Flame Dynamics, Hydrodynamics, and Acoustics

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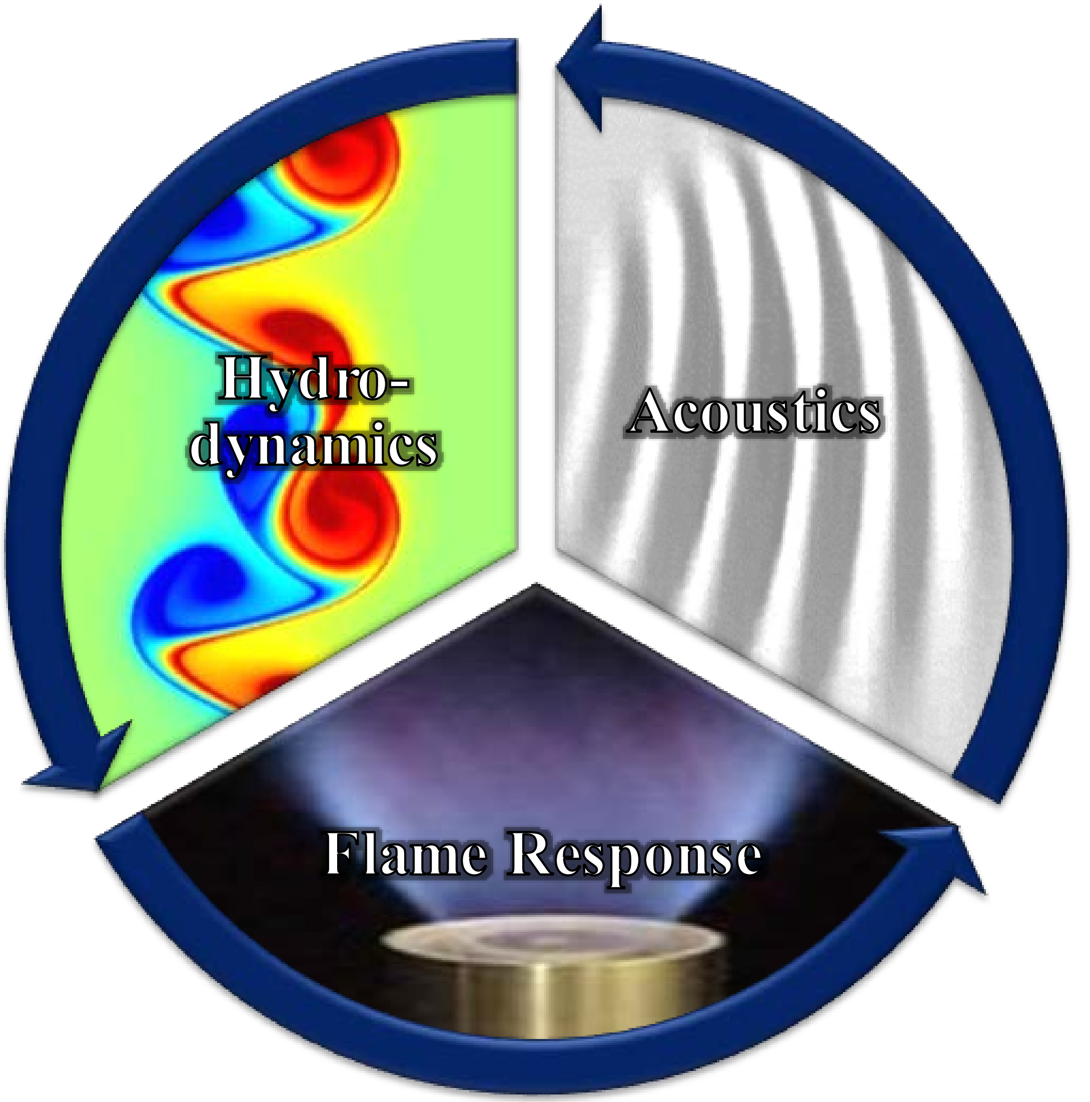
Acknowledgements: Air Force Office of Scientific Research (Chiping Li, Program Monitor) and US Department of Energy (Rich Dennis, Program Monitor)

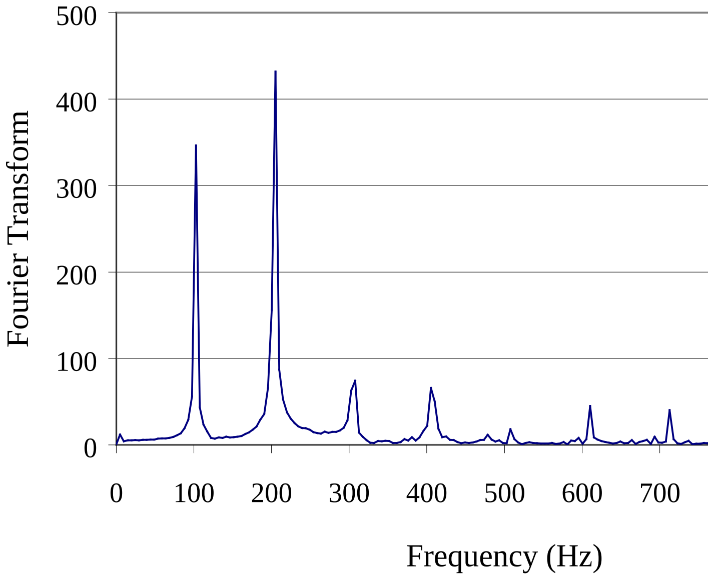
Unsteady Combustor Physics

- Fluid Mechanics
  - Hydrodynamic stability of inhomogeneous flows
- Acoustics
  - Wave propagation in complex flows
- Combustion
  - Response of reaction fronts to disturbances



Combustion Instability

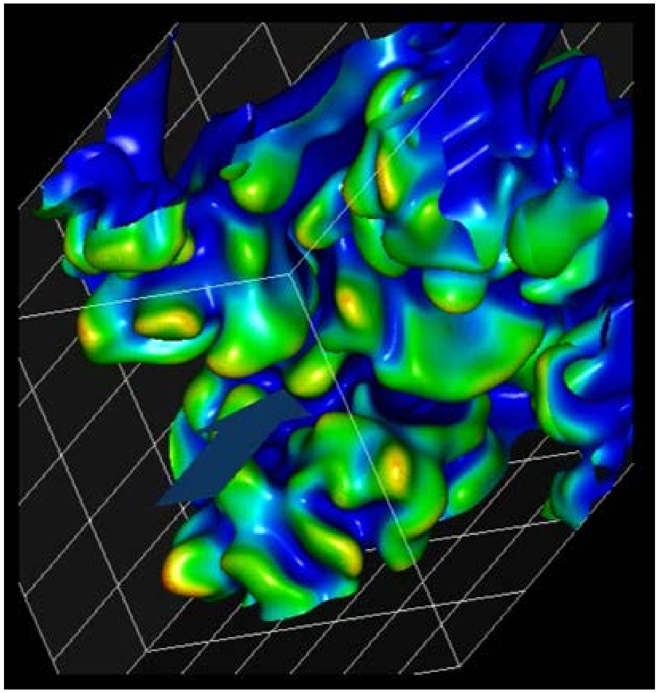
- One of the largest risks associated with development of modern propulsion and energy systems

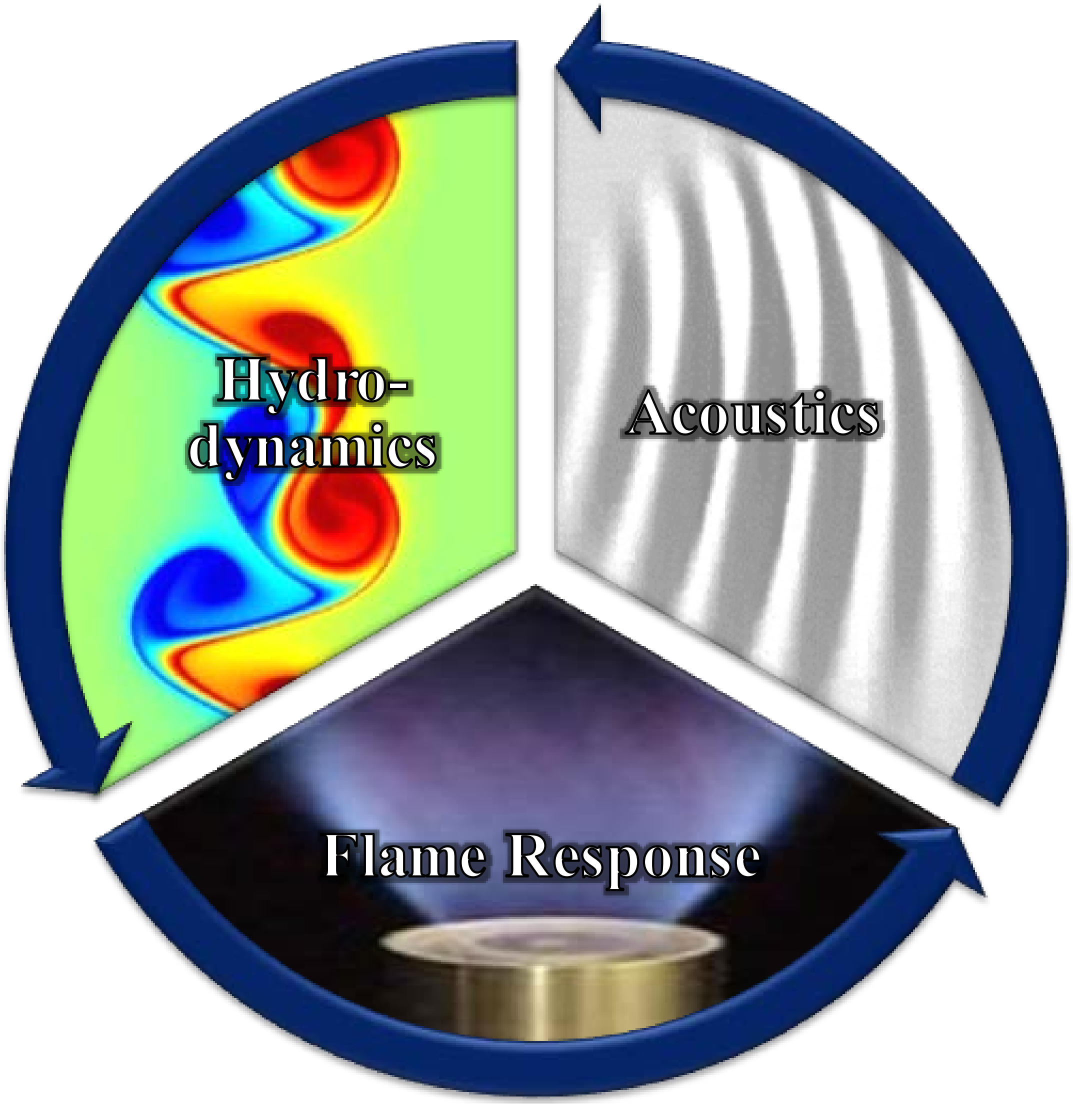


- Manifest themselves as narrowband oscillations at natural frequencies of combustor
  - Key problem lies in understanding how flames respond to harmonic flow perturbations

Flame Response to Disturbances

- Class of more general problems dealing with flame response to flow disturbances:
  - Turbulent combustion: time average response of burning rate to stochastic flow fluctuations
  - Combustion noise: RMS of burning rate
  - Focus here: ensemble averaged response of turbulent flow and flame in harmonically oscillating acoustic field





Hydro-dynamics

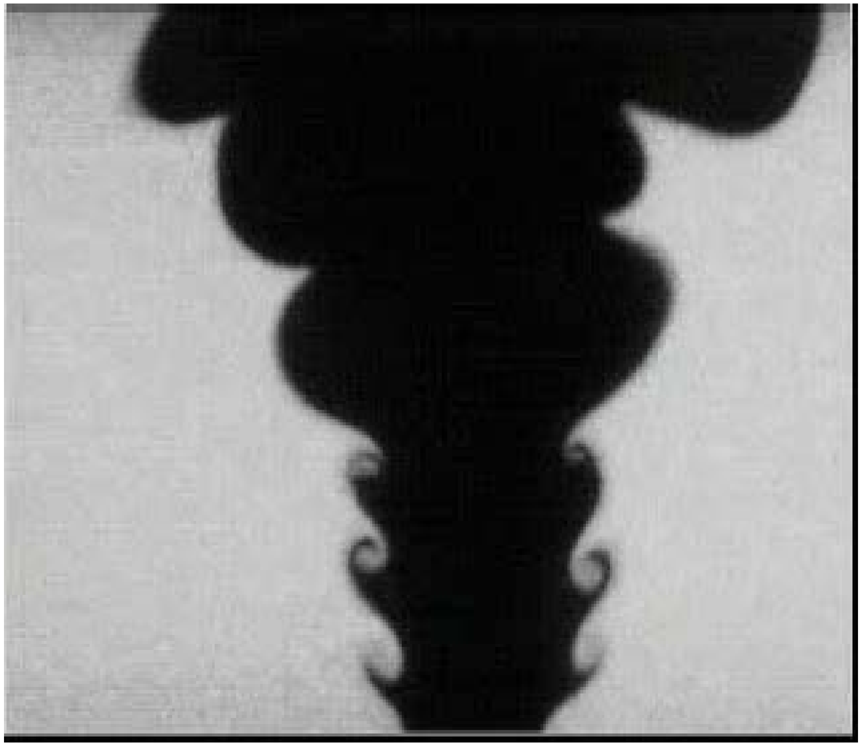
Acoustics

Flame Response

Hydrodynamic Stability of Reacting Flows

- Flame response dominated by large scale coherent structures that arise from underlying hydrodynamic instability of flow

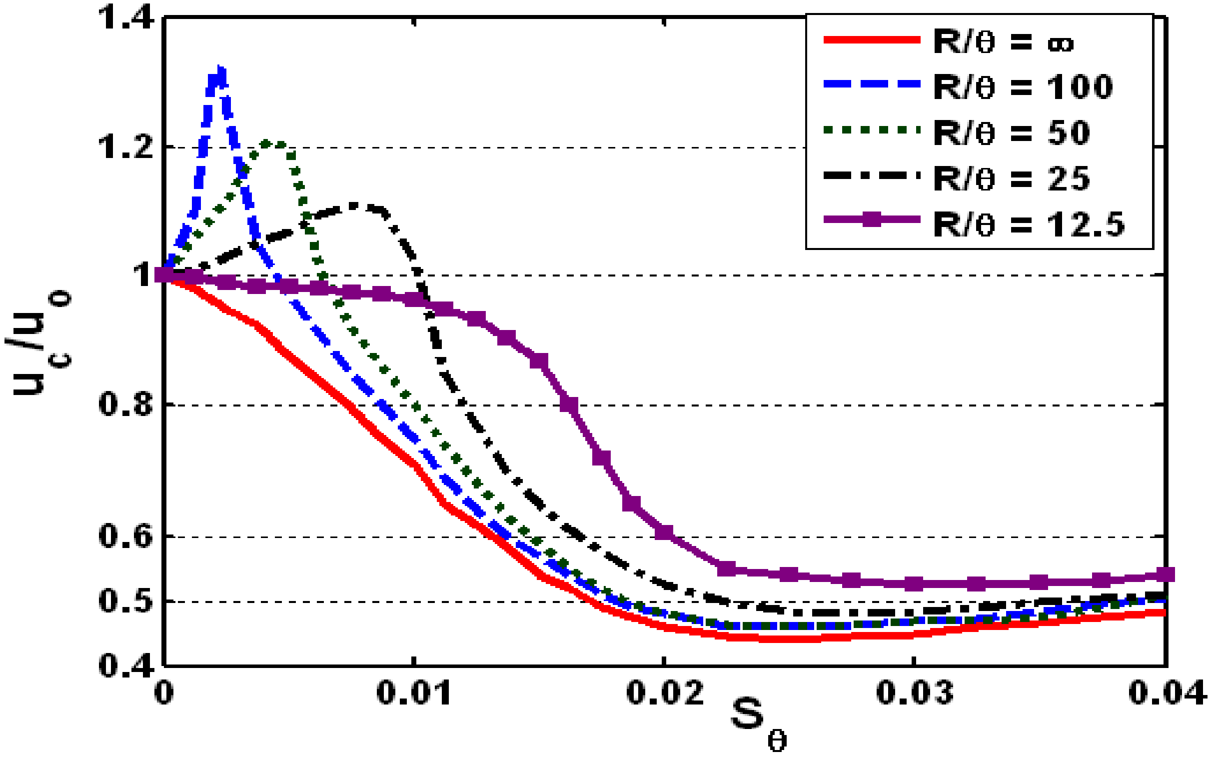
- Key mechanisms:
  - Kelvin-Helmholtz Instability
  - Rayleigh-Taylor Instability



Hydrodynamic Stability of Reacting Flows

- Key mechanisms:
  - Kelvin-Helmholtz Instability
  - Rayleigh-Taylor Instability

- Dispersive

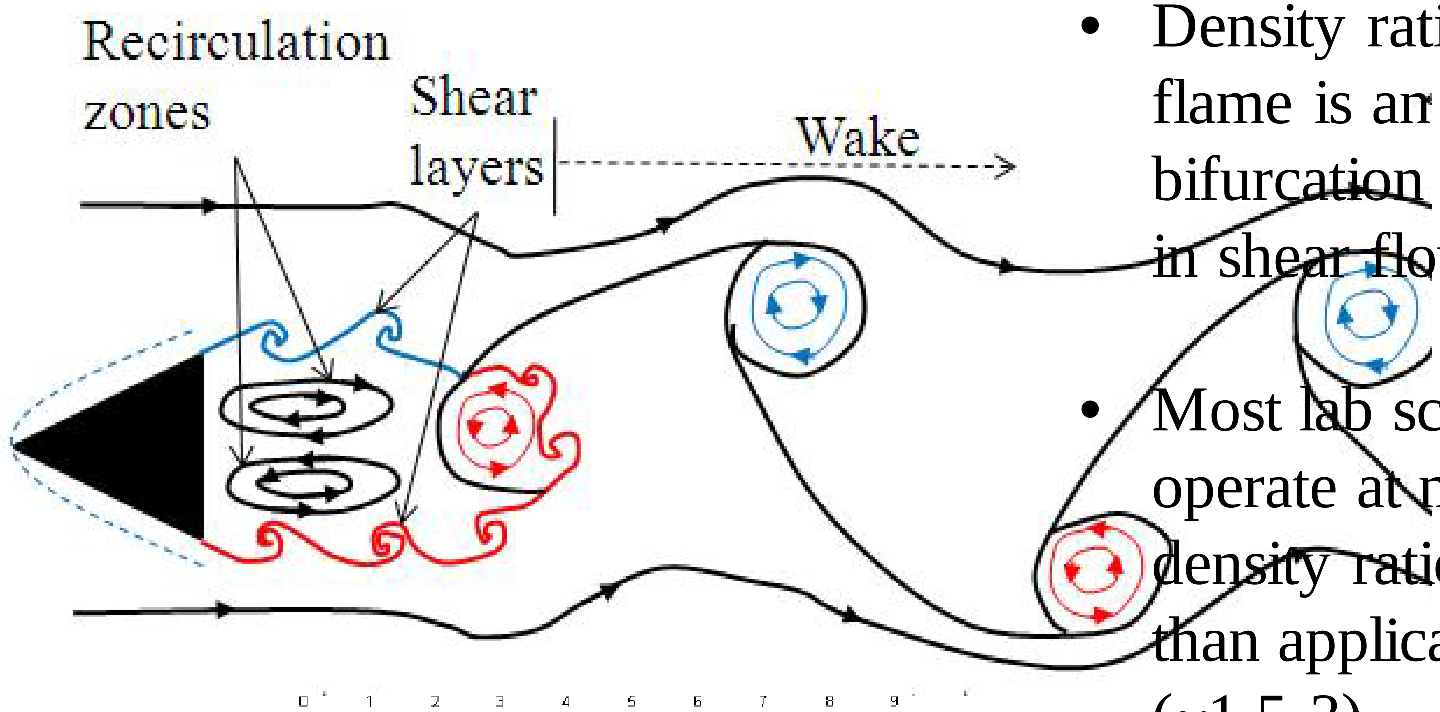


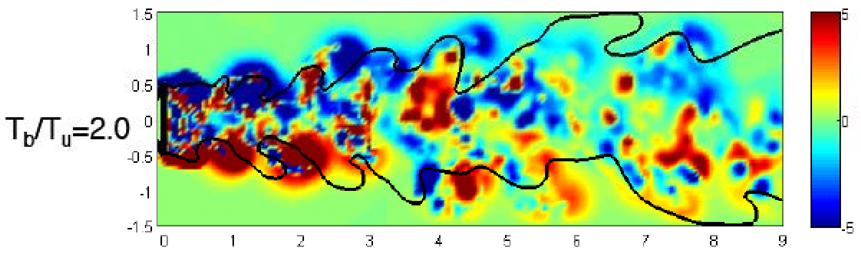
Bechert , D. ,Pfizenmaier, E., JFM., 1975

Hydrodynamic Stability of Reacting Flows

- Key mechanisms:
  - Kelvin-Helmholtz Instability
  - Rayleigh-Taylor Instability
- Dispersive
- Strongly influenced by density stratification

Example: 2-D Wakes

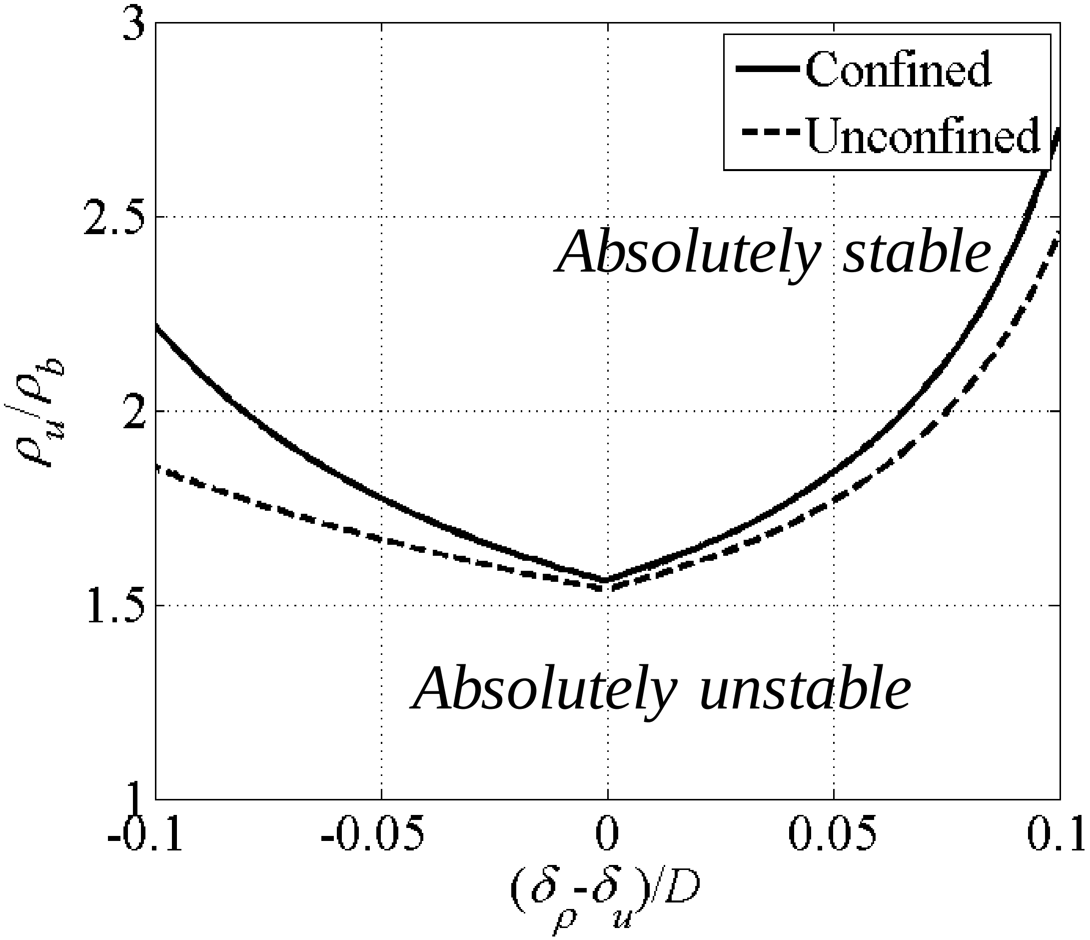




- Density ratio across flame is an important bifurcation parameter in shear flows
- Most lab scale burners operate at much higher density ratios (~6) than applications (~1.5-3)

Erickson, Mehta and Soteriou, Aerospace Sciences Conference, 2006

Results Very Sensitive to Flame - Shear Layer Offset



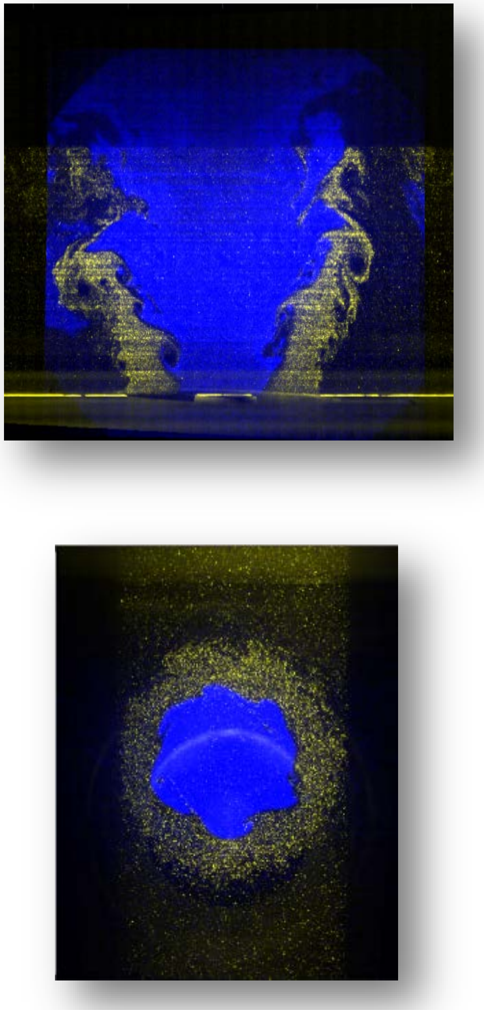
10% shift in flame position causes critical flame density ratio to shift by 70%

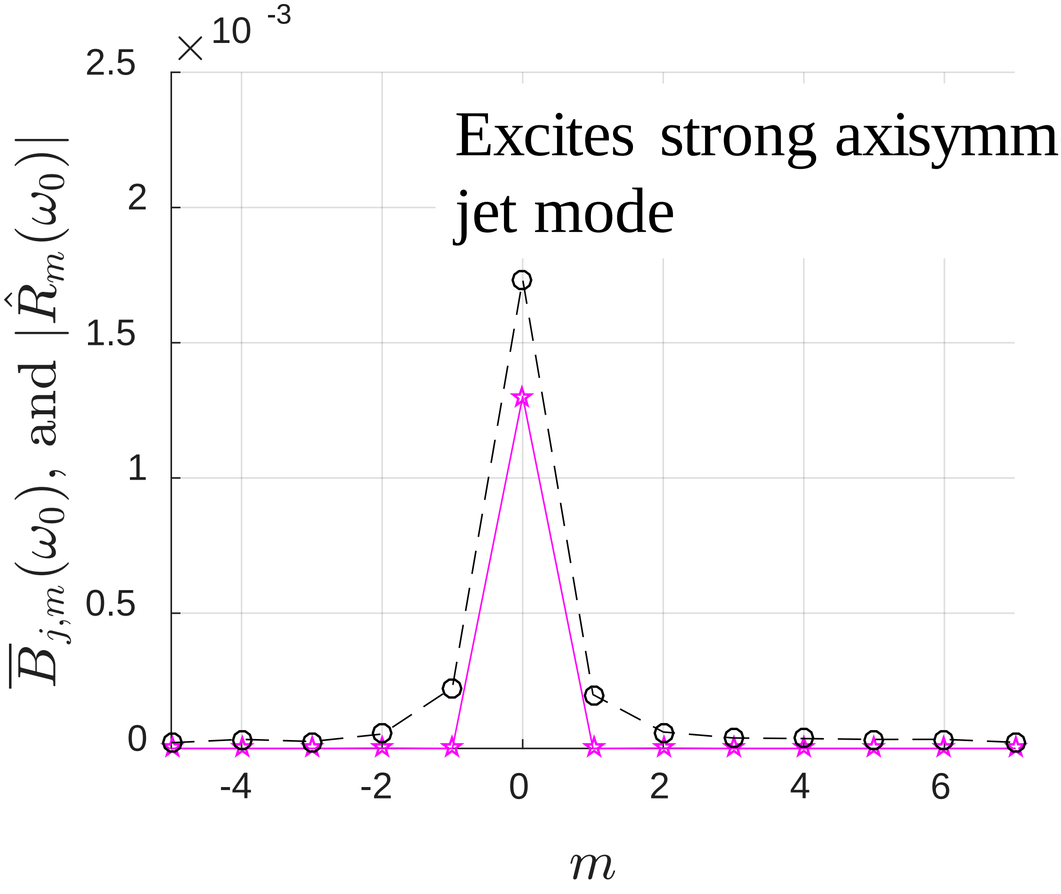
Emerson, B., O'Connor, J., Juniper, M. and Lieuwen, T., *JFM*, 2012.

Hydrodynamic Stability of Reacting Flows

- Key mechanisms:
  - Kelvin-Helmholtz Instability
  - Rayleigh-Taylor Instability
- Dispersive
- Strongly influenced by density stratification
- Multiple hydrodynamic modes
  - Most naturally unstable/amplified, not necessarily the one subjected to strongest excitation by acoustics

Transversely Forced Swirling Flame: Pressure Antinode

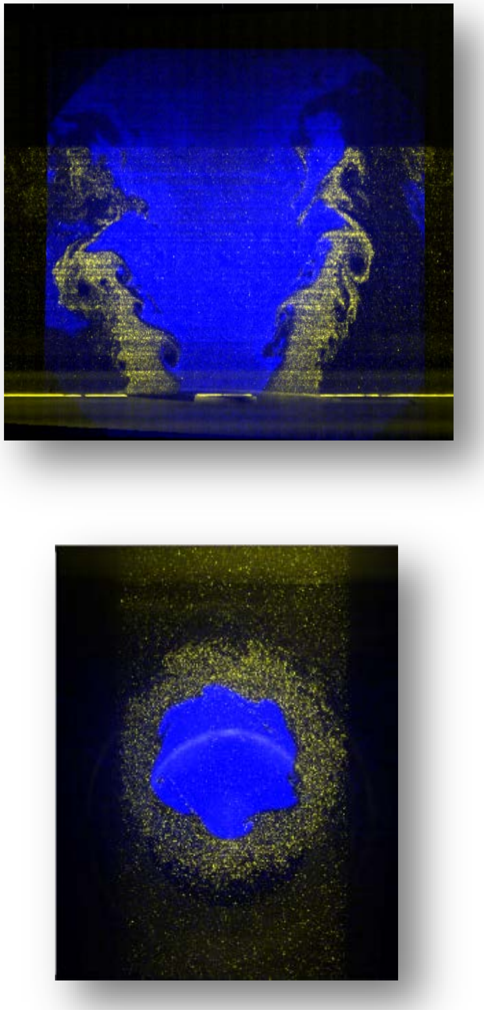


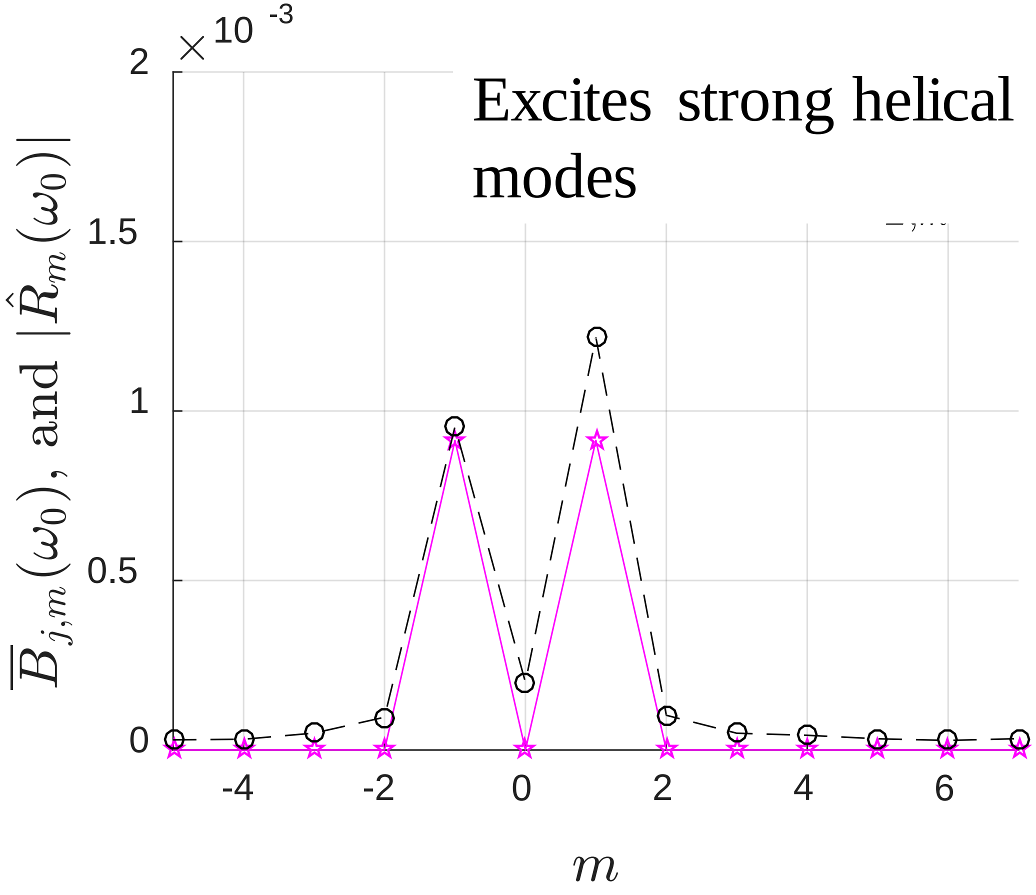


Excites strong axisymmetric jet mode

Smith, T.E. et al., In *55th AIAA Aerospace Sciences Meeting, 2017.*

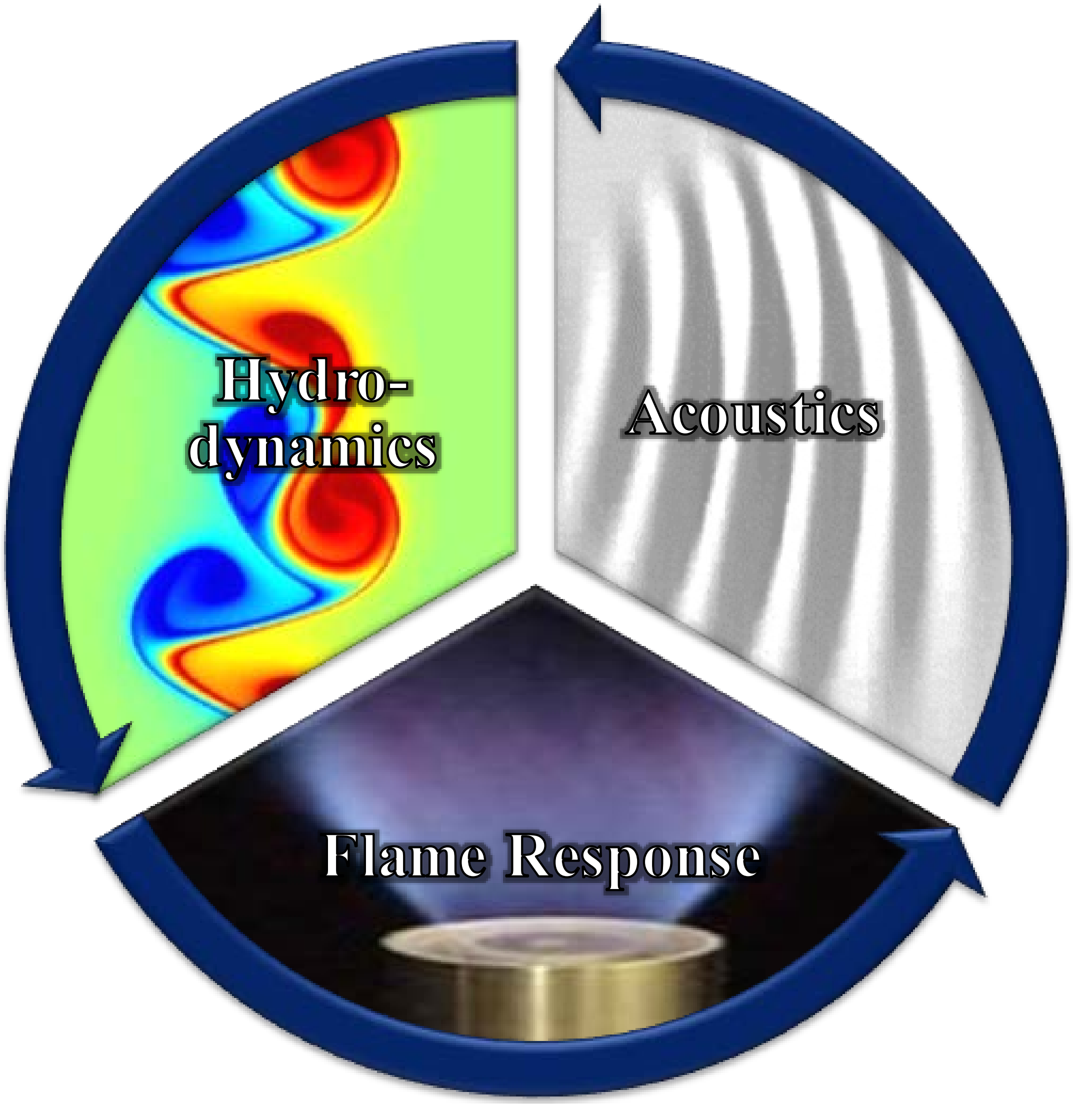
Transversely Forced Swirling Flame: Velocity Antinode





Excites strong helical modes

Smith, T.E. et al., In *55th AIAA Aerospace Sciences Meeting, 2017.*

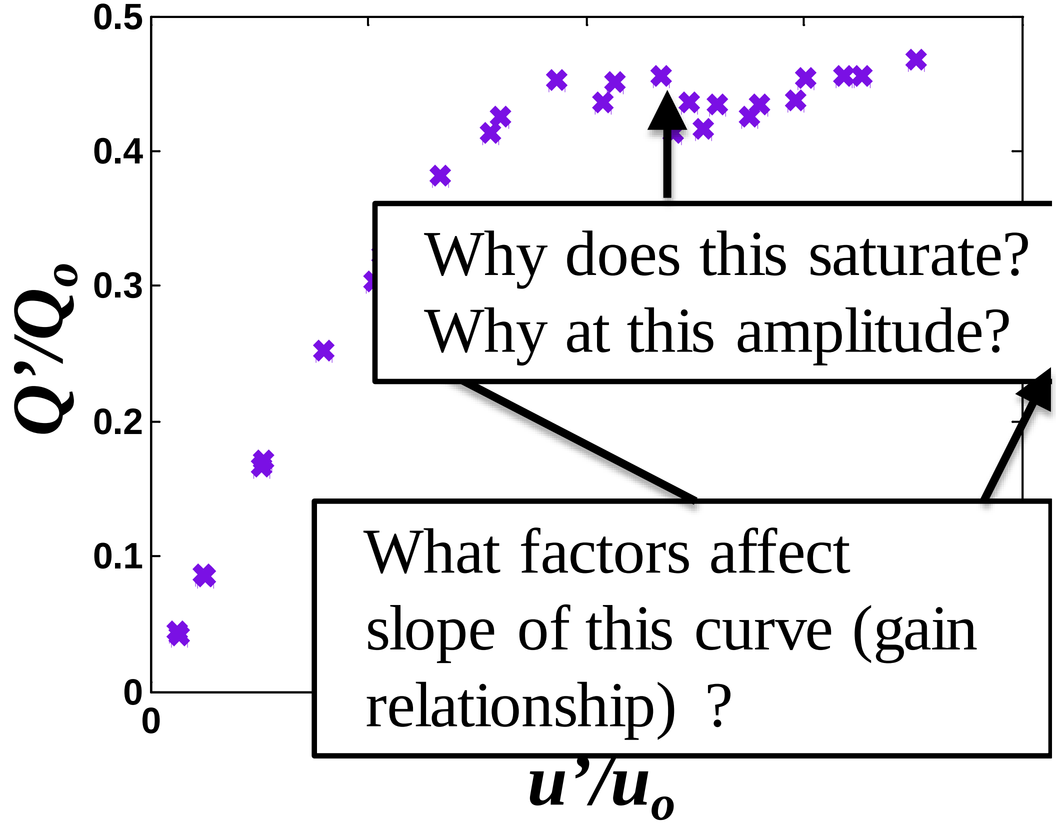


Hydro-dynamics

Acoustics

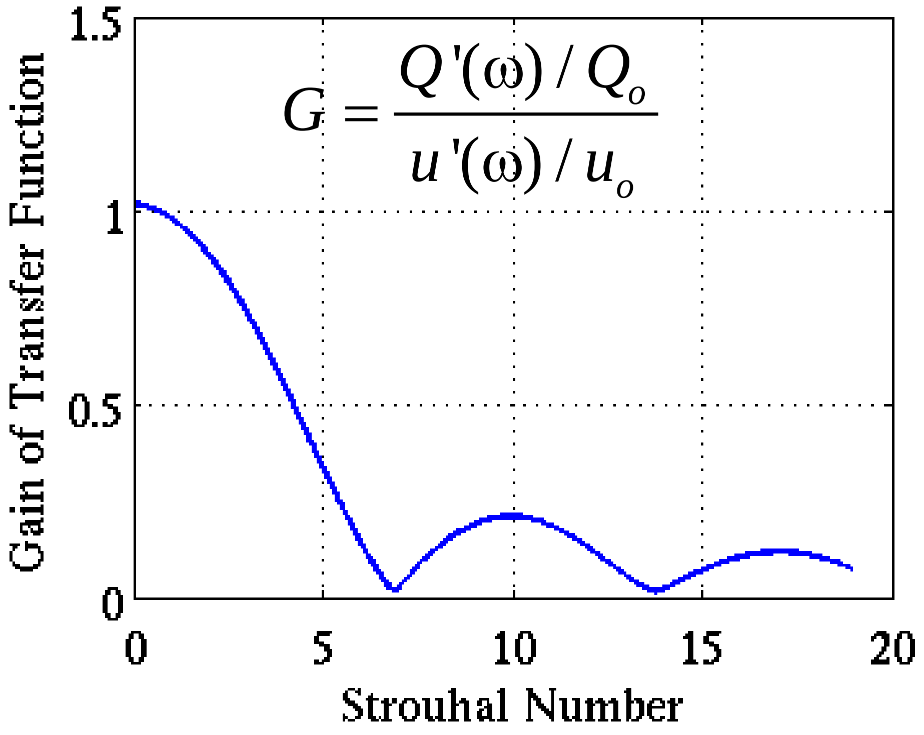
Flame Response

Response of Heat Release to Flow Perturbations



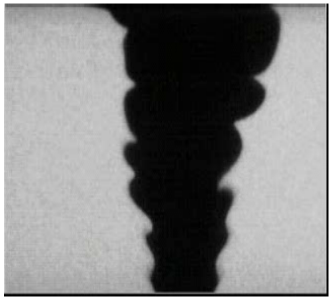
Why does this saturate?
Why at this amplitude?

What factors affect slope of this curve (gain relationship) ?

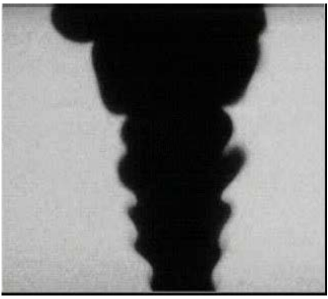


Excited Bluff Body Flames

(Mie Scattering)



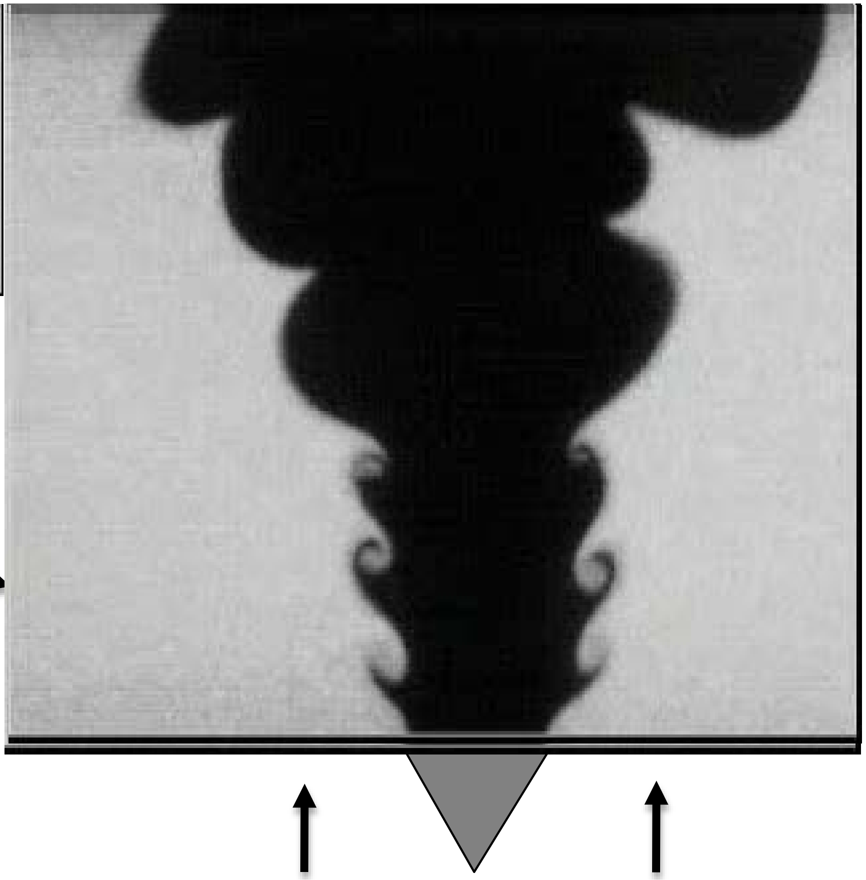
$$\frac{u'}{U_o} = 0.01$$



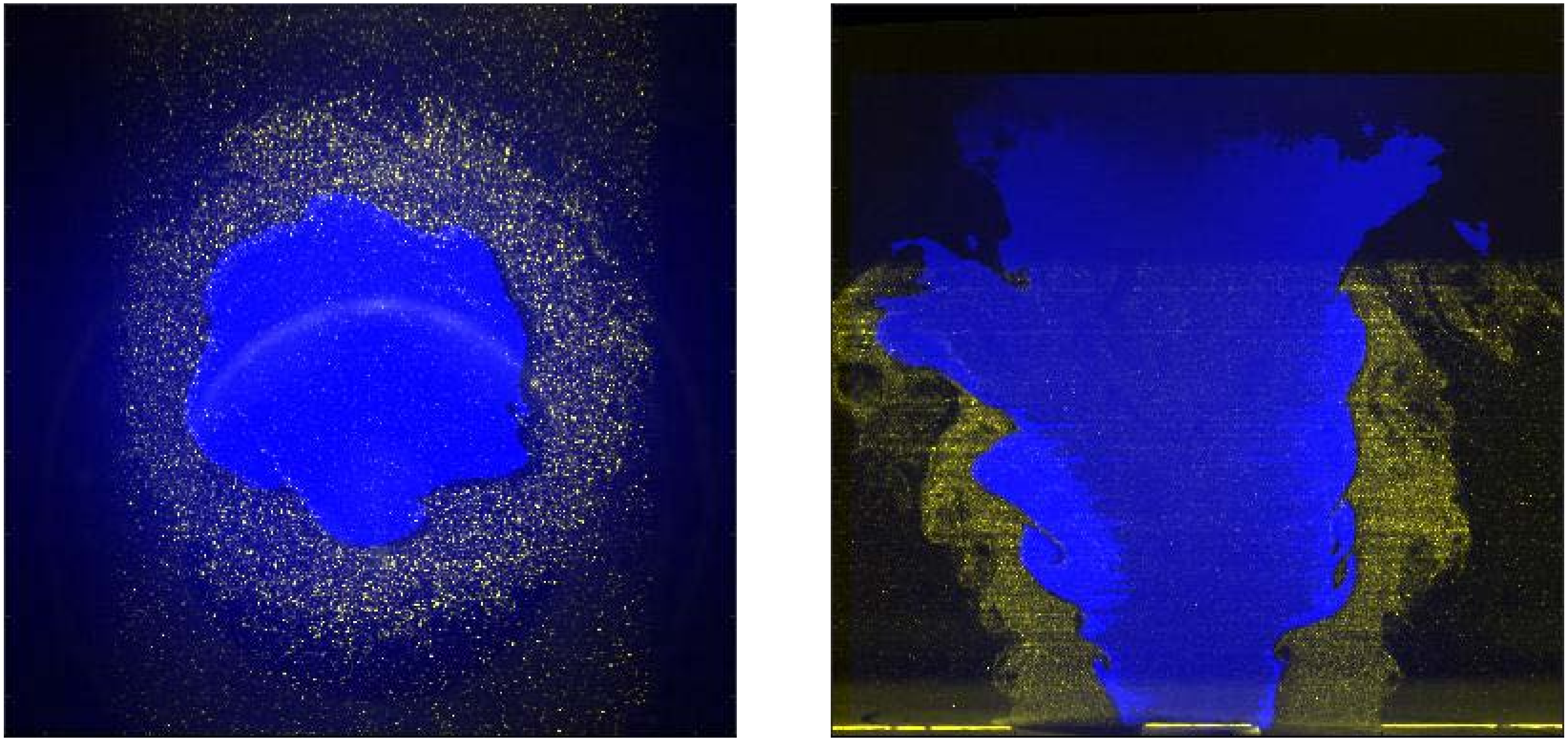
$$\frac{u'}{U_o} = 0.02$$

Increased

Amplitude of Forcing

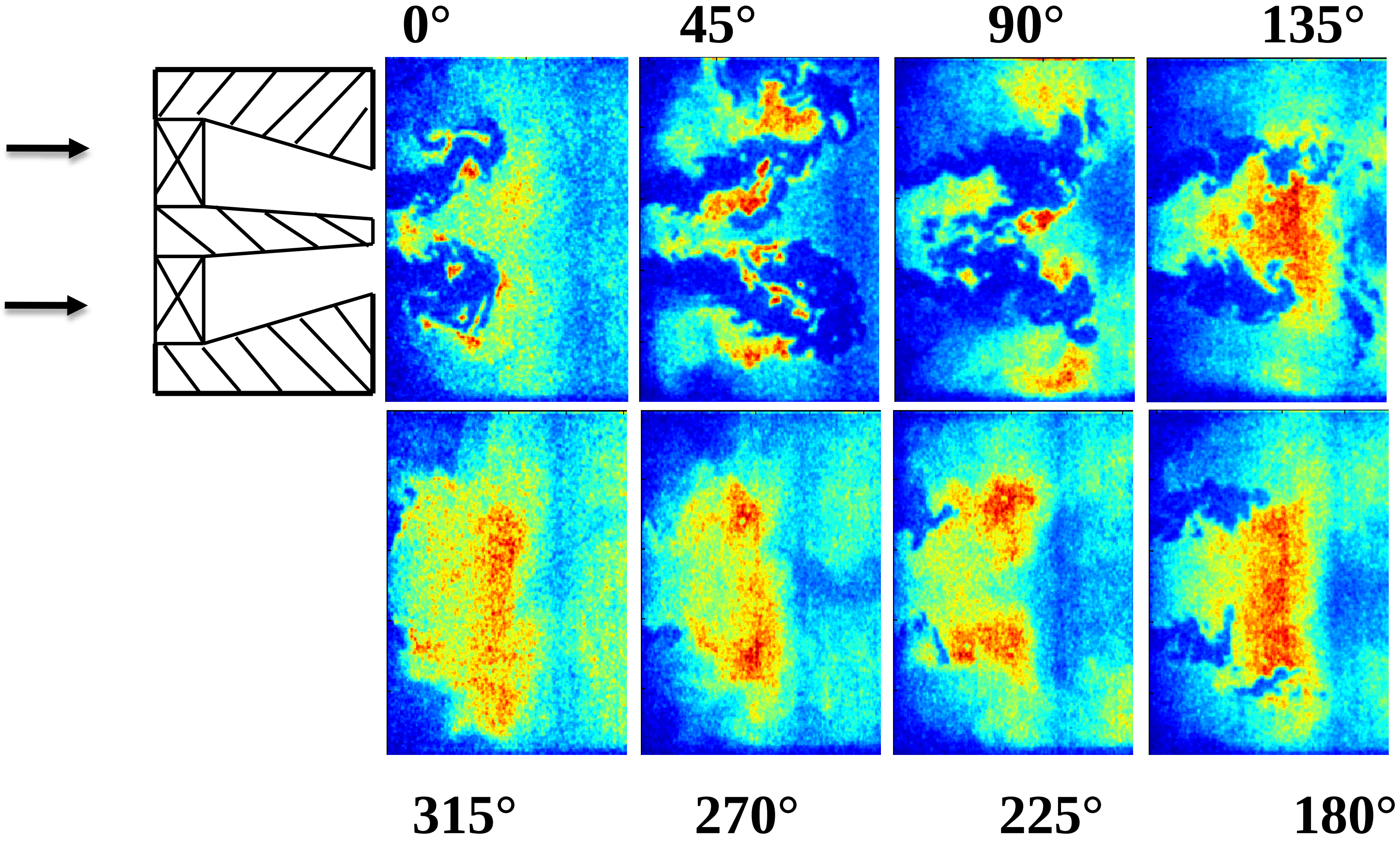


Swirling Jet Flames

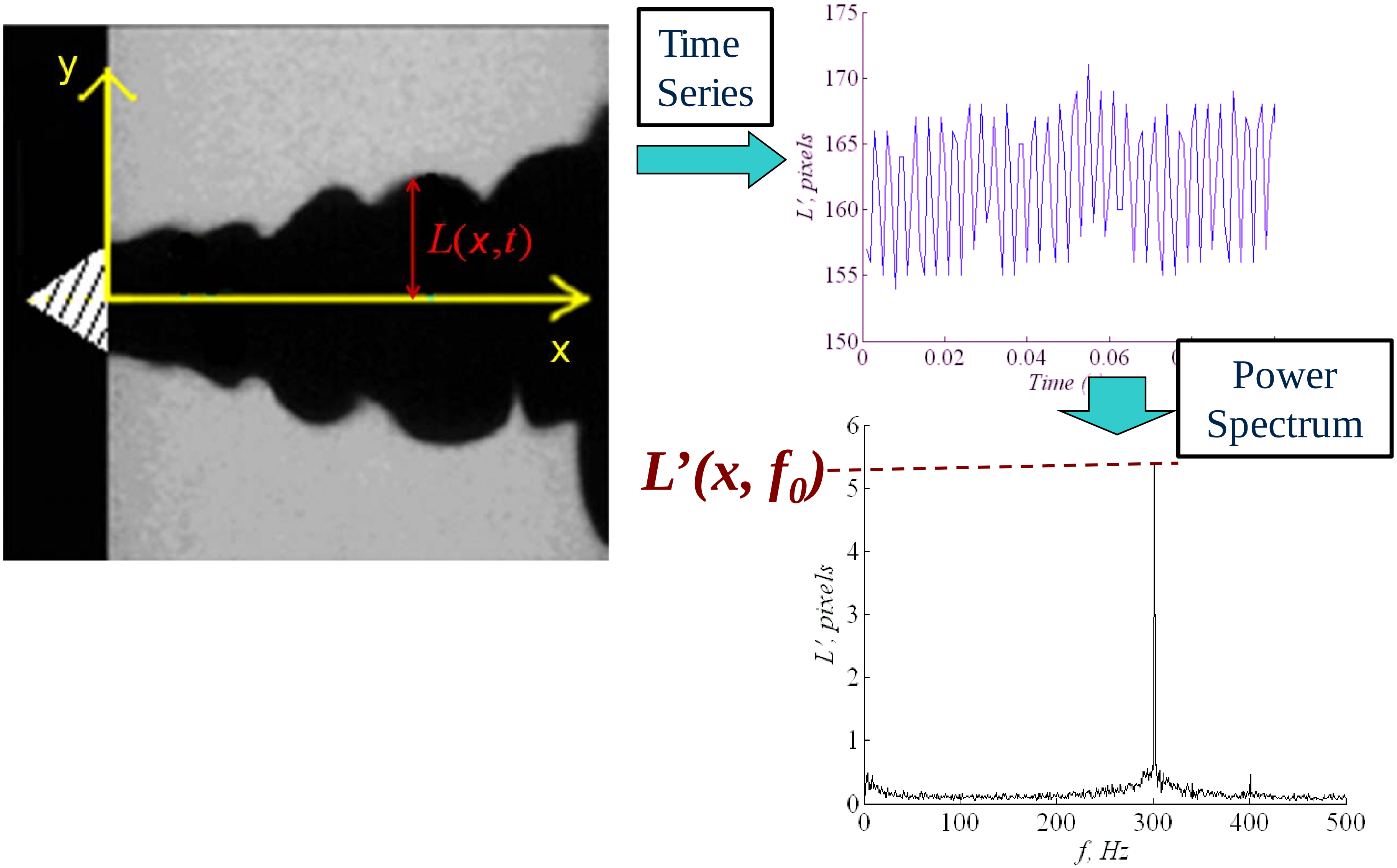


Excited Swirl Flame - Attached

(OH PLIF)



Quantifying Flame Edge Response

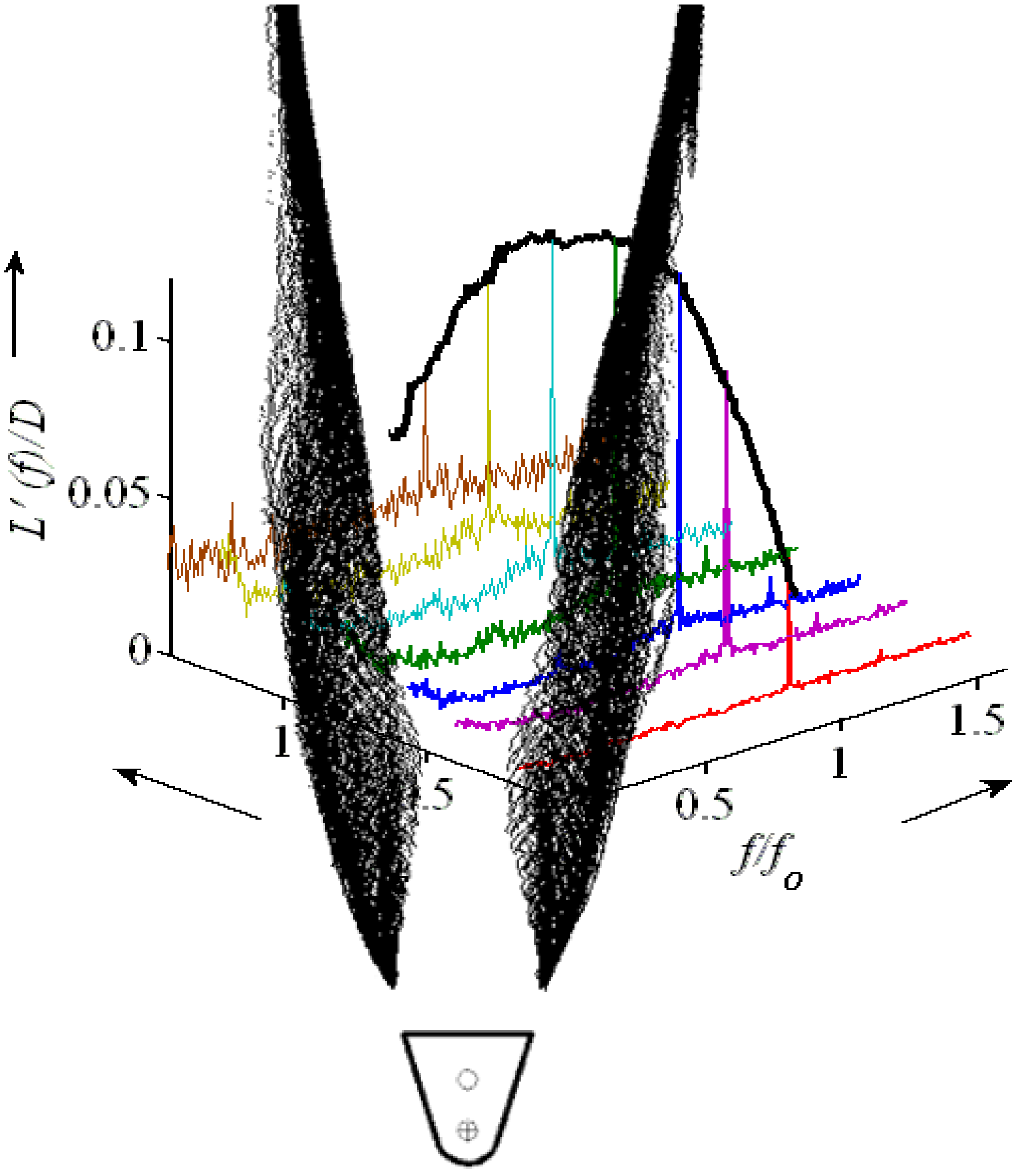


Time Series

Power Spectrum

$L'(x, f_0)$

Spatial Behavior of Flame Response



Convective wavelength:

$\lambda_c = U_o/f_o$

- distance a disturbance propagates at mean flow speed in one excitation period

- Strong response at forcing frequency
  - – Non-monotonic spatial dependence

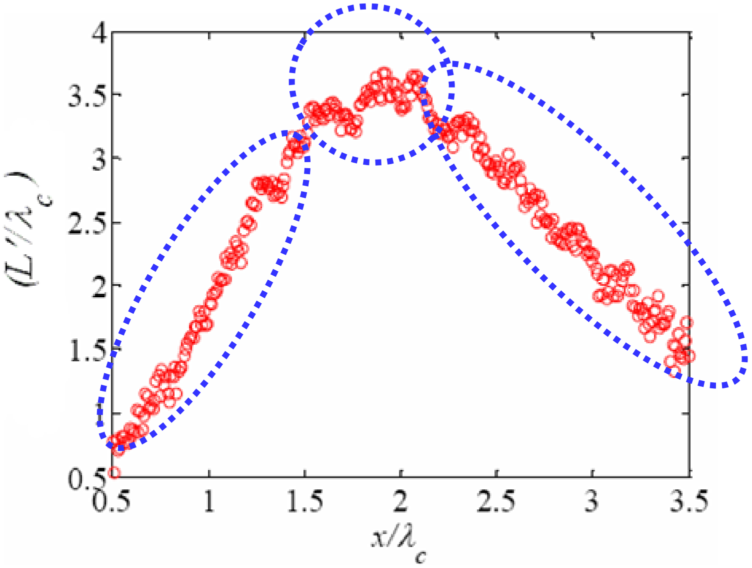
Flame Wrinkling Characteristics

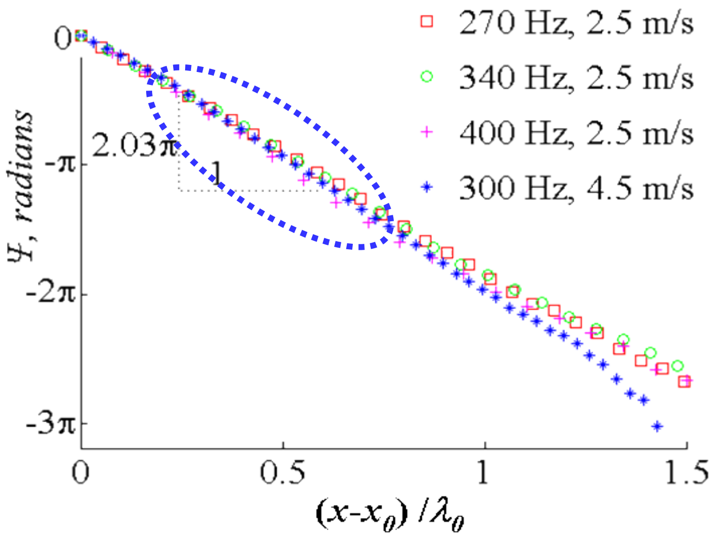
1. Low amplitude flame fluctuation near attachment point, with subsequent growth downstream

2. Peak in amplitude of fluctuation, $L' = L'_{peak}$

3. Decay in amplitude of flame response farther downstream

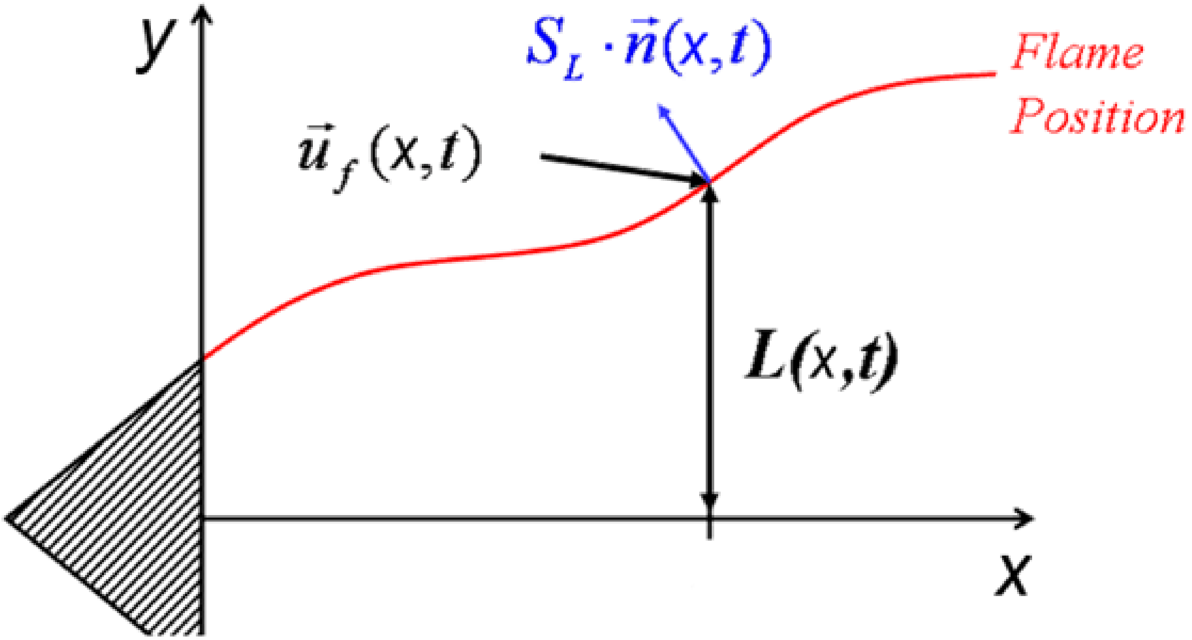
4. Approximately linear phase-frequency dependence
   - Can relate slope to axial convection velocity of flame wrinkle, $u_{c,f}$





Shanbhogue *et al.*, *Proceedings of the Combustion Institute*, 2009.

Flamelet Description of Front Dynamics



G-equation : $$\frac{\partial G}{\partial t} + \vec{u} \cdot \nabla G = S_L \left| \nabla G \right|$$

$$\frac{\partial L}{\partial t} + \left(u \frac{\partial L}{\partial x} - v \right) = S_L \sqrt{1 + \left(\frac{\partial L}{\partial x} \right)^2}$$

F. Williams, *Combustion Theory*

Analysis of Flame Dynamics

1. Wrinkle convection and flame relaxation processes
2. Excitation of wrinkles
3. Destruction of wrinkles

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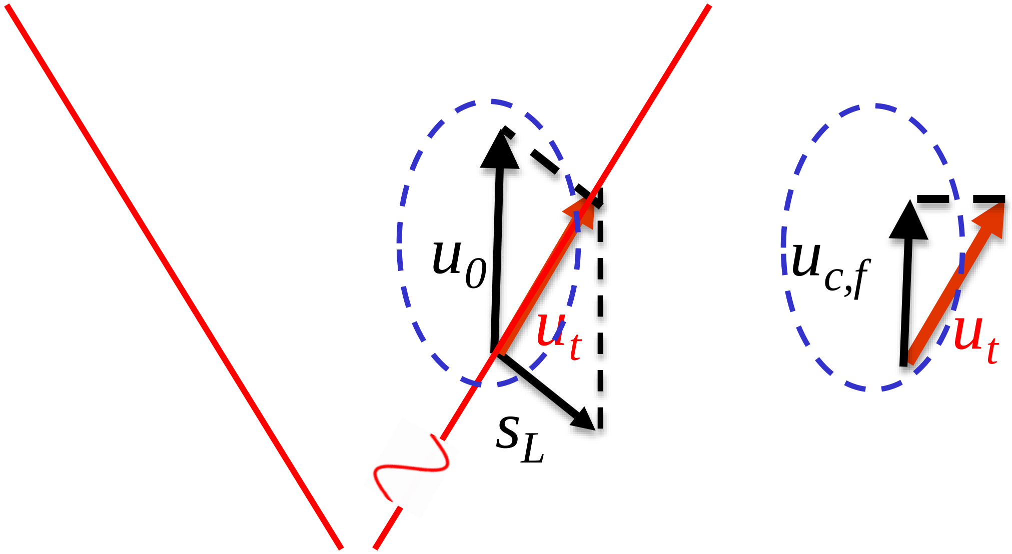
Disturbance Propagation on Premixed Flame Sheets

- Linearized solution of G-equation

$$\frac{\partial L'\left(x,t\right)}{\partial x}=\frac{1}{u_t}\int_0^x \frac{\partial u_n'}{\partial x}(x',t-\frac{x-x'}{u_t})\,dx' \;+\frac{1}{u_t}\cdot u_n'(x=0,t=t-\frac{x}{u_t})$$

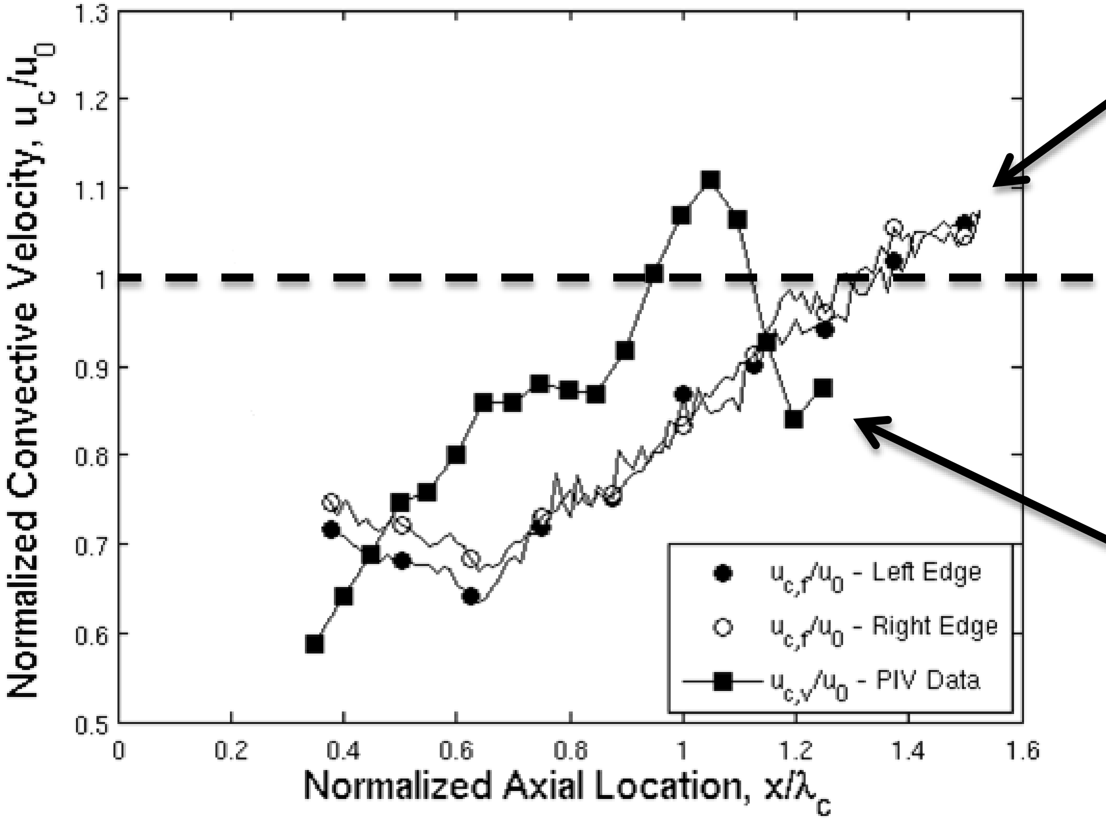
Wrinkle Convection By Tangential Flow



- Small amplitude wrinkles propagate non-dispersively
  - Not true for non-premixed flames

- Non-local character of flame response is probably the most dynamically significant feature of forced flames

Phase Characteristics of Flame Wrinkle



Convection speed of Flame wrinkle, $u_{c,f}$

$\neq$

Mean flow velocity, u_0

$\neq$

Disturbance Velocity, $u_{c,v}$

Shin *et al.*, *Journal of Power and Propulsion*, 2011.

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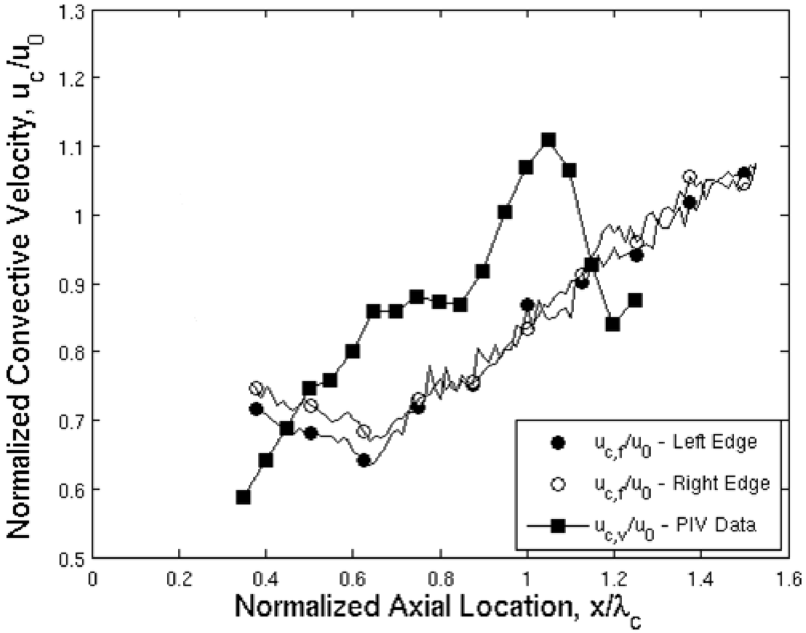
Excitation of Flame Wrinkles – Spatially Varying Disturbance Field

$$\frac{\partial L'\left(x,t\right)}{\partial x} = \frac{1}{u_t}\int_0^x \frac{\partial u_n'}{\partial x}(x', t-\frac{x-x'}{u_t})\ dx' + \frac{1}{u_t}\cdot u_n'(x=0, t=t-\frac{x}{u_t})$$

- Flame wrinkles generated by velocity fluctuations normal to it
- Net flame disturbance at location *x* is convolution of disturbances at upstream locations and previous times
- Convecting vortex is continuously disturbing flame
  - Vortex convecting at speed of $u_{c,v}$
  - Flame wrinkle that is excited convects at speed of u_t



Model Problem: Attached Flame Excited by a Harmonically Oscillating, Convecting Disturbance

- Model problem: flame excited by convecting velocity field,

$$\frac{u_n'}{u_t} = \varepsilon_n \cos(2\pi f (t - x / u_{c,v}))$$

- Linearized solution:

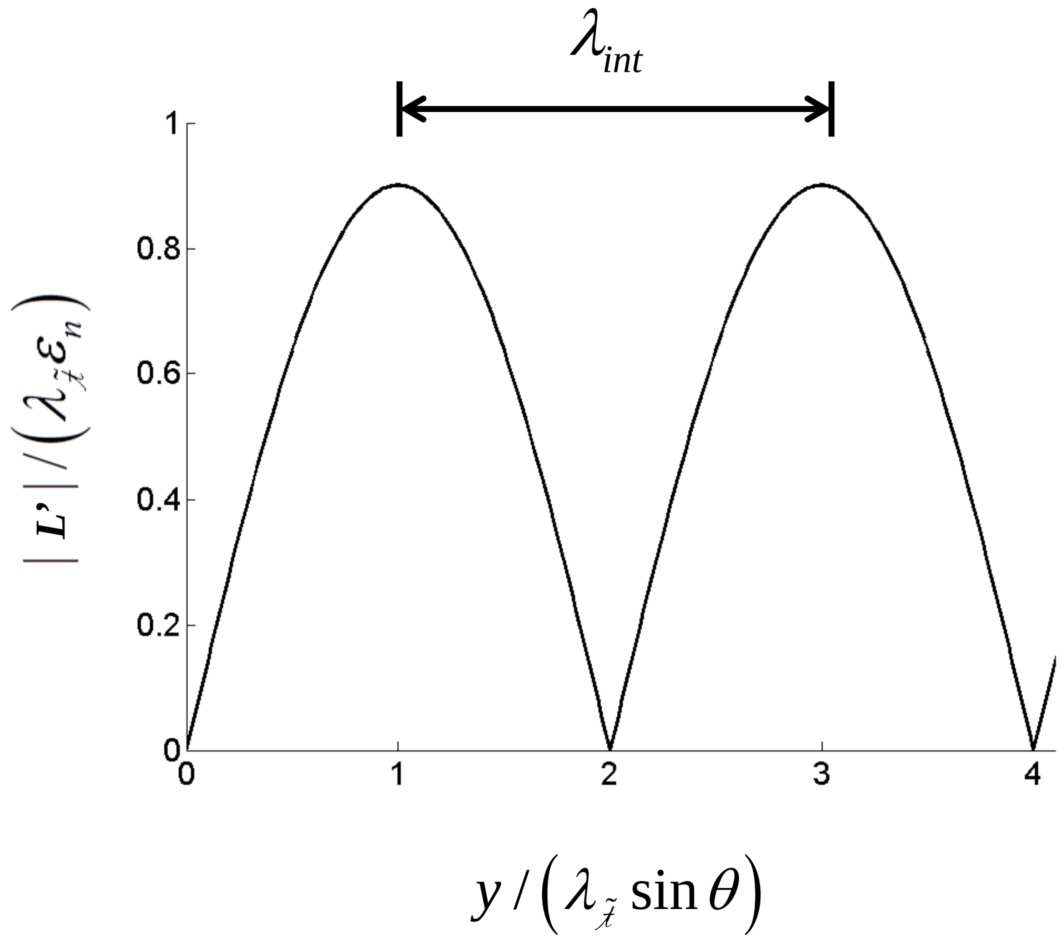
$$\frac{L'}{u_t / f} = \mathrm{Real}\left\{ \frac{-i \cdot \varepsilon_n / \sin\theta}{2\pi \left(u_t \cos\theta / u_{c,v} - 1 \right)} \times \left[e^{i 2\pi f \left(y / \left(u_{c,v} \tan\theta \right) - t \right)} - e^{i 2\pi f \left(y / \left(u_t \sin\theta \right) - t \right)} \right] \right\}$$

Solution Characteristics

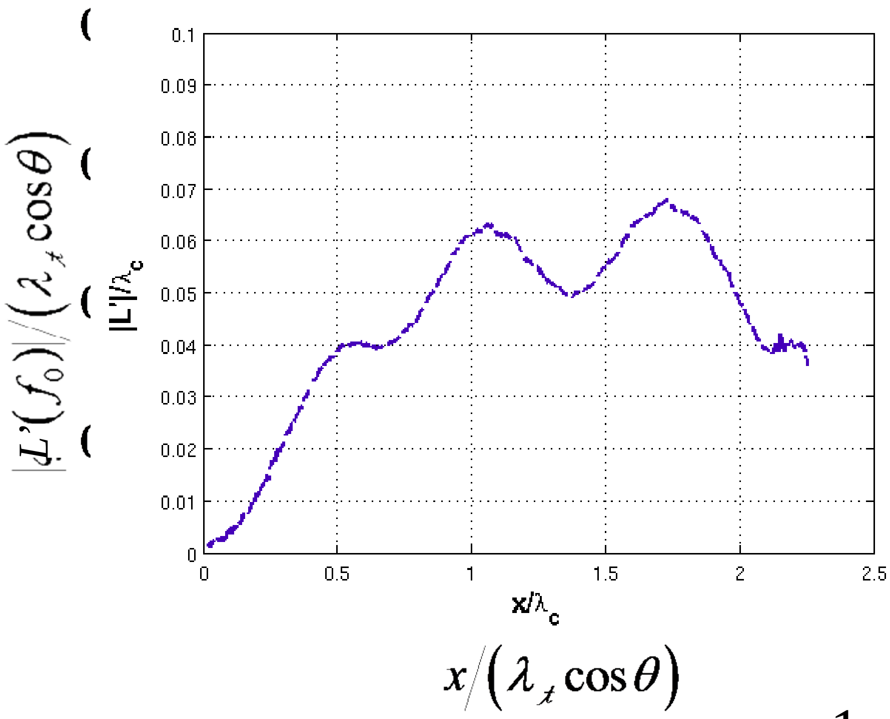
- Note interference pattern on flame wrinkling

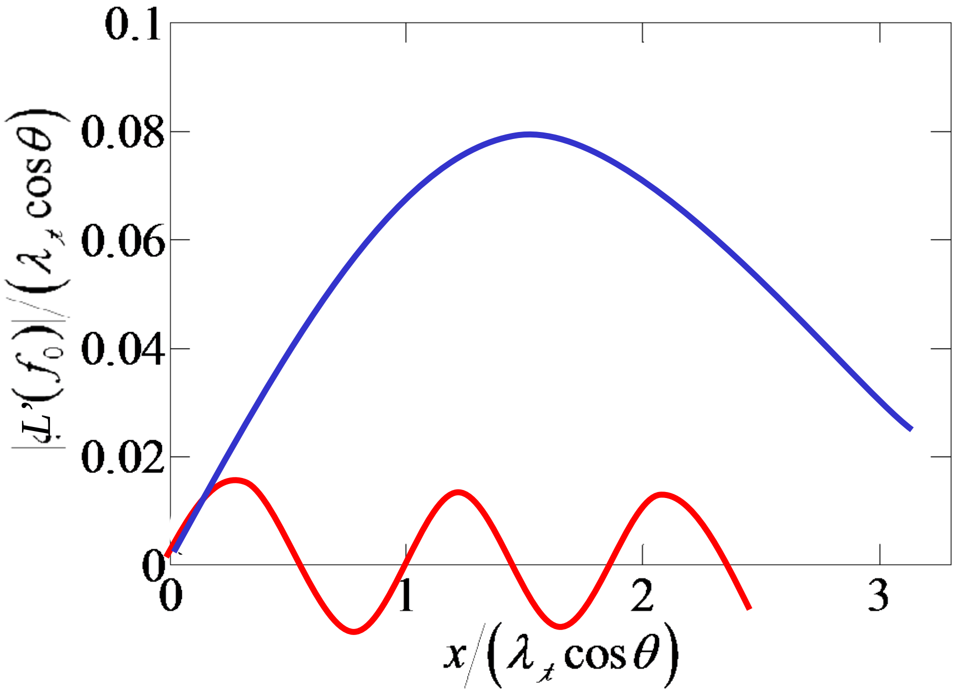
- Interference length scale:

$$\lambda_{int}/\left(\lambda_{\tilde{t}} \sin\theta\right) = \frac{1}{|u_t/u_{c,v} - 1|}$$



Interference Patterns on Flame Sheets





$$\lambda_{int}/(\lambda_t \sin\theta) = \frac{1}{|u_t/u_{c,v} - 1|}$$

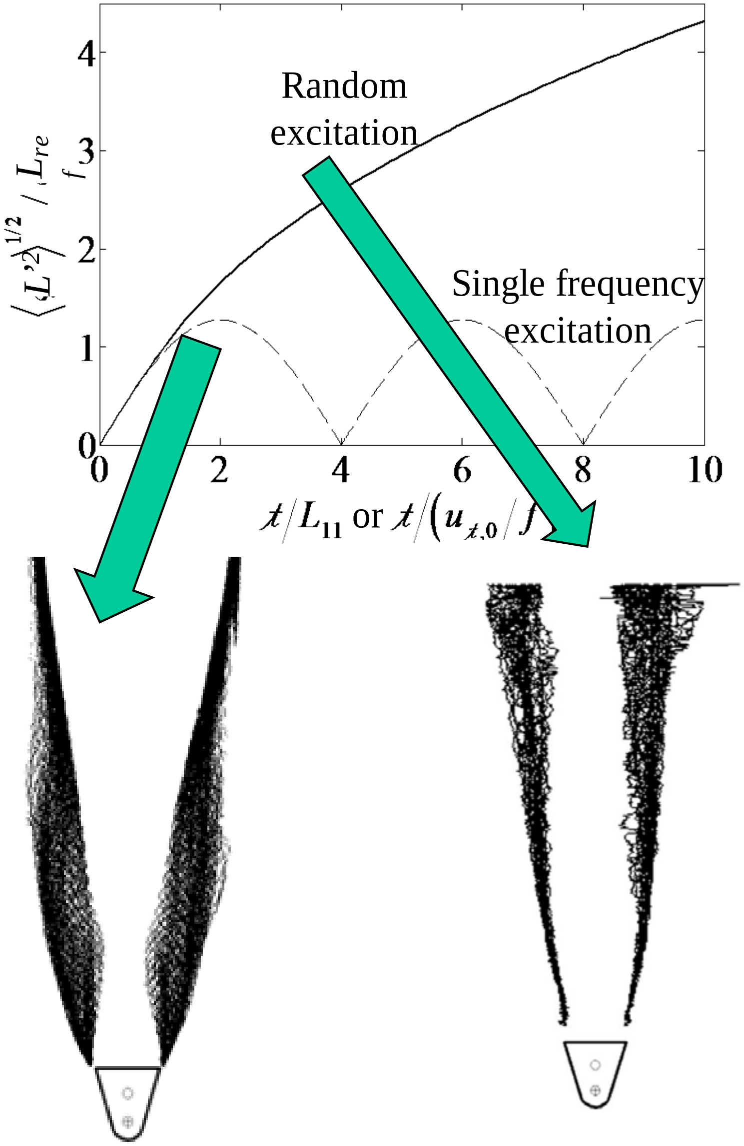
Acharya *et al.*, ASME Turbo Expo, 2011

- High phase acoustic speed disturbances (with long wavelengths) where $u_{c,v} >> u_t$ lead to short length scale disturbances
- Vortical disturbances where $u_t \sim u_{c,v}$ lead to long length scale wrinkling

Aside: Randomly Oscillating, Convecting Disturbances

- Space/time coherence of disturbances key to interference patterns

- Example: convecting random disturbances to simulate turbulent flow disturbances



Analysis of Flame Dynamics

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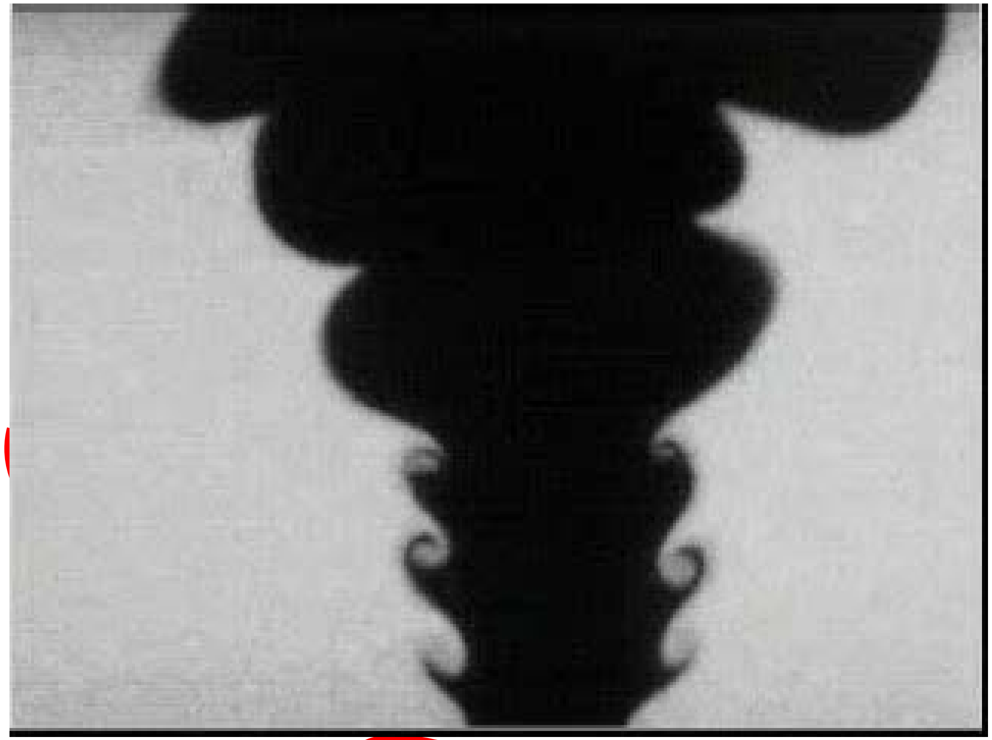
Flame Wrinkle Destruction Processes
: Kinematic Restoration

- Flame propagation normal to itself smoothes out flame wrinkles
- Typical manifestation: vortex rollup of flame
- Process is amplitude dependent and strongly nonlinear
  - Large amplitude and/or short length scale corrugations smooth out faster



Sung & Law, *Progress in Energy and Combustion Science*, 2000.

Analysis of Flame Dynamics

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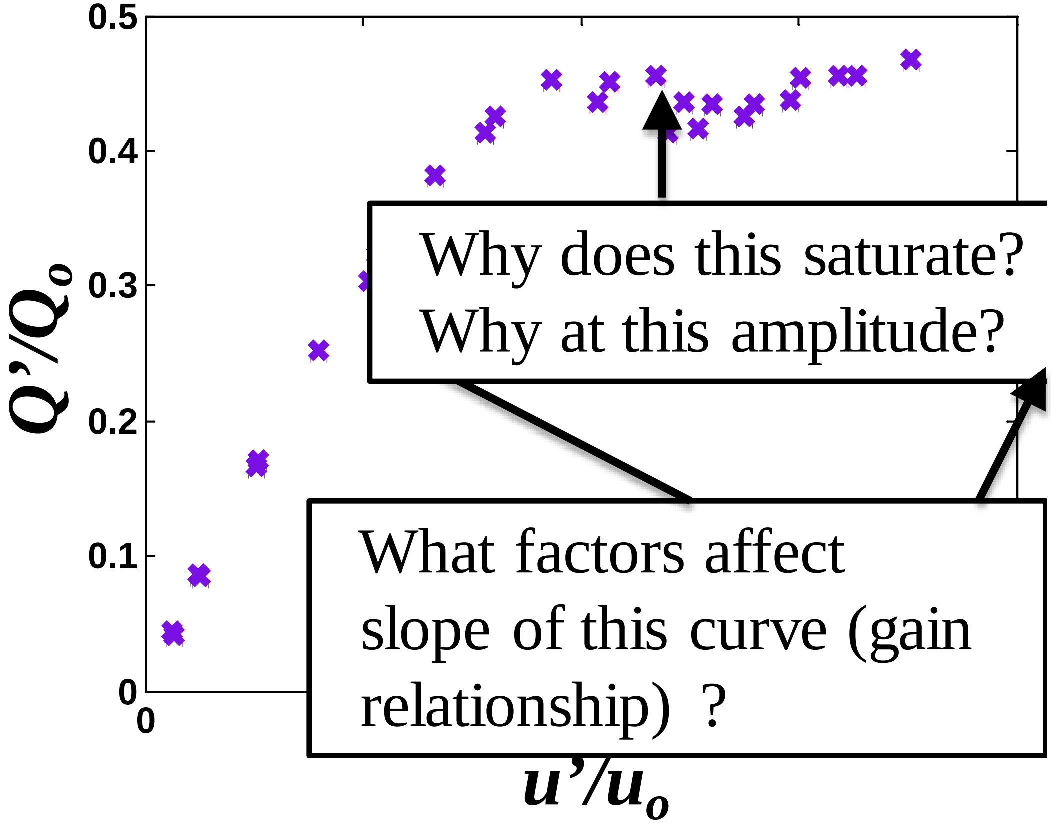
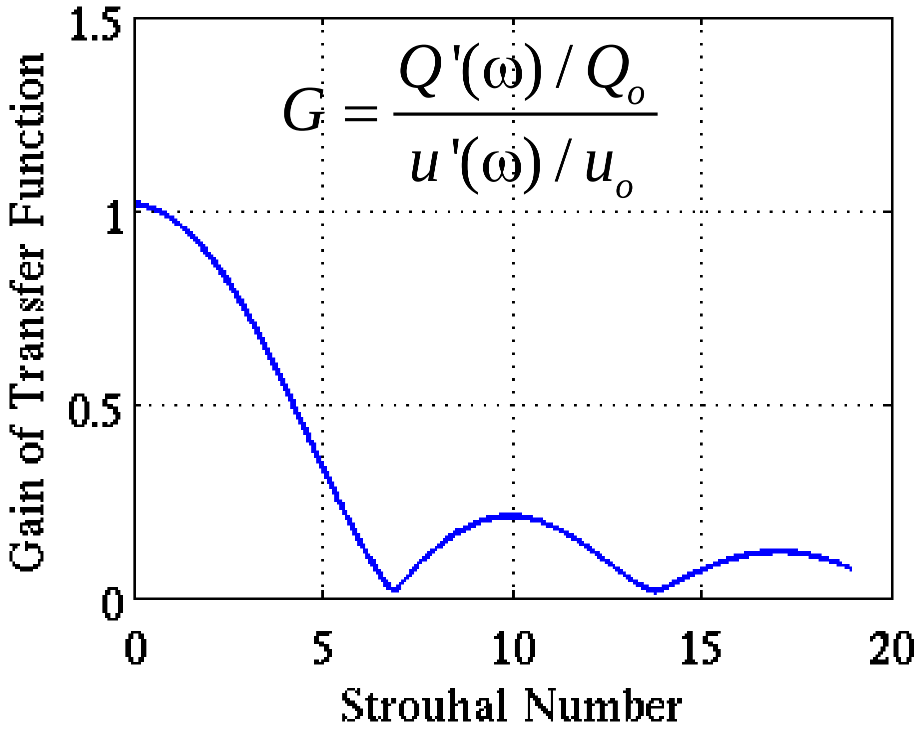
4. Spatially Integrated heat release

Response of Heat Release to Flow Perturbations

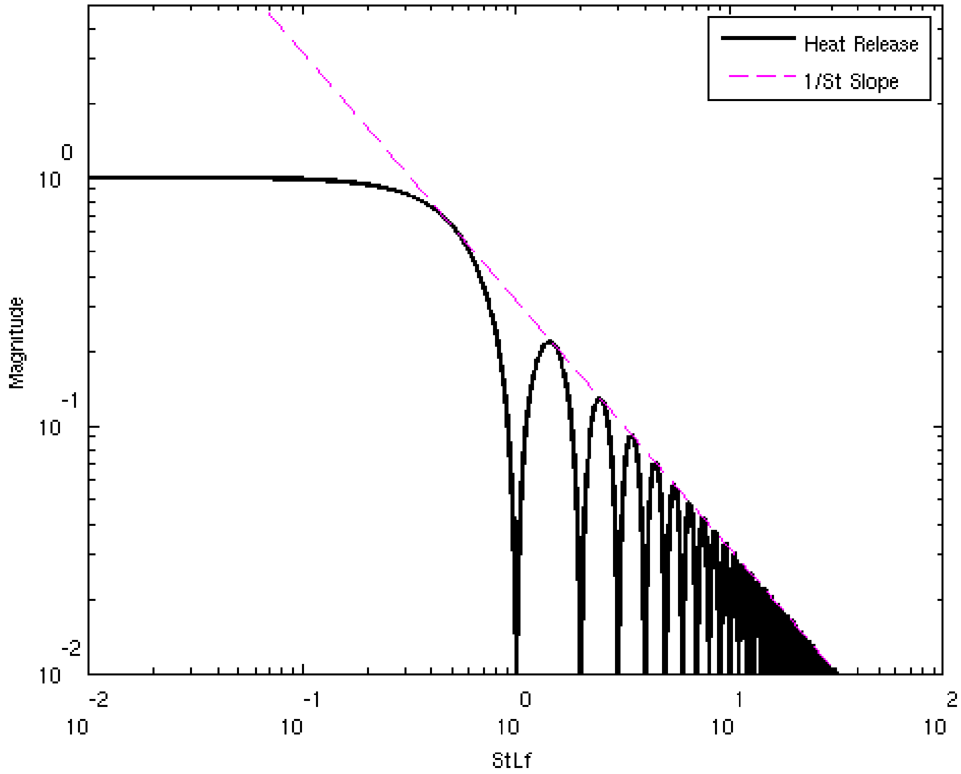


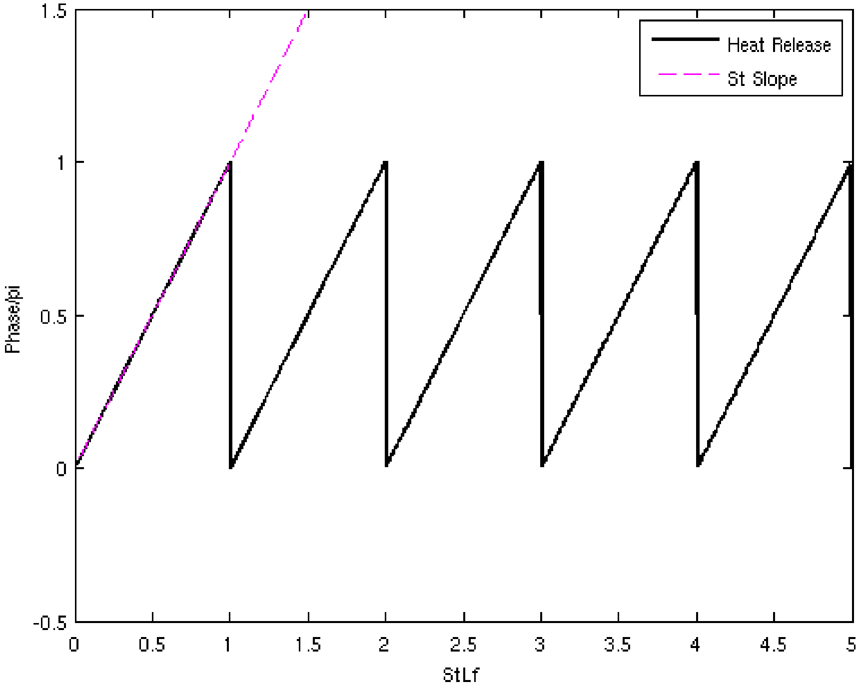
Why does this saturate?
Why at this amplitude?

What factors affect slope of this curve (gain relationship) ?



Spatially Integrated Heat Release





Why the 1/St Rolloff?

- Consider spatial integral of traveling wave disturbance:

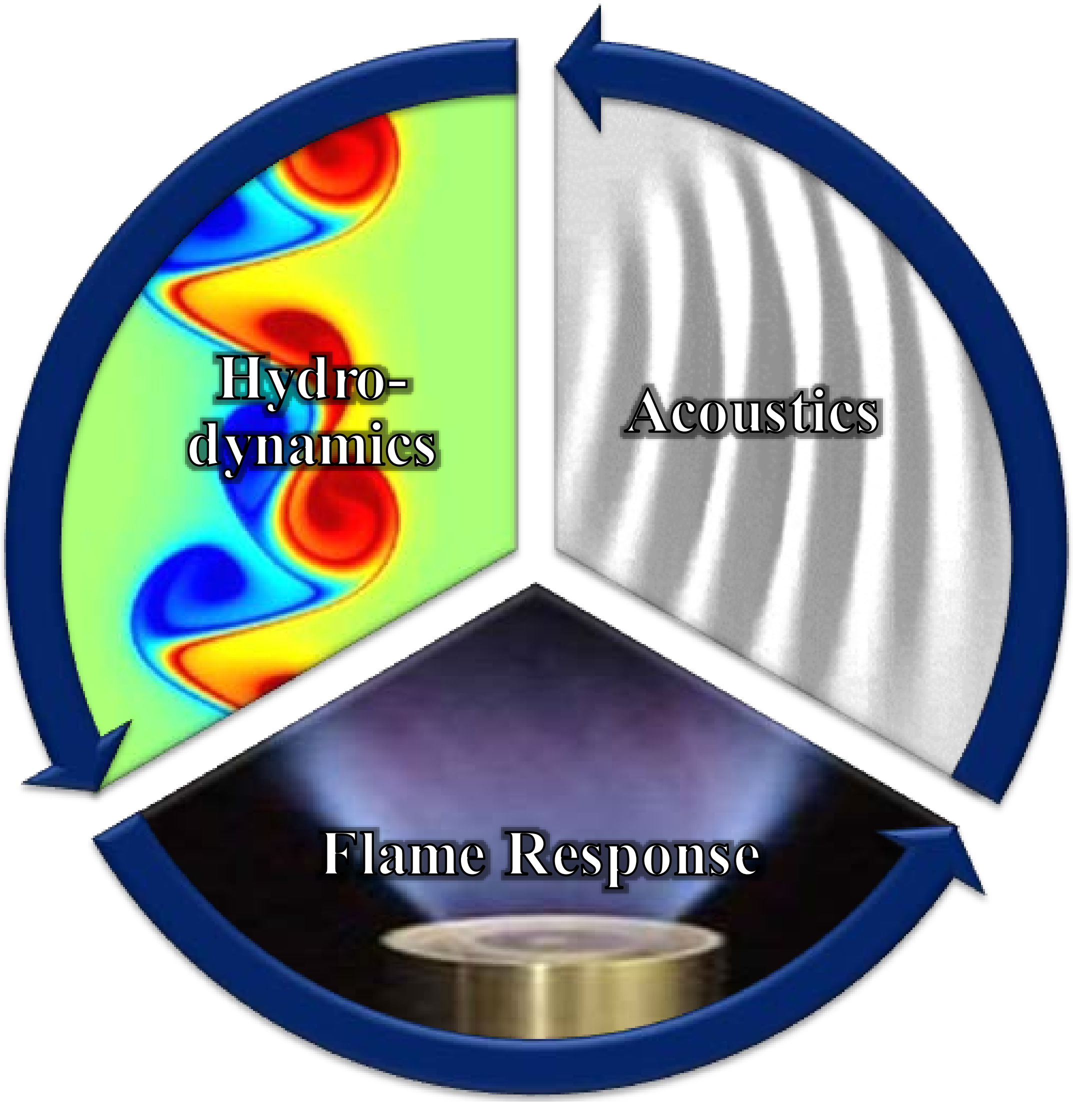
$$\underset{\downarrow}{\int_{x=0}^{L_F} \cos\left[\omega\left(t-\frac{x}{u}\right)\right]dx} = \underset{\downarrow}{-\frac{u}{\omega}}\left\{\sin\left[\omega\left(t-\frac{L_F}{u}\right)\right]-\sin\left[\omega t\right]\right\}$$

Traveling Wave

Low pass filter due to interference effects associated with tangential convection of wrinkles

- Low pass character of heat release response comes from the wrinkle convection and integration!

Key Research Questions



- Hydrodynamics of swirling jets; density stratification effects
- Acoustics – Boundary conditions in reacting, flowing systems
- Harmonically excited turbulent flames

Commercial Aircraft Engine

- Combustion instabilities emerged during full engine testing of GenX engine

F135 Beset By ‘Screech;’ Fix Found

By Colin Clark | Wednesday, January 19th, 2011 5:27 pm
Posted in Air, International, Naval

15 8

It’s not often the Pentagon’s top testers use the term “screech” to describe a problem with a weapons system, but that’s just what they are calling a problem with Pratt & Whitney’s engine for the Joint Strike Fighter.

“The [JSF] program began implementing plans to modify test aircraft to rectify the afterburner ‘screech’ problem, a problem that prevents the engine from sustaining full thrust. These modifications are necessary for the test aircraft to complete envelope expansion at the planned tempo,” said the annual report by Michael Gilmore, director of Operational Test and Evaluation. My colleagues at Defense News first reported the screech problem.

With the continuing political battle over funding for the F136, the screech may become a factor in the debate. However, GE’s often feisty spokesman, Rick Kennedy, was uncharacteristically soft-spoken in his email reply about how this would affect the program.

Financial Times
23 July 99, Issue 49

Daggers Drawn over Nehuenco

“The Patience of Chile’s Colbun power company has finally run out over the continued non-performance of the Siemens-built Nehuenco generating plant. Exasperated by repeated break-downs at the new plant and under pressure from increasingly reluctant insurers – (and with lawsuits looking likely) – the generator announced that it will not accept the $140m combined-cycle plant - built and delivered by the Germany equipment manufacturer.

Siemens, together with Italy’s Ansaldo, took the turnkey contract for the 350 MW plant in 1996 and should have had it in service by May of last year. The startup was delayed till January. Since then matters have worsened. There have been two major breakdowns and, says Colbun, there have been no satisfactory explanations.

The trouble could not have come worse for Colbun. The manly hydroelectric generator, which is controlled by a consortium made up of Belgium’s Tractebel, Spain’s Iberdrola and the local Matte and Yaconi-Santa Cruz groups, has been crippled by severe drought in Chile, which has slashed its output and thrown it back – without Nehuenco – onto a prohibitively expensive spot market.”

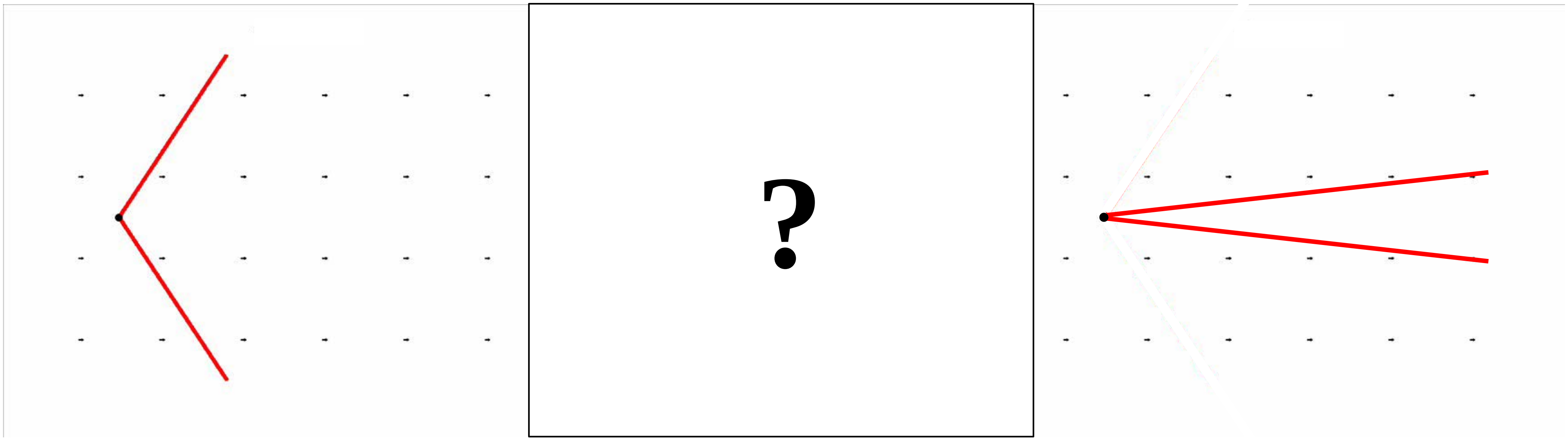
Wrinkle Convection

Flamelet Step Response problem:

Step increase axial velocity from u_a to u_b, :

$$u = \begin{cases} u_a & t < 0 \\ u_b & t \geq 0 \end{cases}$$

$u = u_a$ $t < 0$ $u = u_b$ $t > 0$ $u = u_b$ $t >> 0$



Wrinkle Convection

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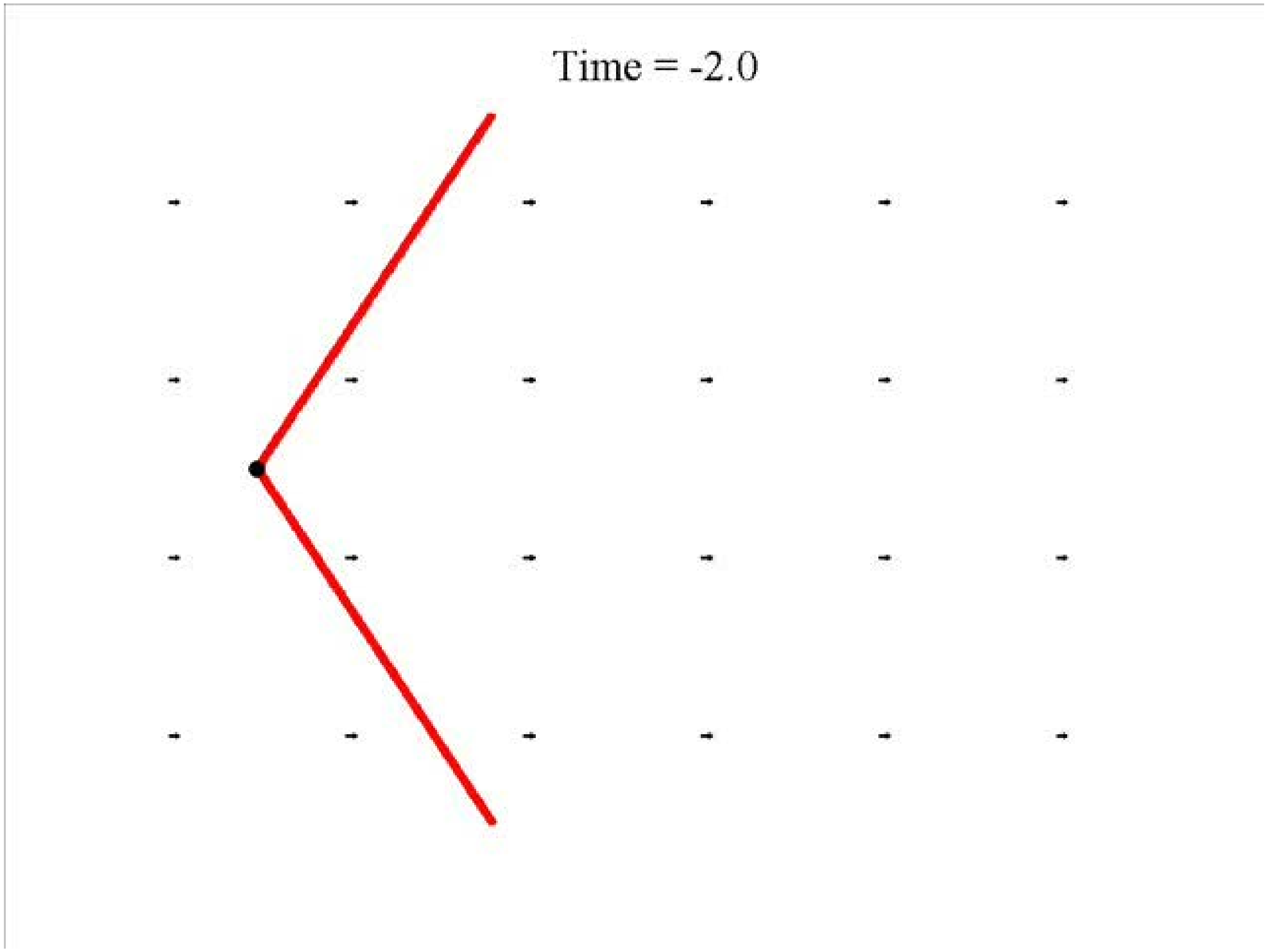

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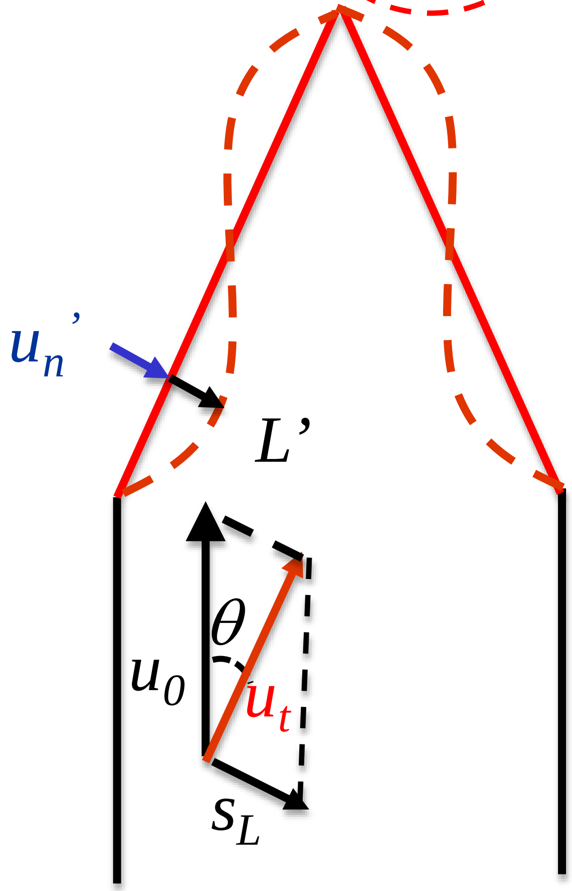
Excitation of Wrinkles on Anchored Flames

$$\frac{\partial L'(x,t)}{\partial x} = \frac{1}{u_t}\int_0^x \frac{\partial u_n'}{\partial x}\left(x',t-\frac{x-x'}{u_t}\right)dx' + \frac{1}{u_t}\cdot u_n'\left(x=0,t=t-\frac{x}{u_t}\right)$$

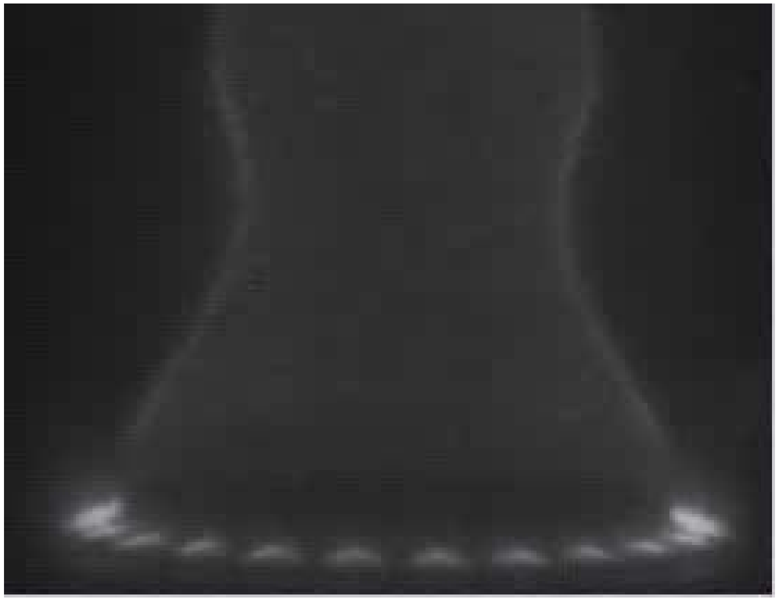
- Linearized solution of G Equation, assume anchored flame
- Wrinkle convection can be seen from delay term



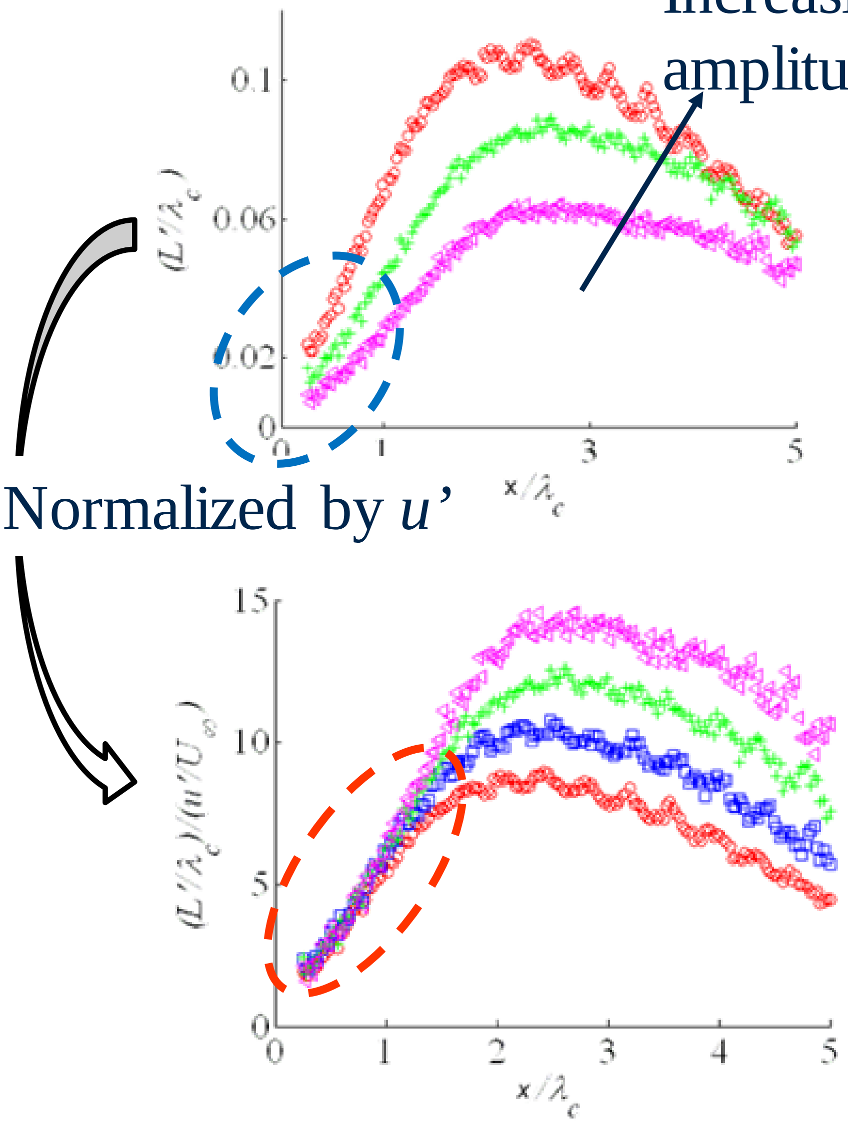
Excitation of Flame Wrinkles – Spatially Uniform Disturbance Field

$$\frac{\partial L'(x,t)}{\partial x} = \frac{1}{u_t}\int_0^x \cancel{\frac{\partial u_n'}{\partial x}}(x',t-\frac{x-x'}{u_t})\,dx' + \frac{1}{u_t}\cdot u_n'(x=0,t=t-\frac{x}{u_t})$$

- Wave generated at attachment point (x=0), convects downstream
- If excitation velocity is spatially uniform, flame response exclusively controlled by flame anchoring “boundary condition”
  - Kinetic /diffusive/heat loss effects, though not explicitly shown here, are very important!



Near Field Behavior



Increasing amplitude, *u'*

Normalized by *u'*

- Flame starts with **small amplitude** fluctuations because of attachment

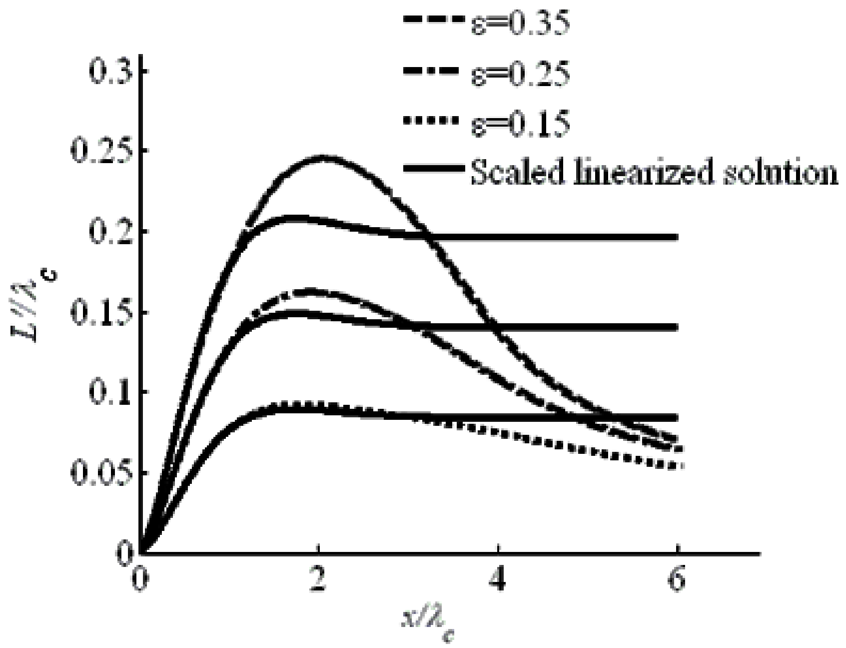
$$L'_{(x=0,\, t)} = 0$$

- Nearfield dynamics are essentially **linear** in amplitude

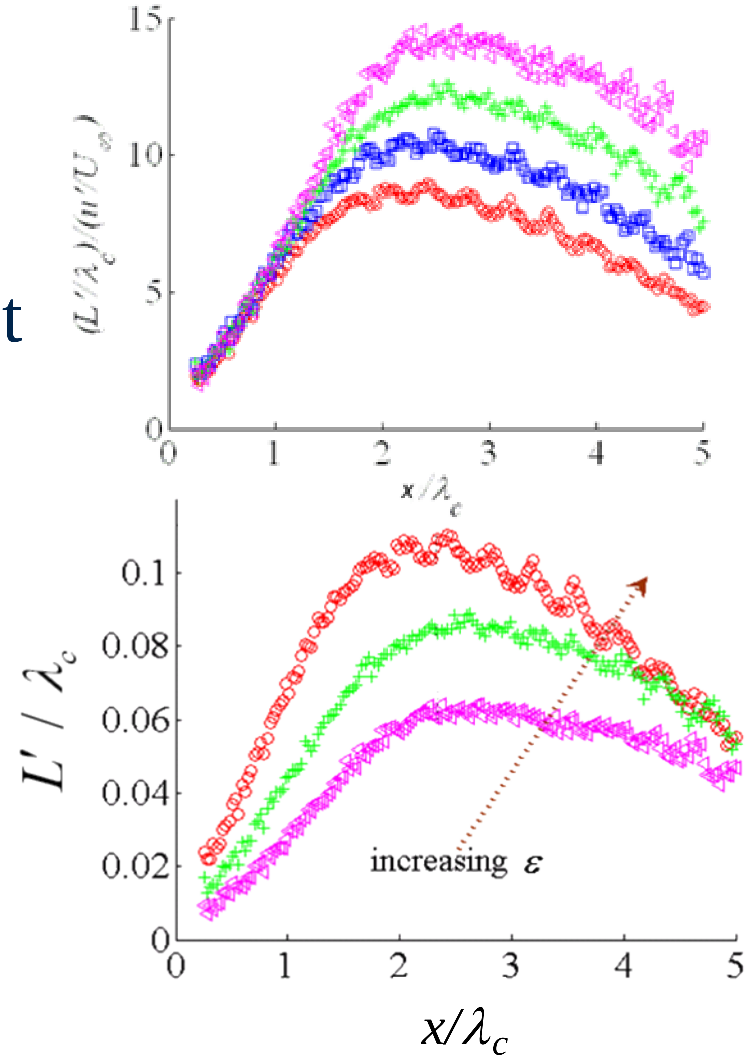
Shanbhogue *et al.*, *Proceedings of the Combustion Institute*, 2009.

Kinematic Restoration Effects

- Leads to nonlinear farfield flame dynamics
- Decay rate is amplitude dependent



Numerical Calculation



Experimental Result