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Swirl-Stabilized Flame Response to Transverse Acoustic Excitation

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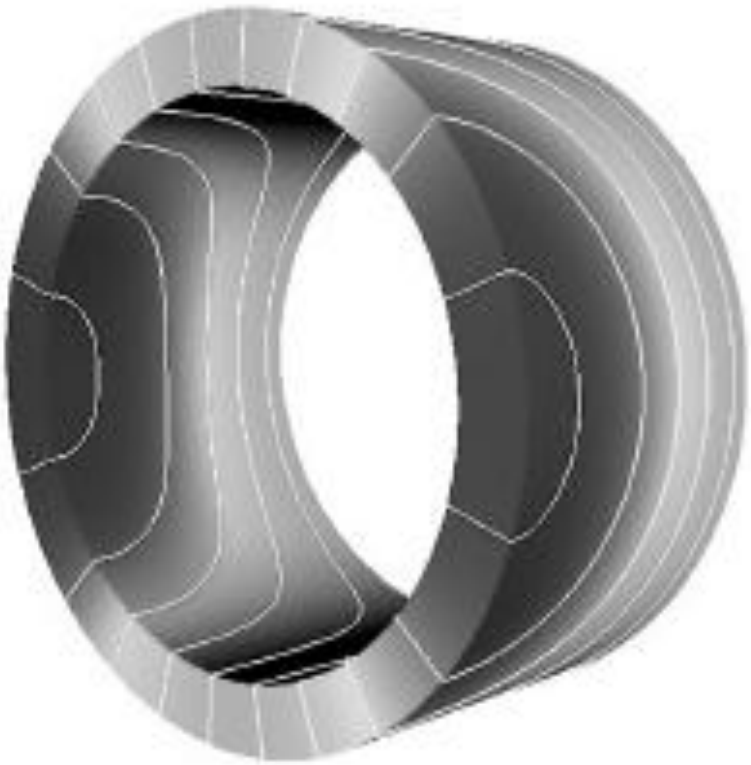
Transverse Modes in Gas Turbine Combustors

- Annular combustors:
  - Azimuthal modes
  - "Low "frequency

- Can combustors
  - Radial and azimuthal modes
  - "High" frequency



Reproduced from C. Sensiau *et al.*, International Journal of Aeroacoustics, 2009

Overview

- Transverse Combustion Instability Physics

- Research to date
  - Experimental measurements of flow field characteristics
  - Analysis of swirl flame dynamics

- Conclusions and future work

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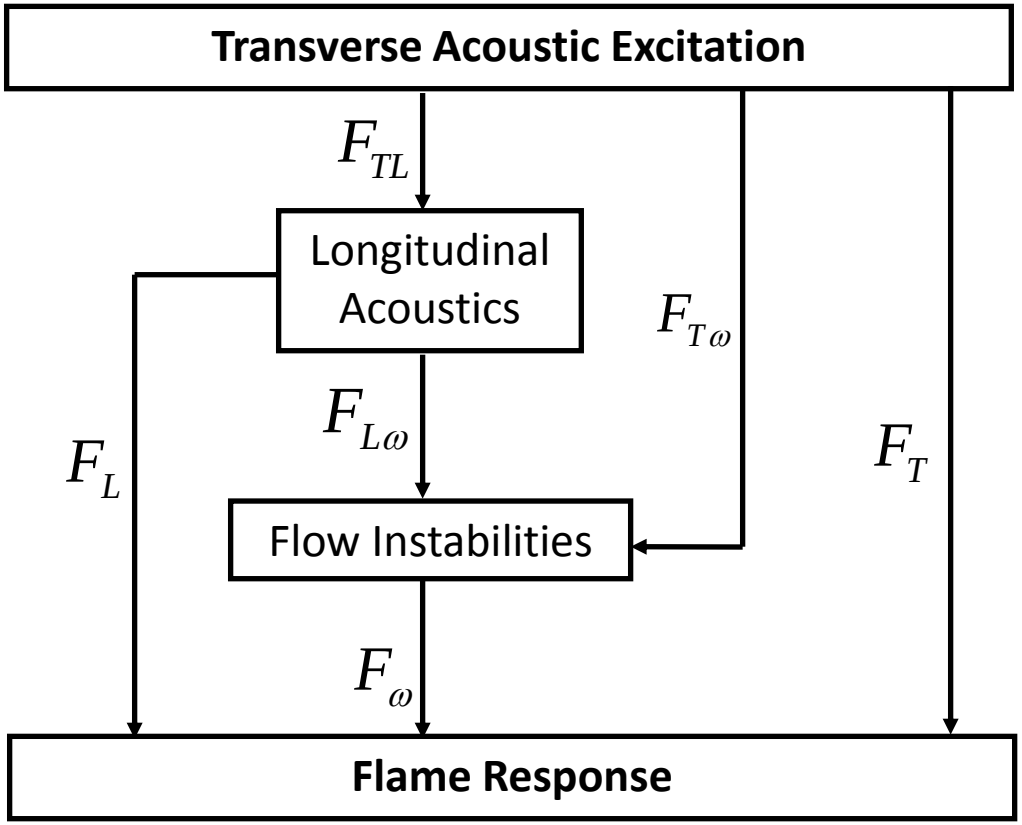
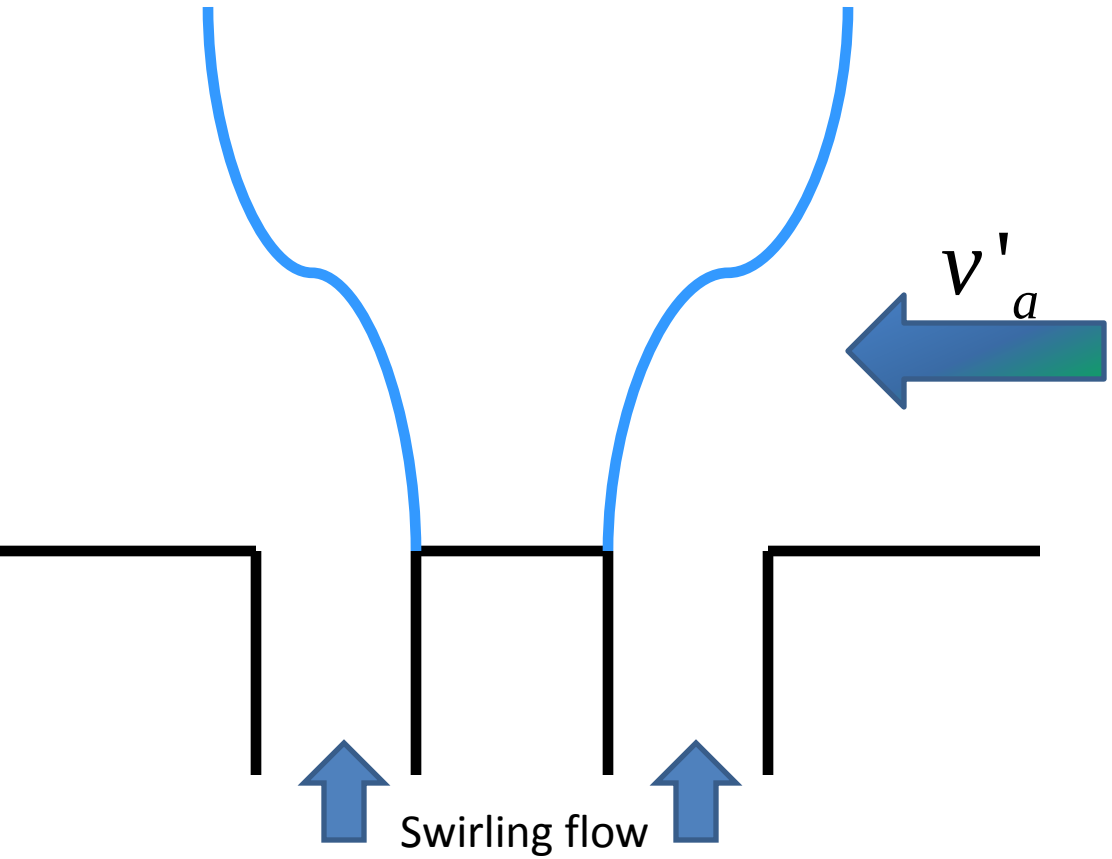
Velocity-Coupled Transverse Instabilities

QUESTION: What are key physical processes controlling flame response during transverse instabilities?



What is the Flame Responding to?

- What is the dominant physical mechanism for velocity coupling for transverse instabilities?



Disturbance Effects

1. Flame disturbed by transverse acoustics (F_T)

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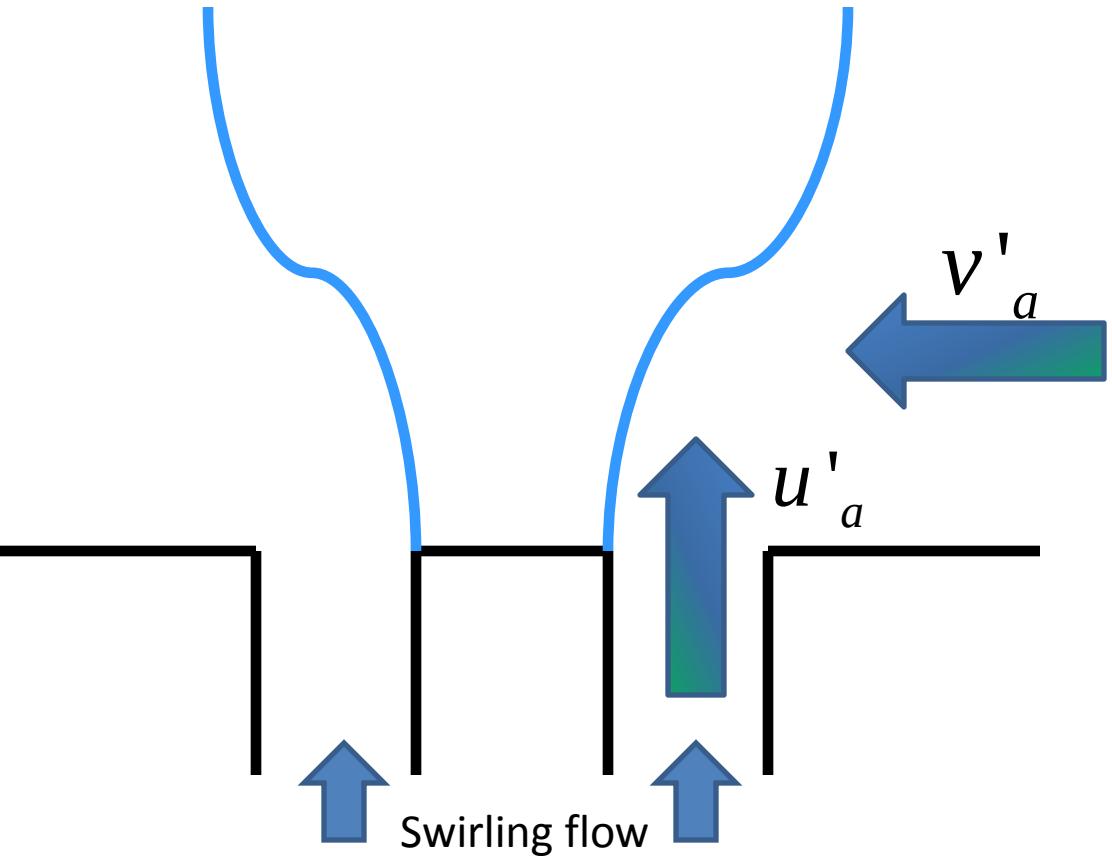

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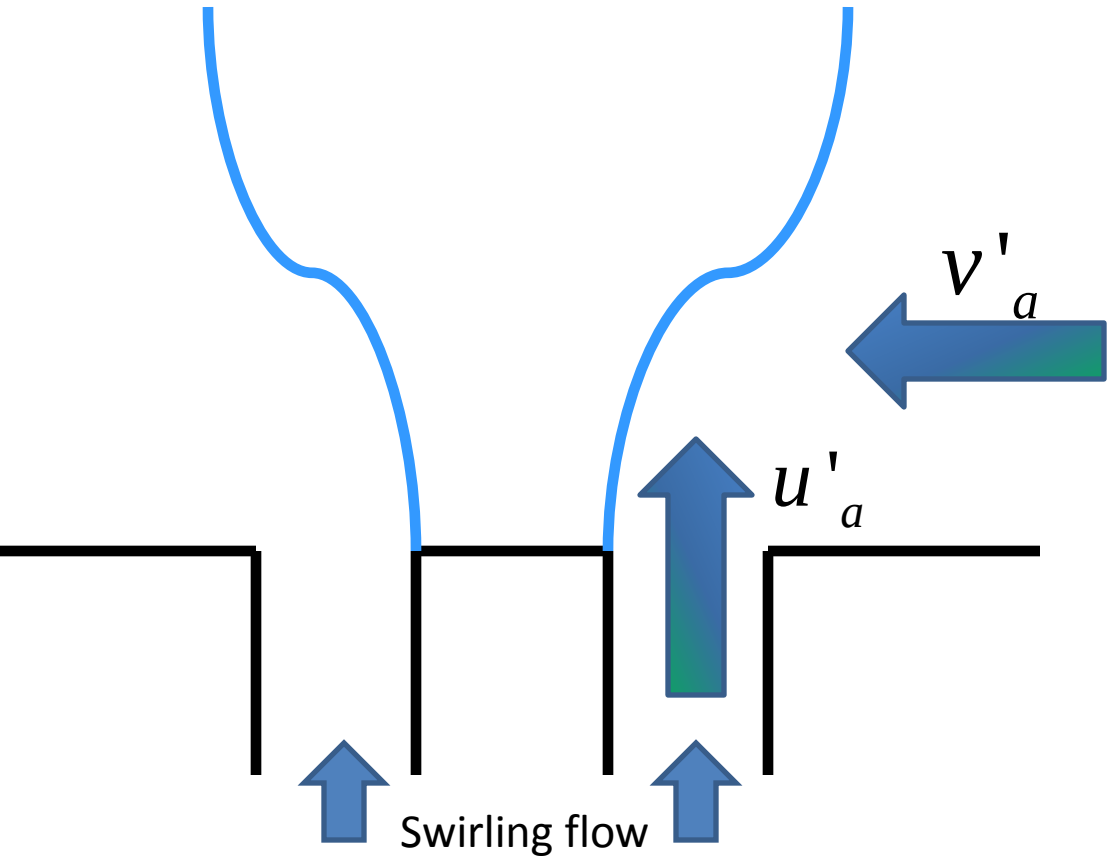

Disturbance Effects

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3. Flame disturbed by longitudinal acoustics (F_L)

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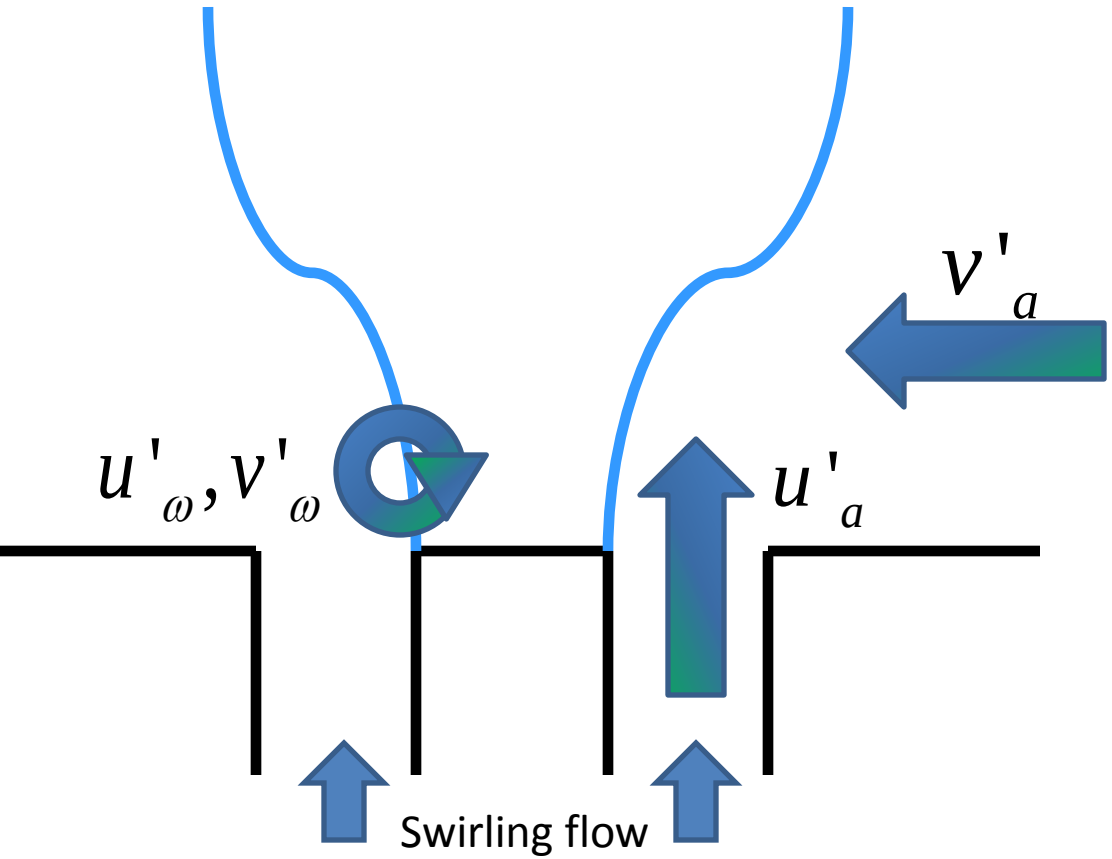
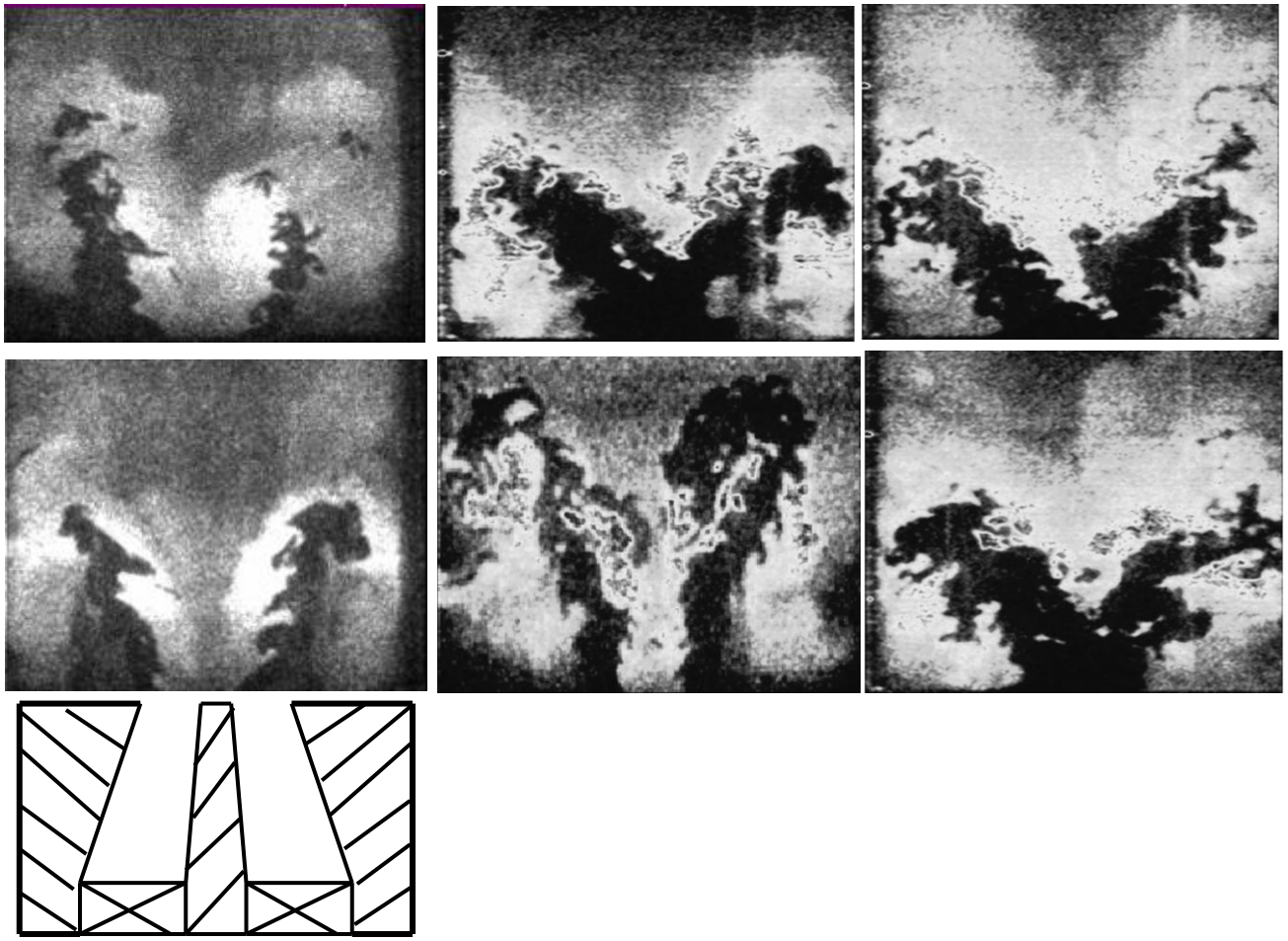


Disturbance Effects

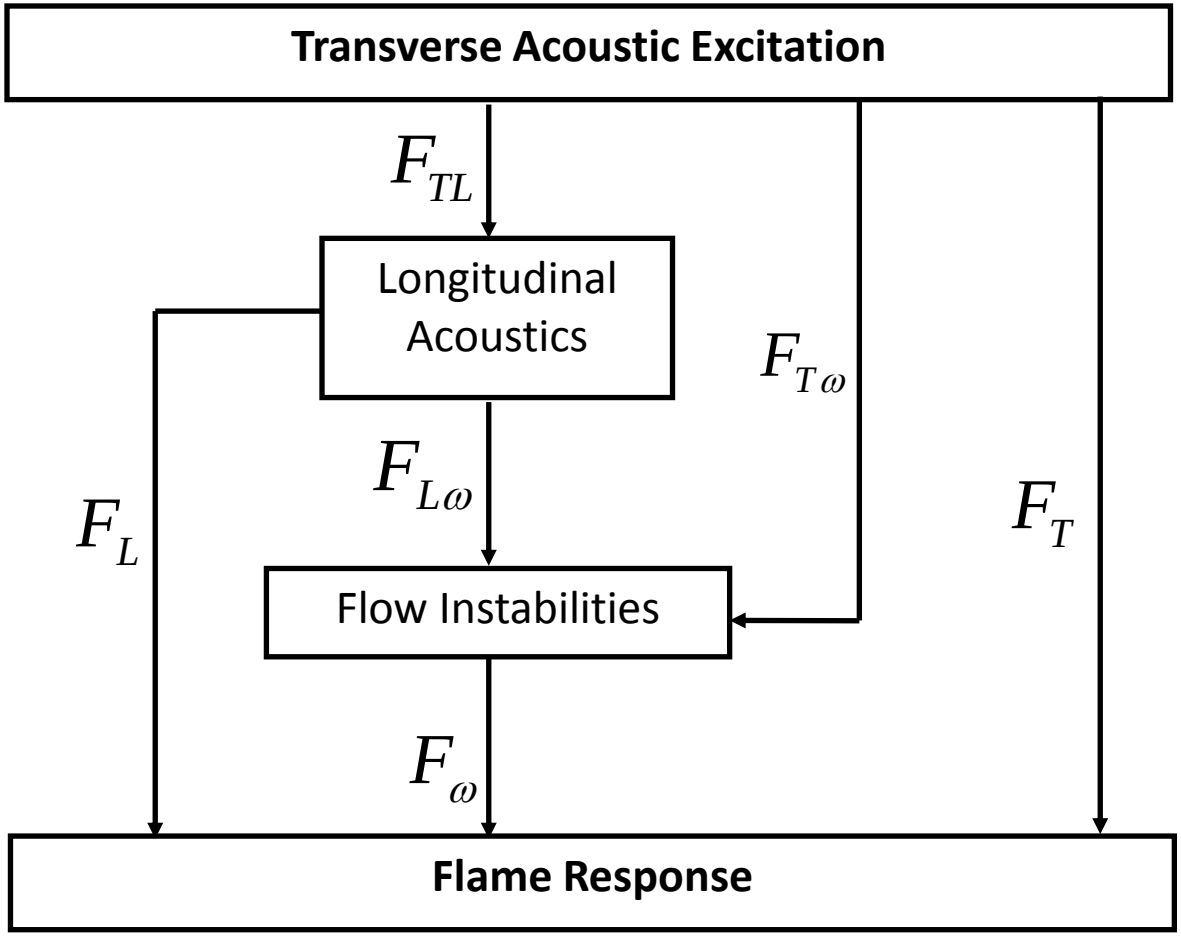
1. Flame disturbed by transverse acoustics (F_T)
2. Transverse acoustics trigger longitudinal acoustics (F_{TL})
3. Flame disturbed by longitudinal acoustics (F_L)
4. Acoustics triggers vortical disturbance (F_ω)

Velocity Coupled Flame Dynamics



Flame Transfer Functions for Transverse Instabilities

- What is the dominant physical mechanism for velocity coupling for transverse instabilities?



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Experimental Facility

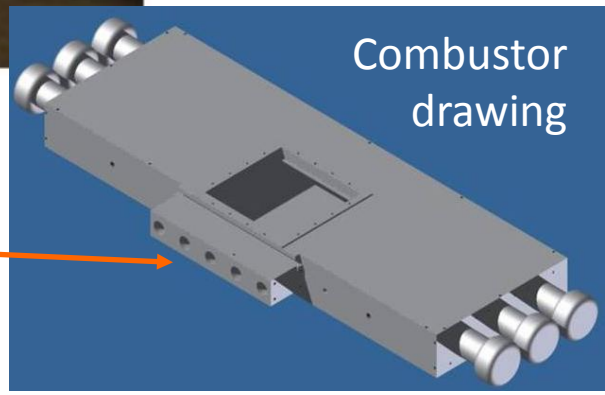
Optical quartz window for laser access

Acoustic drivers

Fuel/air premixing section

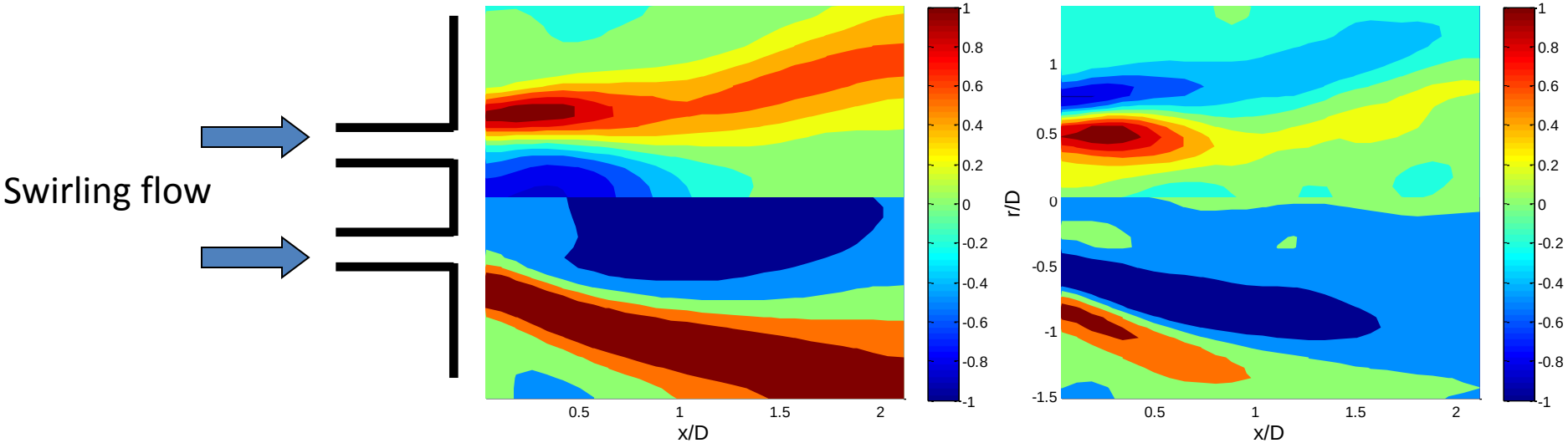
Optical quartz window

Swirler housing (1-5 swirlers)



Basic Flow Field Properties

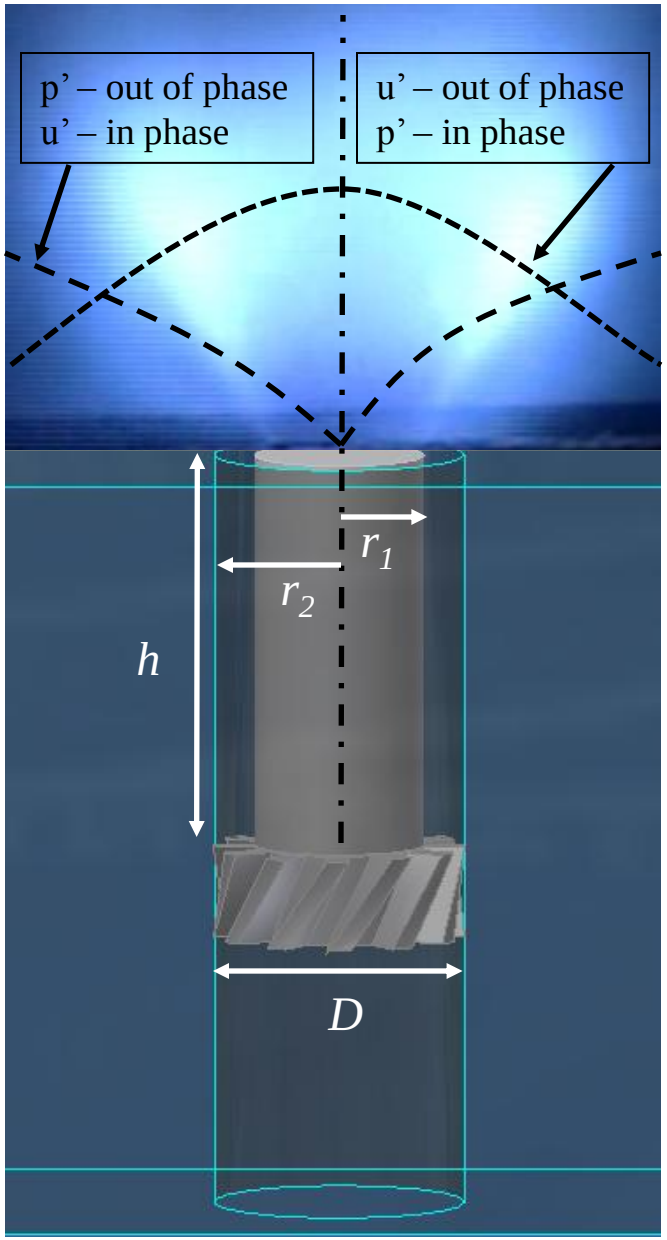
- Mean velocities: 10 m/s and 40 m/s
- Re = 20,500 and 41,000 based on outer nozzle diameter
- Swirl number: 0.85
- Forcing frequency: 400 Hz, 800 Hz, 1200 Hz



- Time-average velocity and z-vorticity contours
  - Top: non-reacting, 10 m/s
  - Bottom: reacting, 10 m/s, ϕ=0.85

Acoustic Forcing

- Phase control
  - Φ = 0º, approximate pressure maximum, velocity node, at center flame
  - Φ = 180º, approximate velocity maximum, pressure node, at center flame
  - Variable phase can create different standing and traveling wave patterns



$r_1 = 1.09cm$

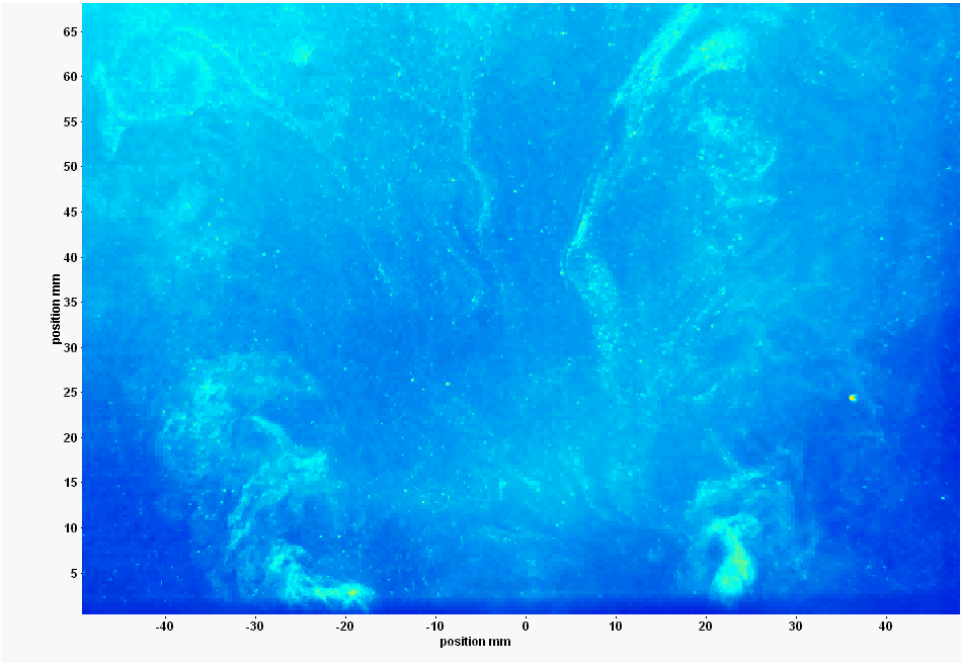
$r_2 = 1.59cm$

$D = 3.18cm$

$h = 5.08cm$

High Speed PIV

- System specifications
  - Litron Lasers, LDY303HE Nd:YLF, 22.5 mJ at 1 kHz
  - Photron Fastcam SA1 high-speed CMOS camera
  - Maximum 10,000 PIV fields per second

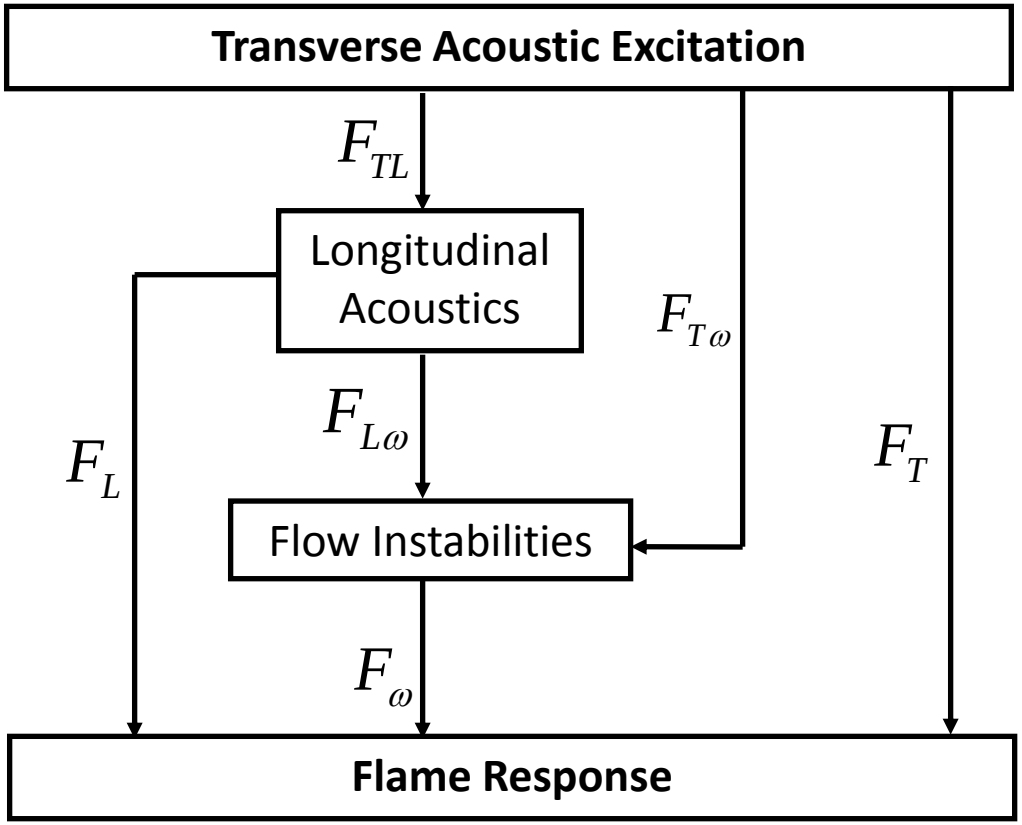


Summary of Diagnostics

- **10 kHz PIV**
  - Axial cuts
  - Radial cuts
- **Smoke visualization**
  - Inner shear layer seeding
  - Outer shear layer seeding
  - Centerbody seeding
- **Flame chemilumenescence**
  - Line of sight high speed videos
  - Global PMT measurements
- **High speed PLIF**

Velocity-Coupled Transverse Instabilities

QUESTION: What are key physical processes controlling flame response during transverse instabilities?

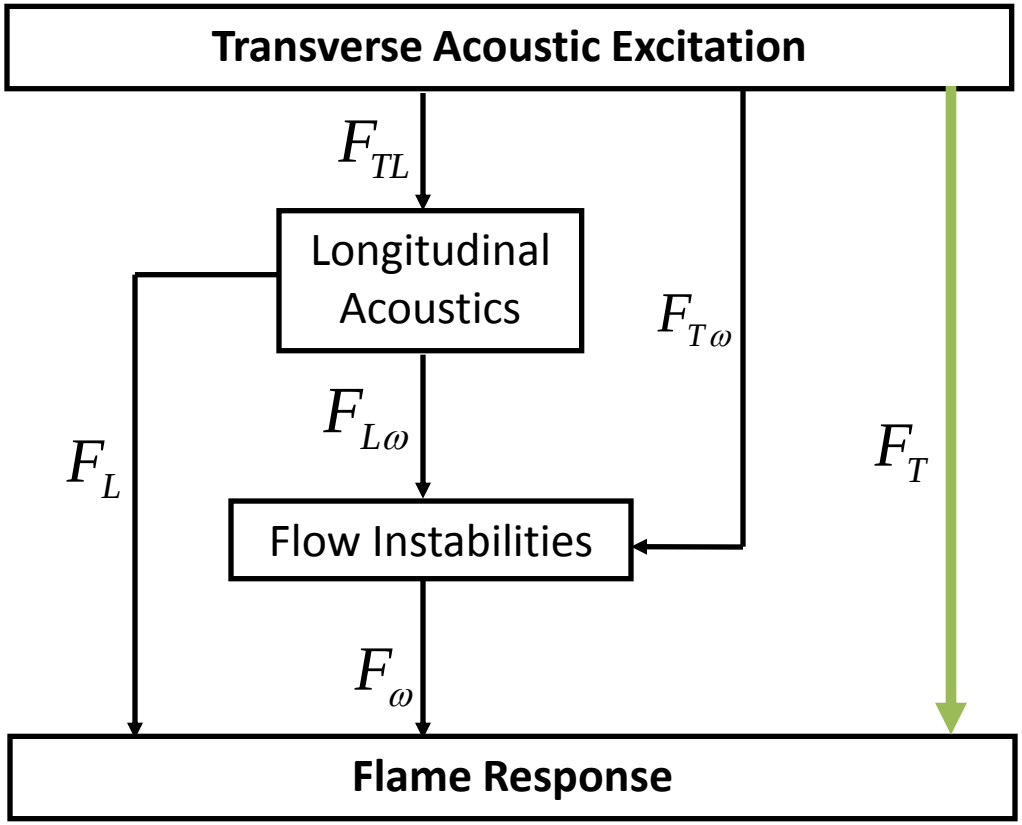


Velocity-Coupled Transverse Instabilities

QUESTION: What are key physical processes controlling flame response during transverse instabilities?

$$F_T(f) = \frac{q'(f)/\bar{q}}{u'_{T,a}(f)/\bar{u}}$$

- **Minimal effect on flame response at most frequencies of interest**

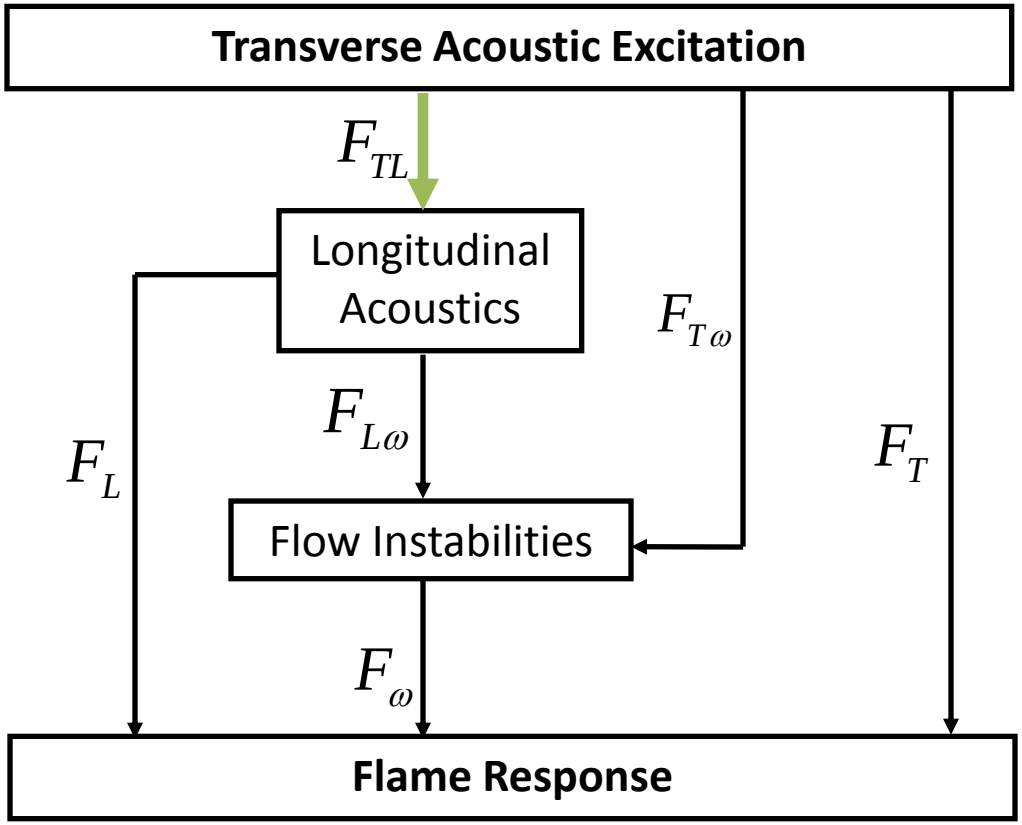


Velocity-Coupled Transverse Instabilities

QUESTION: What are key physical processes controlling flame response during transverse instabilities?

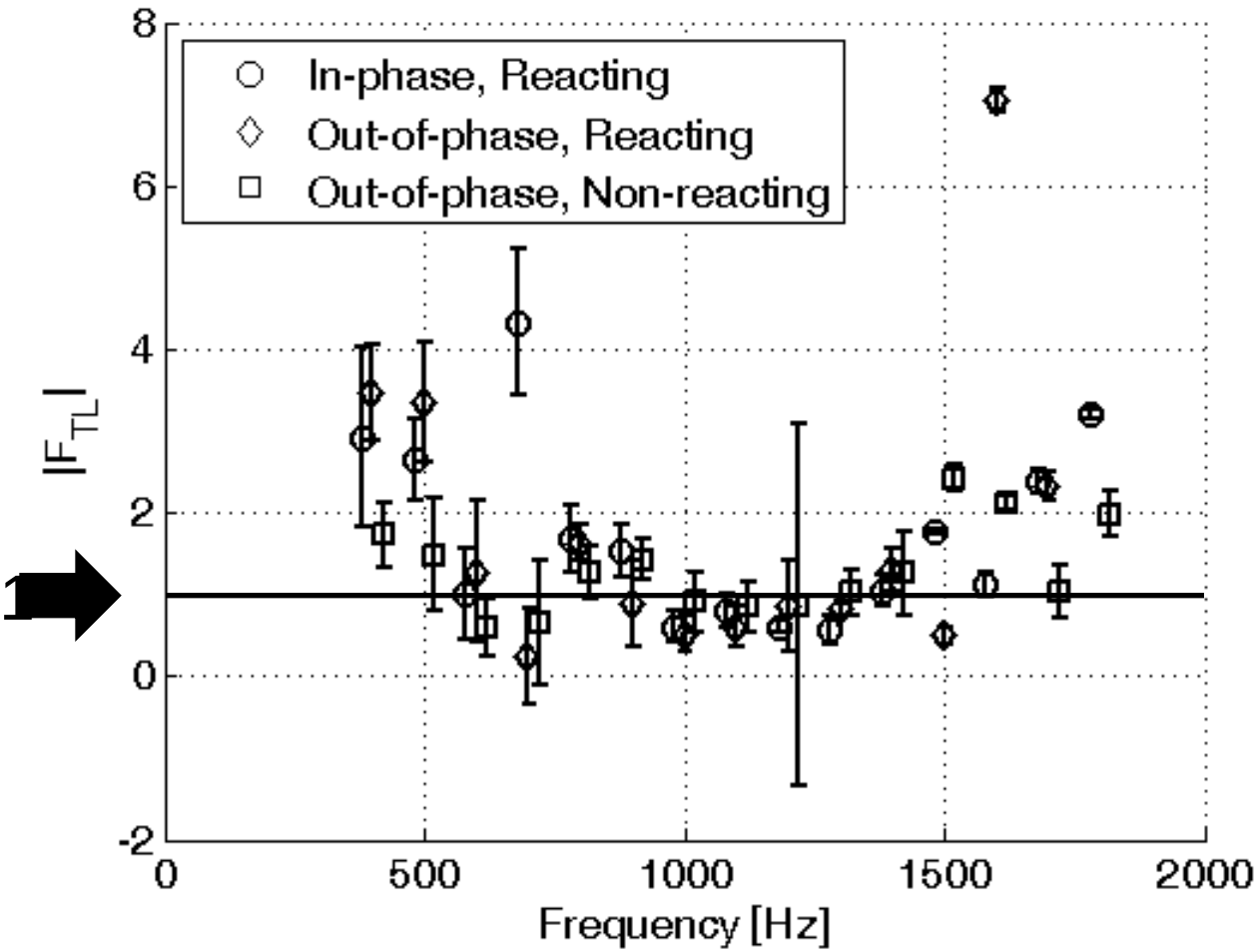
$$F_{TL}(f) = \frac{u'_{L,a}(f)}{u'_{T,a}(f)}$$

- **Key coupling mechanism that determines the relative role of transverse vs. longitudinal motion**
  - Suggests proper reference velocity for flame transfer functions
- **Describes acoustic coupling between combustor and swirler nozzle cavity**



F_{TL} – Gain

$F_{TL} = 1$

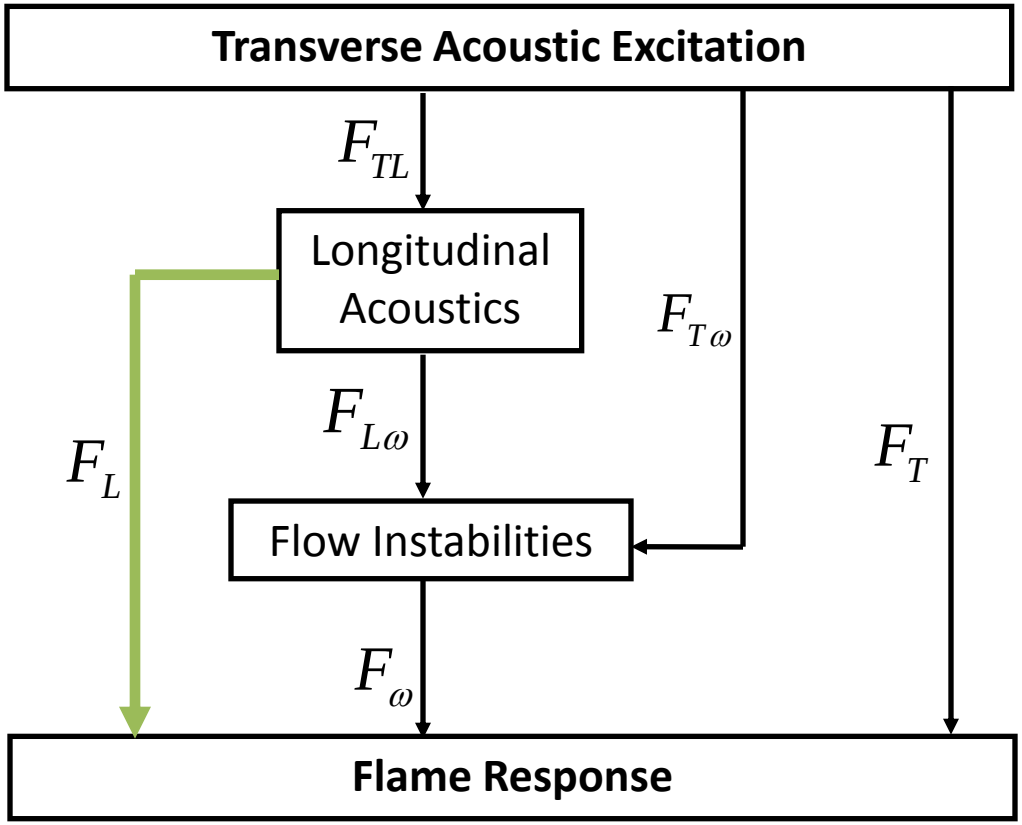


Velocity-Coupled Transverse Instabilities

QUESTION: What are key physical processes controlling flame response during transverse instabilities?

$$F_L(f) = \frac{q'(f)/\bar{q}}{u'_{L,a}(f)/\bar{u}}$$

- **Definition of the flame transfer function of a longitudinally forced flame**
- **Important mechanism in F_{TL}>1 situations**
  - Often greater in magnitude than F_T



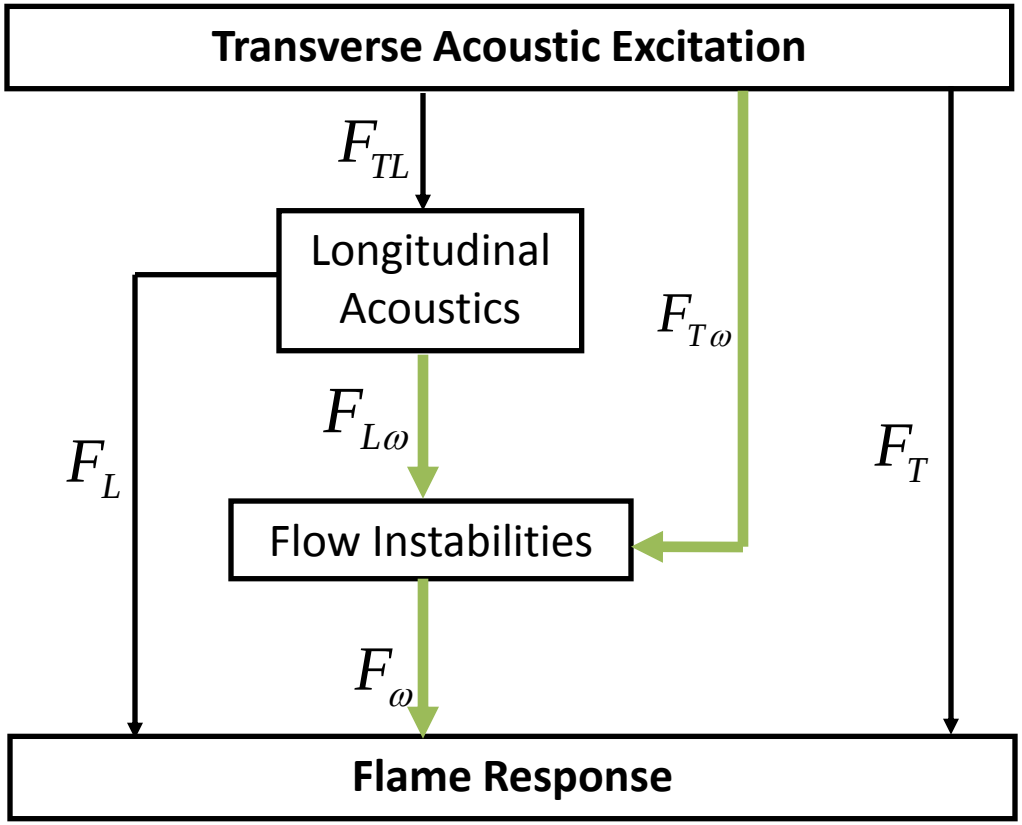
Velocity-Coupled Transverse Instabilities

QUESTION: What are key physical processes controlling flame response during transverse instabilities?

$$F_{L\omega}(f) = \frac{u'_{L,\omega}(f)}{u'_{L,a}(f)}$$

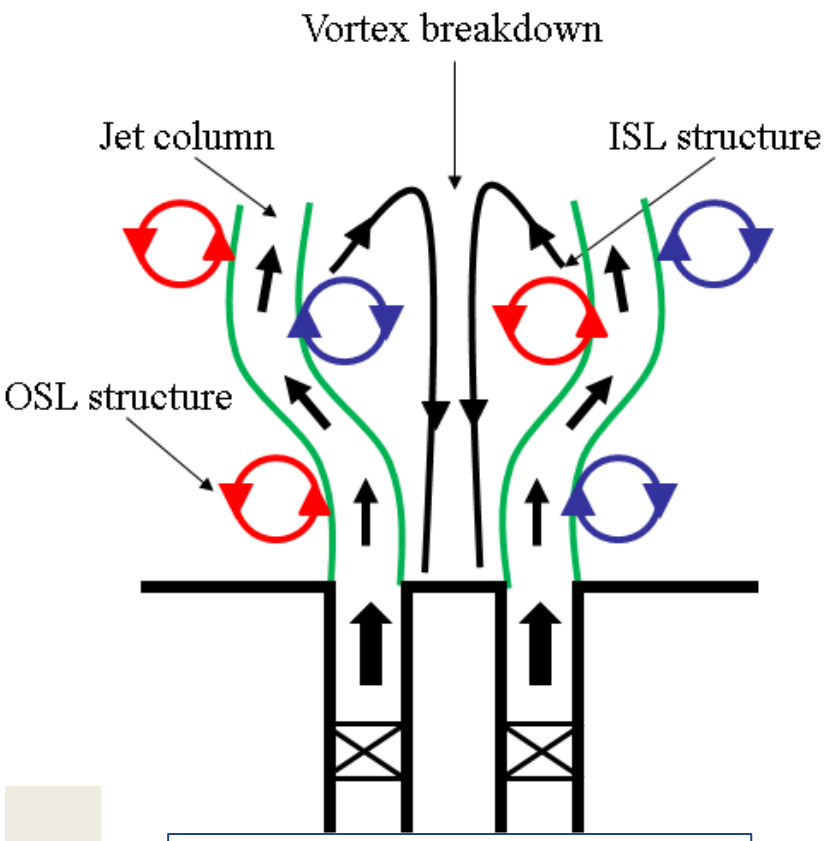
$$F_{T\omega}(f) = \frac{u'_{T,\omega}(f)}{u'_{T,a}(f)}$$

$$F_{\omega}(f) = \frac{q'(f)/\bar{q}}{u'_{\omega}(f)/\bar{u}}$$



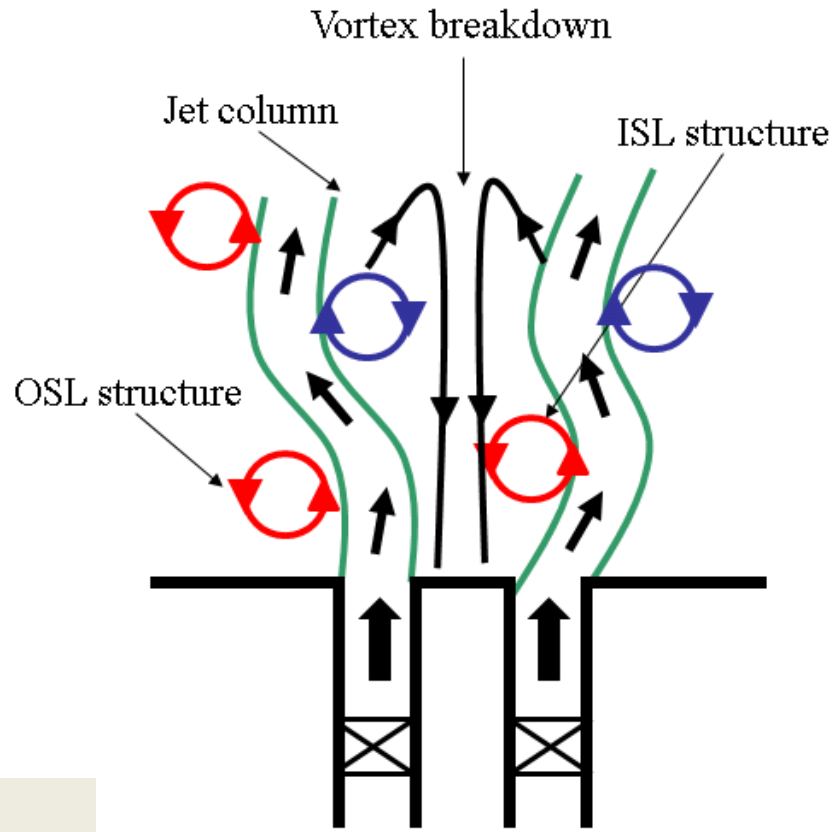
Flow Field Topology

In-phase Forcing



Symmetric acoustic velocity
Ring vortex shedding

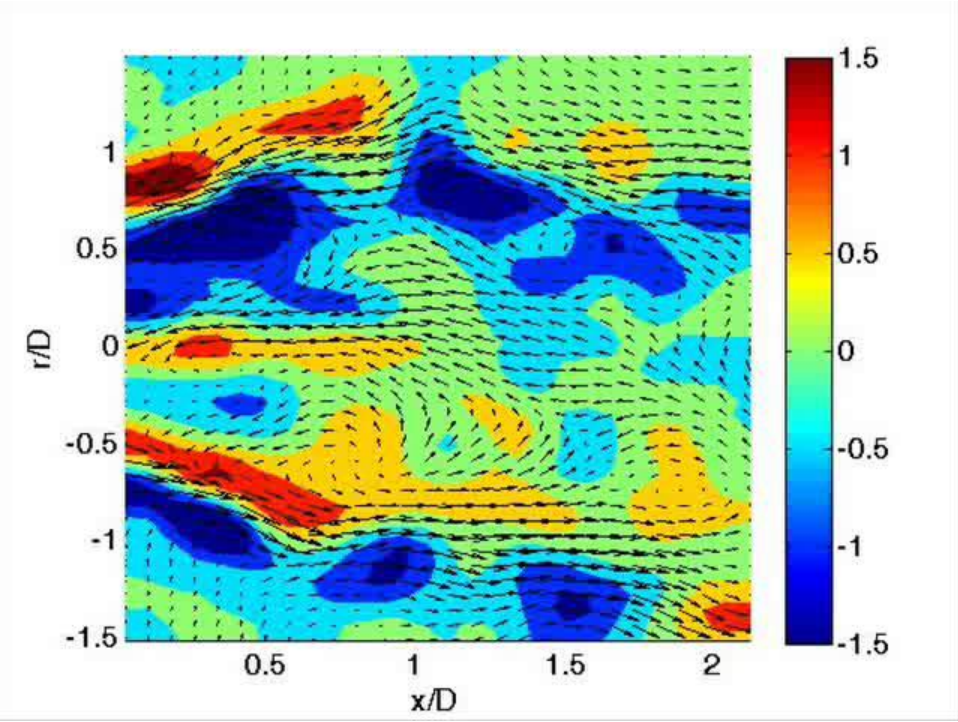
Out-of-phase Forcing



Asymmetric acoustic velocity
Helical shear layer response

Flow Field Topology – Instantaneous Velocity

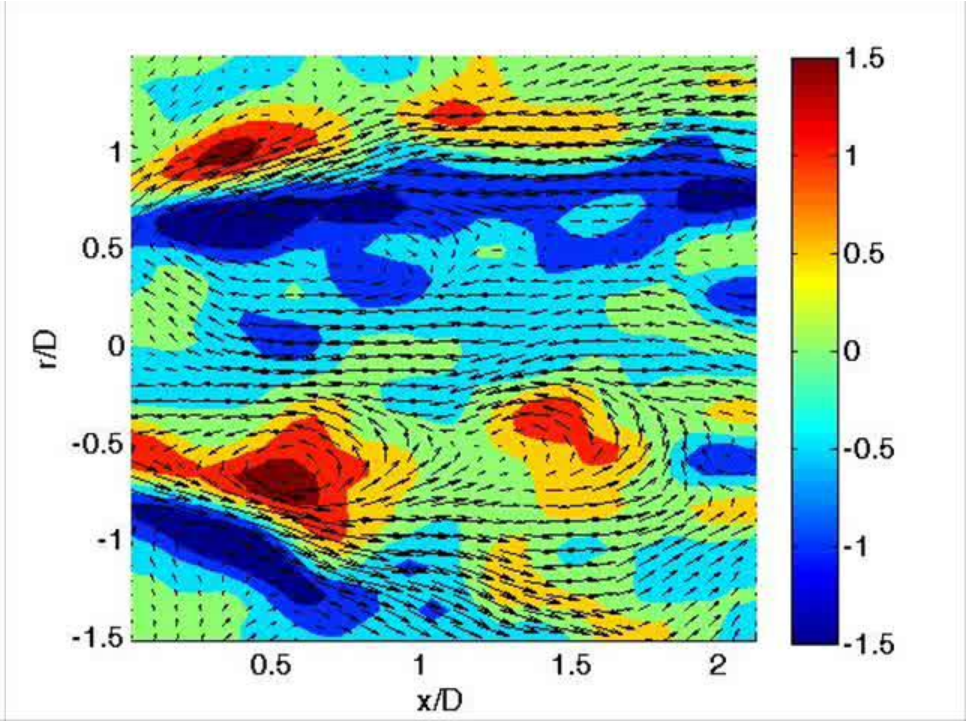
In-phase Forcing



400 Hz in-phase,
U_o=10 m/s

Symmetric acoustic velocity
Ring vortex shedding

Out-of-phase Forcing



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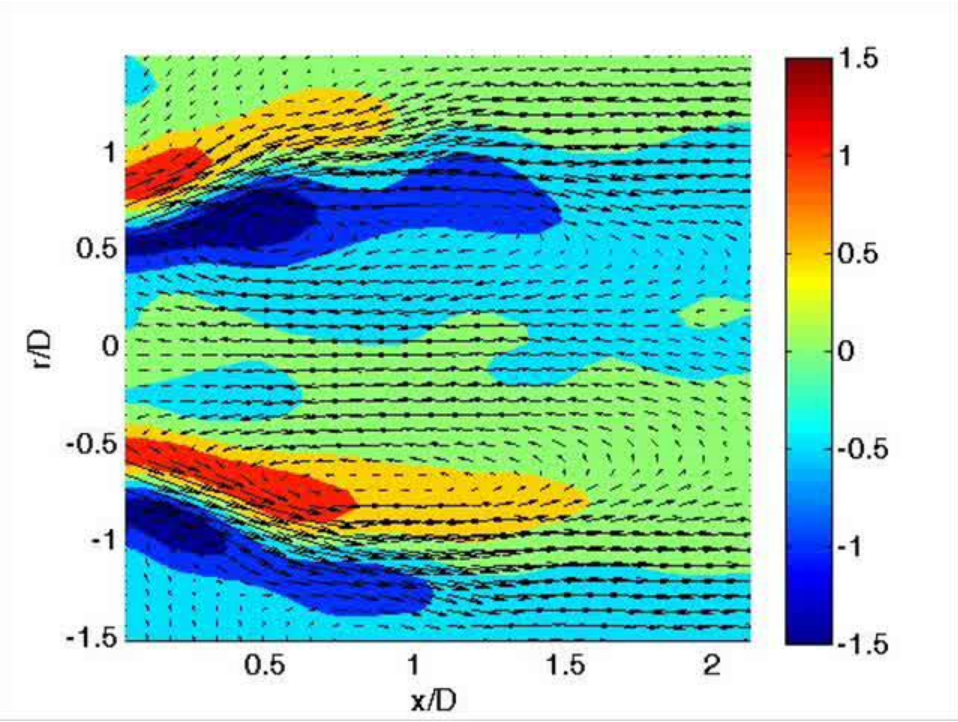
Flow Field Topology – Phase-Averaged Velocity

In-phase Forcing



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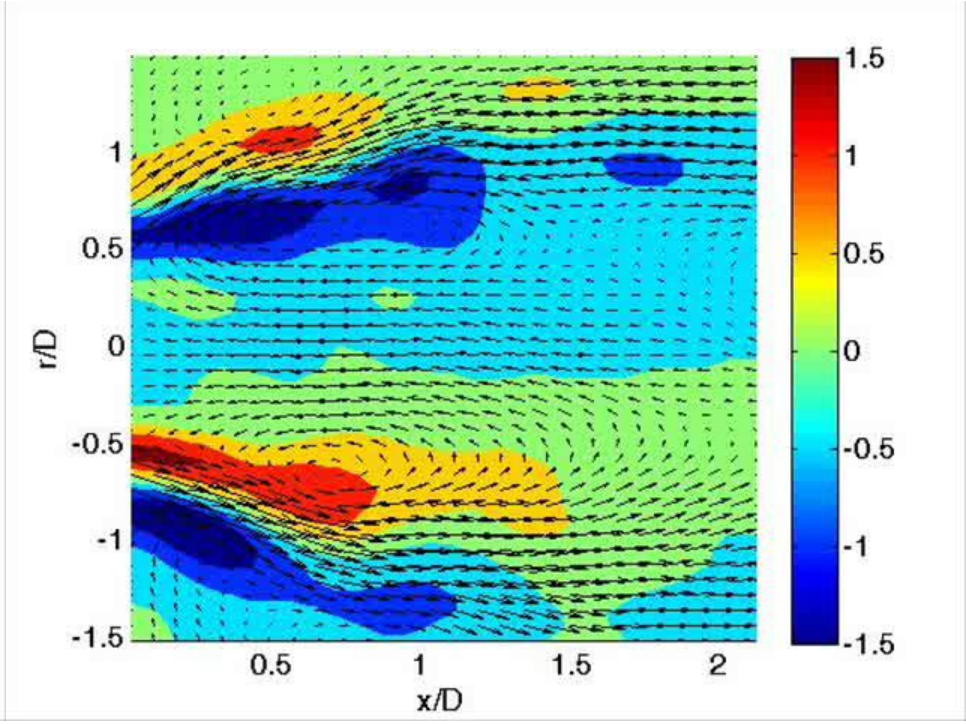

400 Hz out-of-phase,
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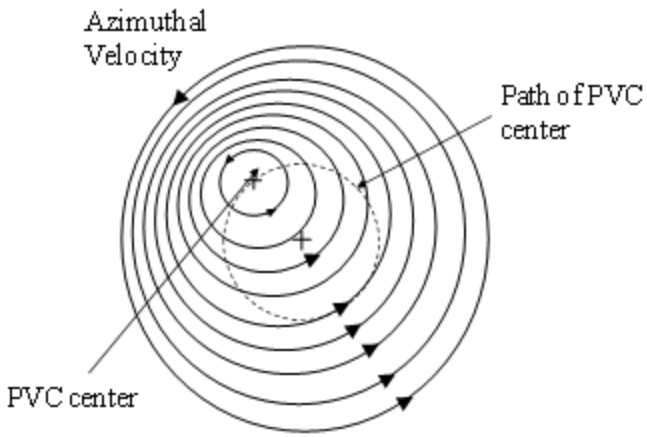
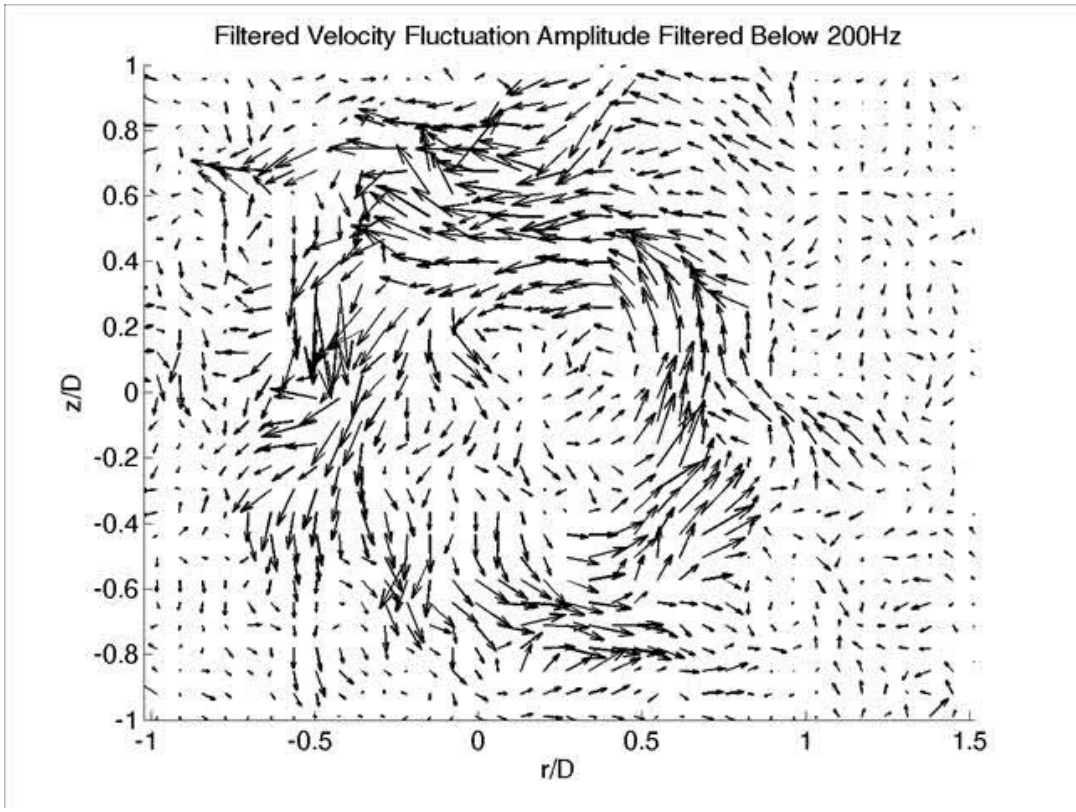
Asymmetric acoustic velocity
Helical shear layer response

Role of Vortex Breakdown in Disturbance Field

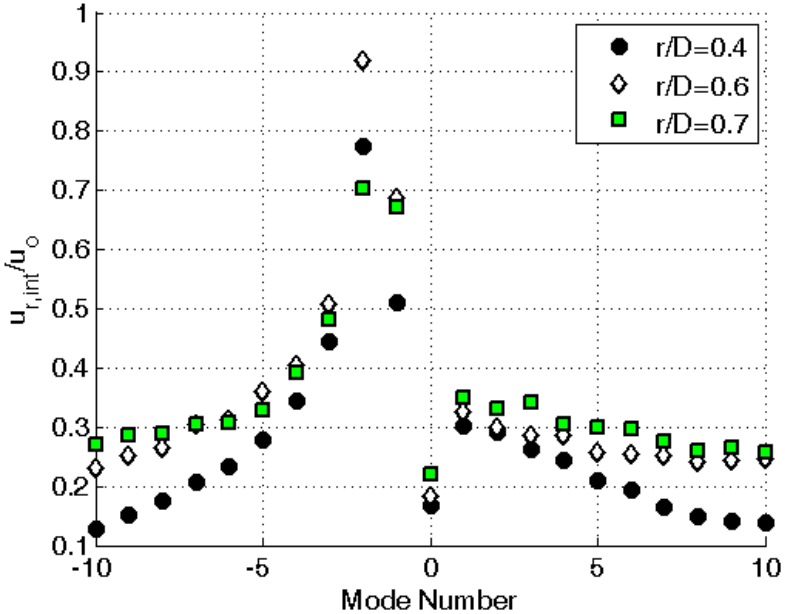
- The vortex breakdown region does have a dynamical role in the flow field, particularly in the form of a precessing vortex core

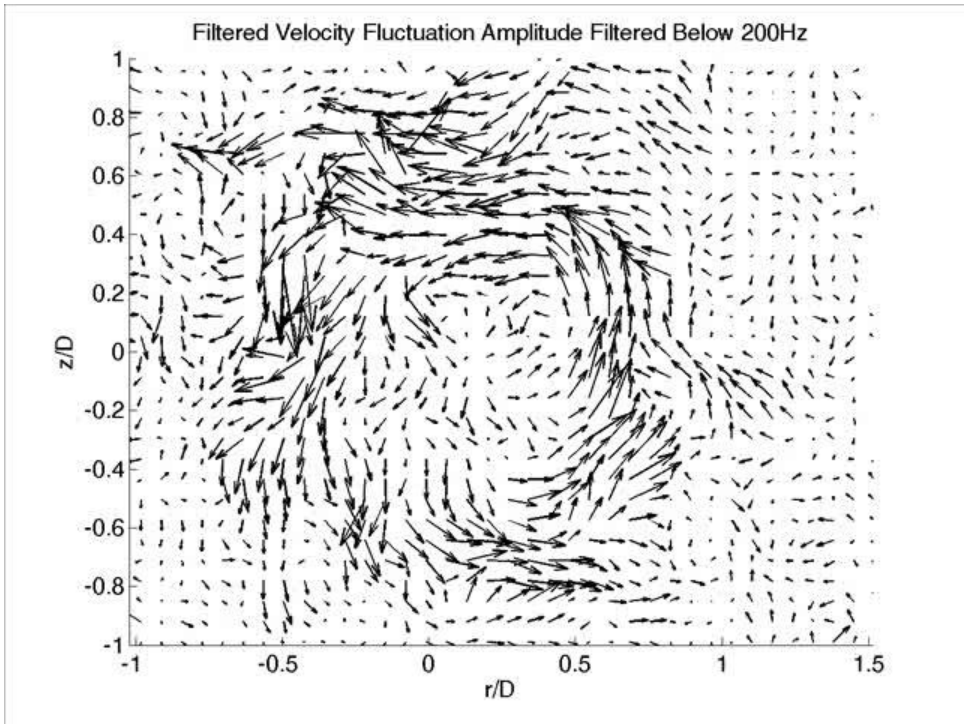




Role of Vortex Breakdown in Disturbance Field

- Several spatial modes of instability are present, but in particular, *m*=-1 and *m*=-2



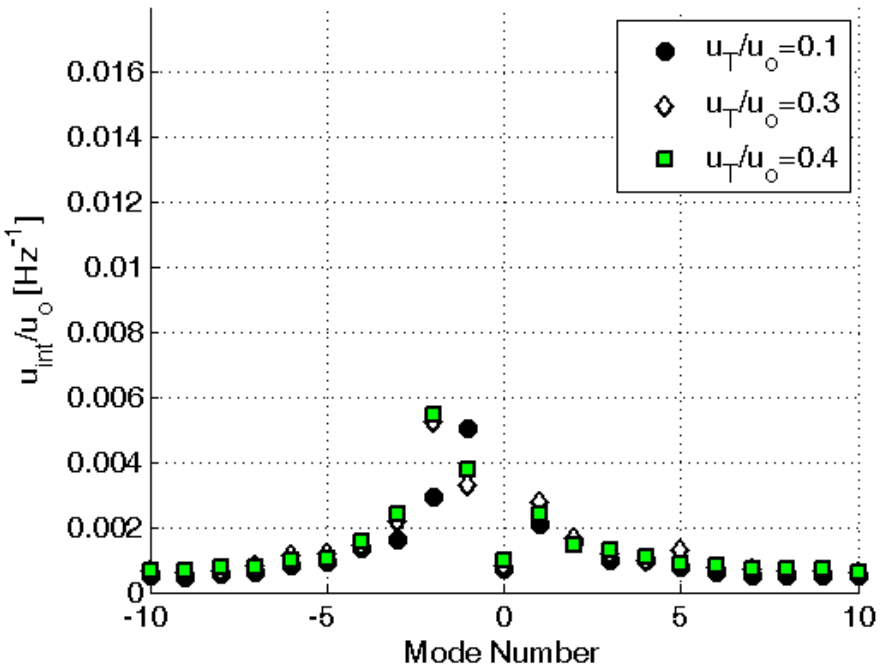


$$\hat{u}(r,\theta,\omega) = \sum_{m=0}^{N} A_m(r,\omega)e^{im\theta} + B_m(r,\omega)e^{-im\theta}$$

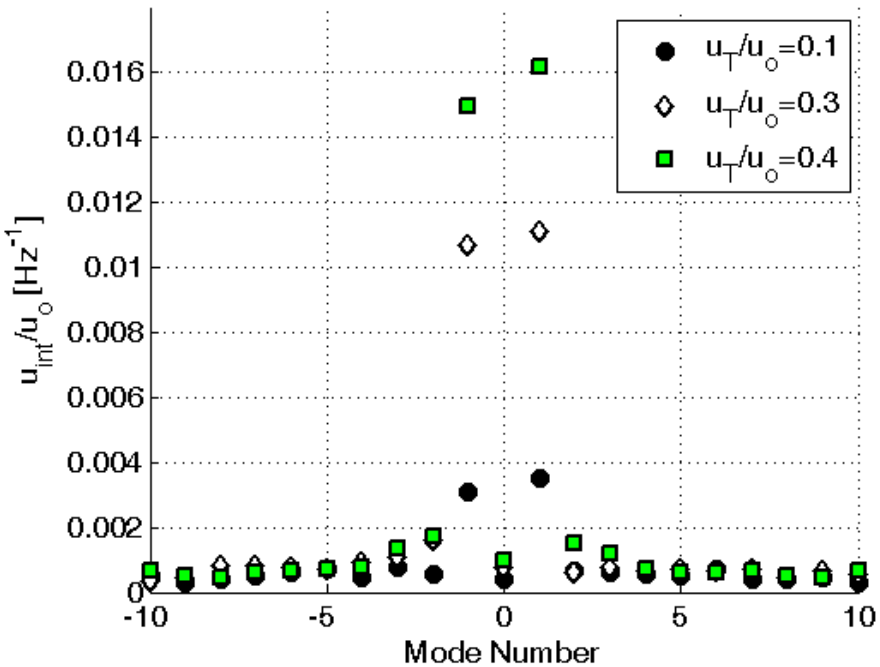
Role of Vortex Breakdown in Disturbance Field

- Compared to the response of the shear layers, the contribution of the precessing vortex core to the overall velocity disturbance field is small

Response at Low Frequency (0-200Hz)

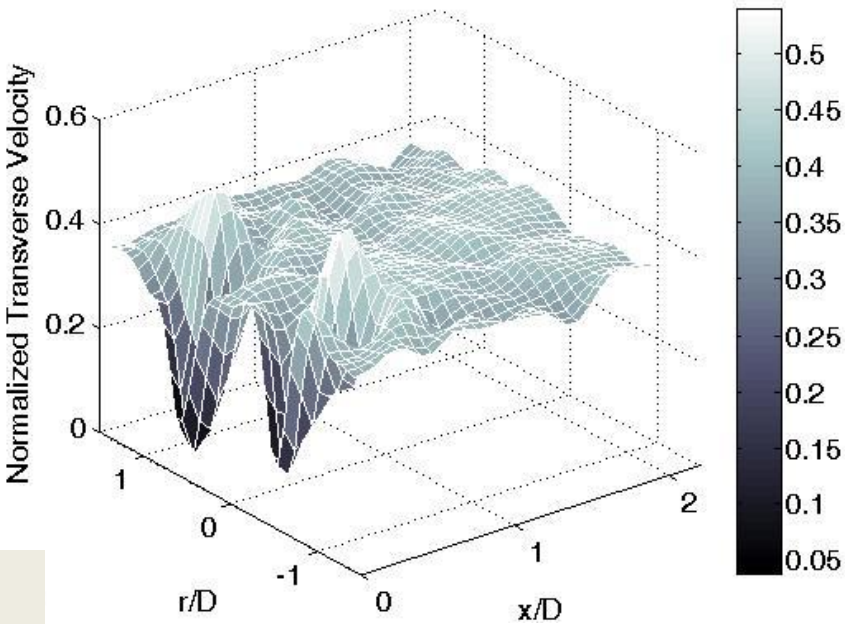


Response at Forcing Frequency (800HzOR

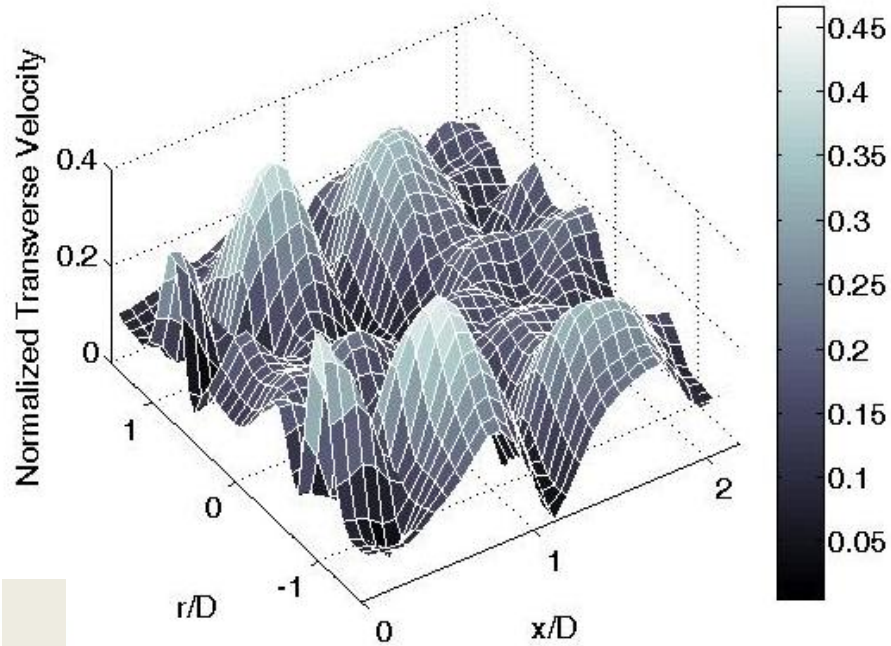


Analysis of Shear Layer Disturbance Field

Non-Reacting Flow



Reacting Flow



400 Hz out-of-phase, U_o=10 m/s

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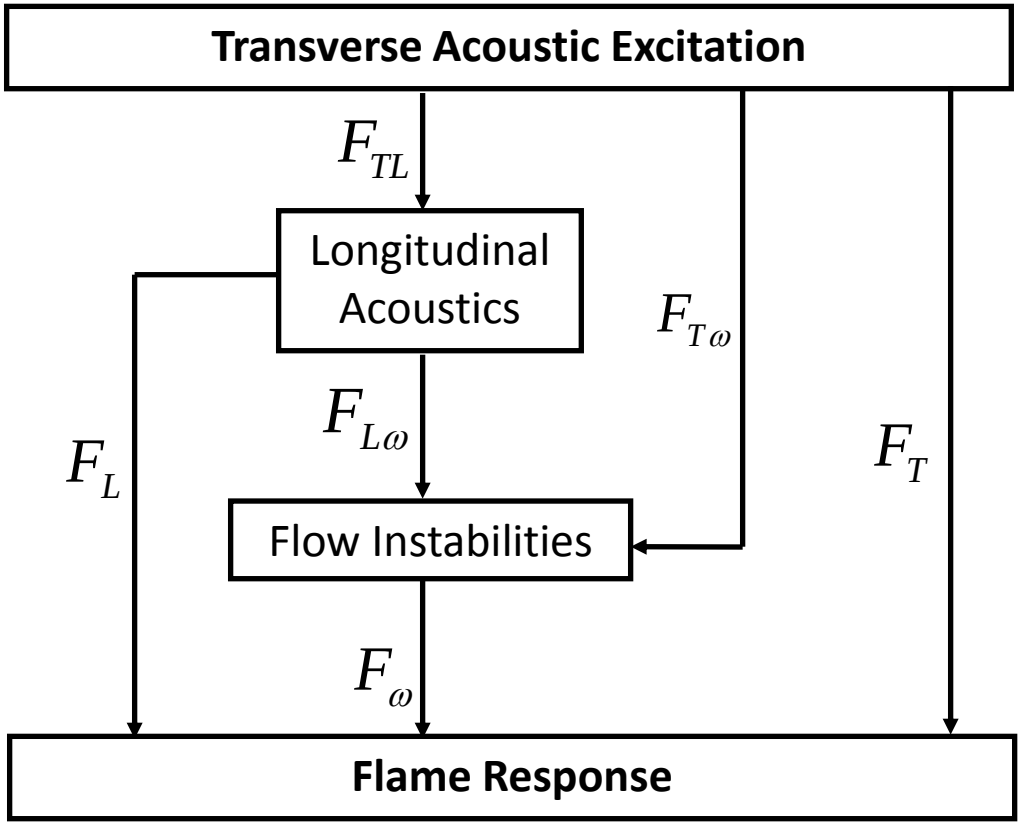
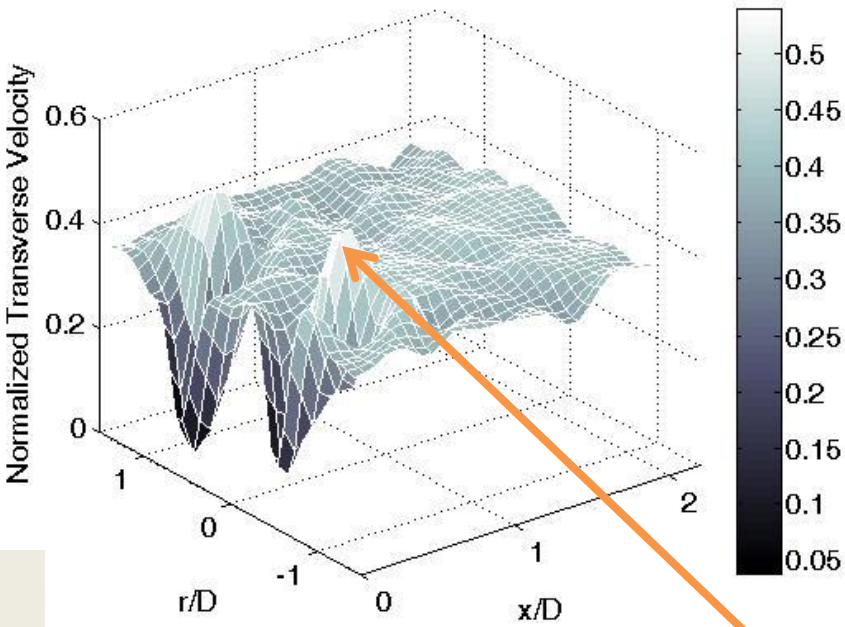
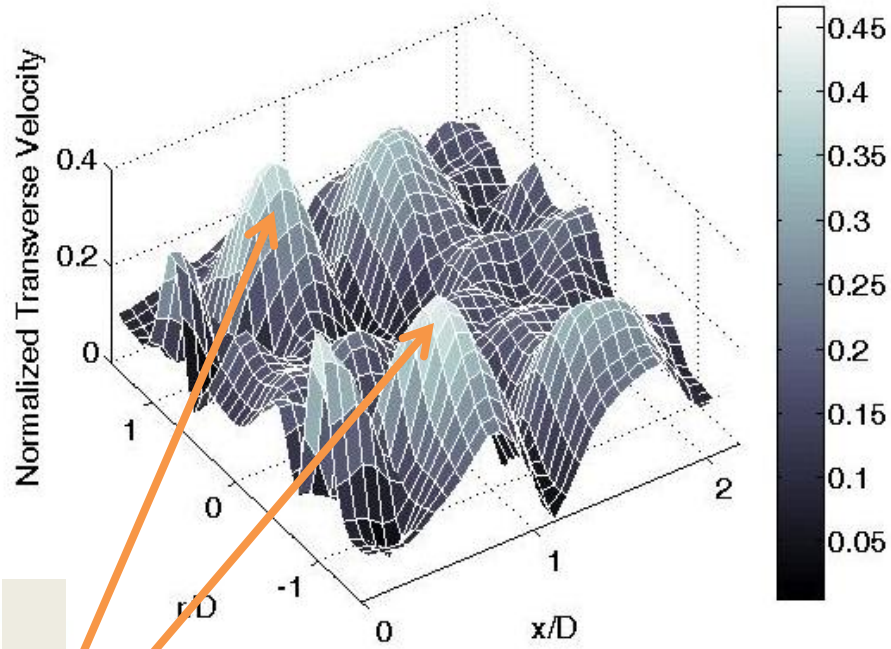


Fluctuating Transverse Velocity

Non-Reacting Flow



Reacting Flow



Constructive Interference of Acoustic and Vortical Waves

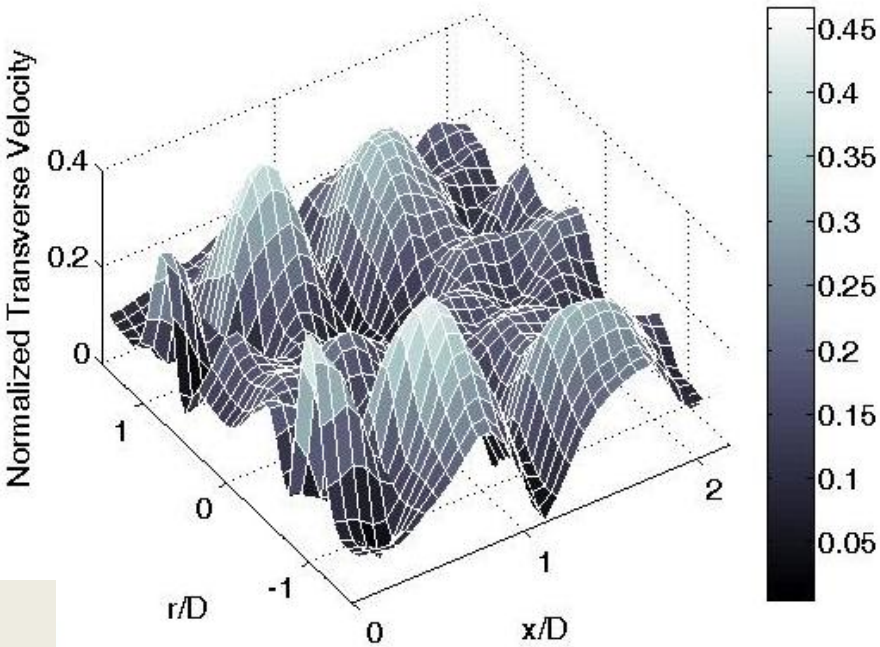
Relative Magnitudes of Acoustic and Vortical Disturbances

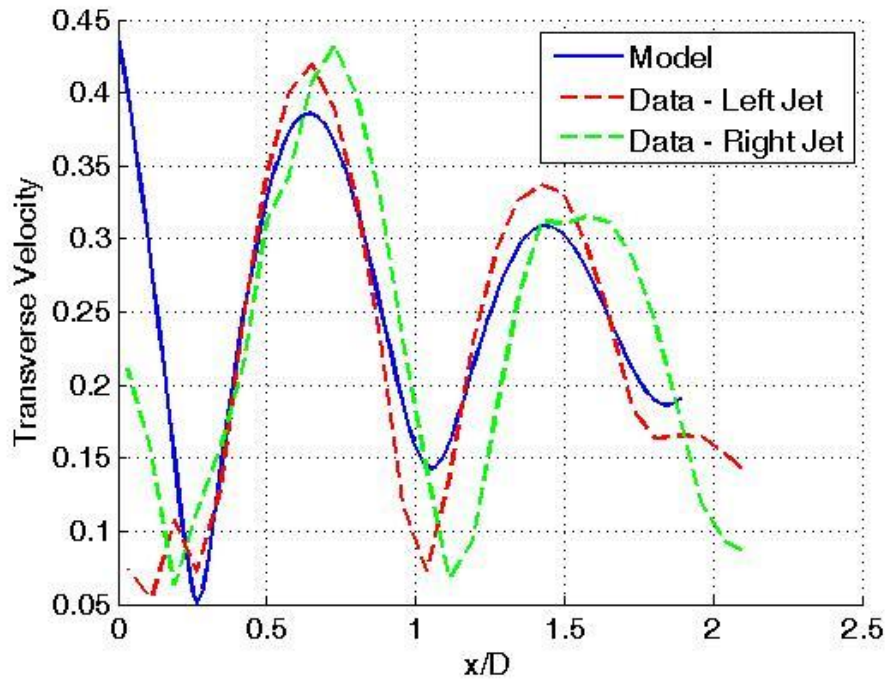
- The interference pattern in the velocity field is a result of the superposition of two waves of similar amplitude but very different convection speeds
  - Acoustic wave – sound speed,
  - Vortical wave – structure convection speed,

- Two wave decomposition can be tested by using parameters from data to fit harmonic waves to velocity field
  - Acoustic wave $u_{acoustic} = A_1 e^{-i(\omega t + \varphi)}$
  - Vortical wave $u_{vortical} = A_2 e^{-i\omega(t - x/u_{c,v})} e^{-\alpha x}$

Two Wave Decomposition – Transverse Velocity

Reacting, 10 m/s, 400 Hz Out-of-Phase





$$u_a' = 0.25$$
$$u_\omega' = 0.25$$

$$\varphi = \pi/4$$

Acoustic-Vortical Coupling

- **Acoustic-vortical coupling in swirling flows is a multi-layered problem as several types of hydrodynamic instability simultaneously exist**
  - Vortex breakdown (AI) requires considerable acoustic forcing amplitudes to respond, but response can be drastic
  - Shear layers (CI) respond to acoustic forcing and provide a significant source of flame disturbance
  - Acoustic field symmetry strongly influences vortical response in swirling flow

- **Acoustic and vortical disturbances can have similar magnitudes yet disparate convection speeds**
  - Leads to interference phenomena
  - Requires modeling that accounts for both sources of excitation

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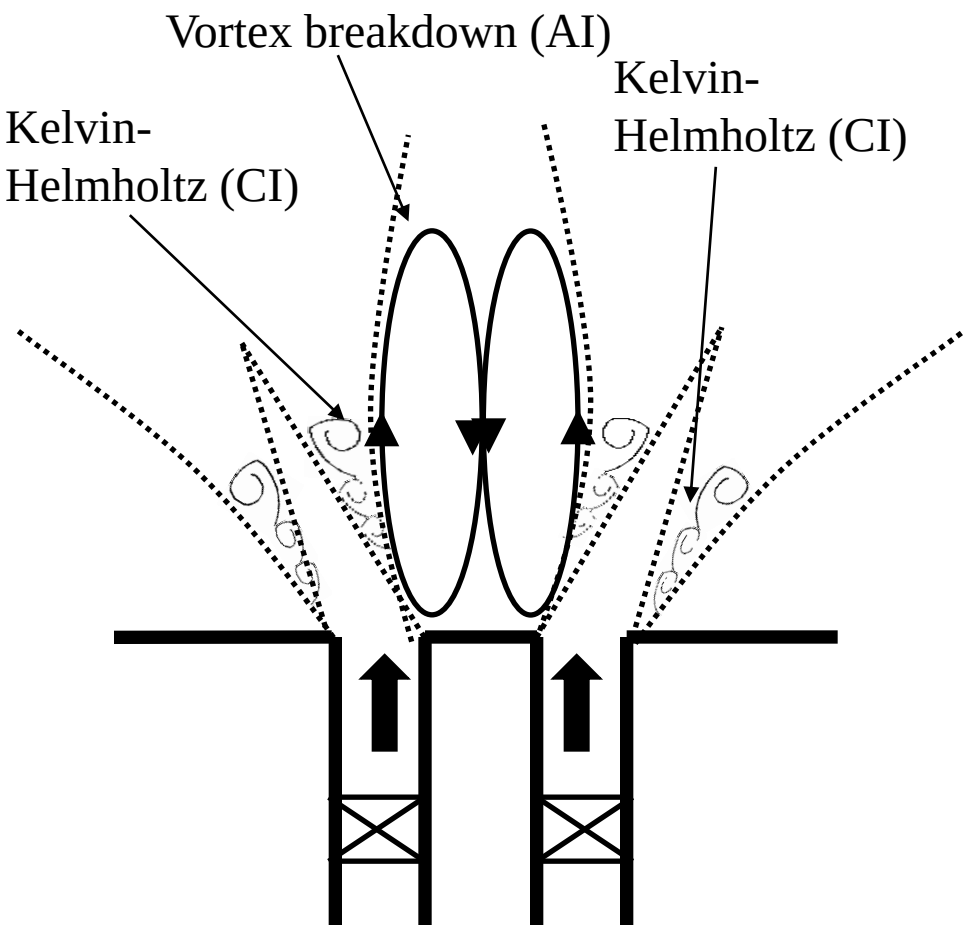
Flame Response to Swirling Flow Instability

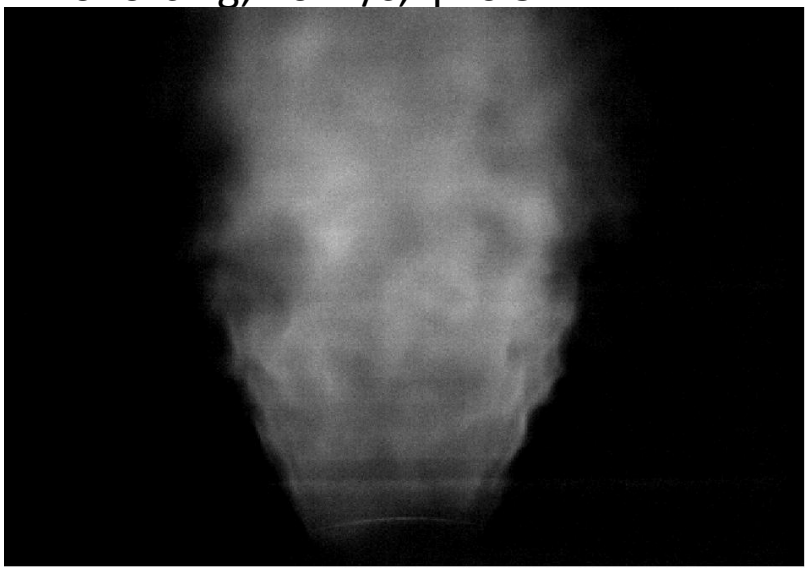
- Swirling flows consist of two types of hydrodynamic instability
  - Swirling jet instability – vortex breakdown (AI)
  - Shear layer instability – Kelvin-Helmholtz (CI)



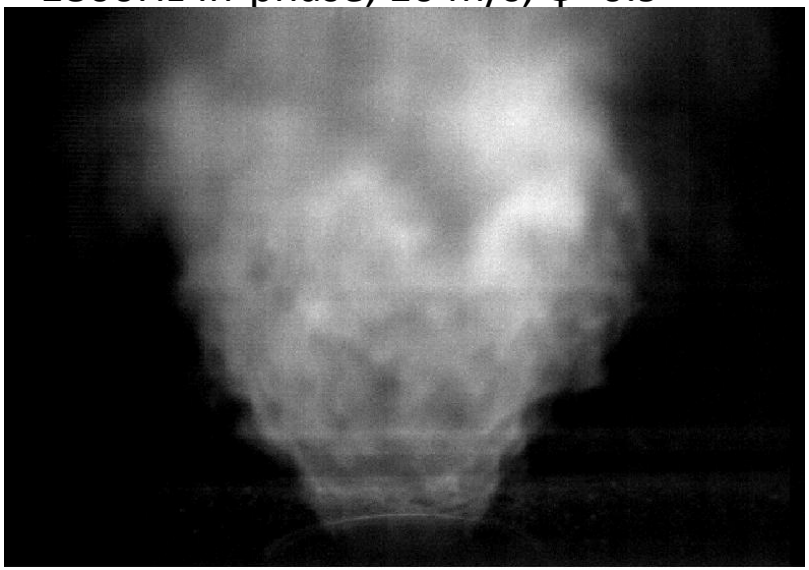
Flame Response – Vortex Breakdown

- Vortex breakdown contribution to flame response (absolute instability):
  - Change in time-average
  - No dynamical effect

No forcing, 10 m/s, ϕ=0.9



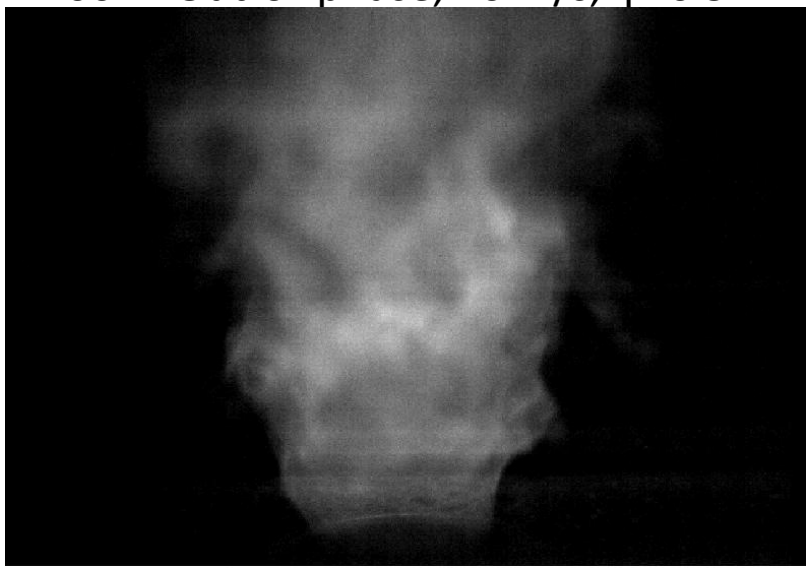
1800Hz In-phase, 10 m/s, ϕ=0.9



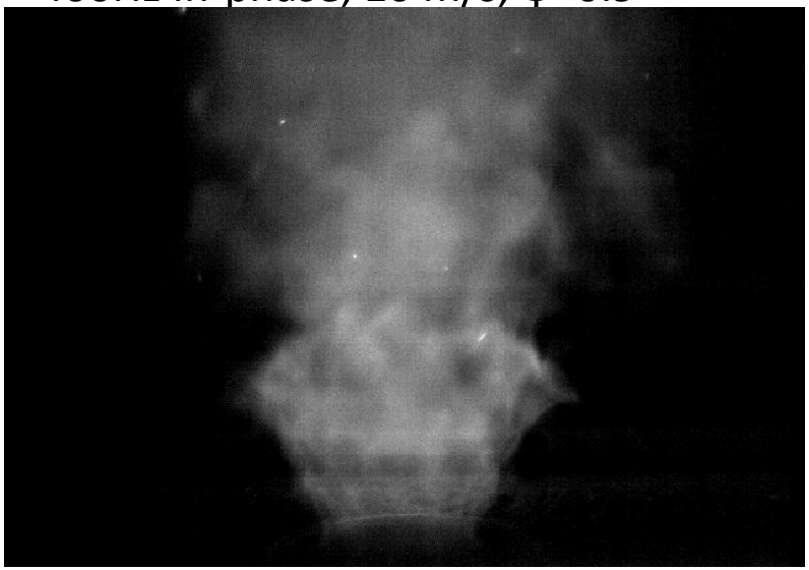
Flame Response – Shear Layers

- Shear layer contribution to flame response (convective instability):
  - Large-scale flame wrinkling at the forcing frequency
  - Responsible for the bulk of the heat release fluctuation

400Hz Out-of-phase, 10 m/s, ϕ=0.9



400Hz In-phase, 10 m/s, ϕ=0.9



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- Research to date
  - Experimental measurements of flow field characteristics
  - Analysis of swirl flame dynamics

- Conclusions and future work

Conclusions

- **The disturbance field is the key to understanding flame response**
  - Transverse to longitudinal acoustic coupling
  - Formation of coherent structures from rollup of the separating shear layers from inner and outer edges of the nozzle
  - Downstream evolution of these structures and their interaction
  - Different effects are dominant at different parts of the flow field
  - Acoustic field has a significant effect on the resultant vortical disturbance field

- **Flame response to the disturbance field is a complicated combination of several effects**

Future Work

- Flame transfer function definition and measurement
  - FTF definition is not obvious in the case of transverse instabilities – neither acoustically nor hydrodynamically independent
  - Proper definition and measurement of FTF can lead to increased physical understanding of coupling mechanisms in disturbance field

- PLIF measurement of flame edge
  - Simultaneous PLIF and PIV will allow for explanation of direct impact of disturbance field on flame

- Formulation of framework for multi-flame interaction
  - Flow and flame effects

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Tim Lieuwen

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