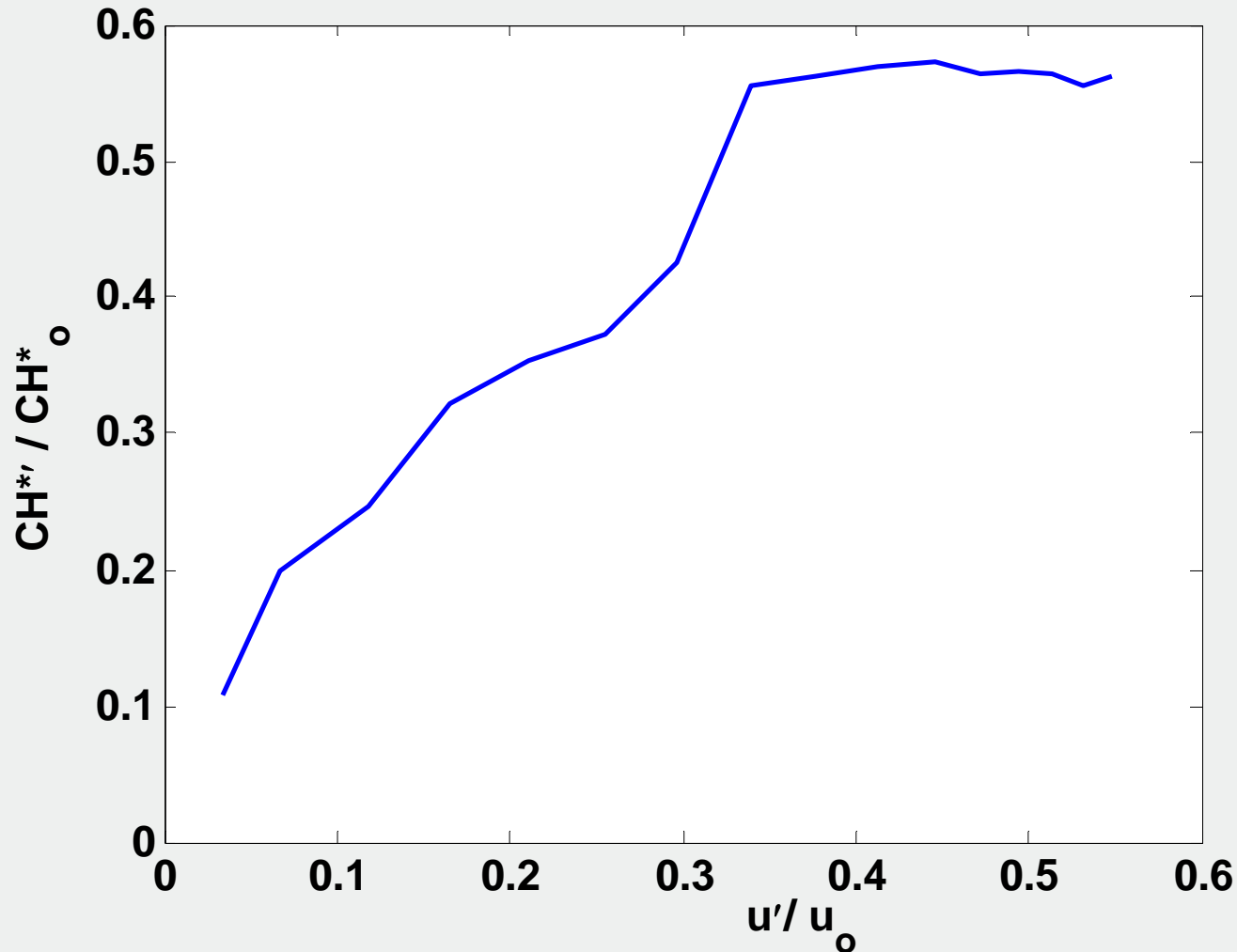
- $CH*' - u'$ relationship remains linear up to $\sim 35\%$ of mean velocity
- $CH*'$ response saturates at large amplitudes of driving

Saturation Amplitude Can Vary Substantially!



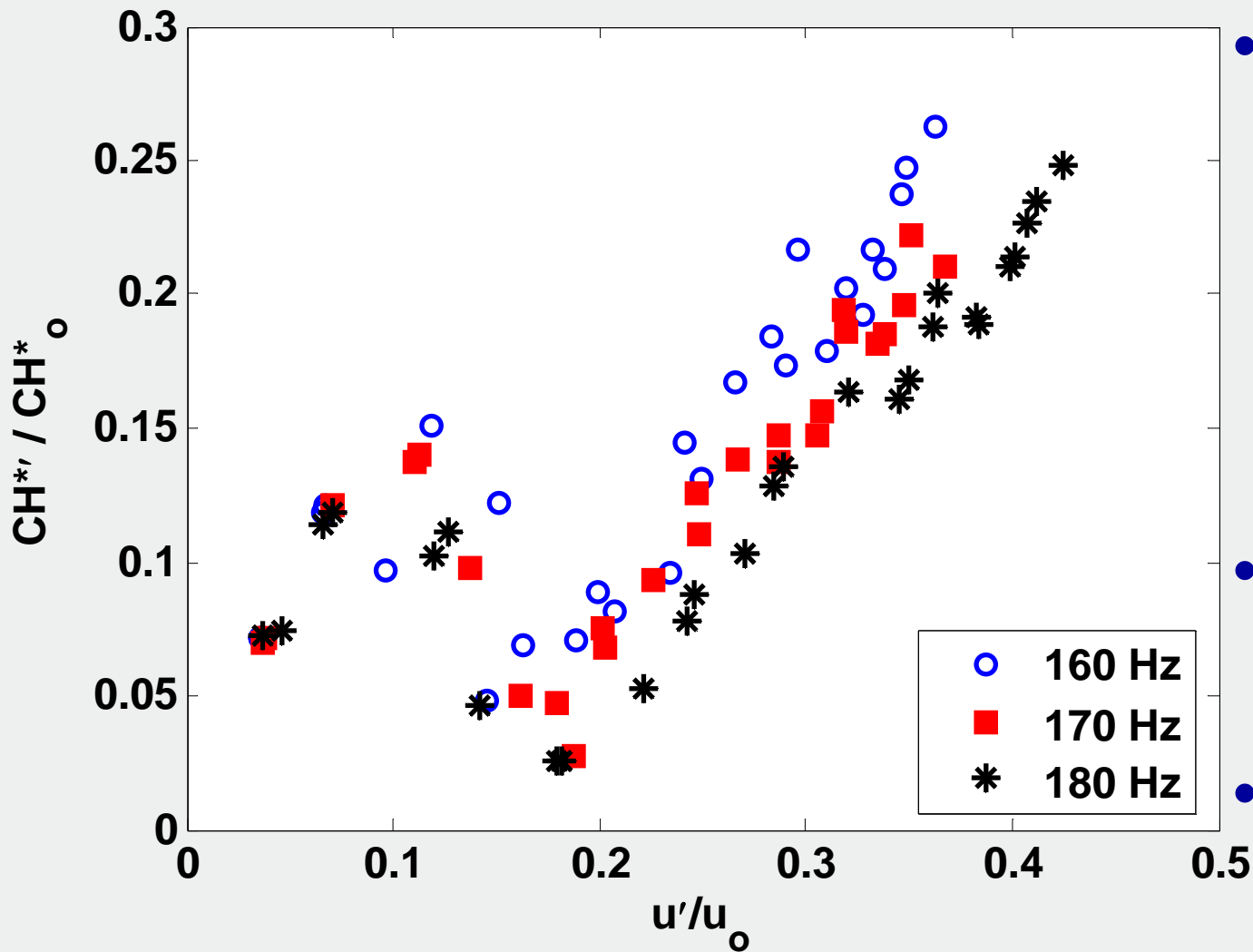
- Similar saturation value as assumed in Dowling nonlinear flame model (temporary global extinction)
- Mechanism is not instantaneous heat release equaling zero here, but flame liftoff

Nonlinear Flame Response More Complicated than Simple Saturation



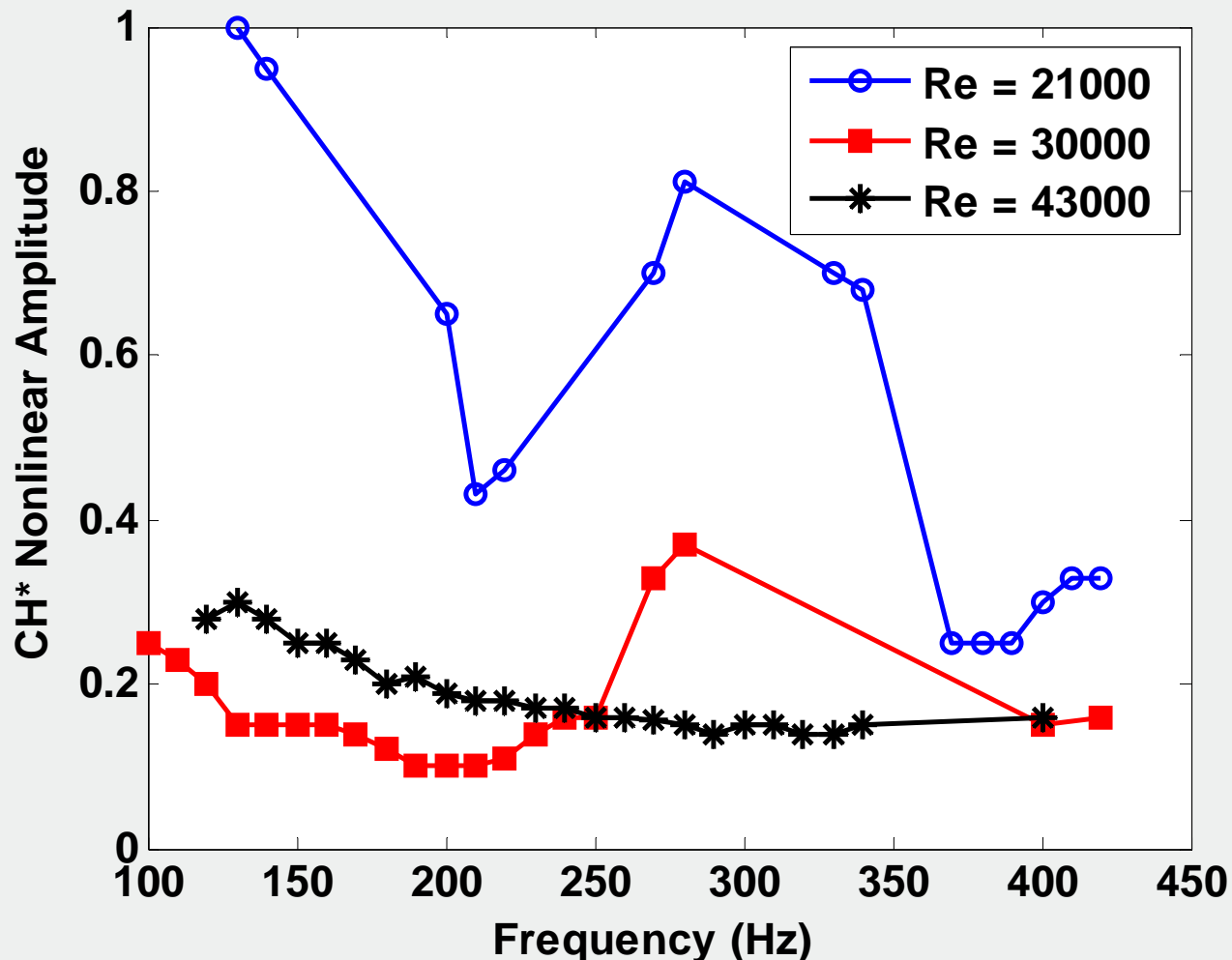
- Very similar behavior to recent observations of Balachandran *et al.* (C&F, 2005)
- Reynolds number ~ 21000 , $f_{\text{drive}} = 410$ Hz

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

Summary of Nonlinear Flame Characteristics

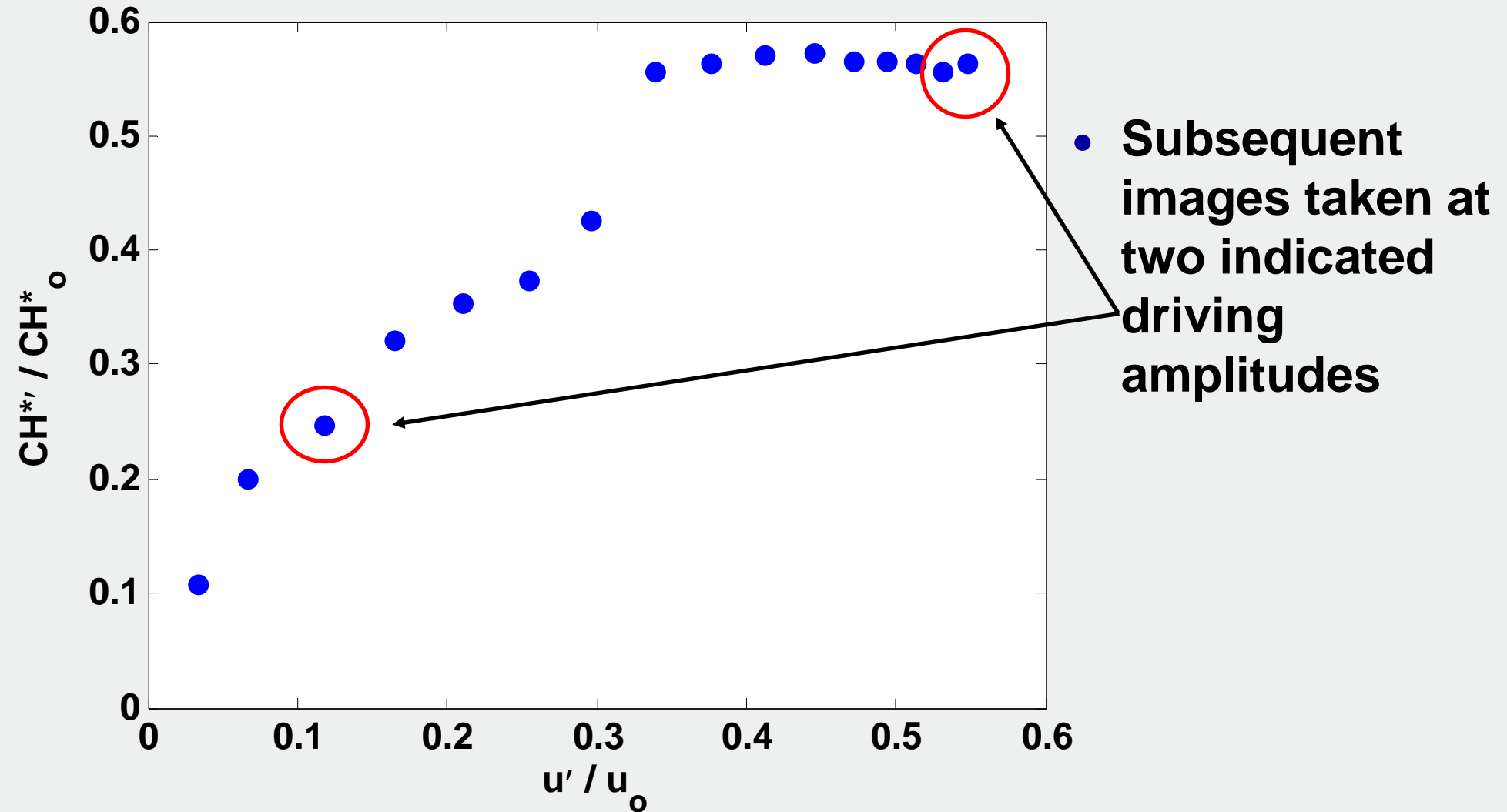


- Characterization of flame nonlinearities substantially more complicated than simple saturation amplitude
- Here, we plot amplitude at which nonlinearity is first observed.
- Results indicate that variety of behaviors (shape, mechanisms) exist in single combustor

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



Low Amplitude Forcing

0°

45°

90°

135°

$F_{\text{drive}} = 410 \text{ Hz}$

Convecting structures can be seen in some images

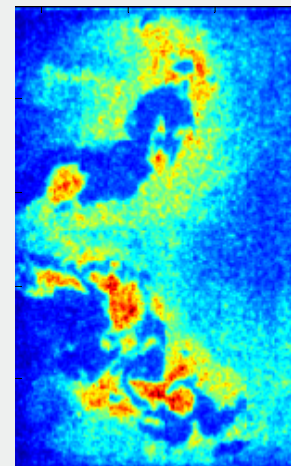
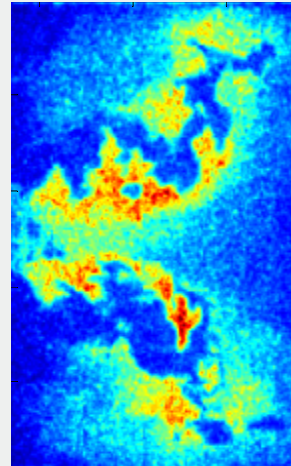
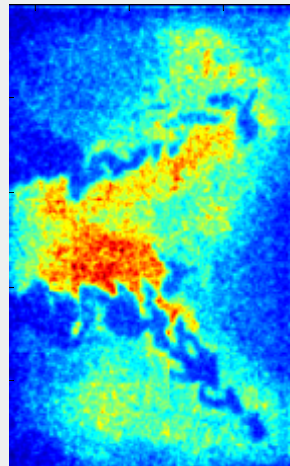
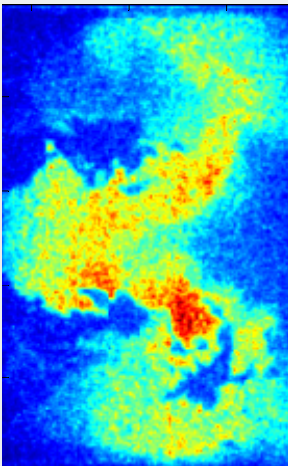
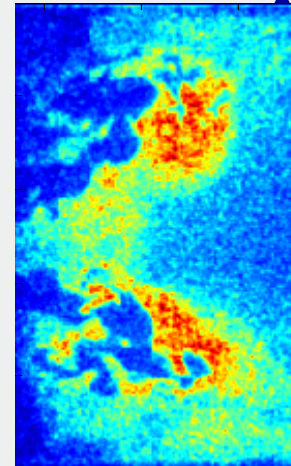
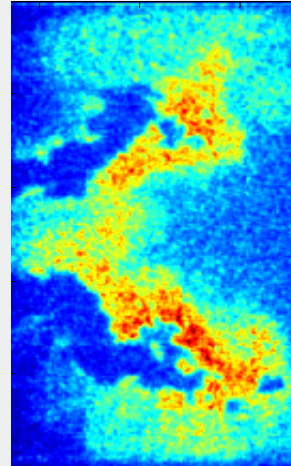
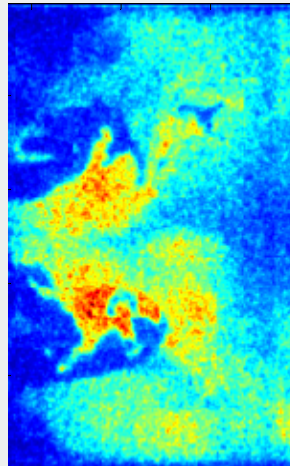
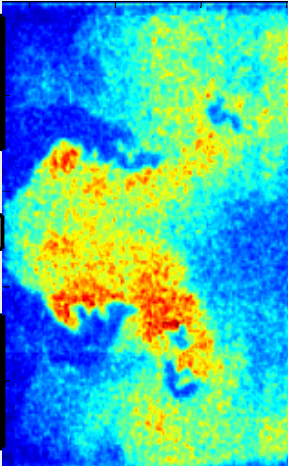
Any suggestions for good averaging techniques that don't turn images into mush?

315°

270°

225°

180°



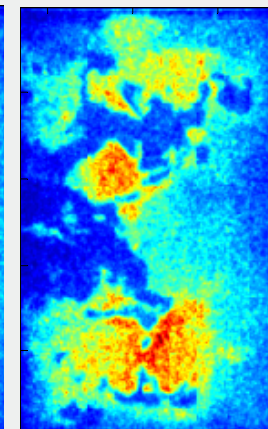
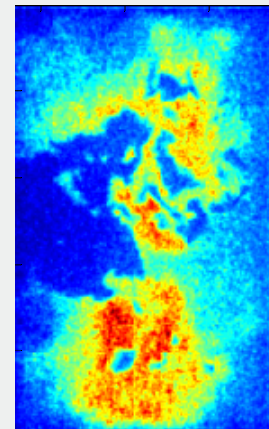
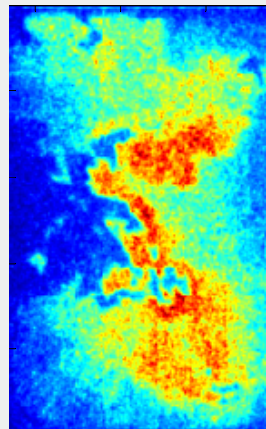
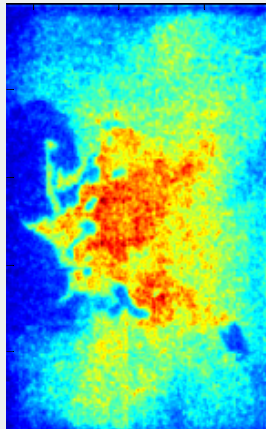
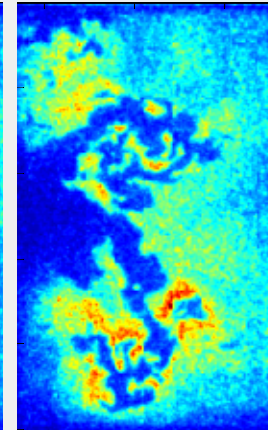
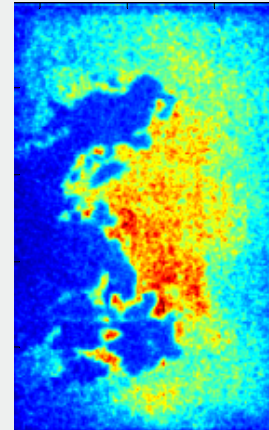
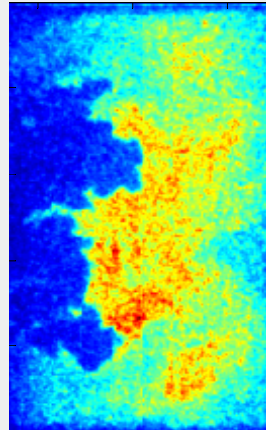
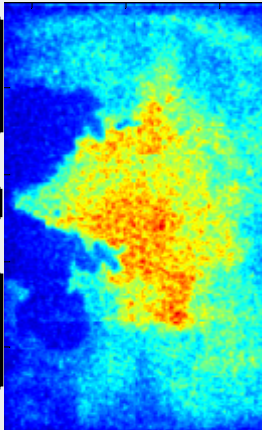
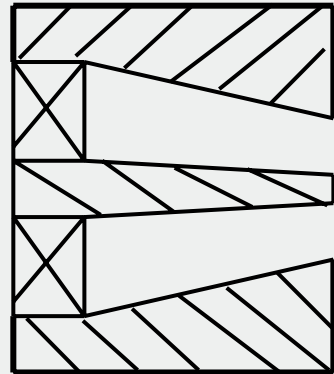
Large Amplitude Forcing

0°

45°

90°

135°



315°

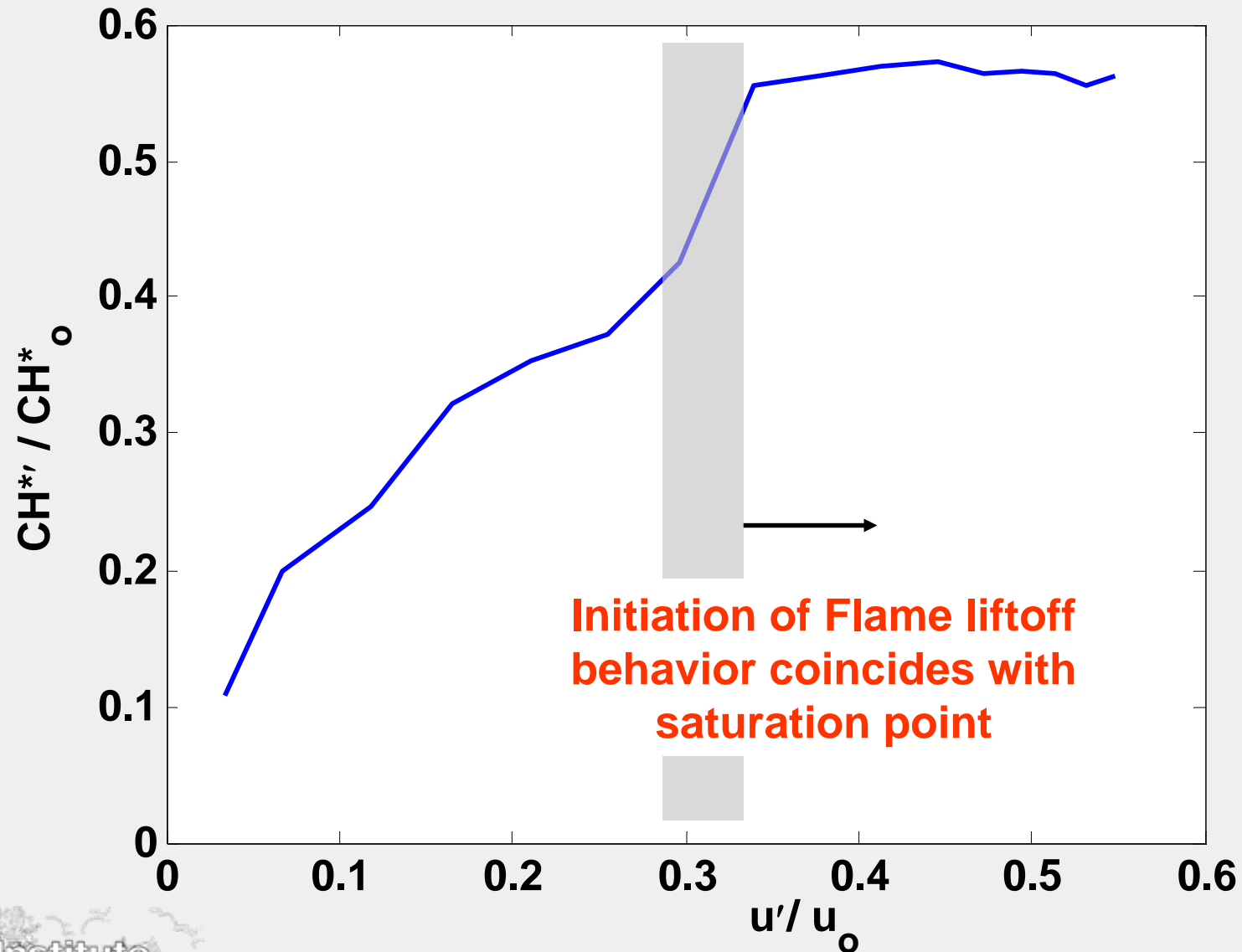
270°

225°

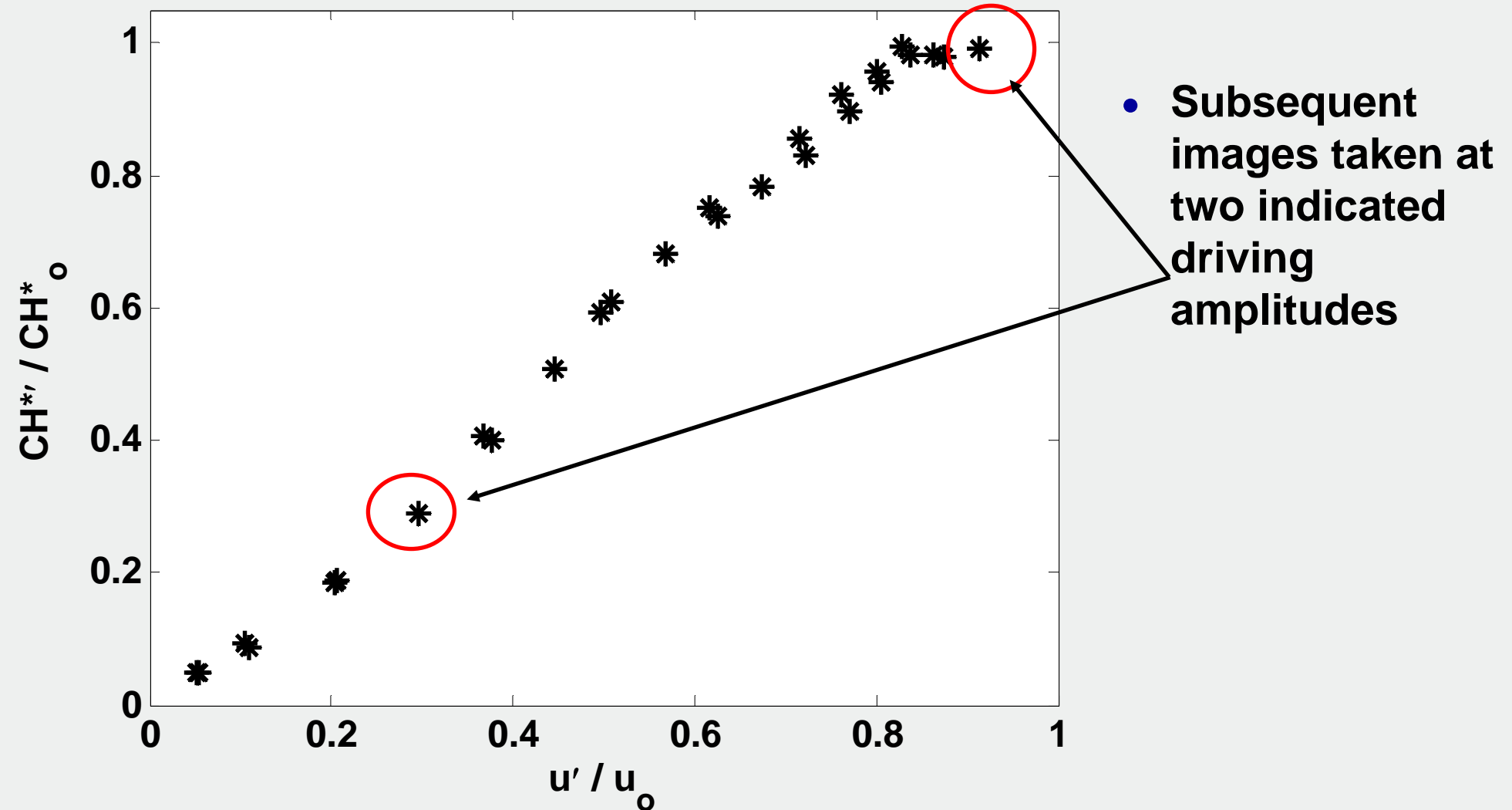
180°

- $F_{\text{drive}} = 410 \text{ Hz}$
- 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



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



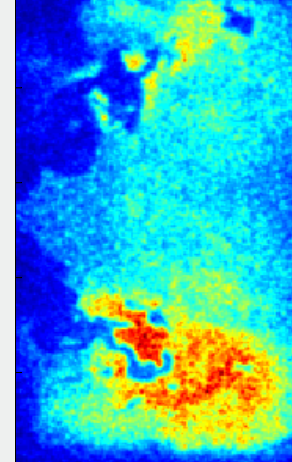
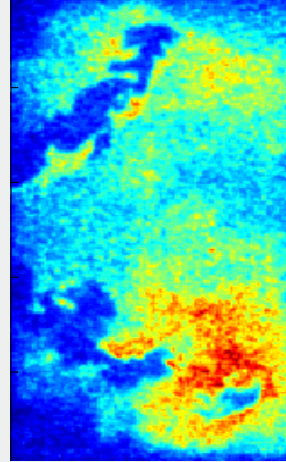
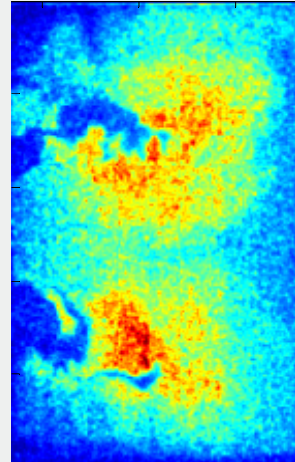
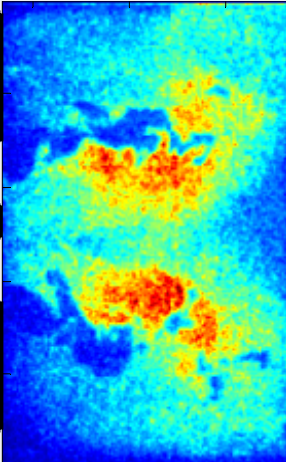
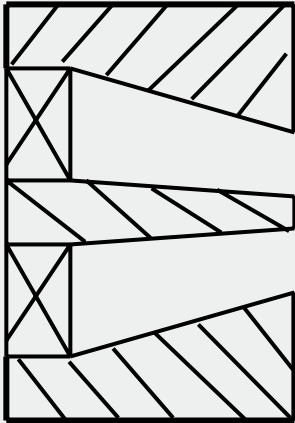
Low Amplitude Forcing

0°

45°

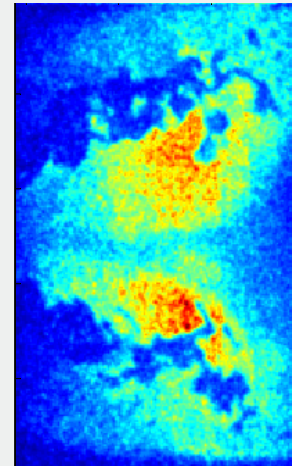
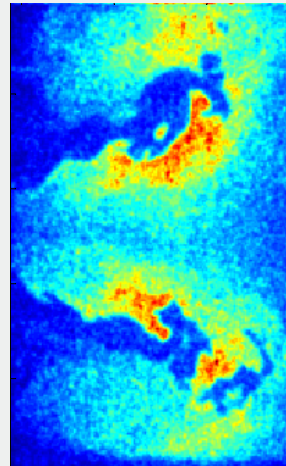
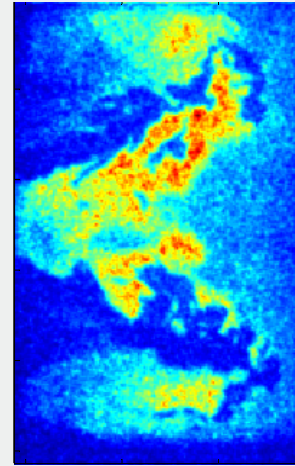
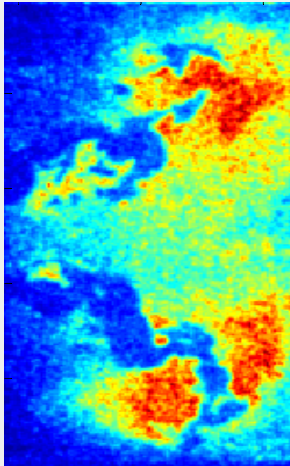
90°

135°



- Well-defined flame position, structure throughout driving cycle

$F_{\text{drive}} = 130 \text{ Hz}$



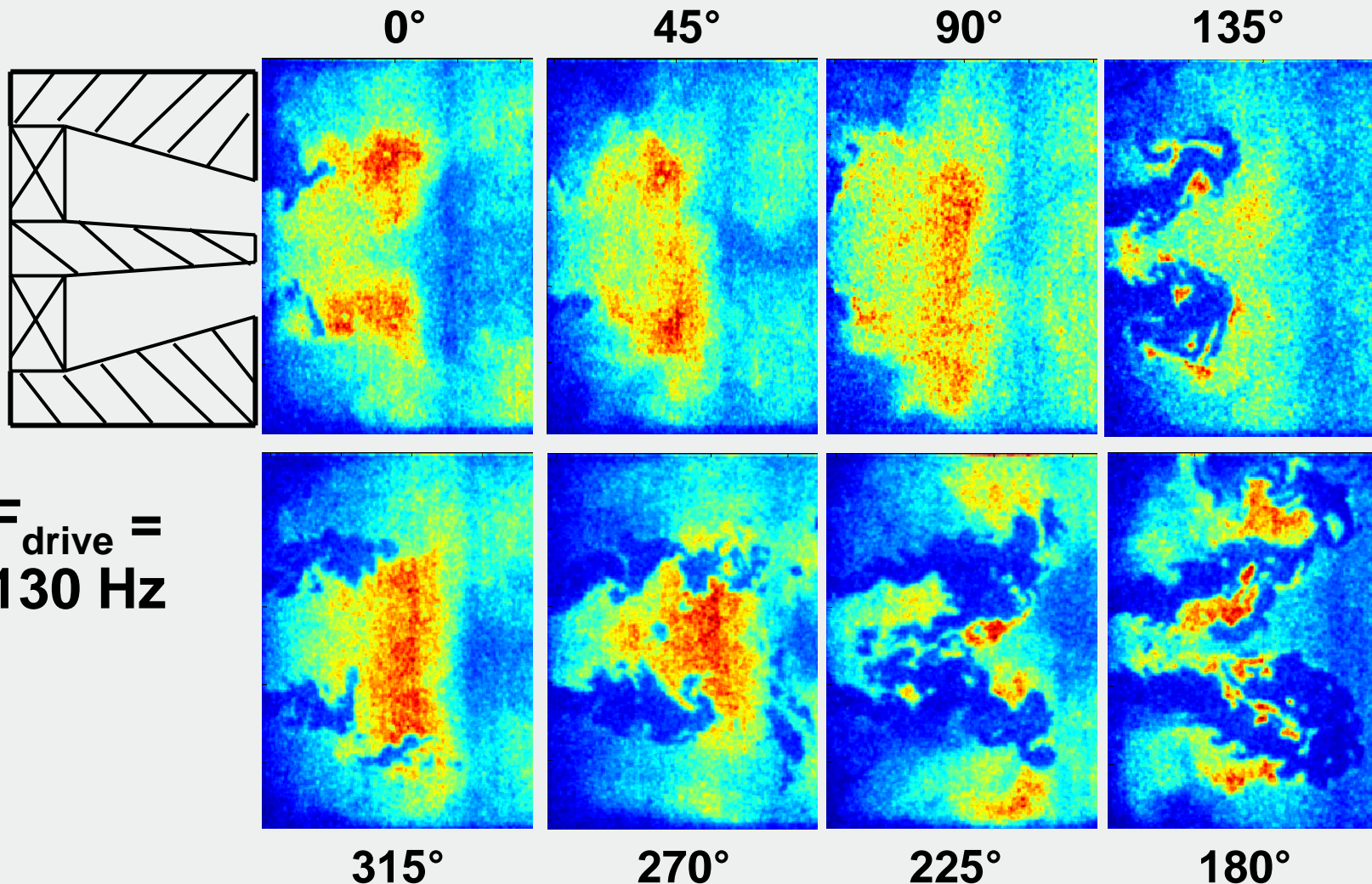
315°

270°

225°

180°

Large Amplitude Forcing



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

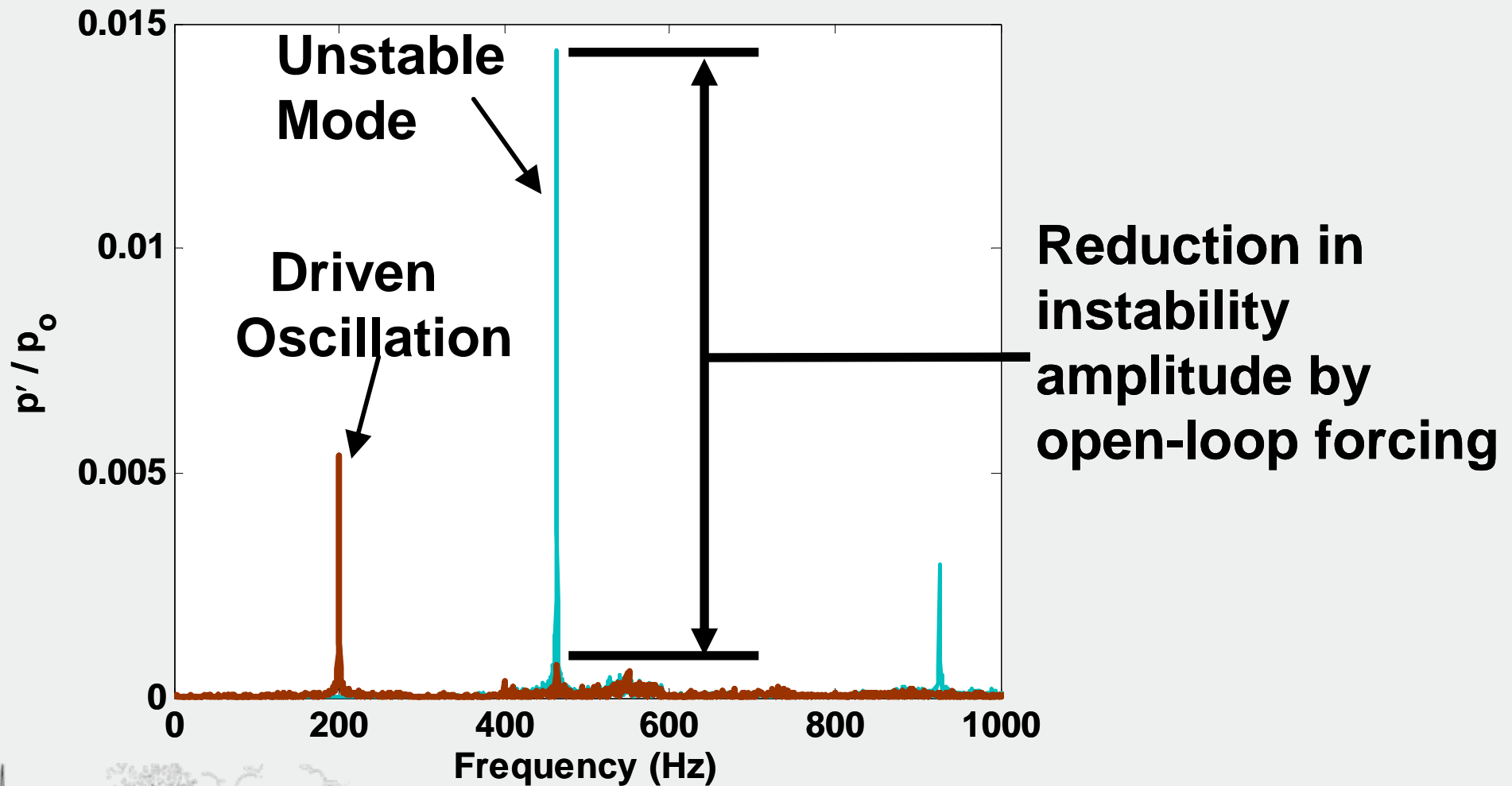
Frequency Locking and Open Loop Control



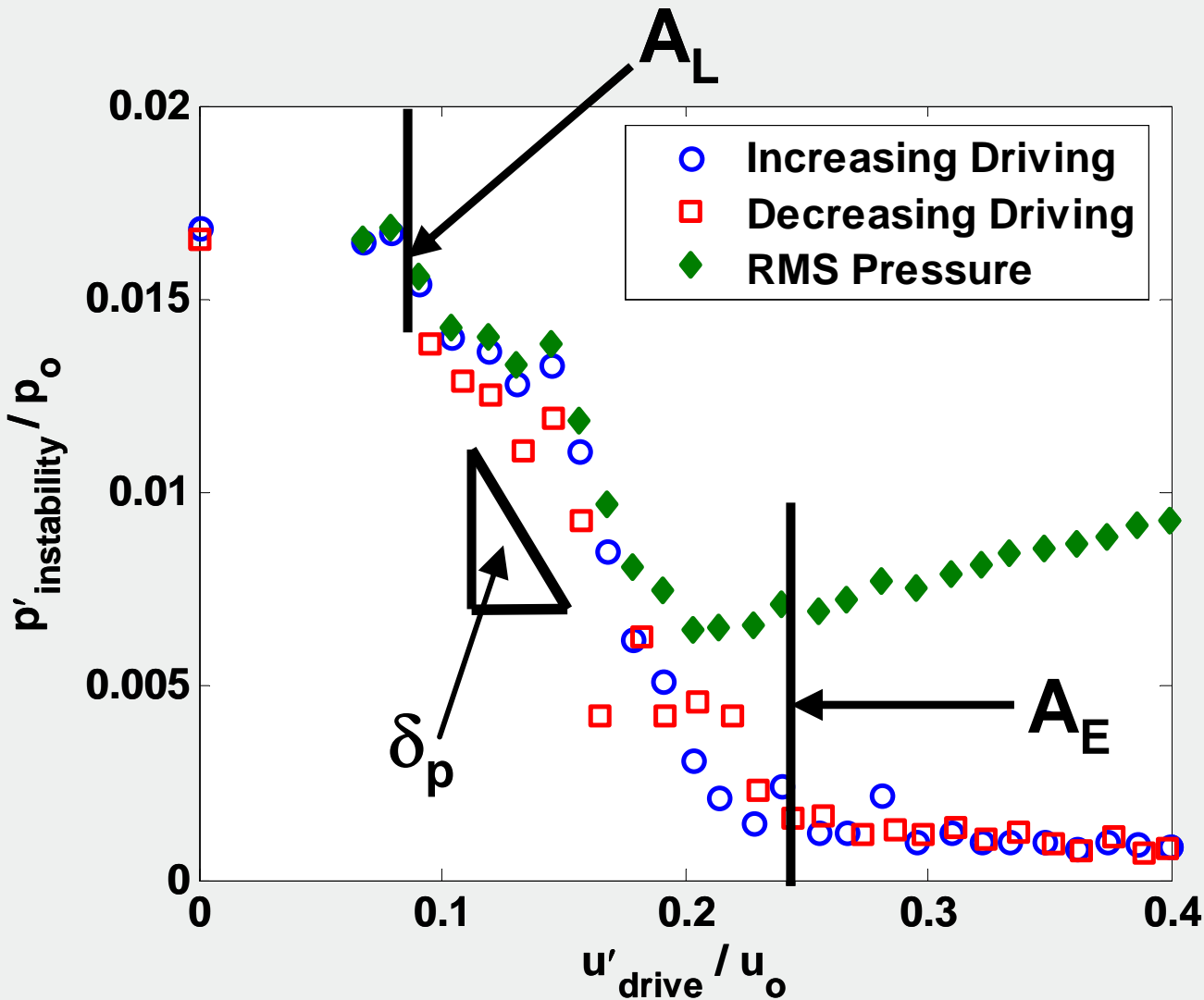
Objective

- 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



Typical Result

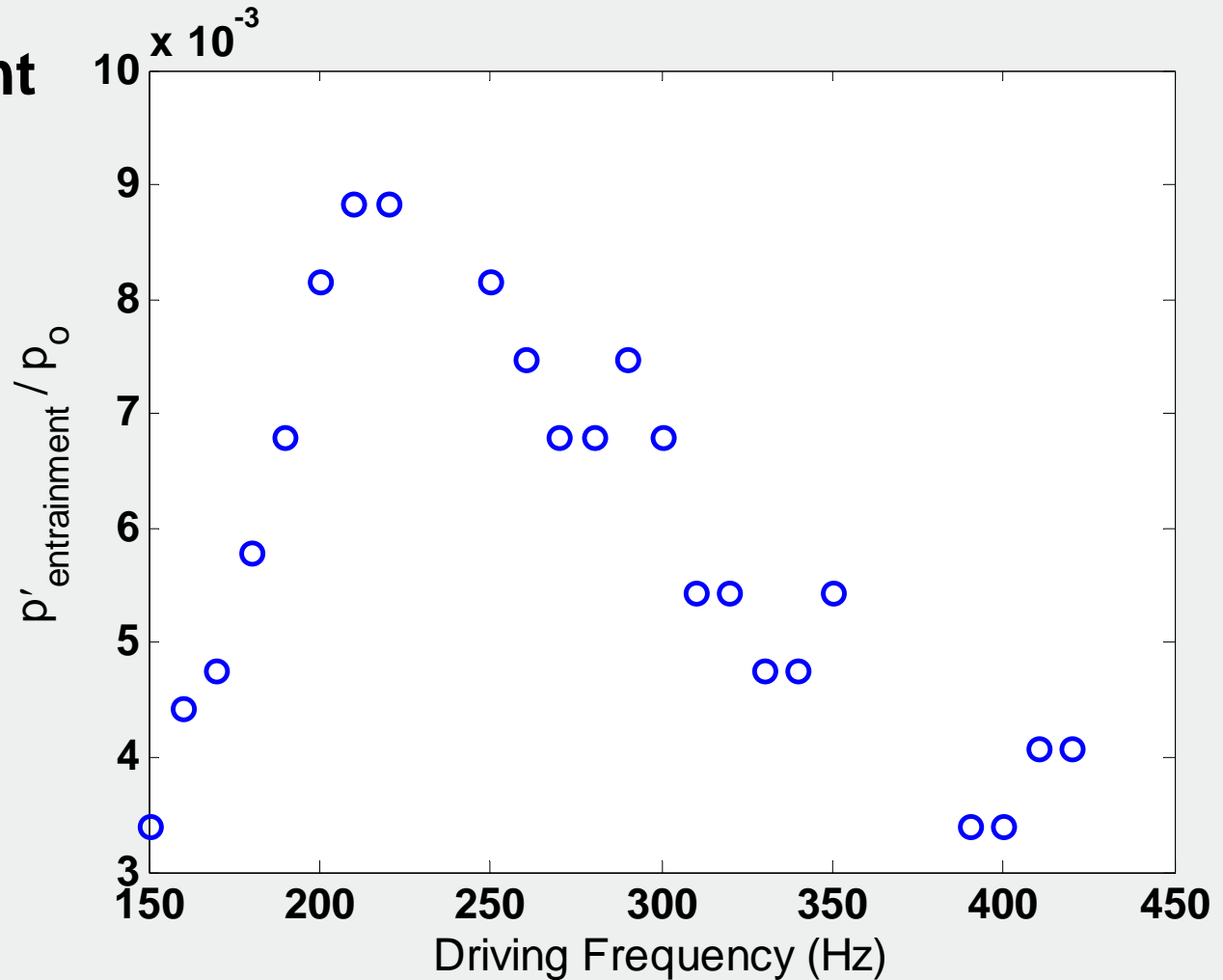


- Investigated parameters in this study

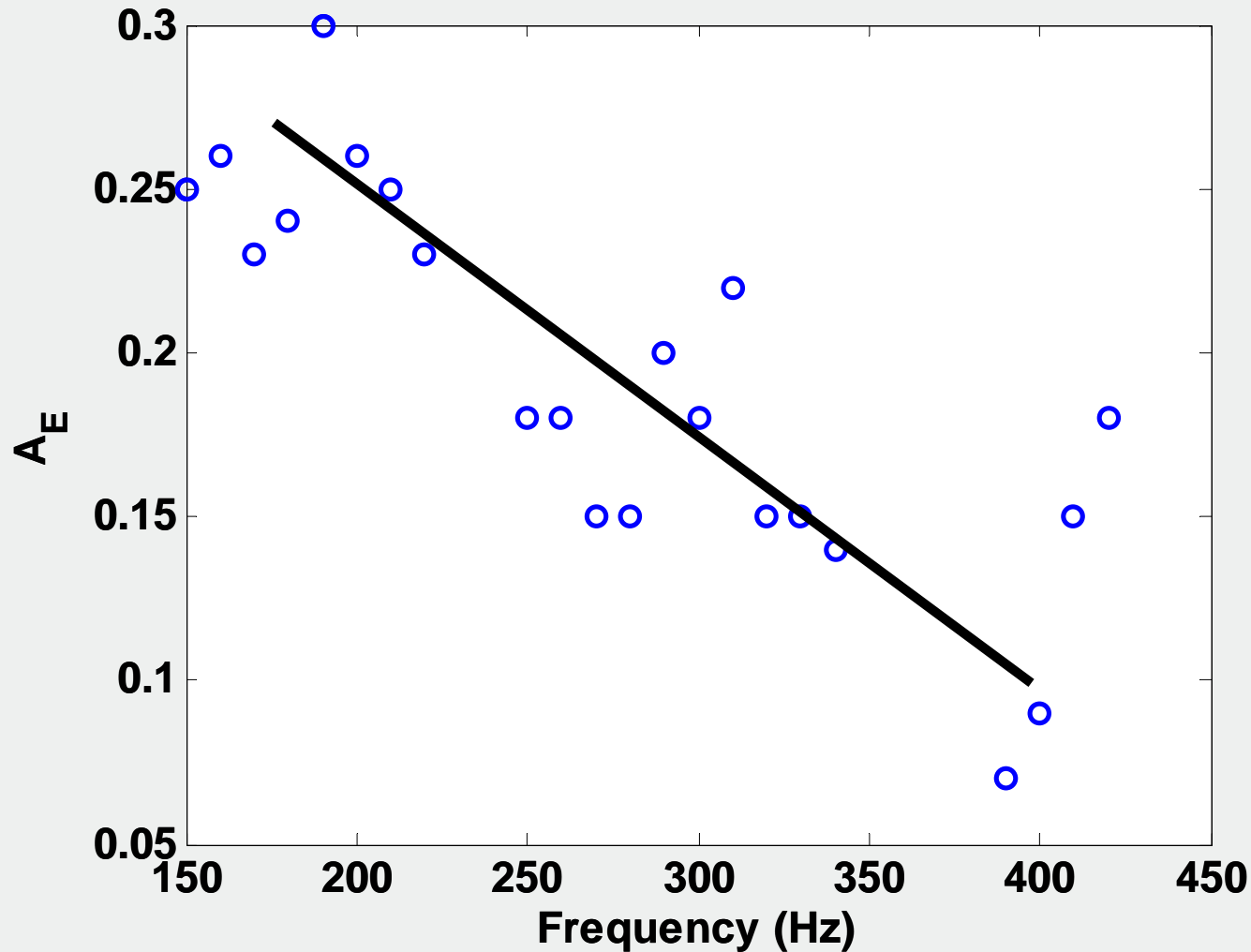
- Ledge Width, A_L
- Instability Rolloff, δ_p
- Entrainment Amplitude, A_E

Pressure Entrainment Amplitude Characteristics

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

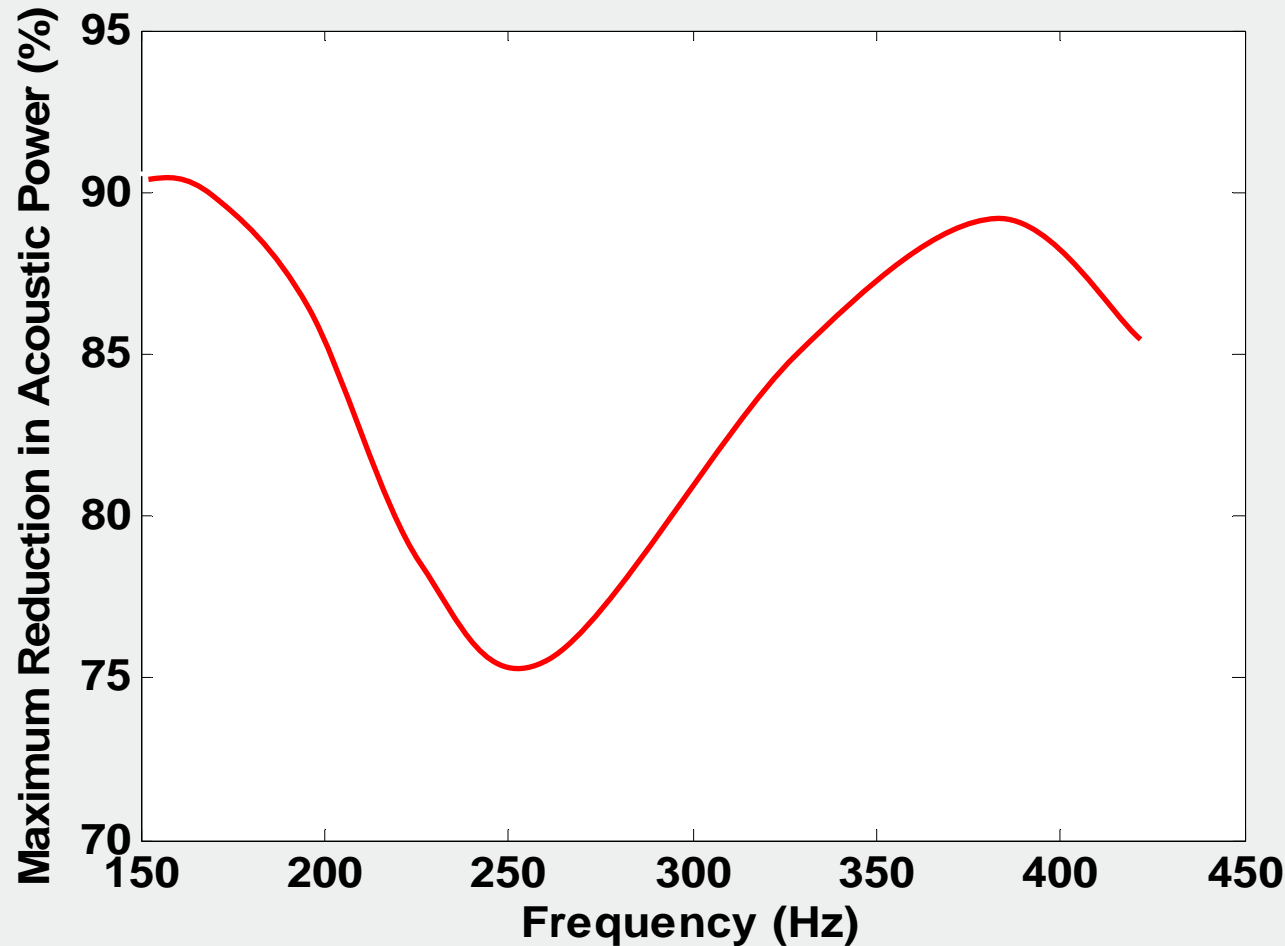


Entrainment Amplitude Characteristics



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

Acoustic Power Reduction



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

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.**