Prediction of Combustion Stability and Flashback in Turbines with High-Hydrogen Fuel

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Motivation

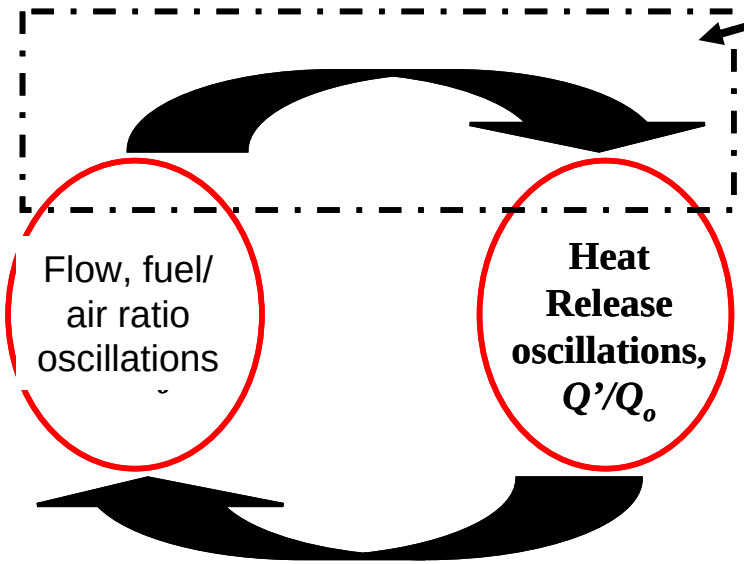
- *Need:* Gas turbines with sufficient flexibility to cleanly and efficiently combust high H_2 fuels
- *Need:* Combustion systems that can stably operate over a wide turndown range
- *Problem*: Combustion instabilities have posed one of most significant issues encountered in low NOx gas turbines
  - Fuel variability poses significant challenges in developing stable combustors

Objectives and Approach

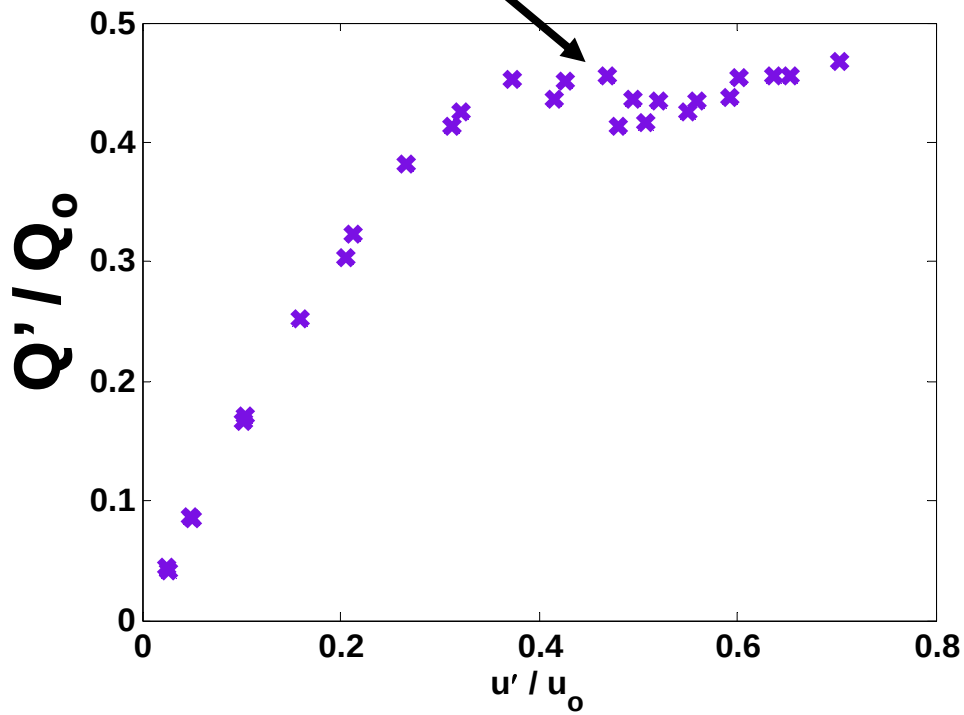
- Objective: Improve understanding of combustion dynamics in high H_2 fueled turbines

- Approach: Parallel theoretical, experimental and computational investigations of
  - Flame response to fuel/air ratio and velocity oscillations
  - Understand phenomenology and how it is influenced by fuel composition

Research Objective



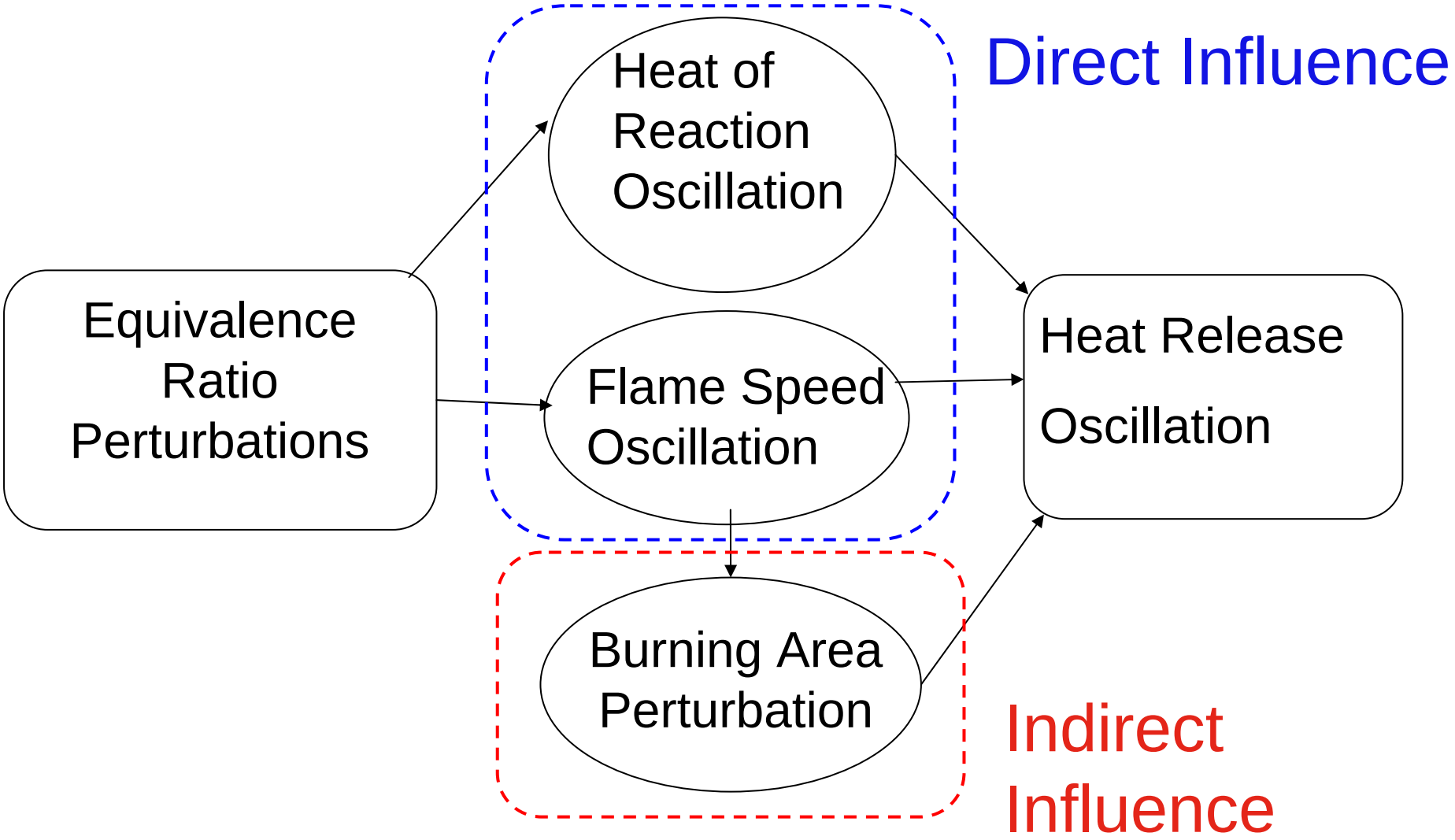
Key unsolved problem;
Very nonlinear relationship



- **Slope in linear regime needed to predict conditions under which instabilities occur**
- **Nonlinear characteristics needed to predict instability amplitude**

Analysis of Flame Response to Fuel/Air Ratio Oscillations

Equivalence Ratio Perturbation Mechanism: Fundamental Processes

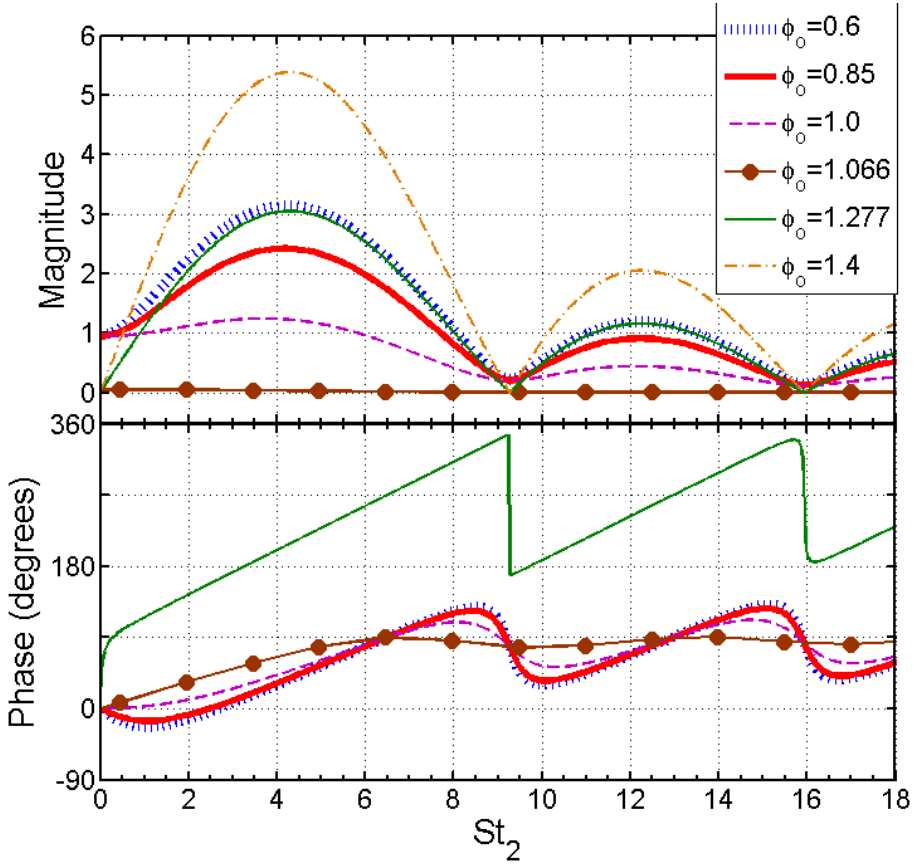


Equivalence Ratio Perturbation Mechanism: Fundamental Processes

- Objectives
  - Identify mechanisms leading to nonlinear heat release response to equivalence ratio perturbations
  - Generalize prior analysis to include non quasi-steady effects

Linear Flame Response

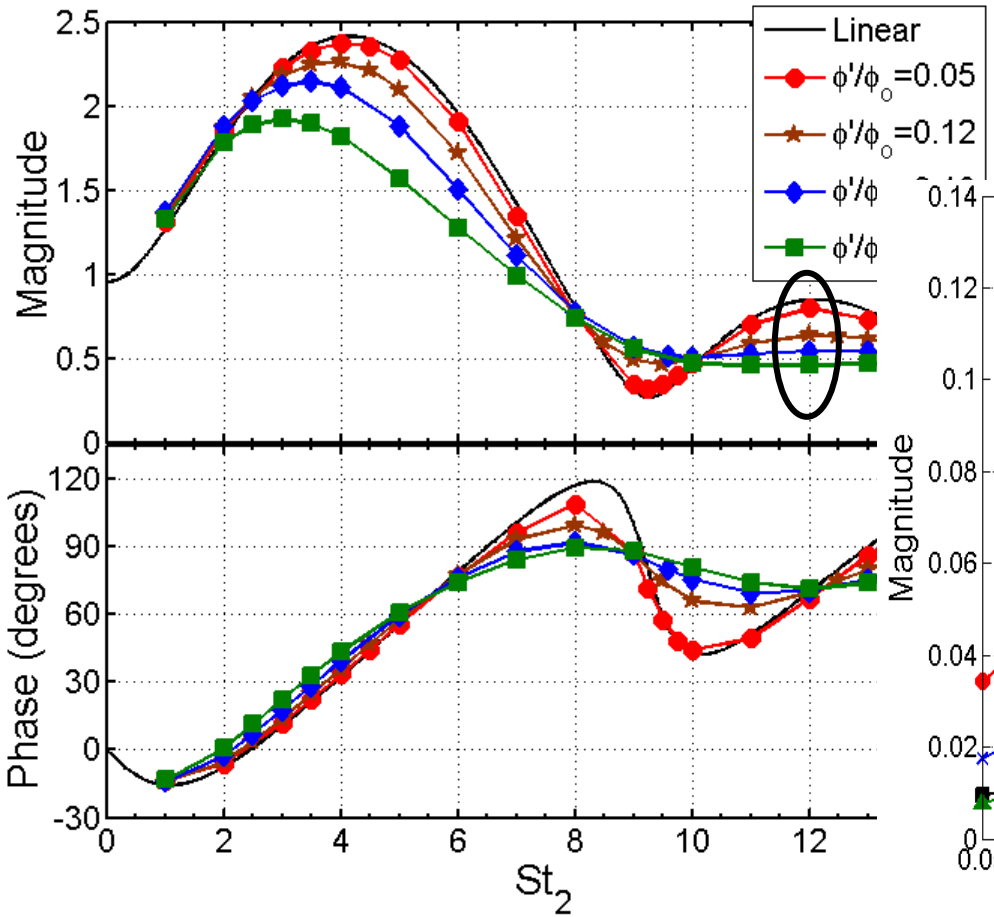
- Response determined by linear sensitivities
  - Flame speed: $\frac{1}{\phi_o}\frac{ds_L}{d\phi_o}$
  - Heat of reaction: $\frac{1}{\phi_o}\frac{dh_R}{d\phi}$
- Flame speed and burning area contributions balance at low excitation frequency
- Vanishingly small low frequency response for rich flames



Transfer Function = $\frac{\hat{q}(\omega)/q_o}{\phi'/\phi_o}$

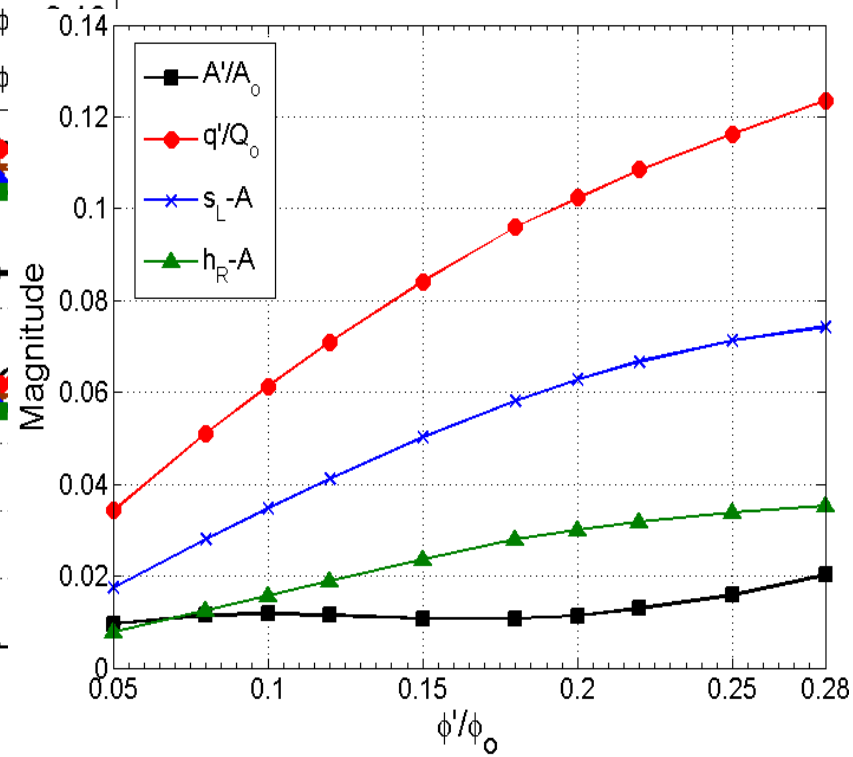
Non-Linear Response - Lean

Transfer Function



- ϕ_o=0.85

Heat release response



Key Findings

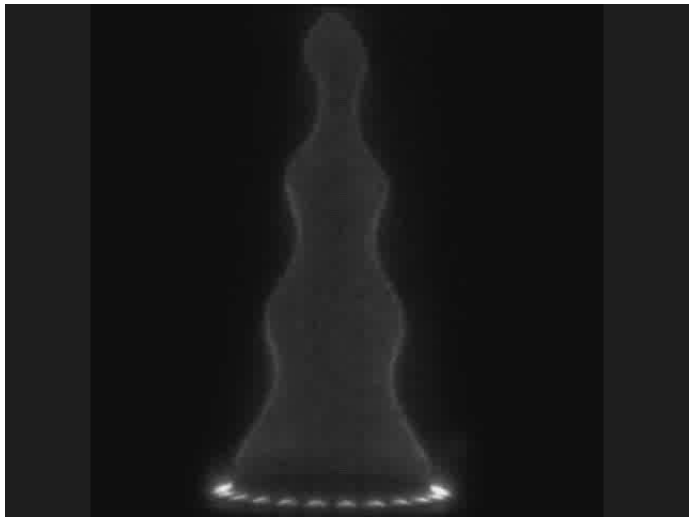
- Two fundamental mechanisms of non-linearity
  - Kinematic Non-Linearities
    - Occurs at high excitation amplitudes and frequencies
  - Nonlinear ϕ-h_R-s_L relationship -
    - Quasi steady nonlinear relations between ϕ-h_R and ϕ-s_L
    - "Cross-over" Occurs when equivalence ratio oscillations cross over from one region in stoichiometric space to another

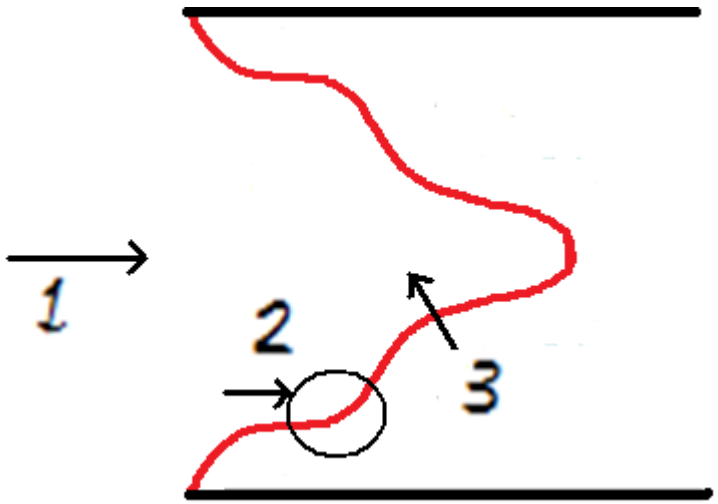
- Non quasi steady effects
  - Negligible at typical GT conditions
  - Very important for typical conditions at ambient P and T

Analysis of Flame-Acoustic Field Coupling

Flame-Acoustic Flow Field Interactions

- Harmonic excitation of flame results in convecting wrinkles propagating at speed of U_o
- Low amplitude acoustic excitation
  - Waves reflect off impedance discontinuity, form complex, multi-dimensional standing wave field
- High amplitude acoustic excitation
  - Convecting flame wrinkles influence character of upstream disturbance field
  - Gives it a local, convecting component





Analogy – Acoustic "Wavy Wall" Problem

- Consider wave moving along boundary at speed U_c
  - Excites acoustic field with phase velocity of U_c in axial direction
  - Flame looks like finite impedance "wavy wall"

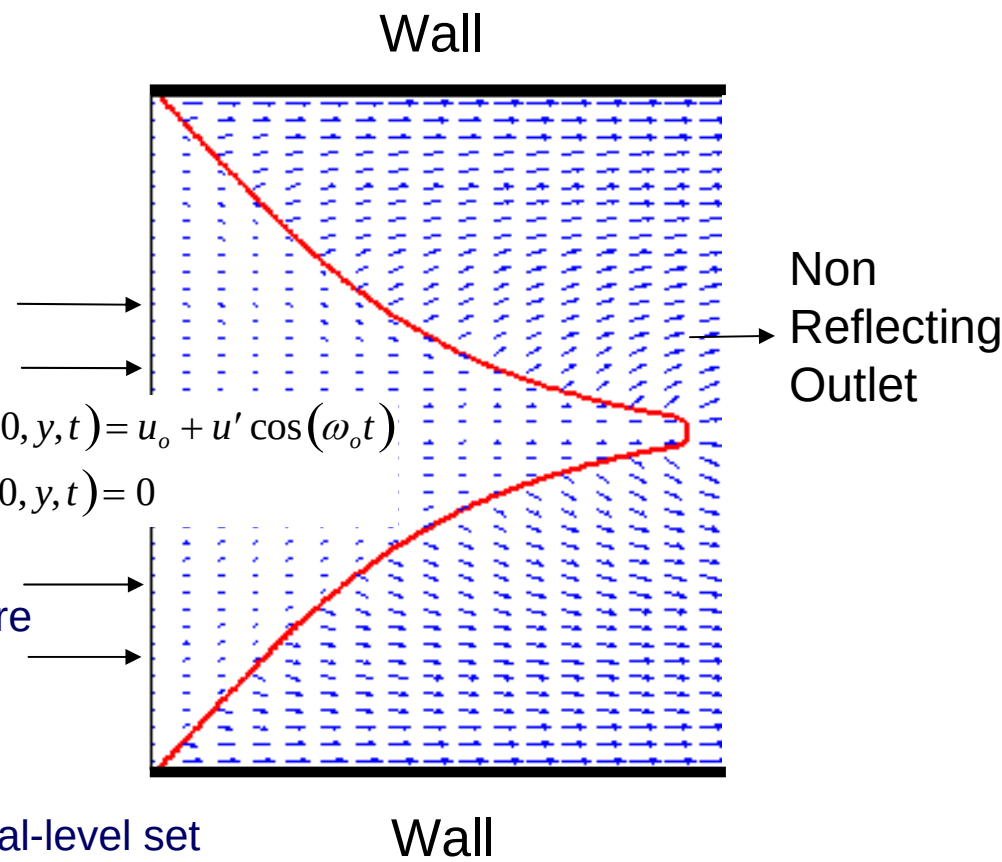
- Research Questions:
  - Are disturbances with phase speed $U_c \sim U_o$ purely vortical or do they have an acoustic component?
  - What are relative magnitudes?
  - Problem requires computational approach, as not possible to eliminate vortical disturbances in experiment

Numerical Formulation

- Flow solution
  - Compressible inviscid Euler equations
- Flame front tracking
  - Level set approach
  - Represent the flame as a contour of a 2D surface $z = G(x,y)$
  - Evolve surface in time using P.D.E.

$$\frac{\partial G}{\partial t} + \vec{v}.\nabla G = s_L \left|\nabla G\right|$$

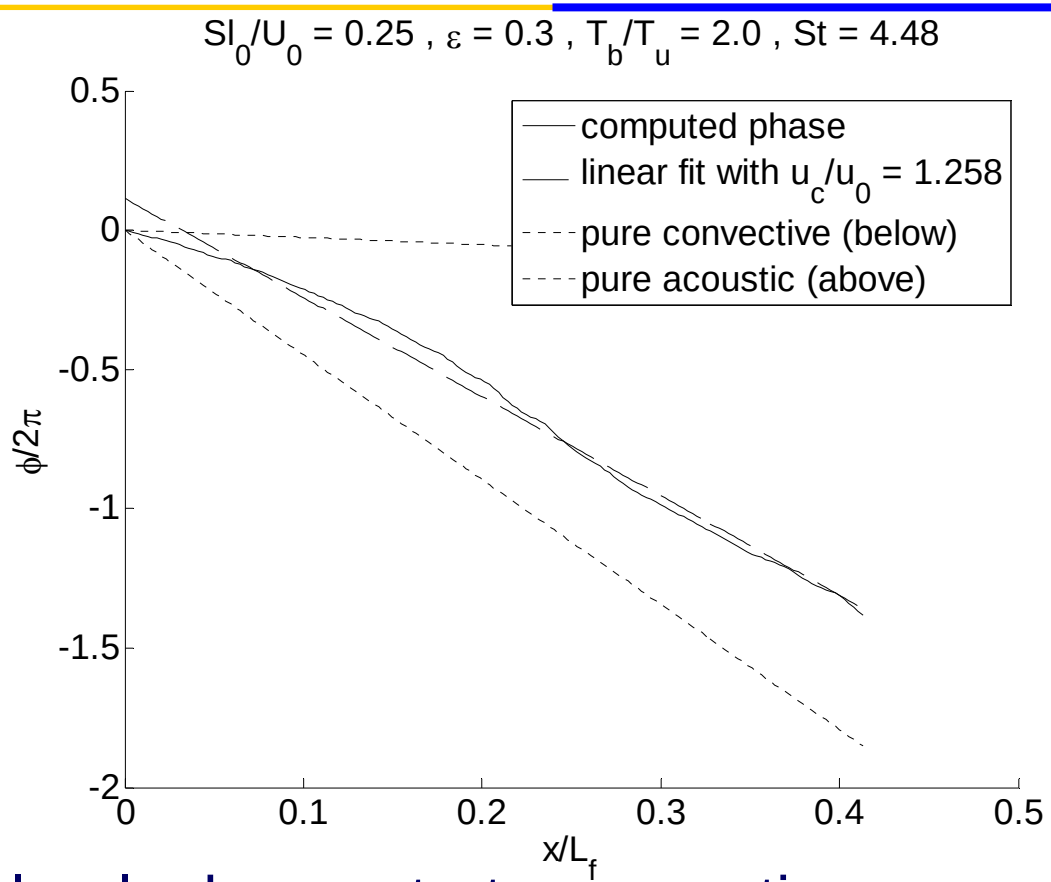
  - Ghost Fluid Method to implicitly capture temperature jump at flame
  - flame speed depends on local curvature
- Numerical scheme
  - 5th order (WENO) in space
  - 3rd order in time (TVD-RK3)
  - Implemented using the LSGEN2D local-level set framework



$$u(x=0,y,t) = u_o + u' \cos(\omega_o t)$$

$$v(x=0,y,t) = 0$$

Phase Of Flame: Centerline Velocity Difference



- Result clearly demonstrates acoustic component has phase velocity component that propagates axially *with velocity proportional to mean flow*

Key Findings

- Acoustic interaction with flames excites
  - Traveling wave vortical structures propagating at local flow velocity
  - Complex standing wave composed of long wavelength acoustic disturbances propagating at sound speed
  - Acoustic disturbances in flame nearfield with phase velocity (not group velocity) related to flow velocity

- In general, convecting phase velocity measurements could be indicative of vortical or acoustic disturbances

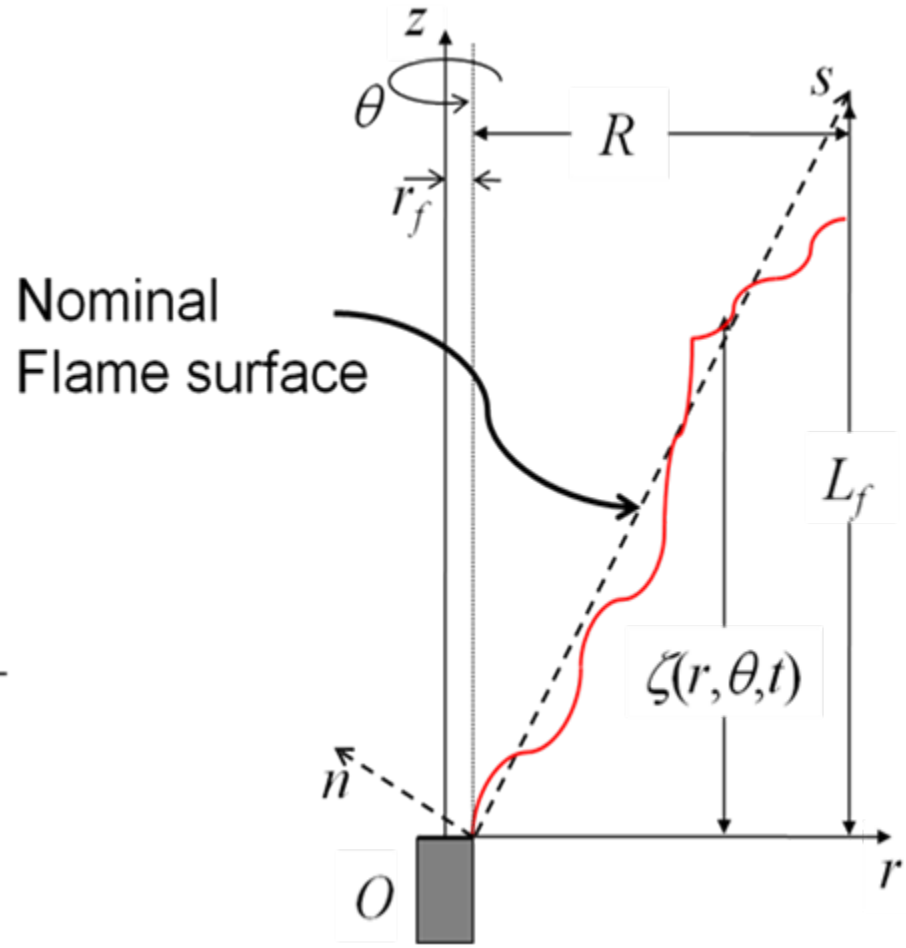
3rd Order Perturbation Analysis of Velocity Response of Turbulent Flames

Theoretical Framework

- Extensive prior work using level set based formulations to rigorously analyze laminar flame response to flow oscillations
  - Current implementations assume that this can be generalized to turbulent flames by replacing S_L by S_T
- Study objective: Perform perturbation analysis of turbulent flame response to flow oscillations
- Approach:
  - Consider flame response to superposition of broadband (turbulent) and narrowband flow oscillations

$$\frac{\partial \zeta}{\partial t} + \frac{u_\theta}{r}\frac{\partial \zeta}{\partial \theta} + u\frac{\partial \zeta}{\partial r} - v = -s_L\sqrt{1 + \frac{1}{r^2}\left(\frac{\partial \zeta}{\partial \theta}\right)^2 + \left(\frac{\partial \zeta}{\partial r}\right)^2}$$

- Using asymptotic expansions to find solutions
  - System of stochastic PDEs for the instantaneous flame shape



Theoretical Framework

- Asymptotic expansion

$$\zeta(r,t)=\left[\zeta_o(r)+\varepsilon_T\zeta_{1t}(r,t)+\varepsilon_T^2\zeta_{2t}(r,t)+O\left(\varepsilon_T^3\right)\right]$$
$$+\varepsilon_a\left[\zeta_{1c}(r,t)+\varepsilon_T\zeta_{2ct}(r,t)+\varepsilon_T^2\zeta_{3ctt}(r,t)+O\left(\varepsilon_T^3\right)\right]+O\left(\varepsilon_a^2\right)$$

- Typical form of the system of PDEs

$$\frac{\partial\zeta_{1t}}{\partial t}+a\frac{\partial\zeta_{1t}}{\partial r}=\frac{f_n\left(r,\theta,z=r-r_f,t\right)}{\sqrt{1-a}}$$

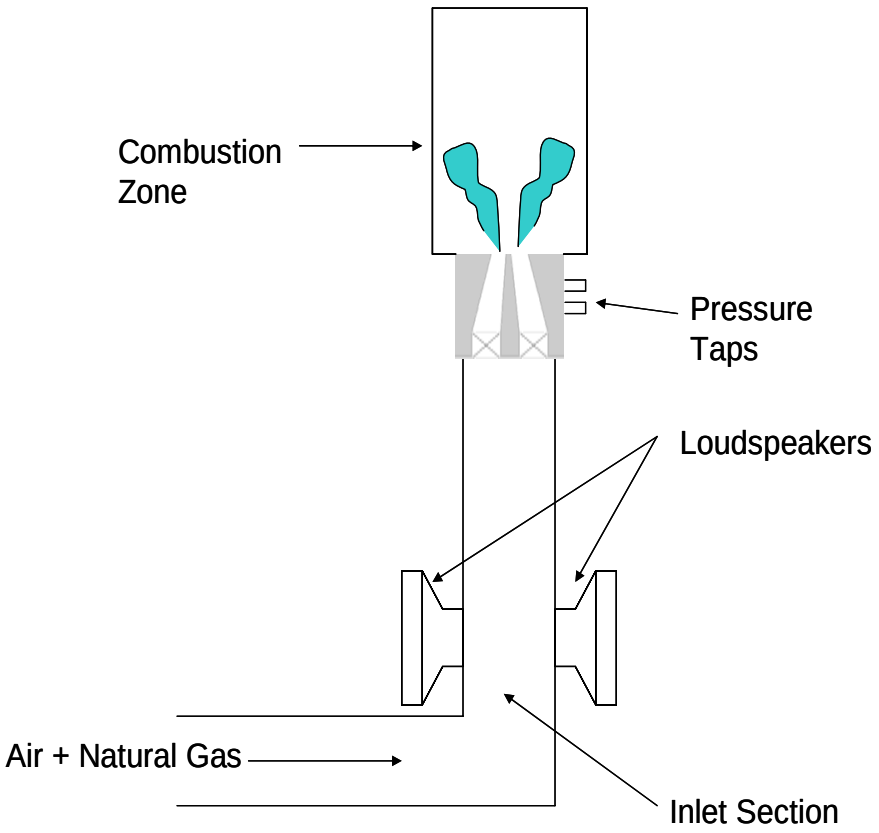
Advection along flame

Local source (turbulence)

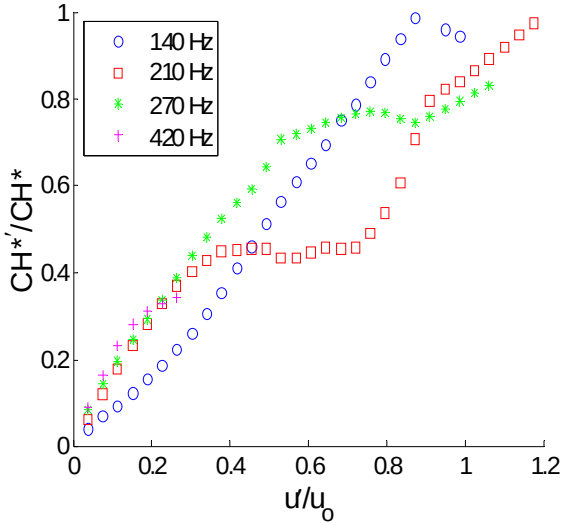
Experimental Characterization of Acoustically Forced Swirl Flames

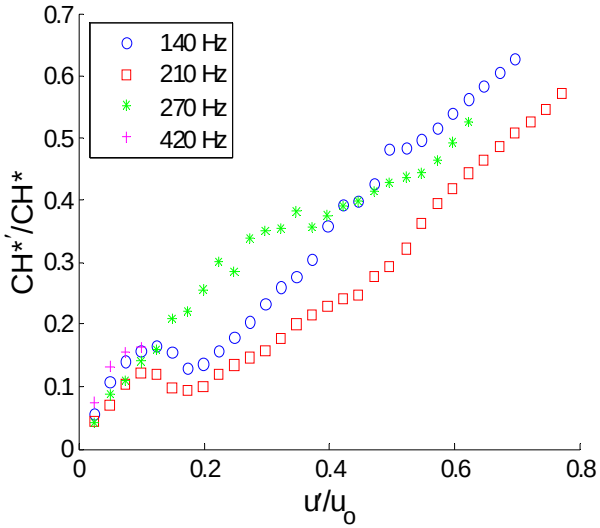
Experimental Facility

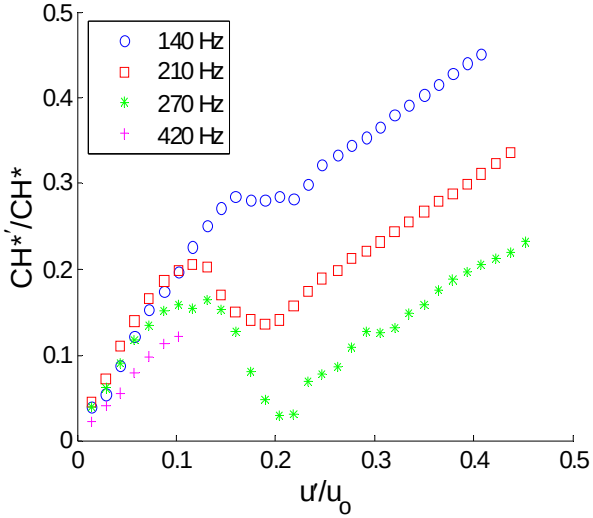
- Extensive parametric study of:
  - Flame transfer functions
  - Phase-locked OH PLIF
- Enables comparison of global flame response characteristics (transfer function measurement) to details of spatio-temporal flame evolution (OH PLIF)



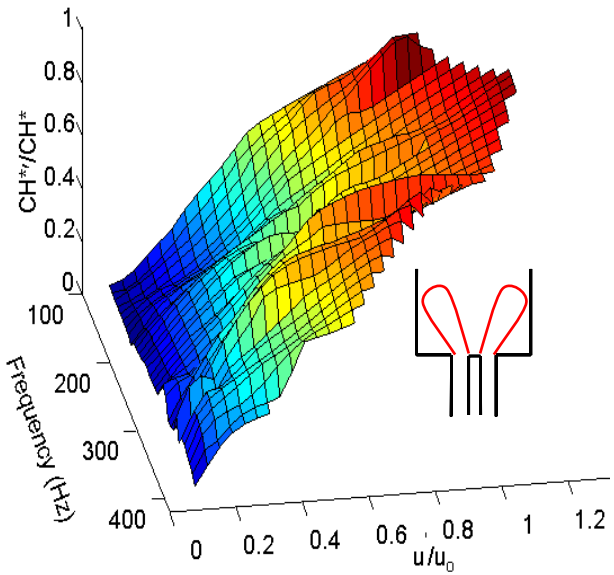
Typical Transfer Functions Relating Heat Release to Fluctuating Velocity



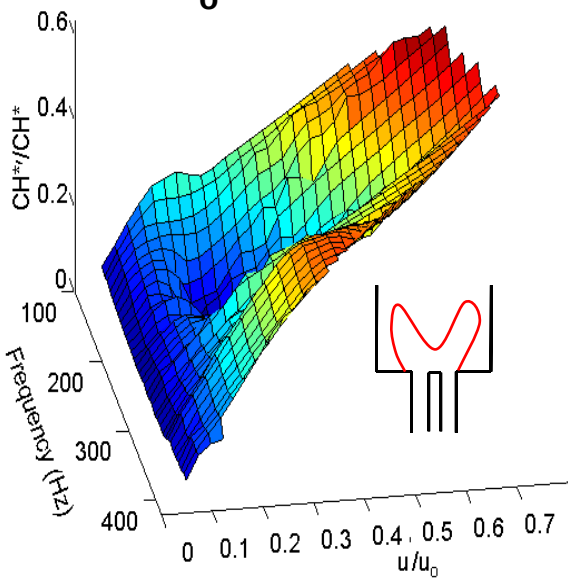




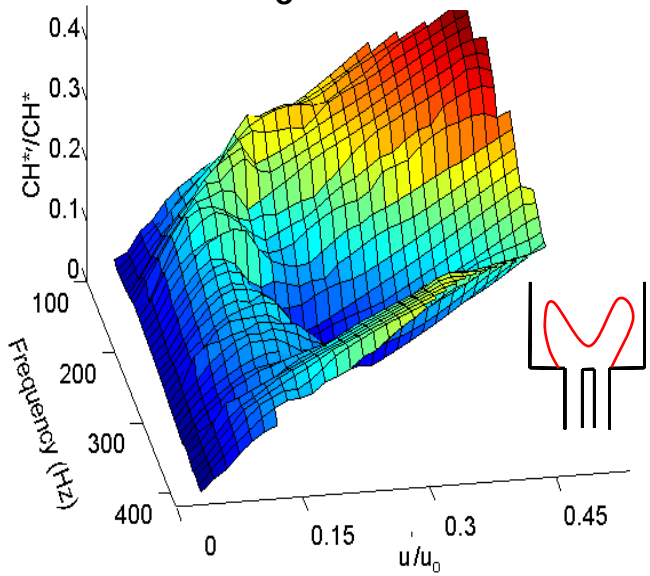
u_o = 21 m/s



u_o = 30 m/s



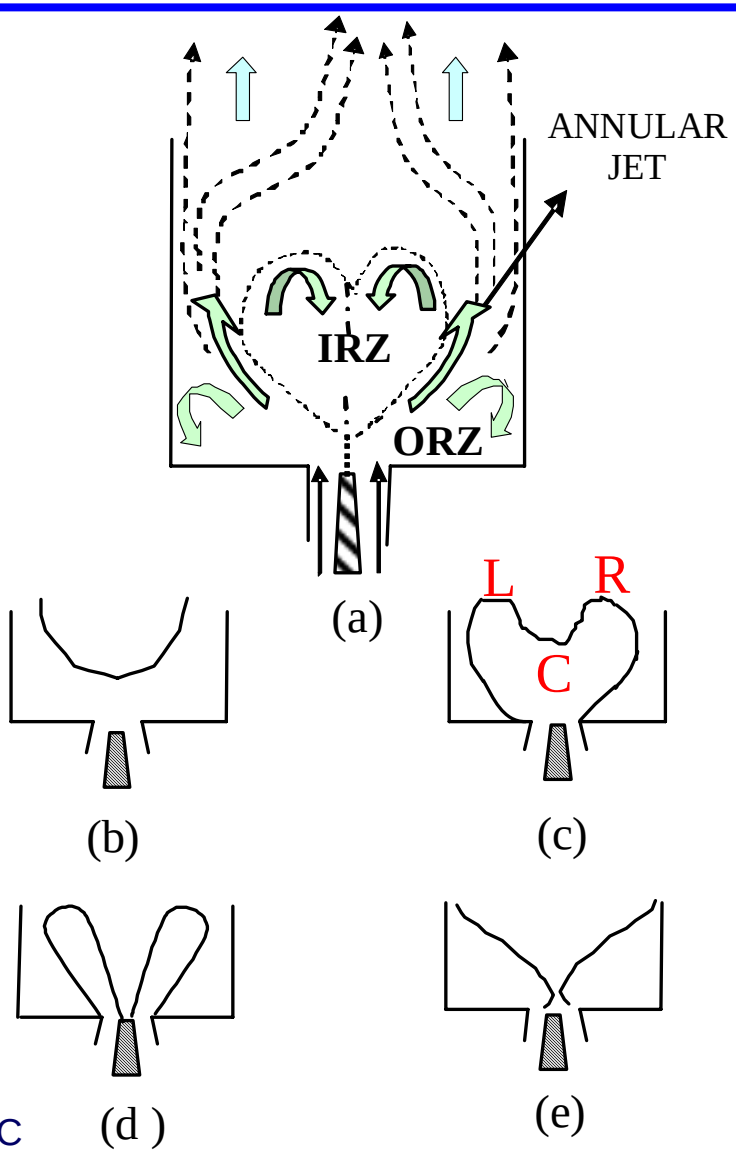
u_o = 44 m/s



Basic Flow/Flame Features

- Flow
  - Outer Recirculation Zone (ORZ)
  - Internal recirculation zone/vortex breakdown bubble (IRZ)
  - Annular fluid jet

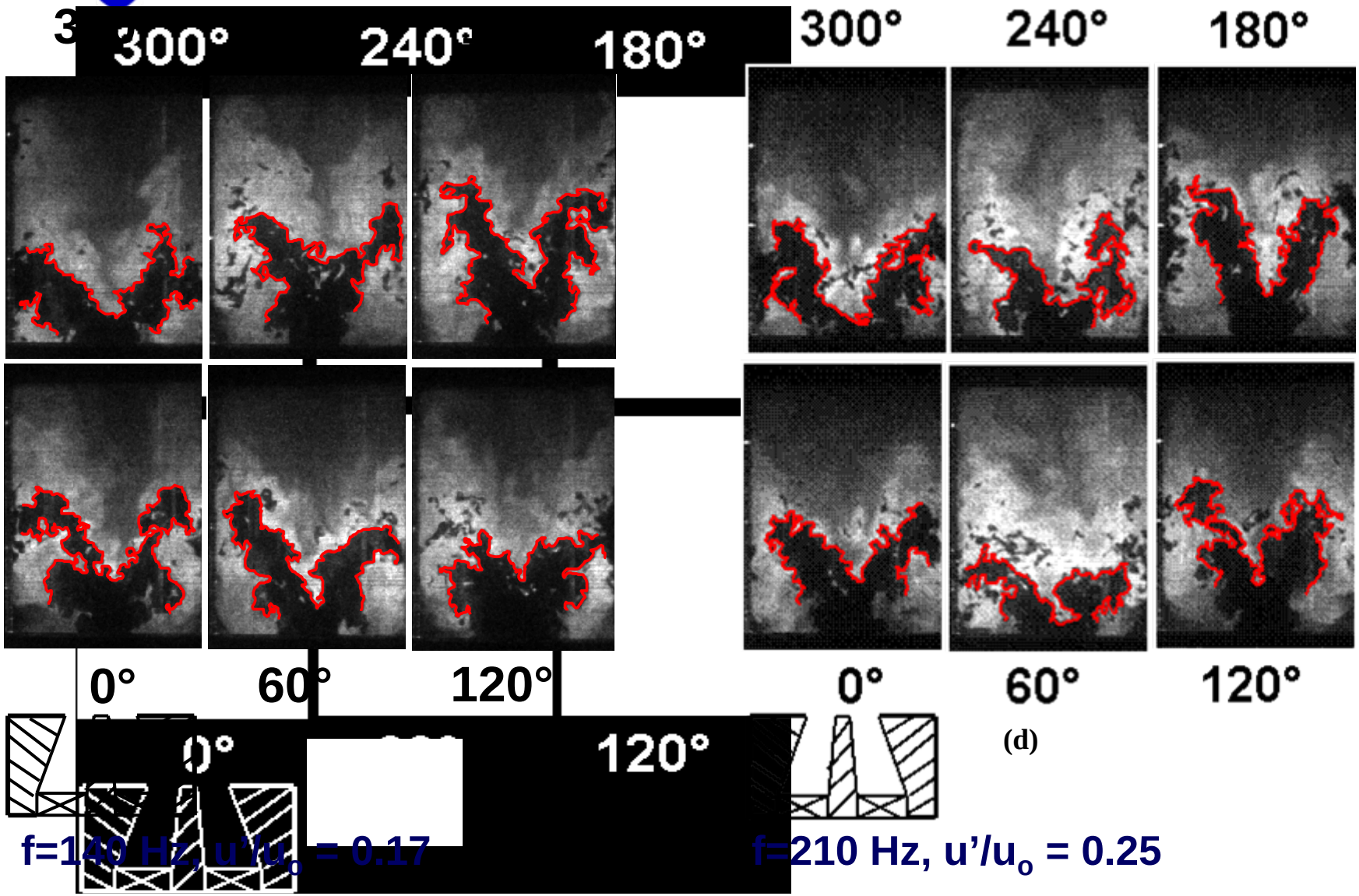
- Flame stabilization
  - Leading edge of IRZ
  - Nozzle exit
  - Centerbody exit



Characterization of Flow/Flame Dynamics

1. Fluctuating Annular Jet Velocity
2. Oscillatory Flame Brush Development
3. Flame Stabilization
4. Fluid Mechanical Instabilities

1. Annular Jet Fluctuations

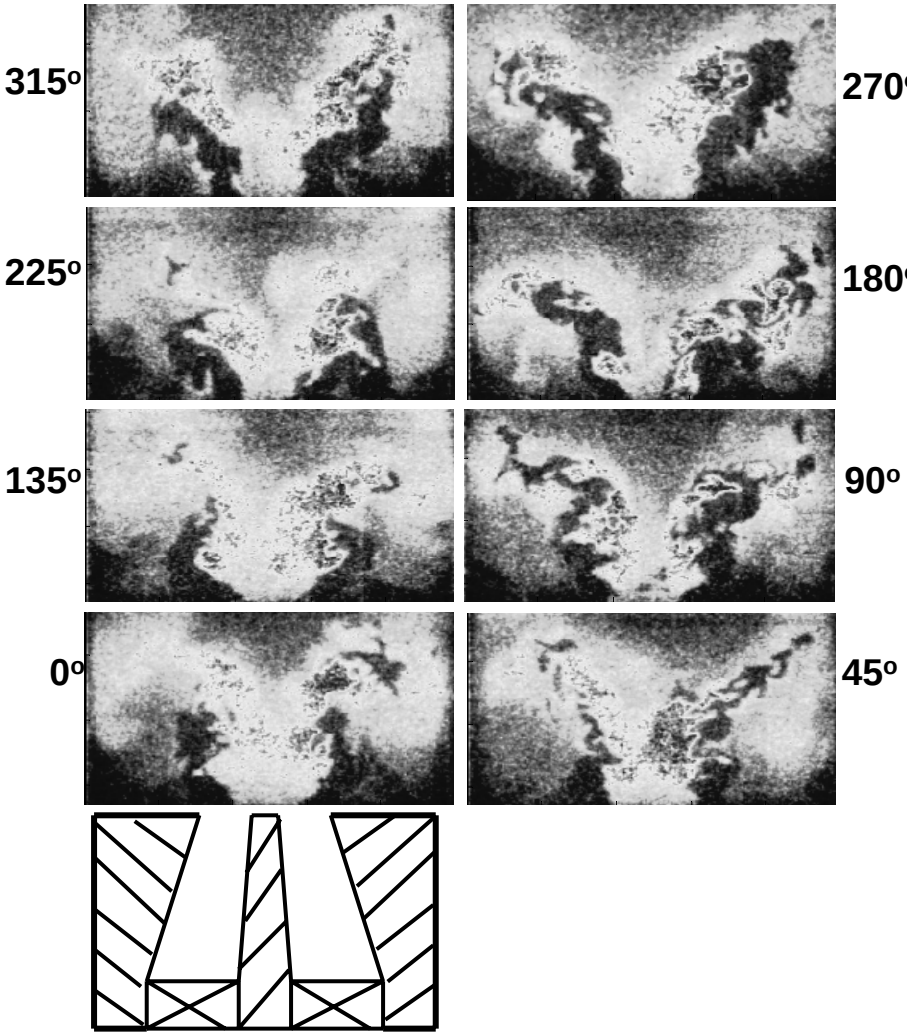


f=140 Hz, u'/u_o = 0.17

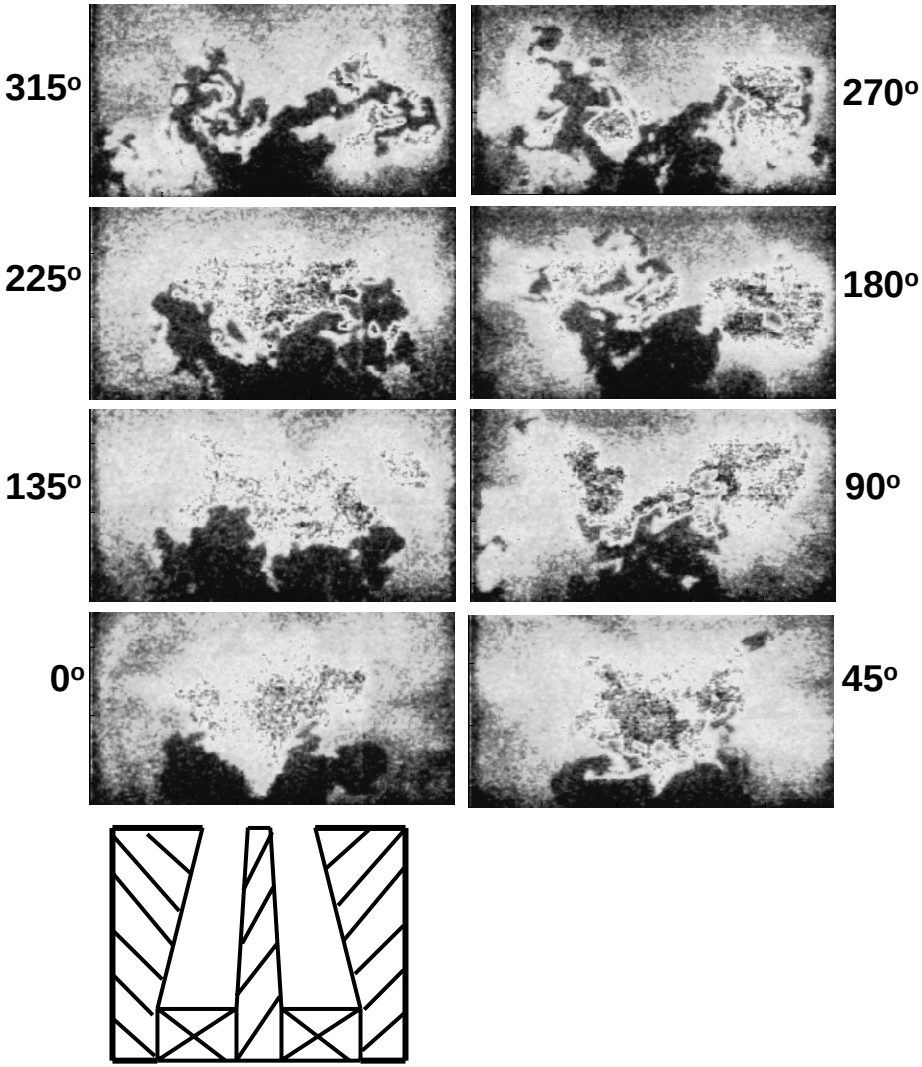
f=210 Hz, u'/u_o = 0.25

Re = 44,000

3. Amplitude Dependant Flame Stabilization



410 Hz, *Re*=21,000 and u'/u_0 = 0.2.



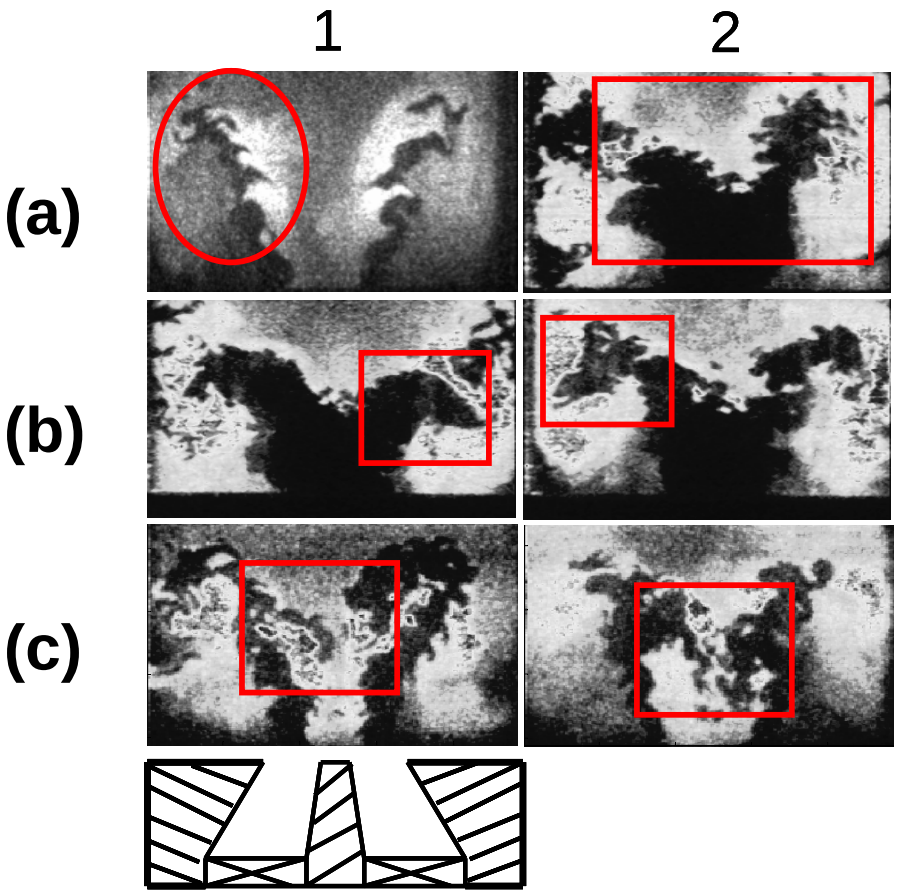
410 Hz, *Re*=21,000 and u'/u_0 = 0.6.

4. Fluid Mechanical Instabilities: Shear Layer, ORZ, and IRZ Dynamics

(a) Shear layer

(b) ORZ

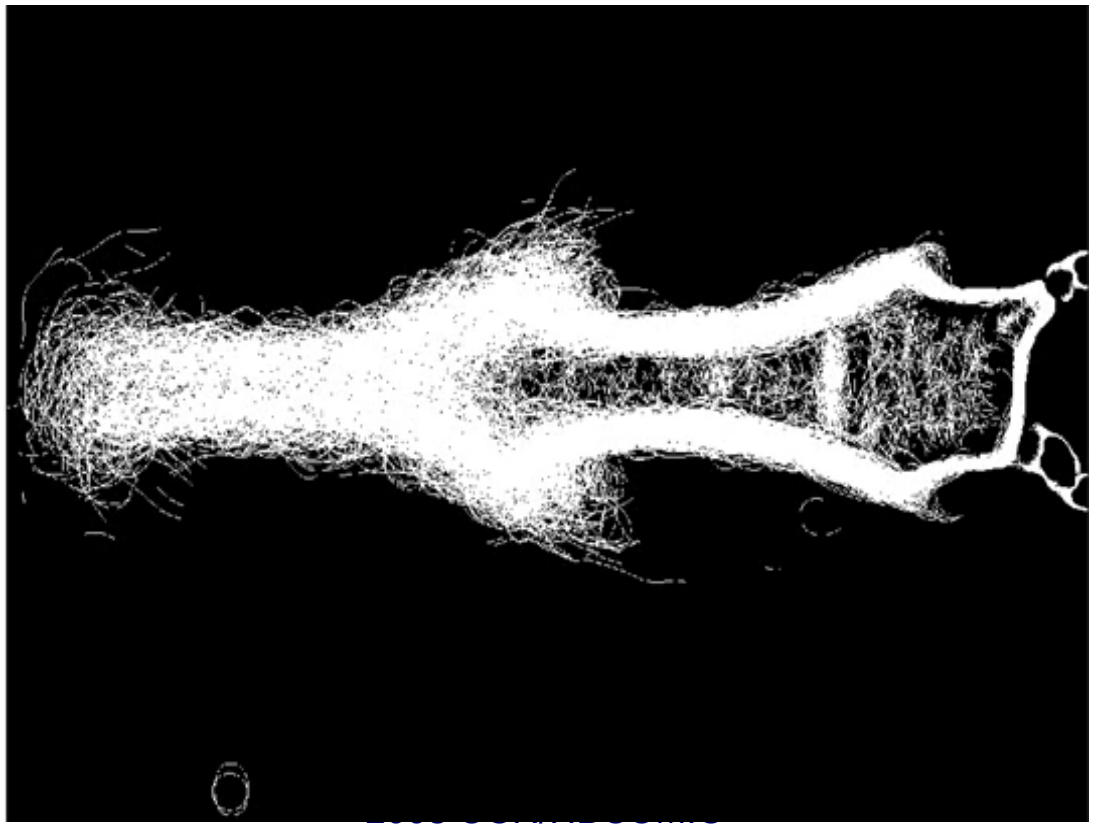
(c) IRZ



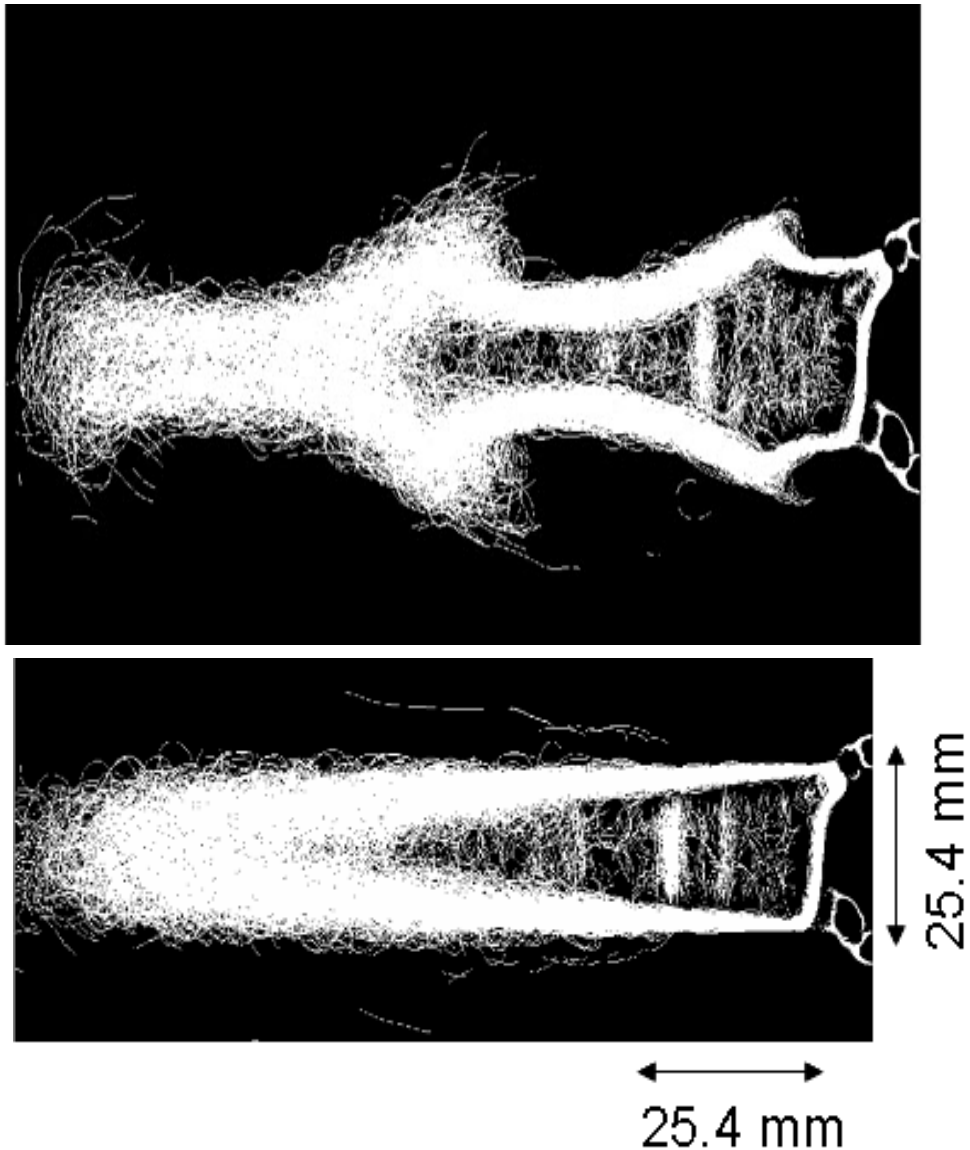
Experimental Characterization of Acoustically Forced Turbulent Flame Brush Dynamics

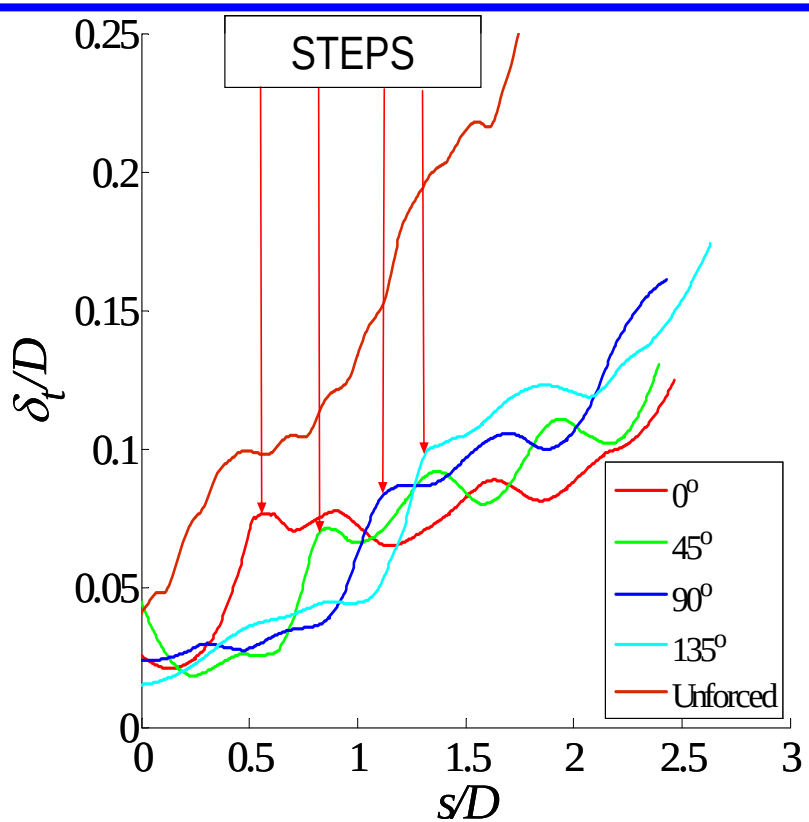
Acoustically Excited Turbulent Bunsen Flame

- Acoustically Forced Bunsen Flame
  - Oscillating flame length
  - Convecting ring vortices



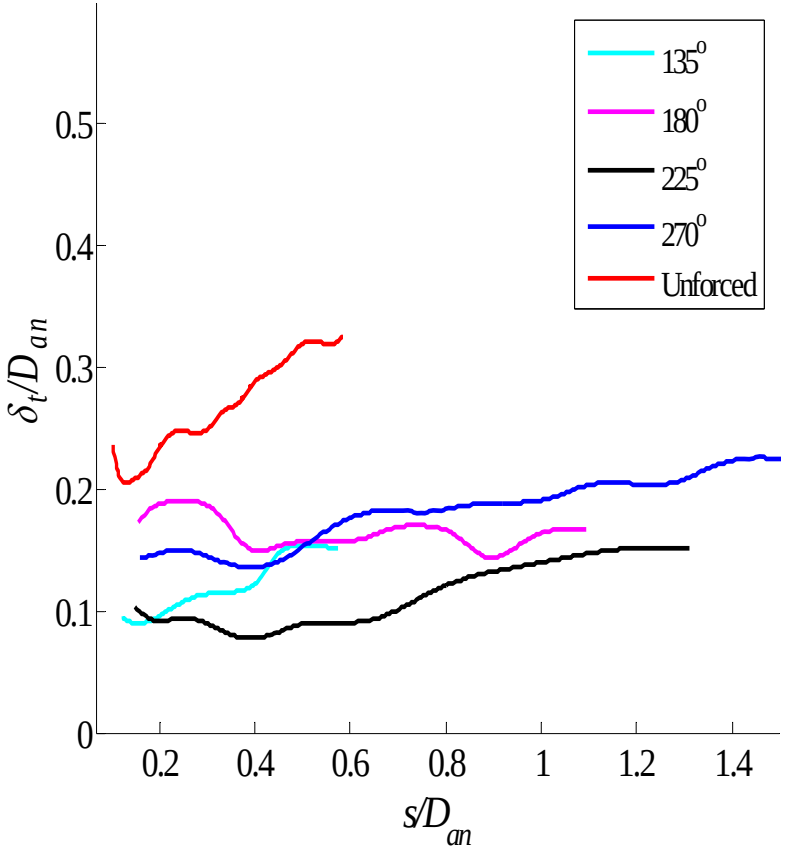
Flame Brush Evolution: Unforced vs. With Acoustics

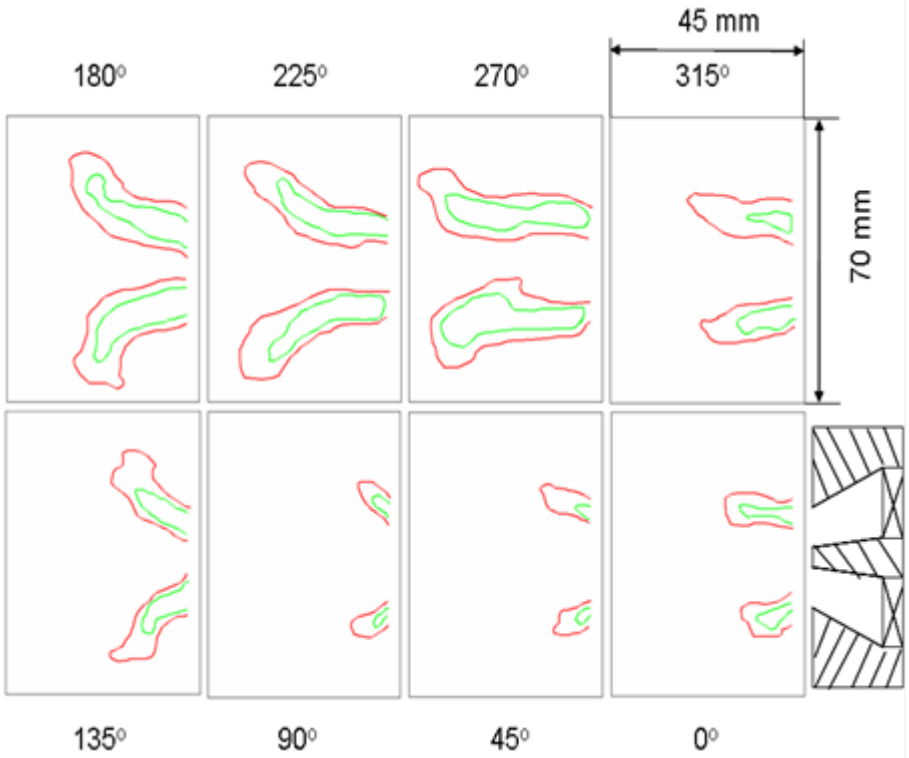




- Very slow growth relative to unforced case
- Step like increases across vortical structures

Flame Brush Evolution: Unforced vs. With Acoustics (Swirl Flame)





Re **=21,000, f= 130 Hz, u'/u_o = 0.6**

- **Flame brush growth suppressed/inhibited in forced case**
- **Modulations in flame length**