SAND2012-6536P

Role of Hydrodynamic Stability in Velocity-Coupled Combustion Instability

Jacqueline O'Connor

August 7th, 2012
IWFSCI-2012
Session III: Combustion instability – observations, mechanisms, & control

Overview

- Velocity coupled combustion dynamics
  - Mechanism
  - Examples
- Hydrodynamic instability of swirling flow
- Forced response characteristics of swirling flow
- Local and global flame response considerations
- Future research directions

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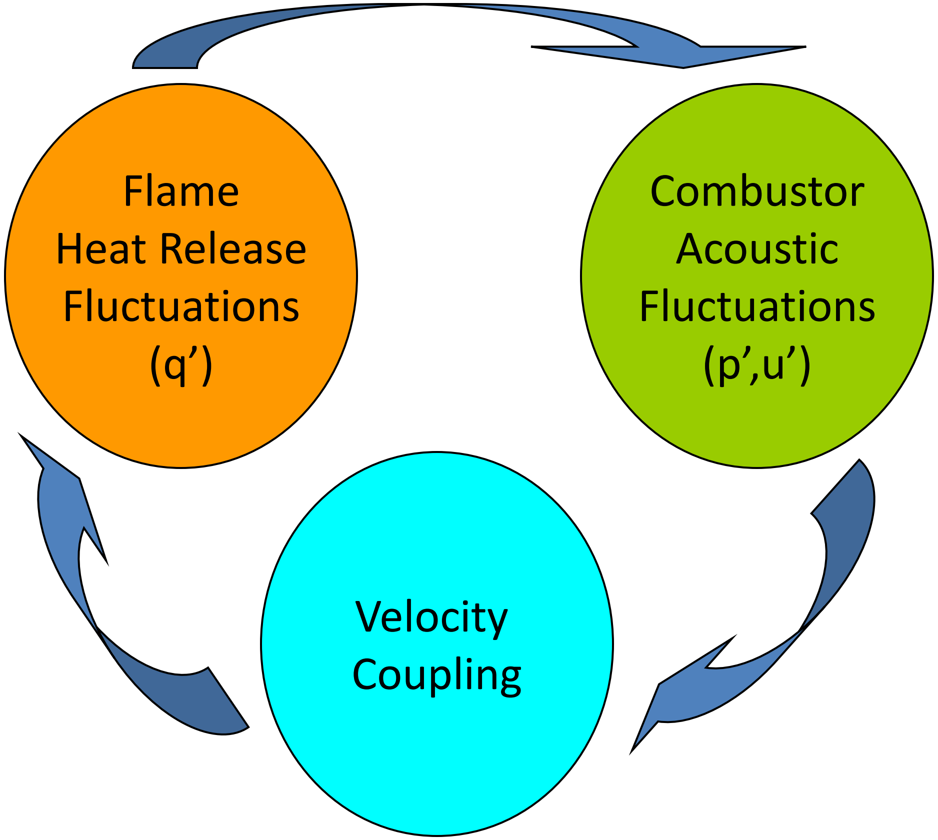
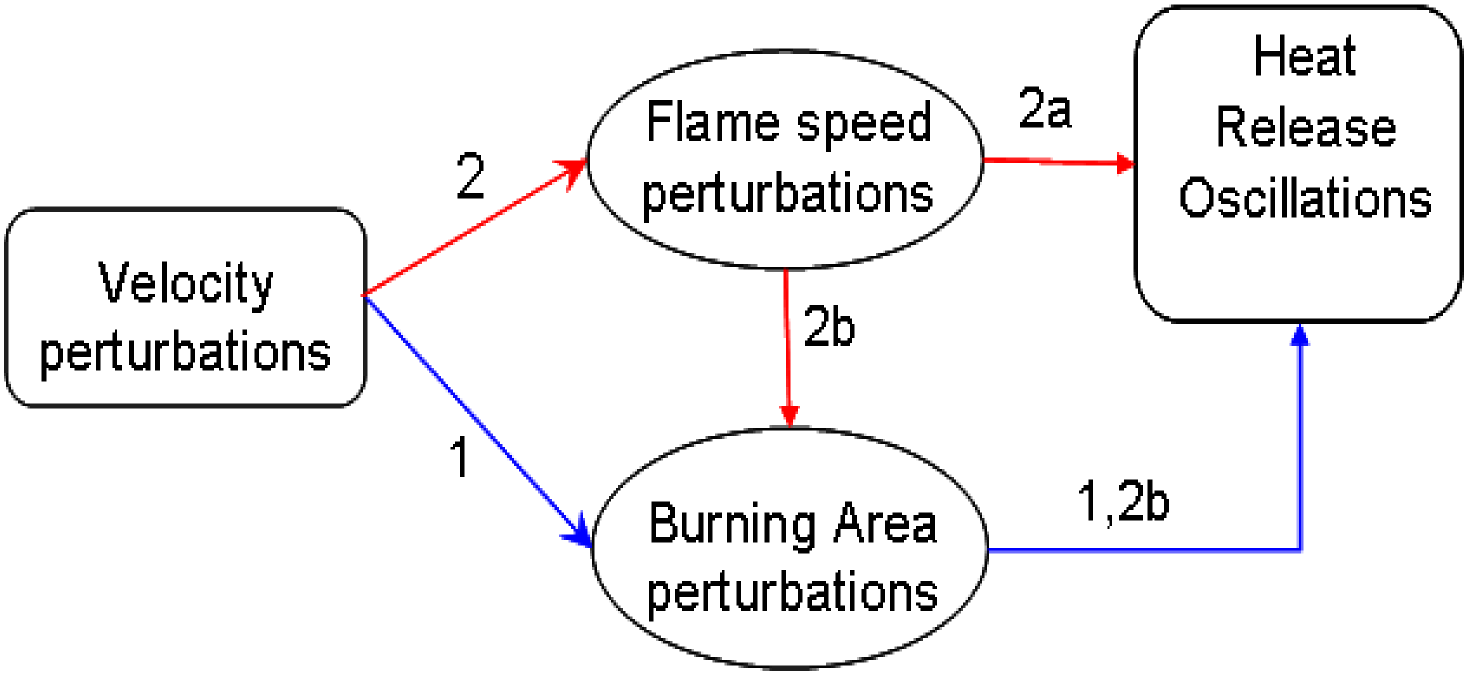
Velocity-Coupled Combustion Instability – Mechanism

- Velocity fluctuations stem from both acoustic and vortical velocity fluctuation sources



Velocity-Coupled Combustion Instability – Mechanism

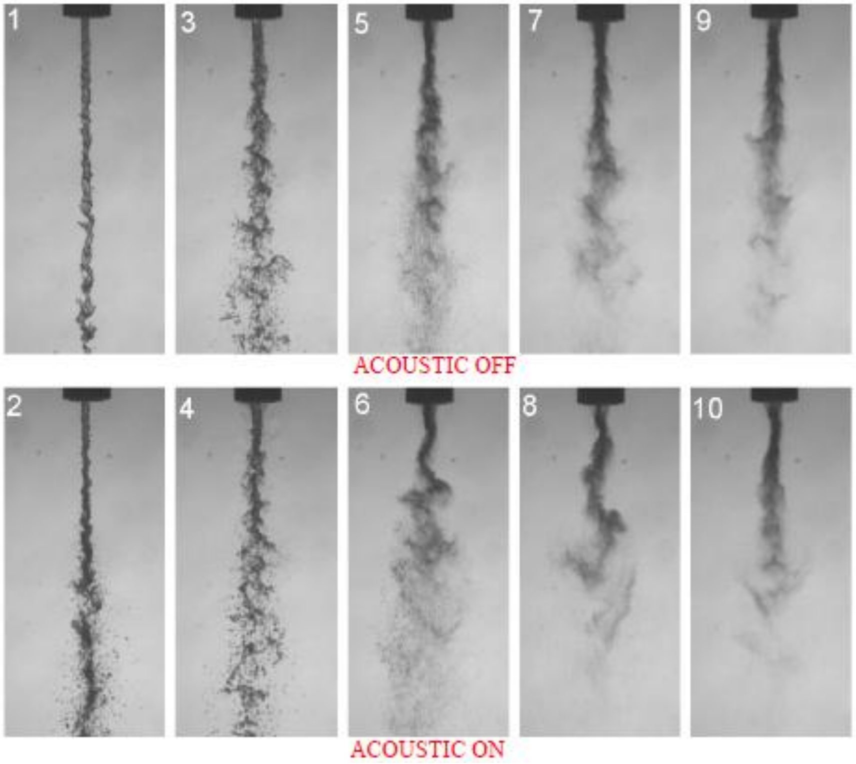
- Velocity fluctuations lead to global heat release fluctuations largely through a flame area fluctuation mechanism



Shreekrishna and Lieuwen, AIAA, 2009

Velocity-Coupled Combustion Instability – Rockets

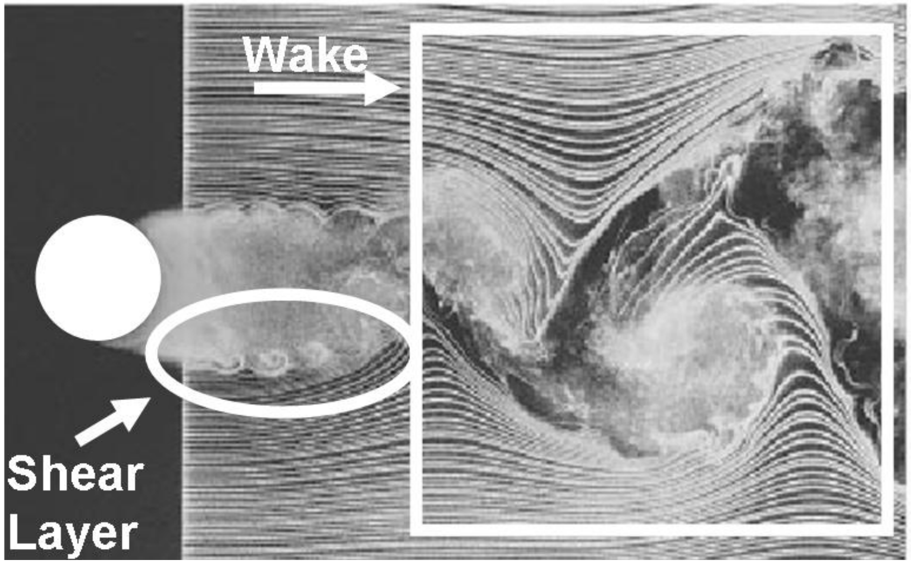
- Acoustic velocity fluctuations lead to variable jet breakup and high-amplitude heat release fluctuations

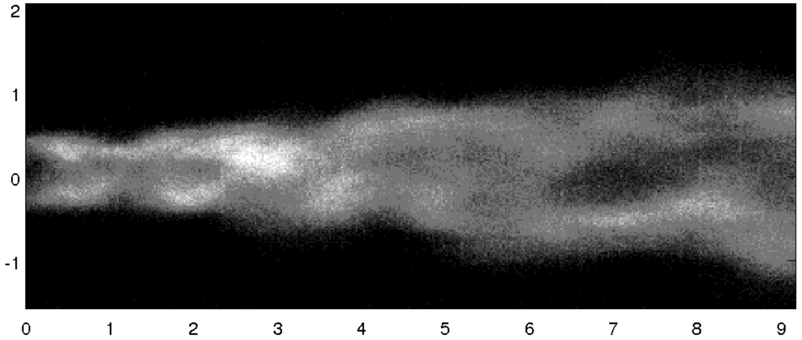


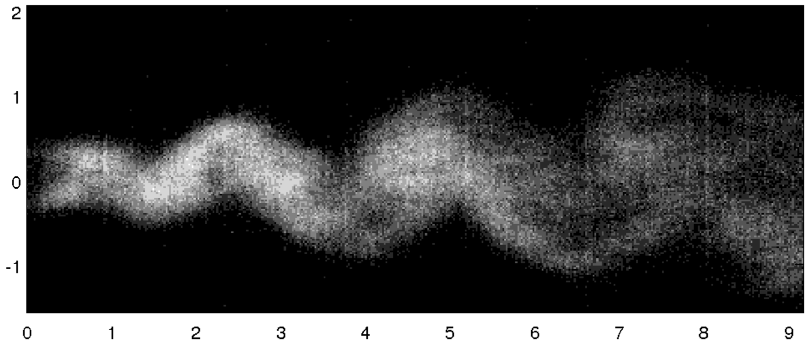
Davis and Chehroudi, AIAA2004-1330

Velocity-Coupled Combustion Instability – Augmentors

- Flame fluctuations are due to both wake and shear layer instability





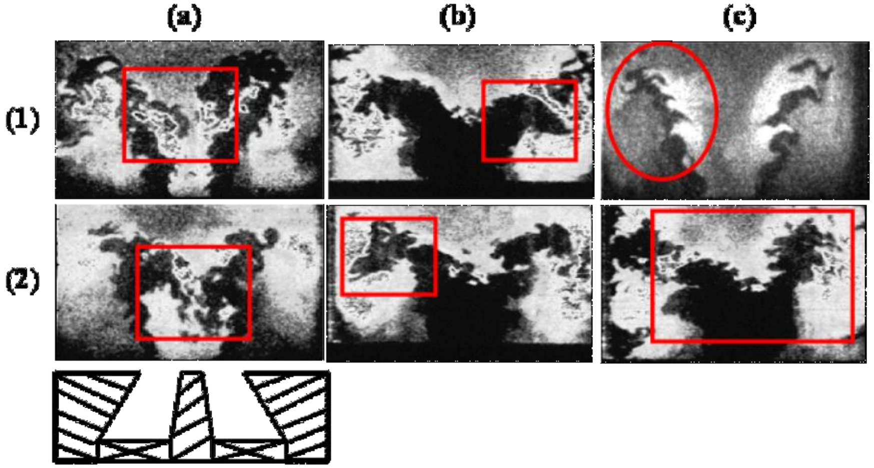


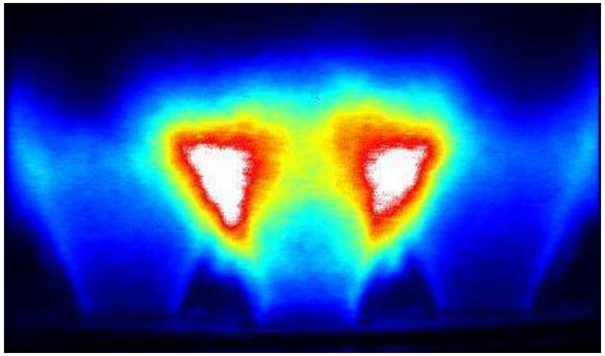
Prasad and Williamson, JFM, 1997

Emerson et al., AIAA, 2011

Velocity-Coupled Combustion Instability – Gas Turbine Combustors

- Several instability modes in swirling flows disturb the flame

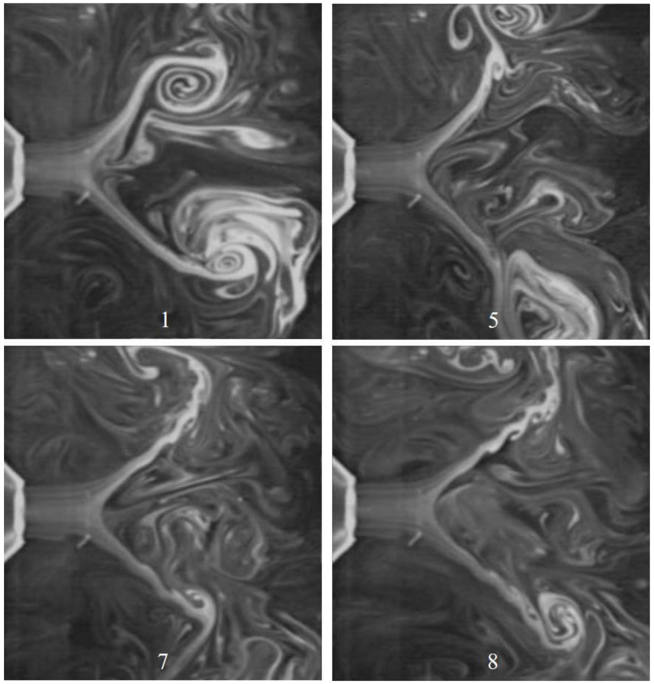


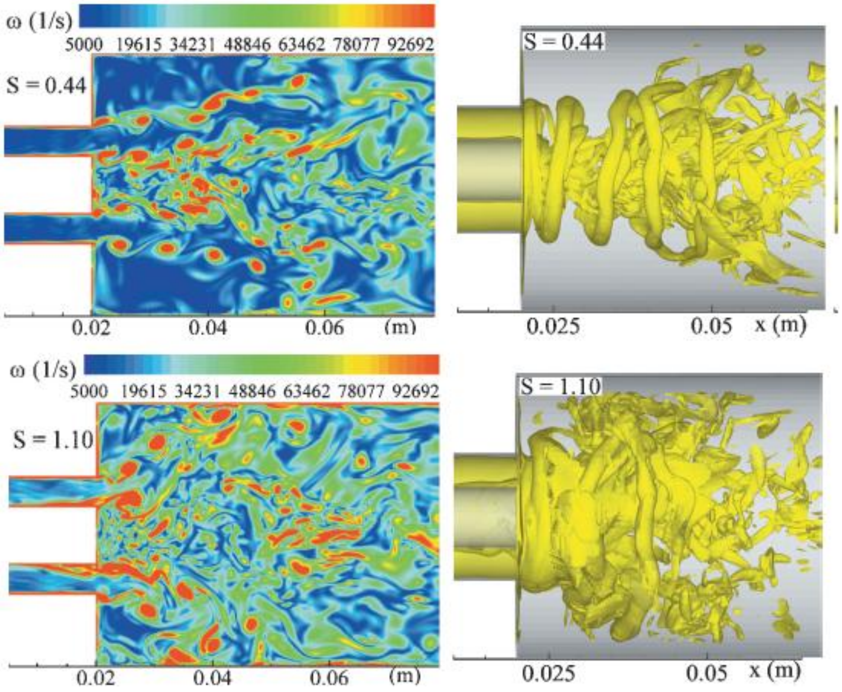


Lieuwen and Yang, AIAA, 2005
Thumuluru and Lieuwen, Proc. Comb. Inst., 2009
Szedlmayer et al., GT2011-46080

Combustion Instabilities in Gas Turbines

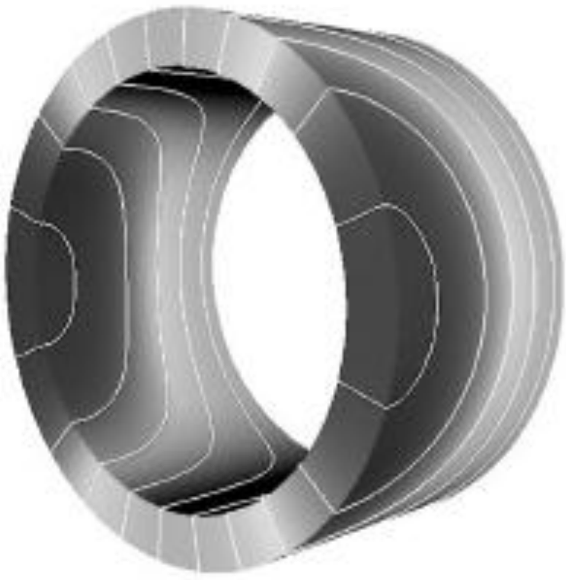
- What are some of the specific issues in gas turbine combustor instabilities?
    - Complicated flow fields – swirling flows are hydrodynamically unstable and susceptible to acoustic forcing

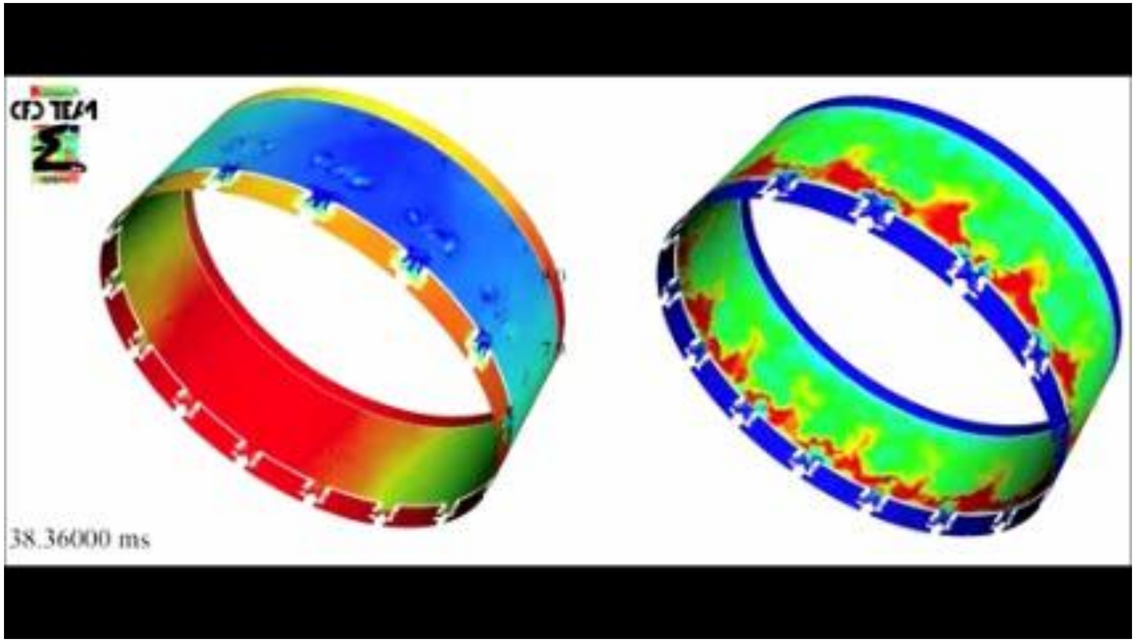




Billant et al., JFM, 1998, Huang et al., AIAA J., 2006

- What are some of the specific issues in gas turbine combustor instabilities?
  - Mixed acoustic mode shapes





C. Sensiau et al., Int. J. of Aeroacoustics, 2009
P. Wolf, G. Staffelbach, L. Gicquel and T. Poinsot, CERFACS, 2010

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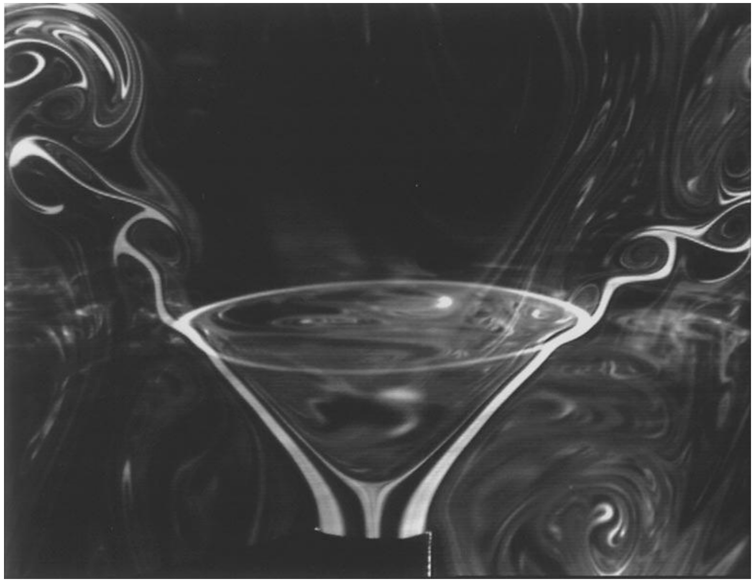
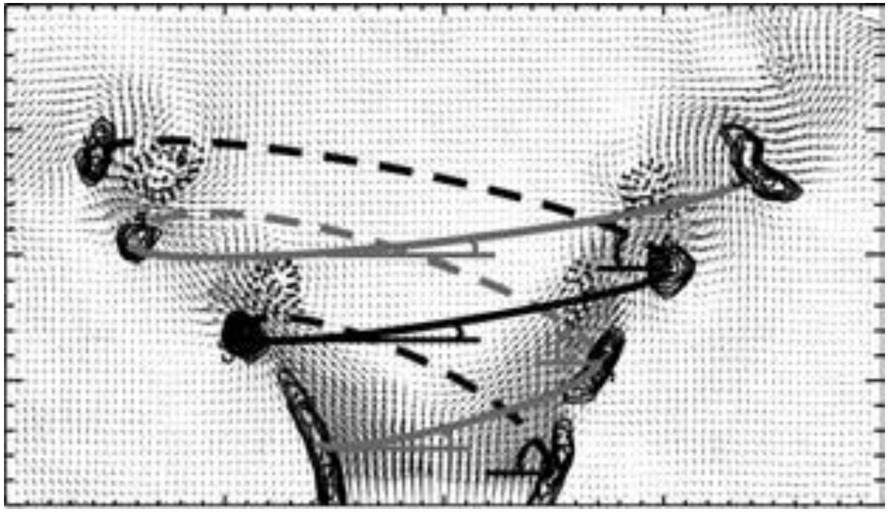
Velocity Fluctuations from Hydrodynamic Instability

- Unsteady motions in swirling flows due to at least two hydrodynamic instability mechanisms
  - Swirling jet instability – vortex breakdown (AI)
  - Shear layer instability – Kelvin-Helmholtz (CI)



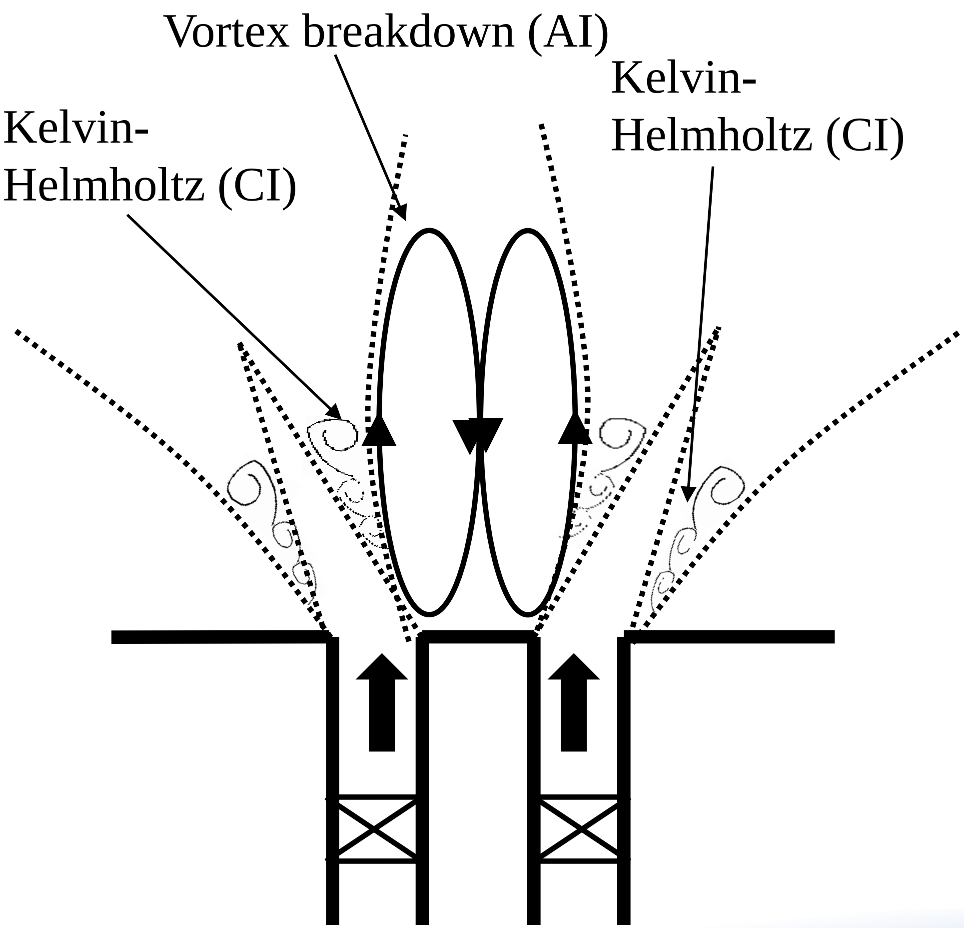


Liang and Maxworthy, JFM, 2006

Billant et al., JFM, 1998

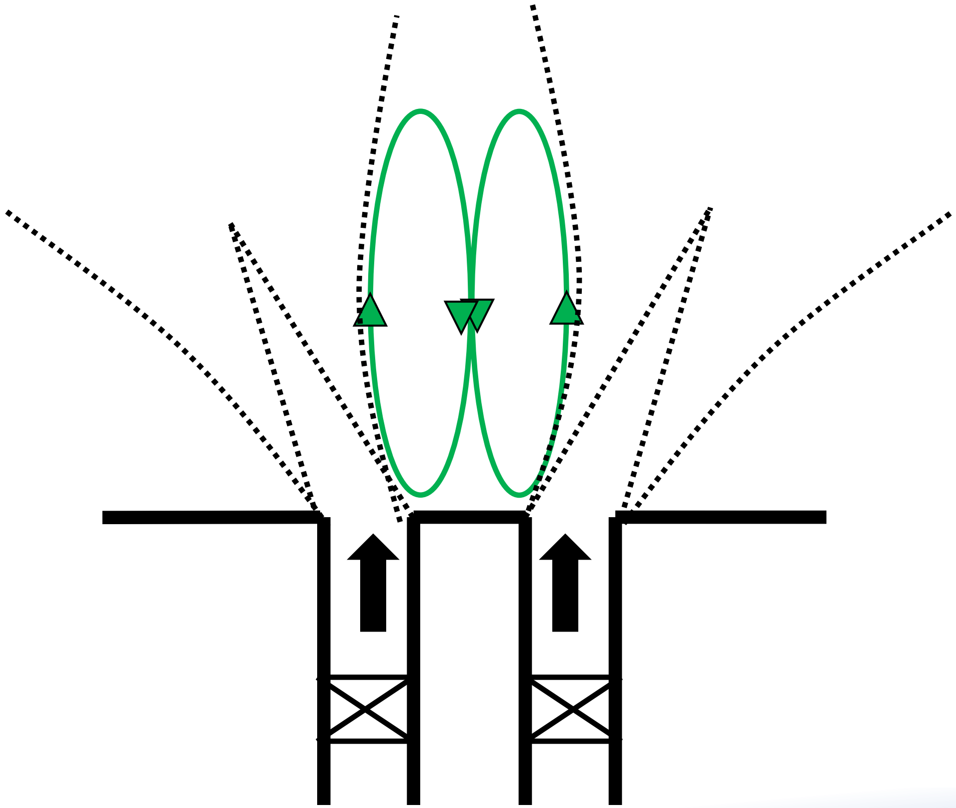
Velocity Fluctuations from Hydrodynamic Instability

- Unsteady motions in swirling flows due to at least two hydrodynamic instability mechanisms



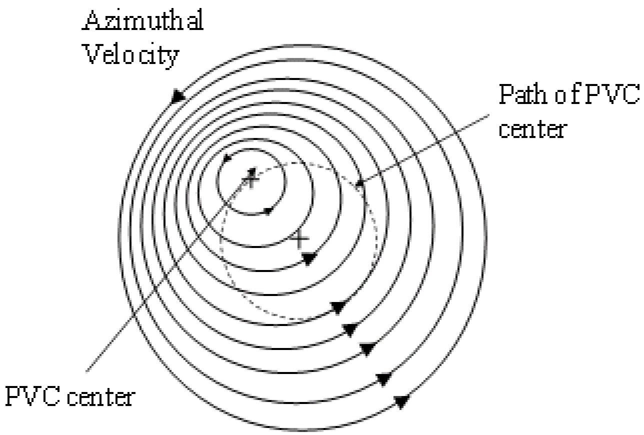
Swirling Flow Instability

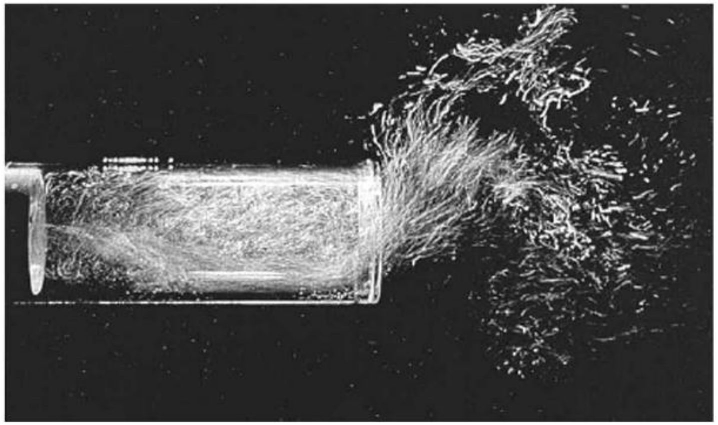
- Swirling jet instability – vortex breakdown (AI)
  - Absolute instability – self-excited oscillator
    - Displays intrinsic dynamics except at high-amplitude forcing
  - Function of Reynolds number, swirl number, geometry

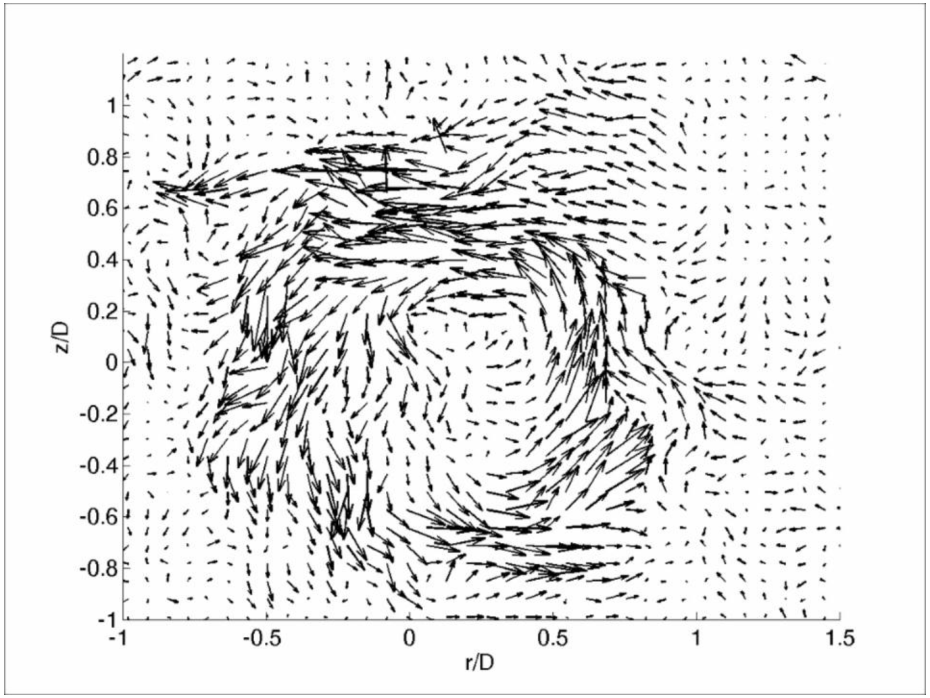


Dynamical Role of Vortex Breakdown

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







Syred, Prog. Energy and Comb. Sci., 2006

Spatial Modal Decomposition

- Spatial mode decomposition in the *r*-ϑ plane

$$u(t,x,r,\theta)$$

Fourier Transform

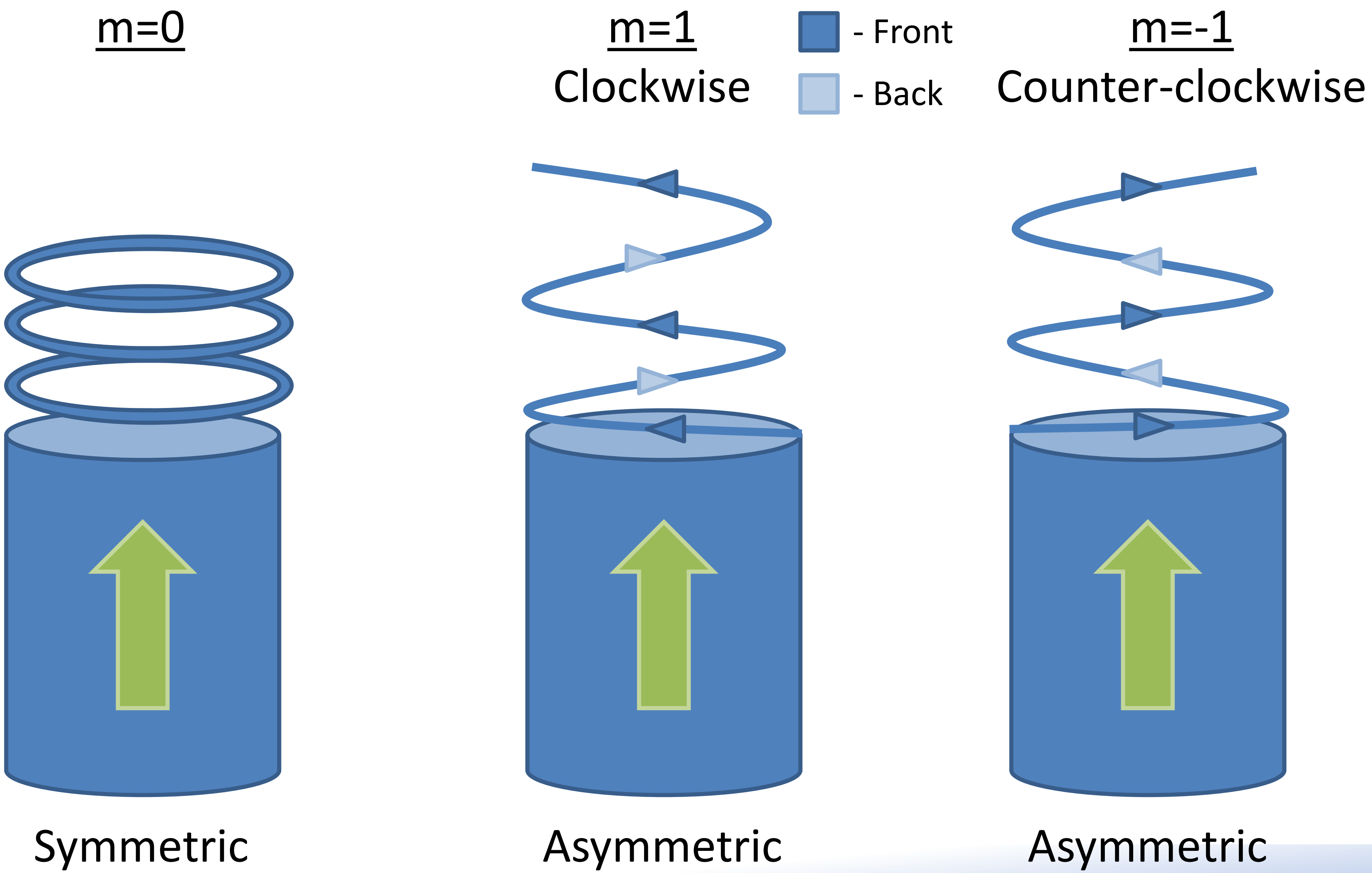
$$\hat{u}(\omega,x,r,\theta)$$

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

A_m, $m<0$ – co-swirling (counter-clockwise)

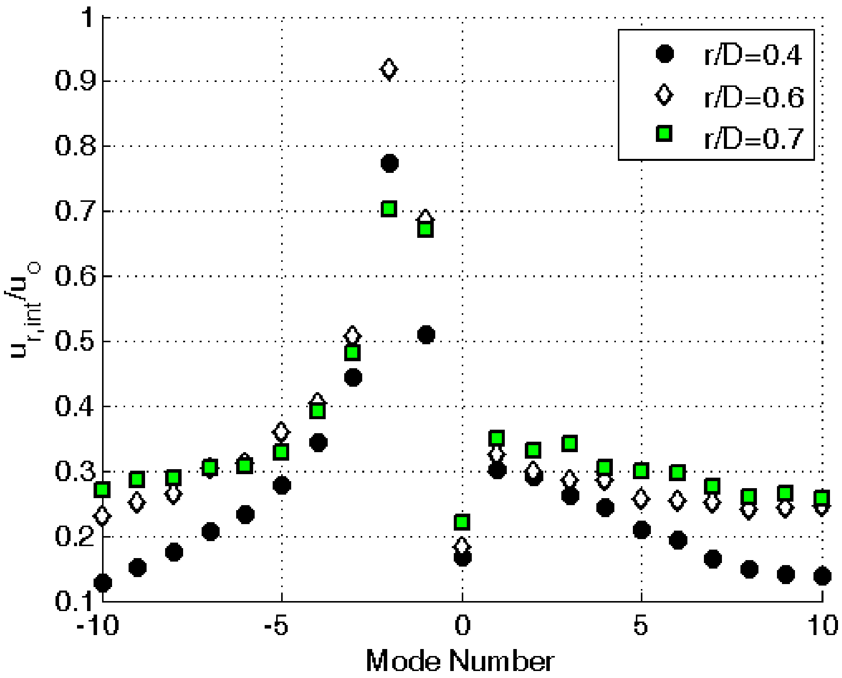
B_m, $m>0$ – counter-swirling (clockwise)

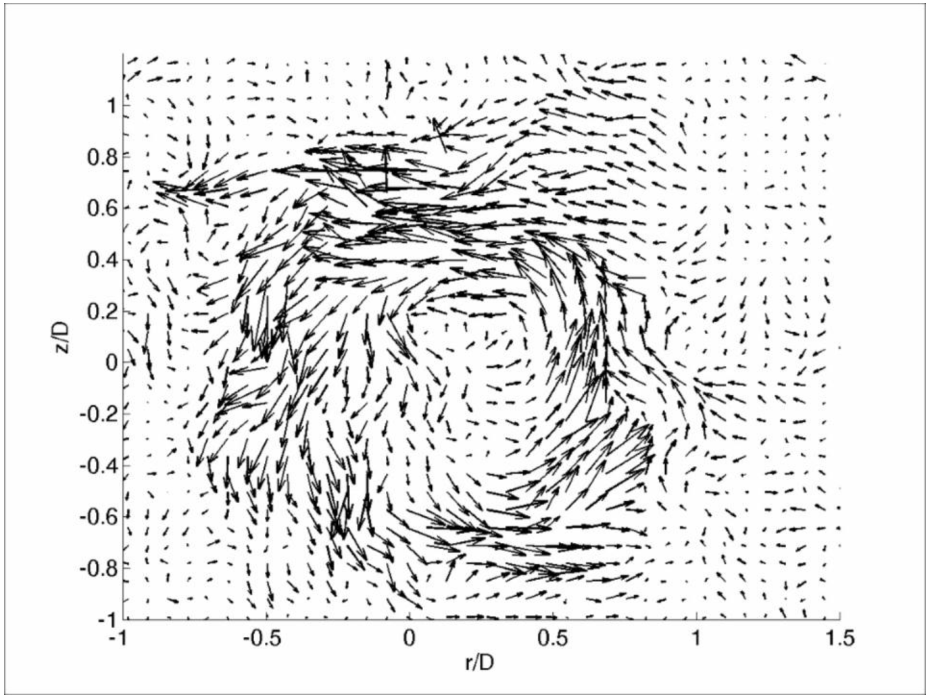
Spatial Modal Decomposition



Role of Vortex Breakdown in Disturbance Field

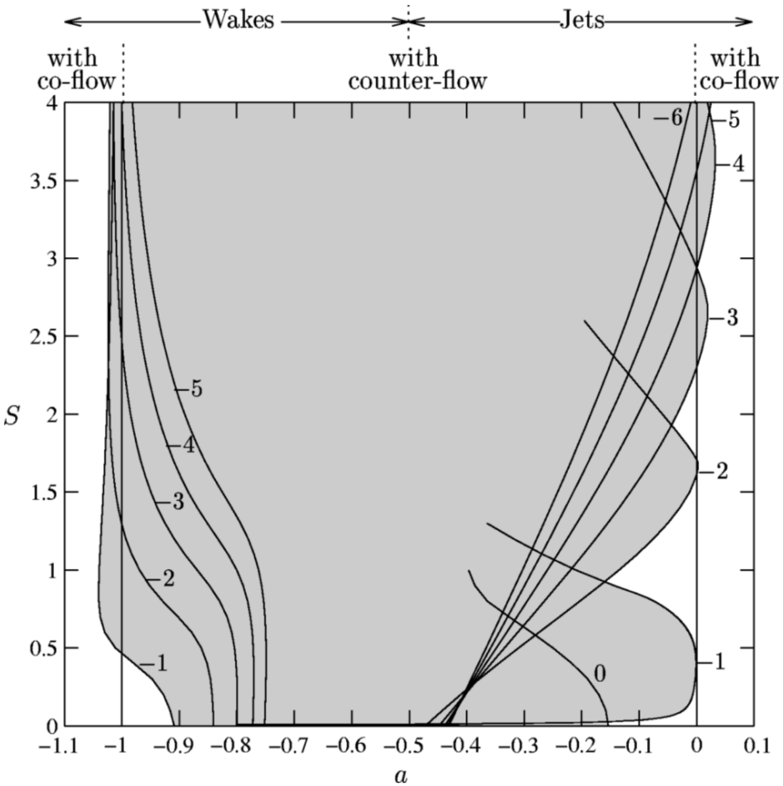
- Several spatial modes of instability are present, but in particular, *m*=-1 and *m*=-2

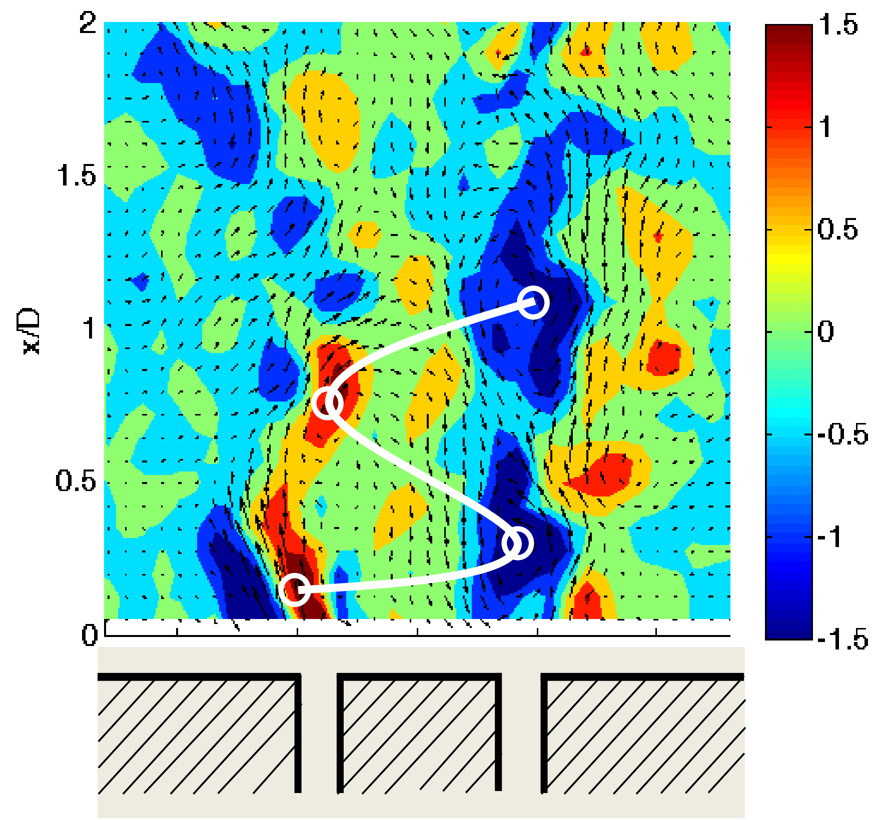




Swirling Flow Instability

- Shear layer instability – Kelvin-Helmholtz
  - Most amplified shear layer mode is helical
  - Bias due to the action of swirl



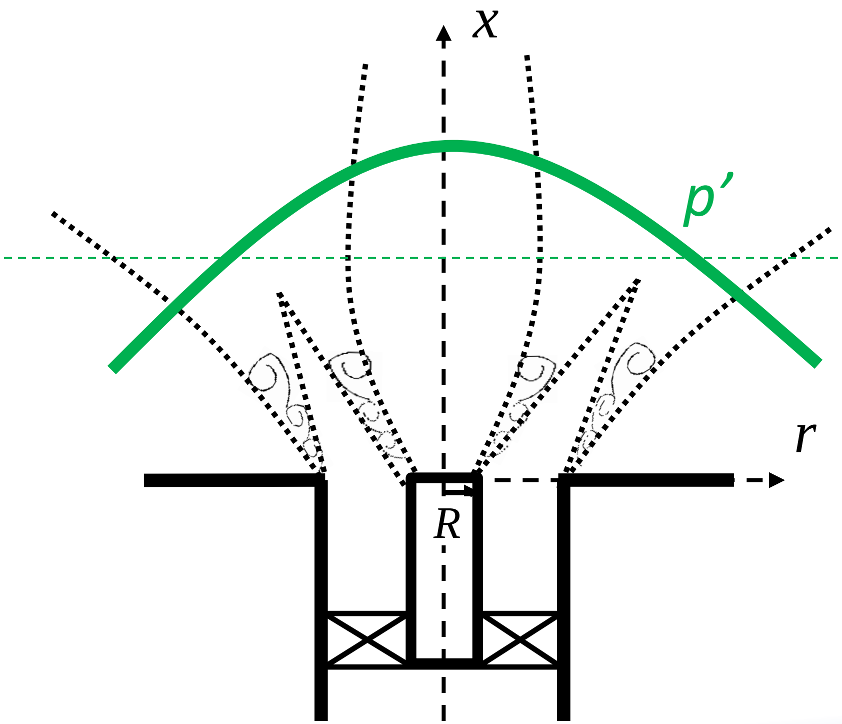


Loiseleux et al., Phys. of Fluids, 1998

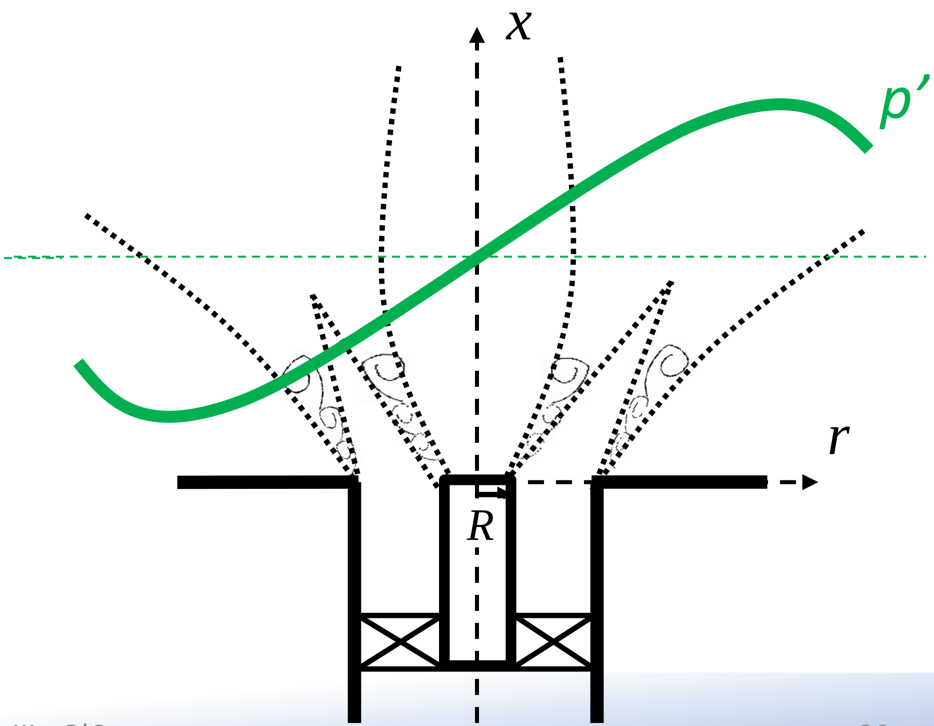
Swirling Flow Instability

- Shear layer instability – Kelvin-Helmholtz
  - Convectively unstable – disturbance amplifier
  - Strong response to external excitation (acoustic forcing)
  - Response is a function of frequency, amplitude, ***symmetry***

Symmetric Forcing



Asymmetric Forcing



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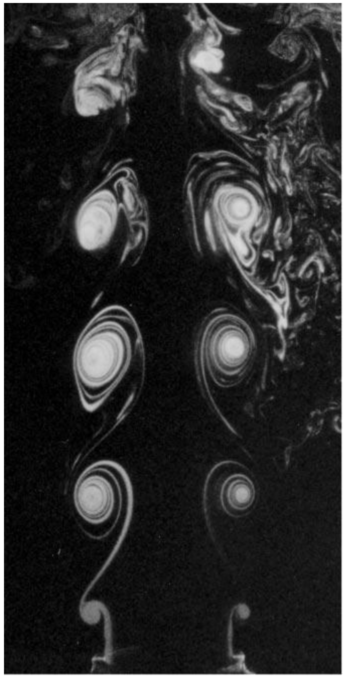
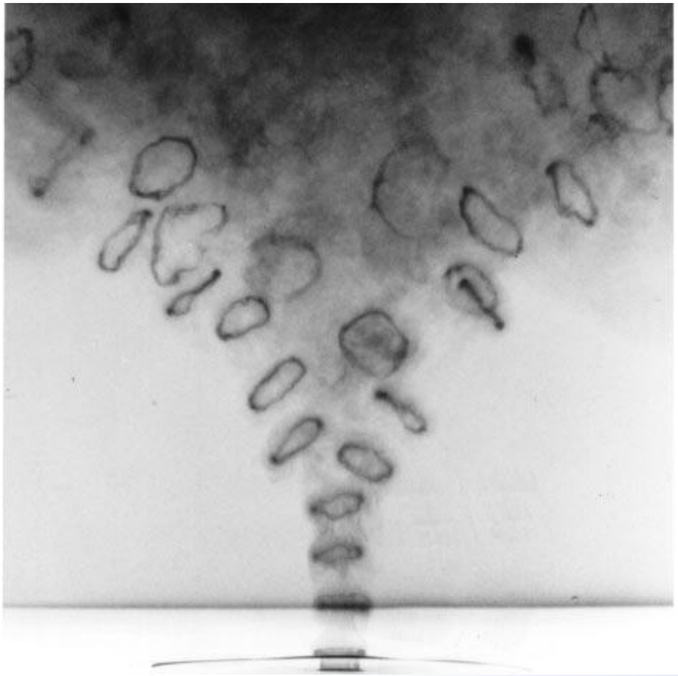


Asymmetric Forcing



Reynolds et al., ARFM, 2003

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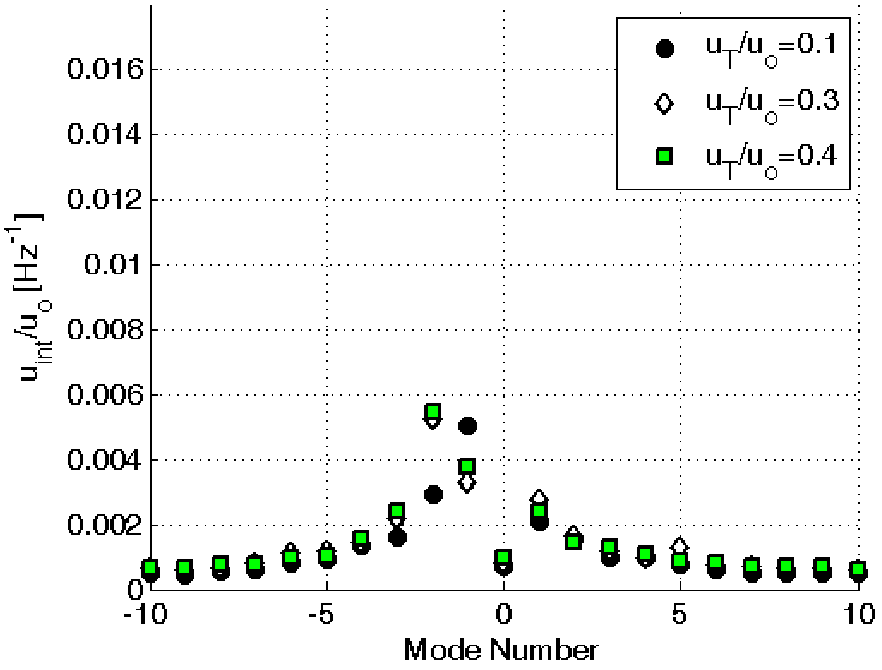
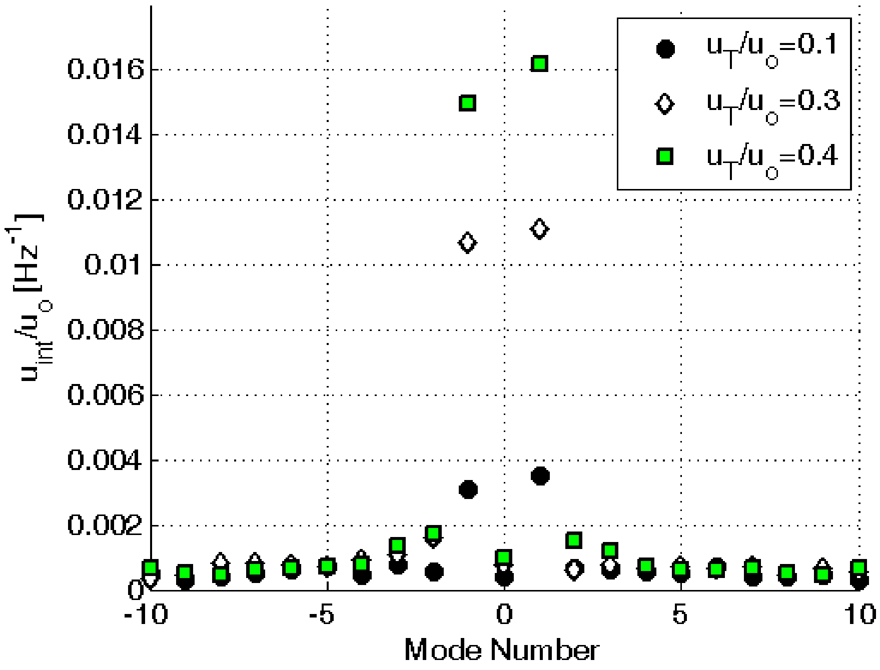
Role of Vortex Breakdown in Disturbance Field

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

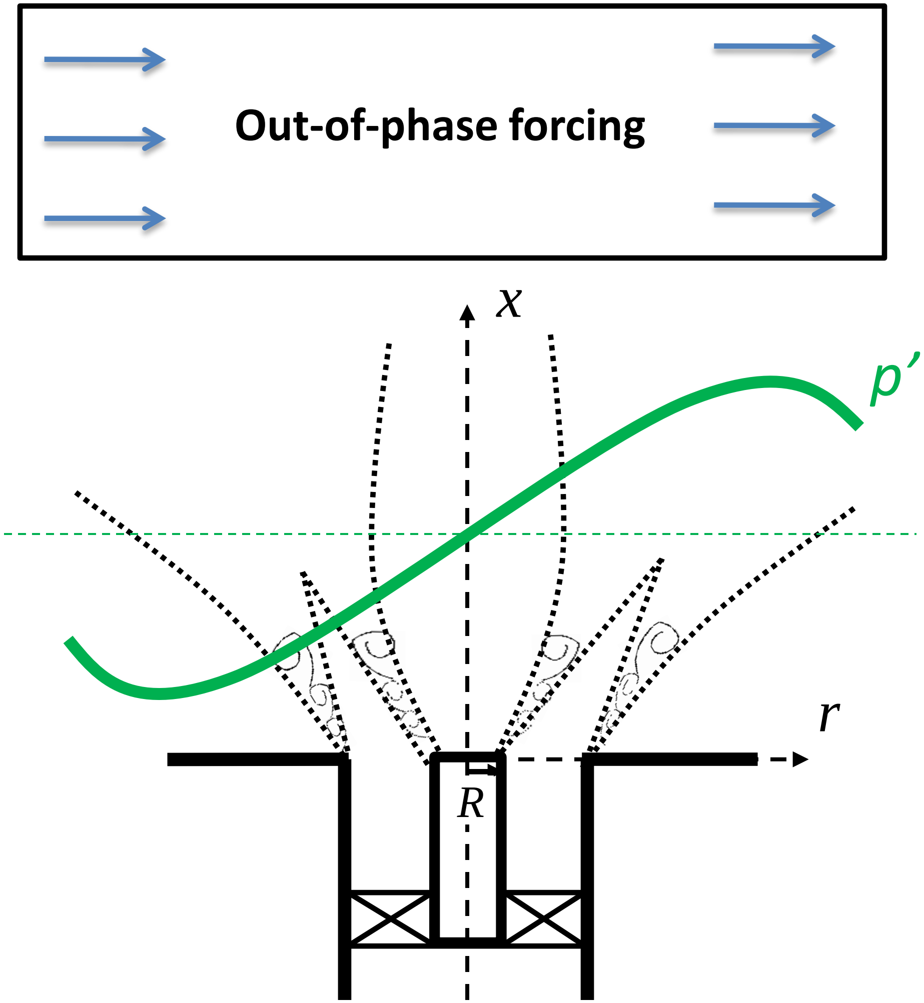
Response at Low Frequency (0-200Hz)



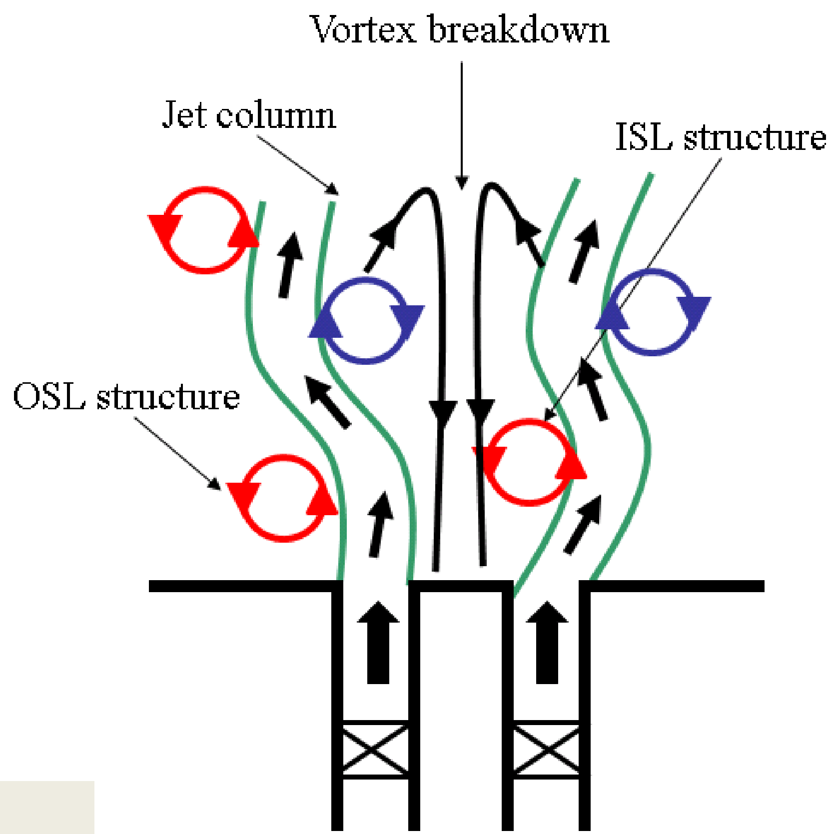
Response at Forcing Frequency (800HzOP)



Flow Field Topology



Out-of-phase Forcing



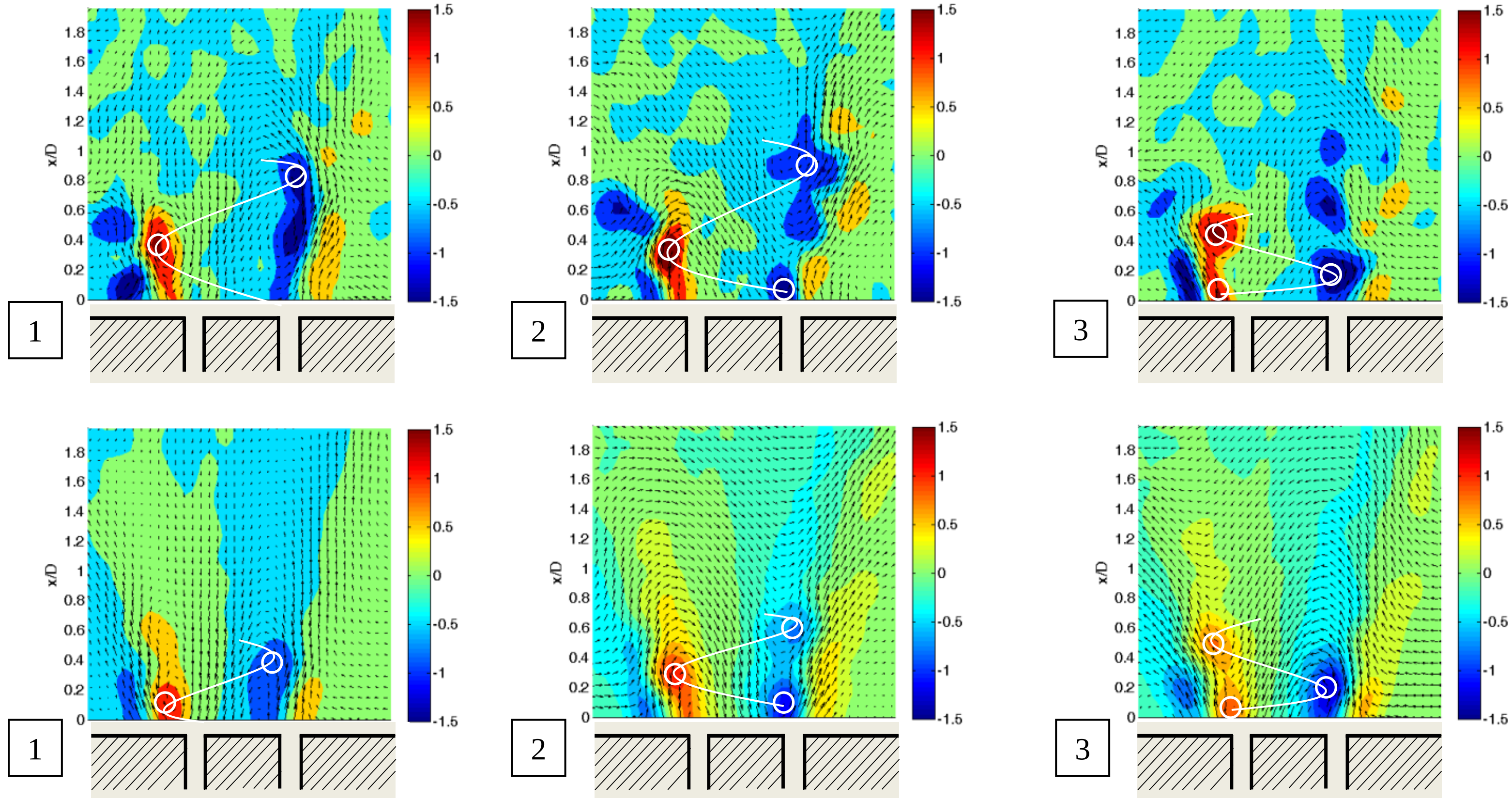
Asymmetric acoustic velocity
Helical shear layer response

Flow Field Topology – Phase-Averaged Velocity

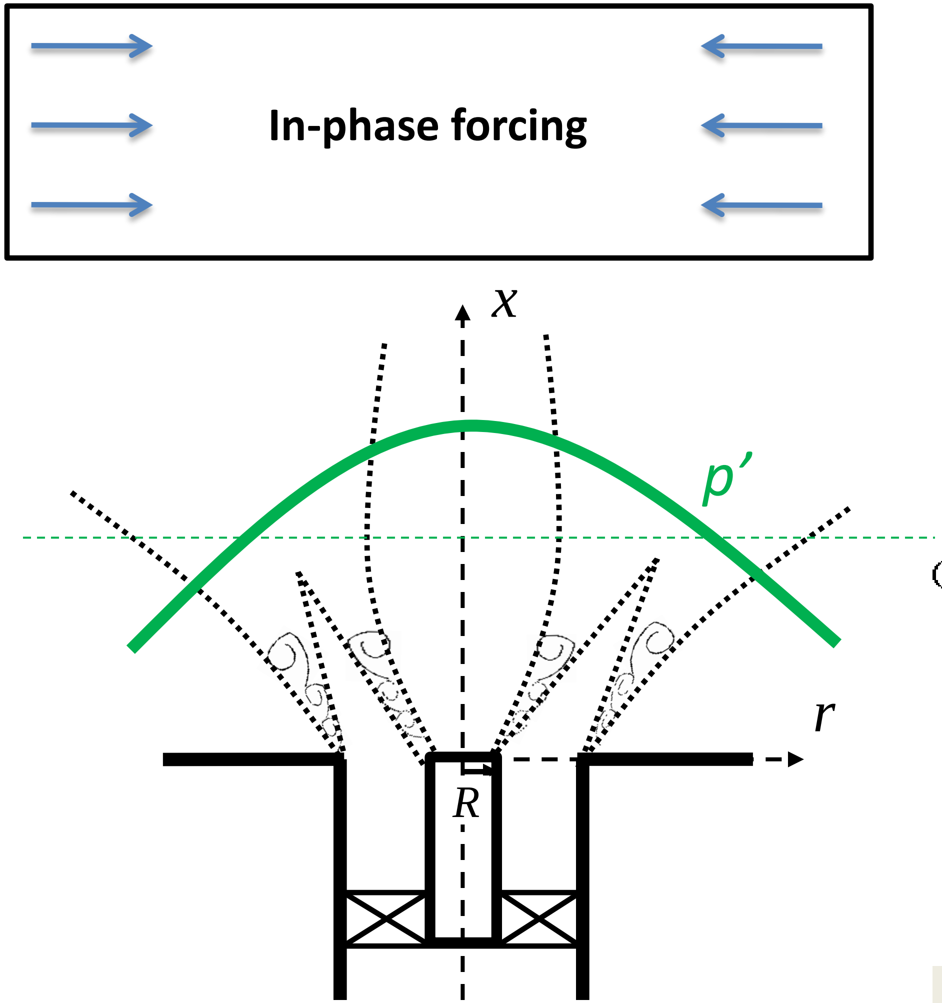
Out-of-phase Forcing

Instantaneous

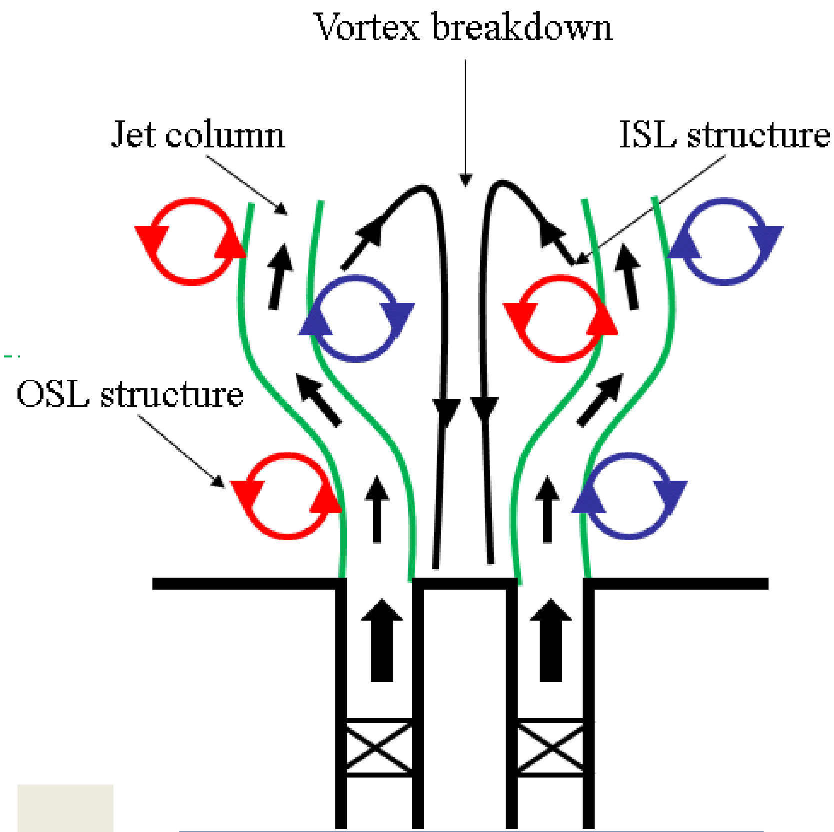
Phase-average



Flow Field Topology



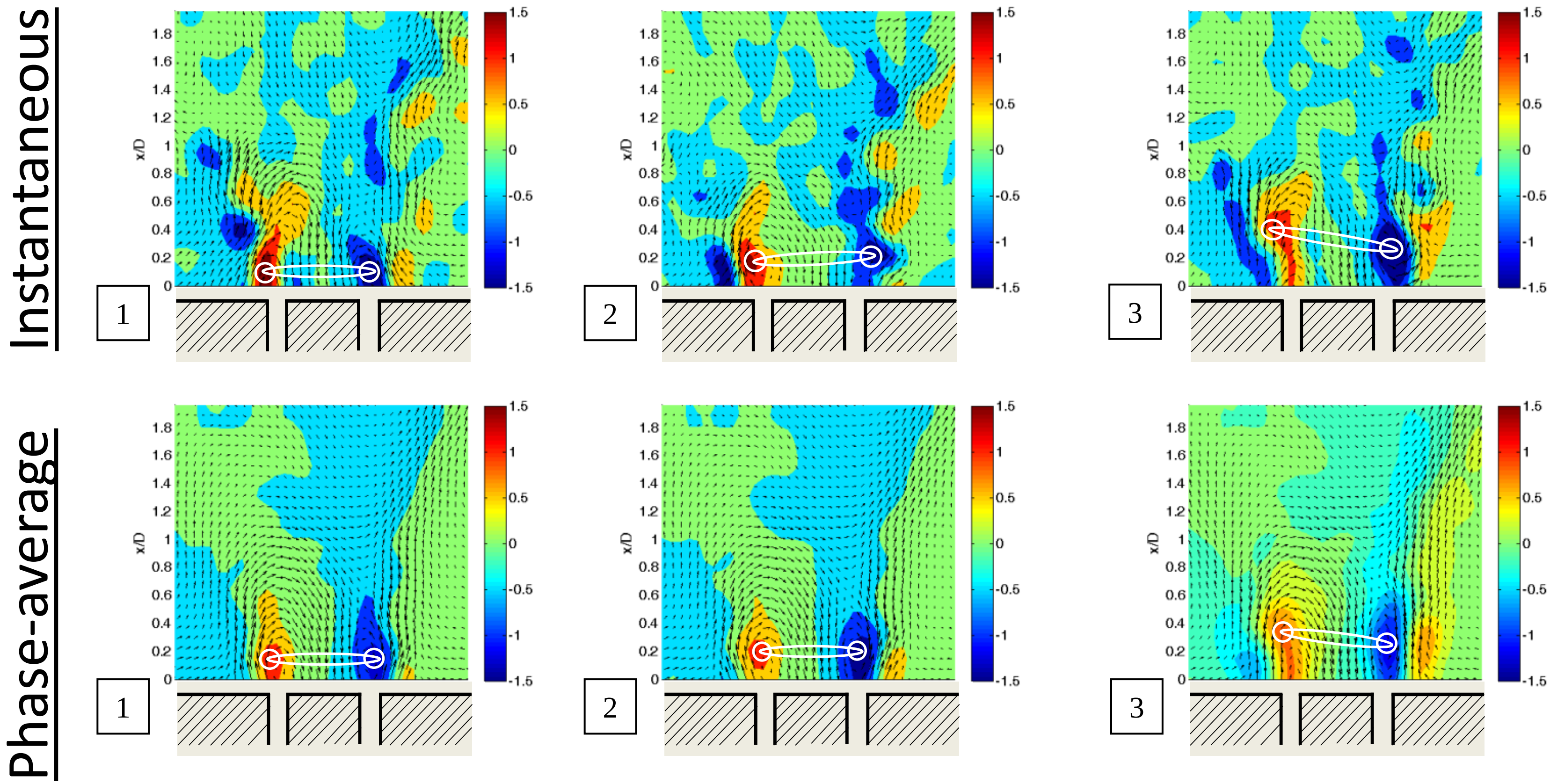
In-phase Forcing



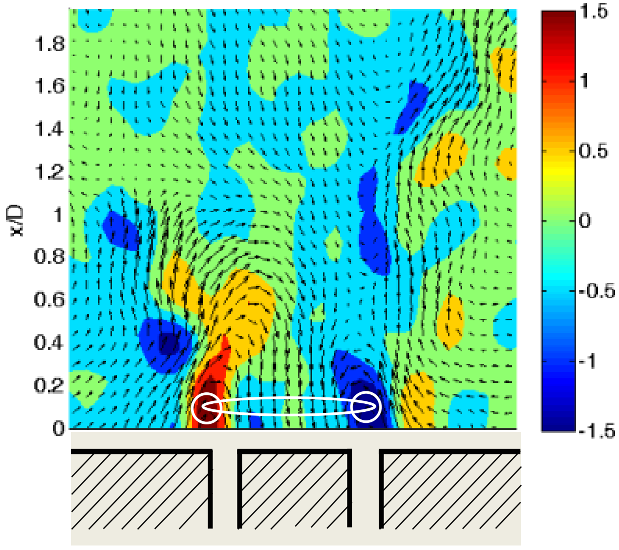
Symmetric acoustic velocity
Ring vortex shedding

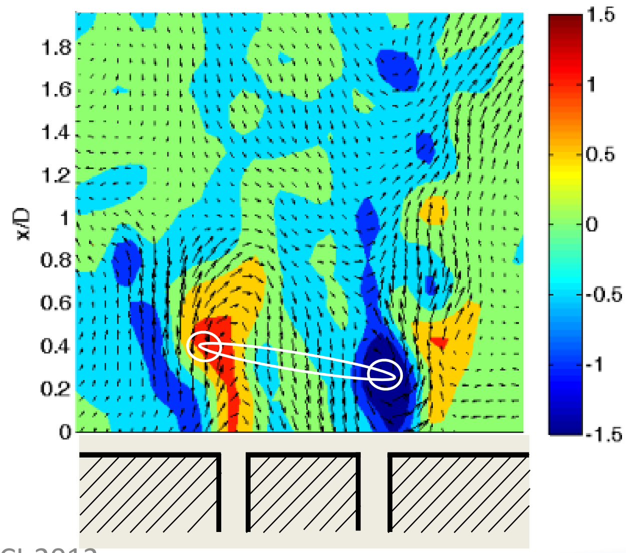
Flow Field Topology – Phase-Averaged Velocity

In-phase Forcing

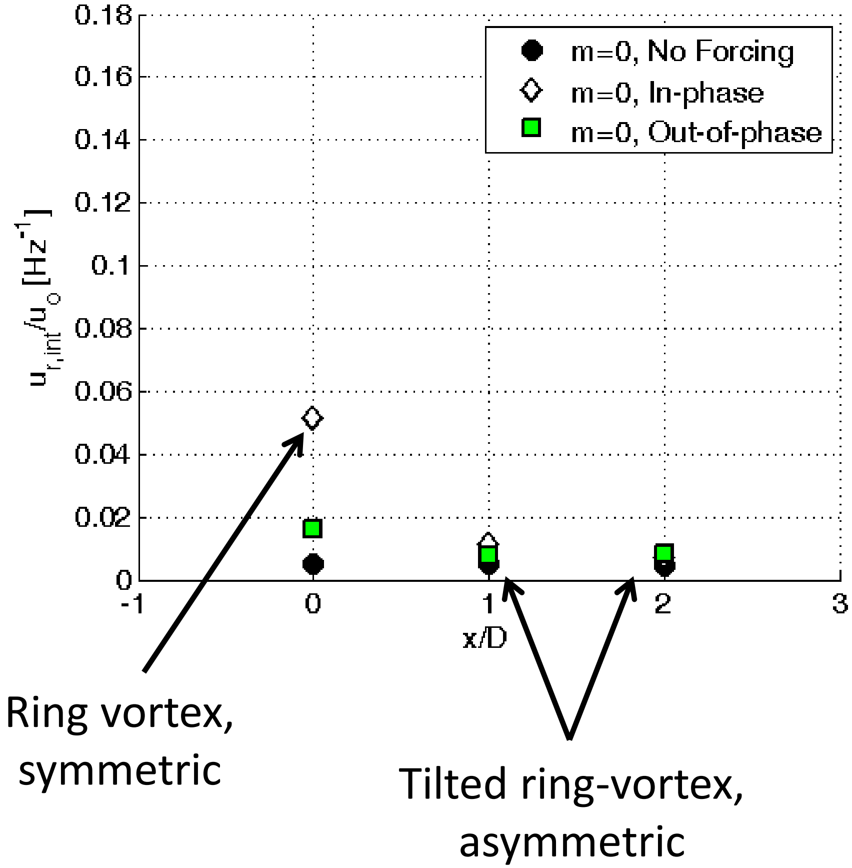


Flow Field Topology – Downstream Development





Mode *m*=0



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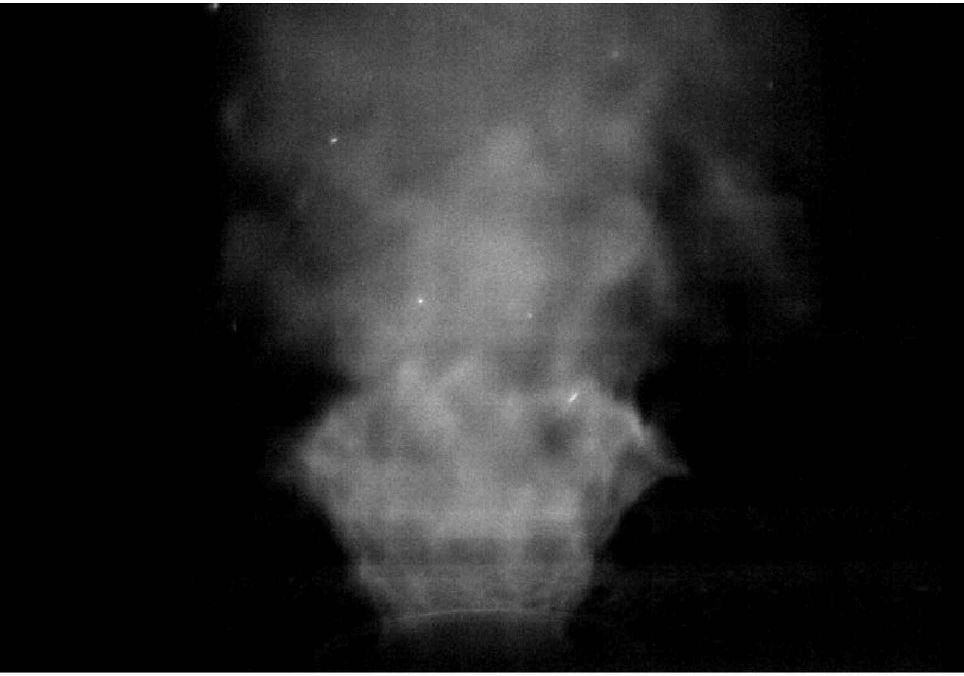
Role of Acoustic Field Symmetry in Flame Response

Symmetric Forcing

Asymmetric Forcing



400 Hz in-phase,
U_o=10 m/s, ϕ=0.9

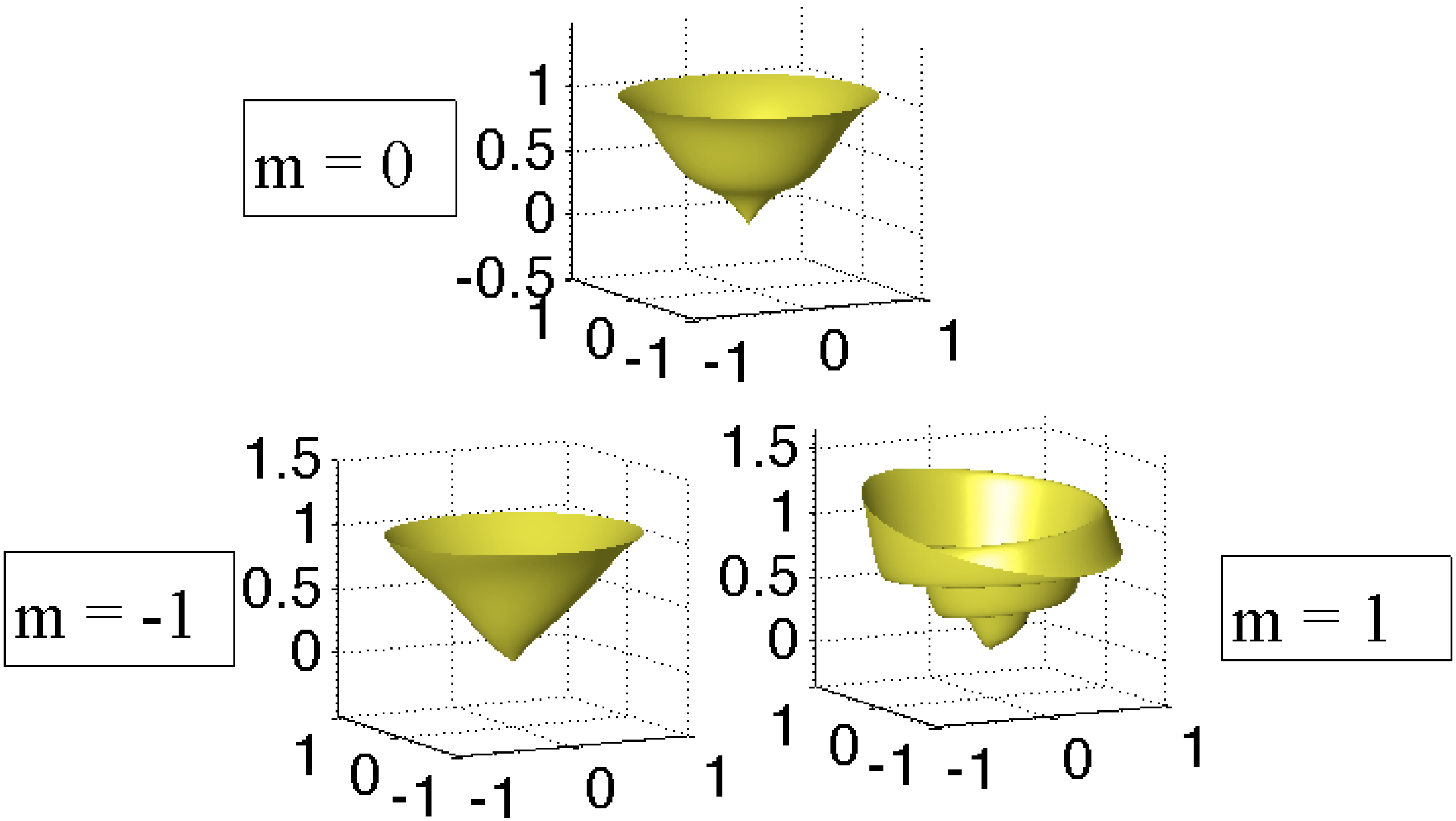
400 Hz out-of-phase,
U_o=10 m/s, ϕ=0.9

Symmetric acoustic velocity
Ring vortex shedding

Asymmetric acoustic velocity
Helical shear layer response

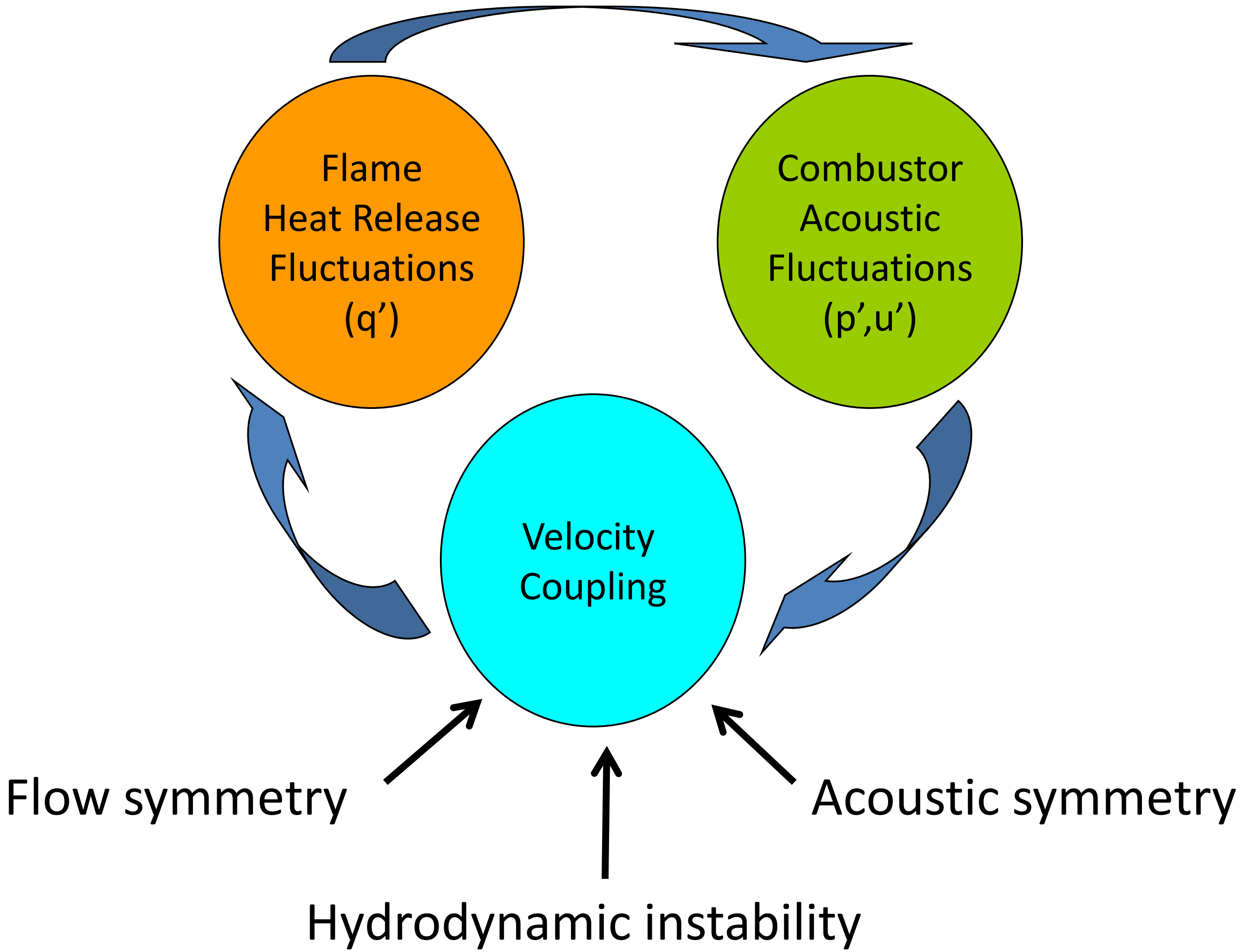
Role of Acoustic Field Symmetry in Flame Response

• Analytical results show significant difference in ***global*** flame response characteristics between symmetric and asymmetric vortical velocity disturbance fields



Results courtesy of Vishal Acharya

Velocity-Coupled Combustion Instability



Key Points

- Combustor flows are often hydrodynamically unstable
  - Rockets – jet instability, jet breakup
  - Augmentors – shear layer instability, wake instability
  - Gas turbines – shear layer instability, vortex breakdown

- Characteristics of these instabilities dictates how these flows will respond to combustor acoustic fields
  - Convectively unstable – disturbance amplifiers
  - Absolutely unstable – self-excited disturbances
  - Acoustic/flow instability symmetries

- Flow response determines local flame disturbances; varying response symmetries can produce vastly different global flame heat release fluctuations

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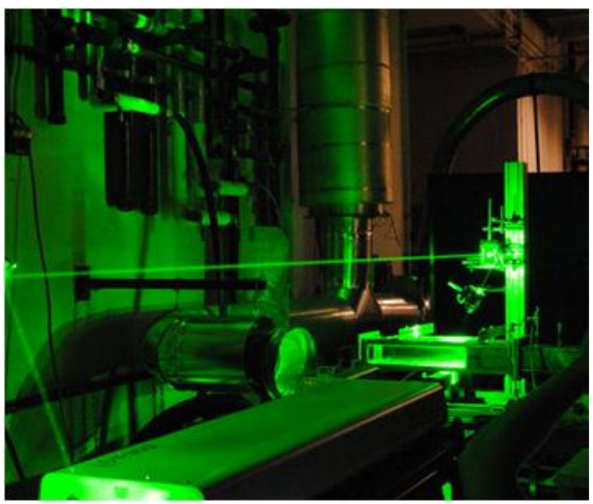
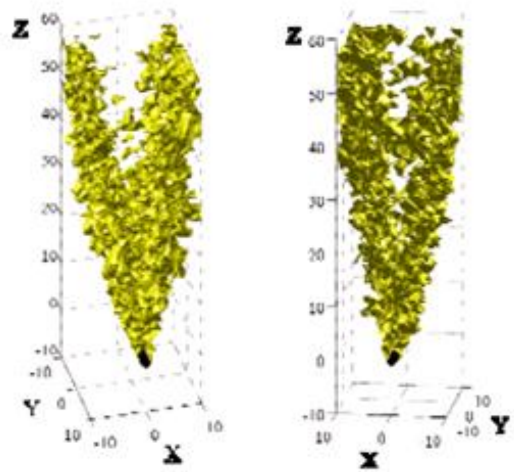
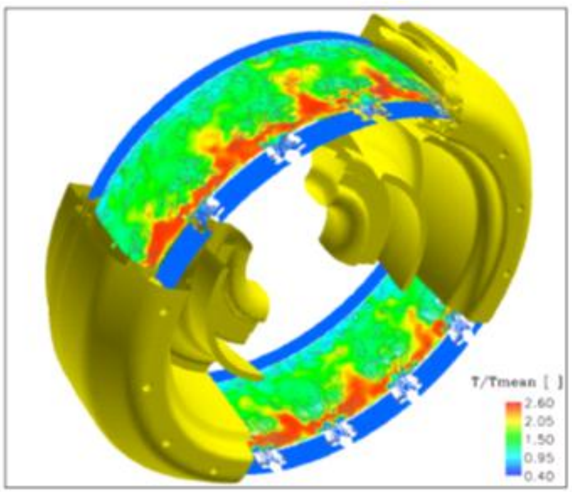
Future Research Directions

• Several research needs address not only the subjects under investigation, but also the methodology:

- Multi-physics understanding
- High-fidelity diagnostics
- Comparison between experiment and model
- Transition of fundamental research to applications







Sources: D. Noble; Hemchandra and Lieuwen, Comb. And Flame, 157, 2010 ; Staffelbach et al., Proc. Comb. Inst., 2008

Acknowledgements

- Georgia Tech, Ben T. Zinn Combustion Laboratory
  - Tim Lieuwen, Professor
  - Michael Malanoski, Michael Aguilar, Vishal Acharya, Ben Emerson

- US Department of Energy under contract DEFG26-07NT43069 and contract monitor Mark Freeman

Questions?

Backup Slides

Experimental Facility

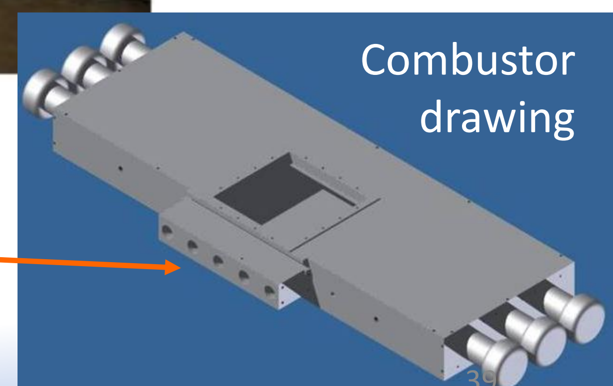
Optical quartz window for laser access

Acoustic drivers

Fuel/air premixing section

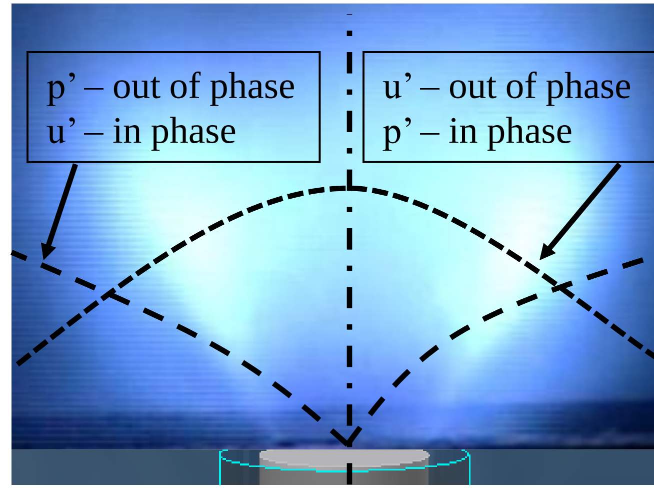
Optical quartz window

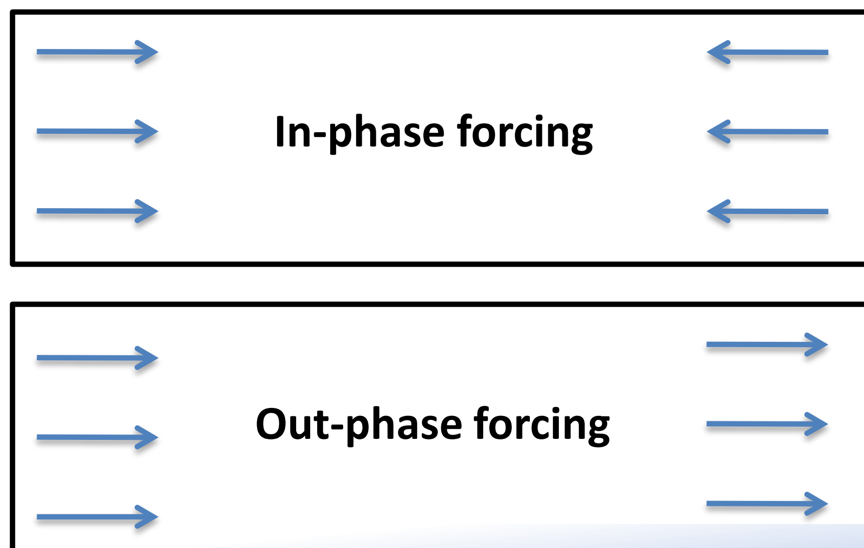
Swirler housing (1-5 swirlers)



Transverse Motion in the Combustor

- Phase control
  - Φ = 0º, approximate pressure maximum, velocity node, at center flame
  - Φ = 180º, approximate velocity maximum, pressure node, at center flame

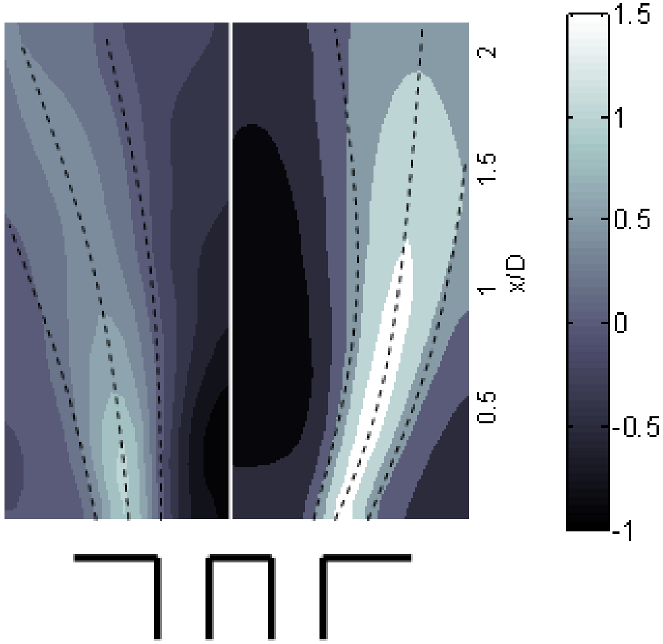




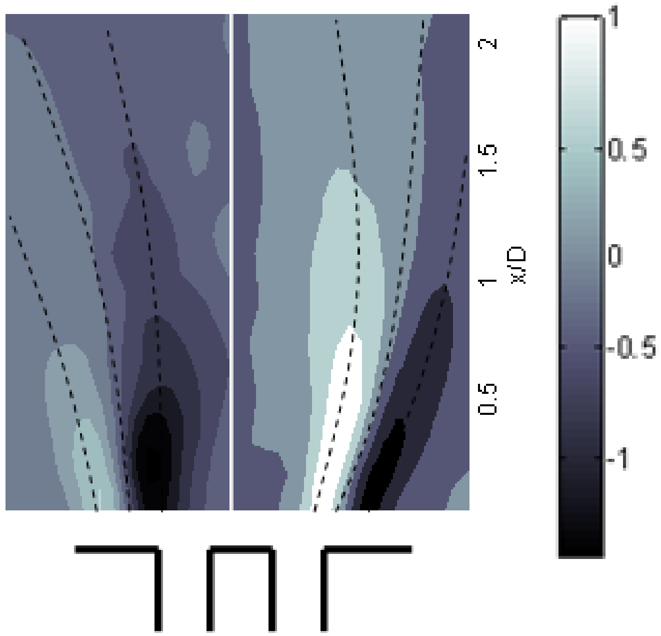
Time-Average Flow Field

- Experimental conditions:
  - U_o = 10 m/s, S = 0.85
  - φ = 0.95
  - f_o = 400 Hz – 1800 Hz

Time-average axial velocity

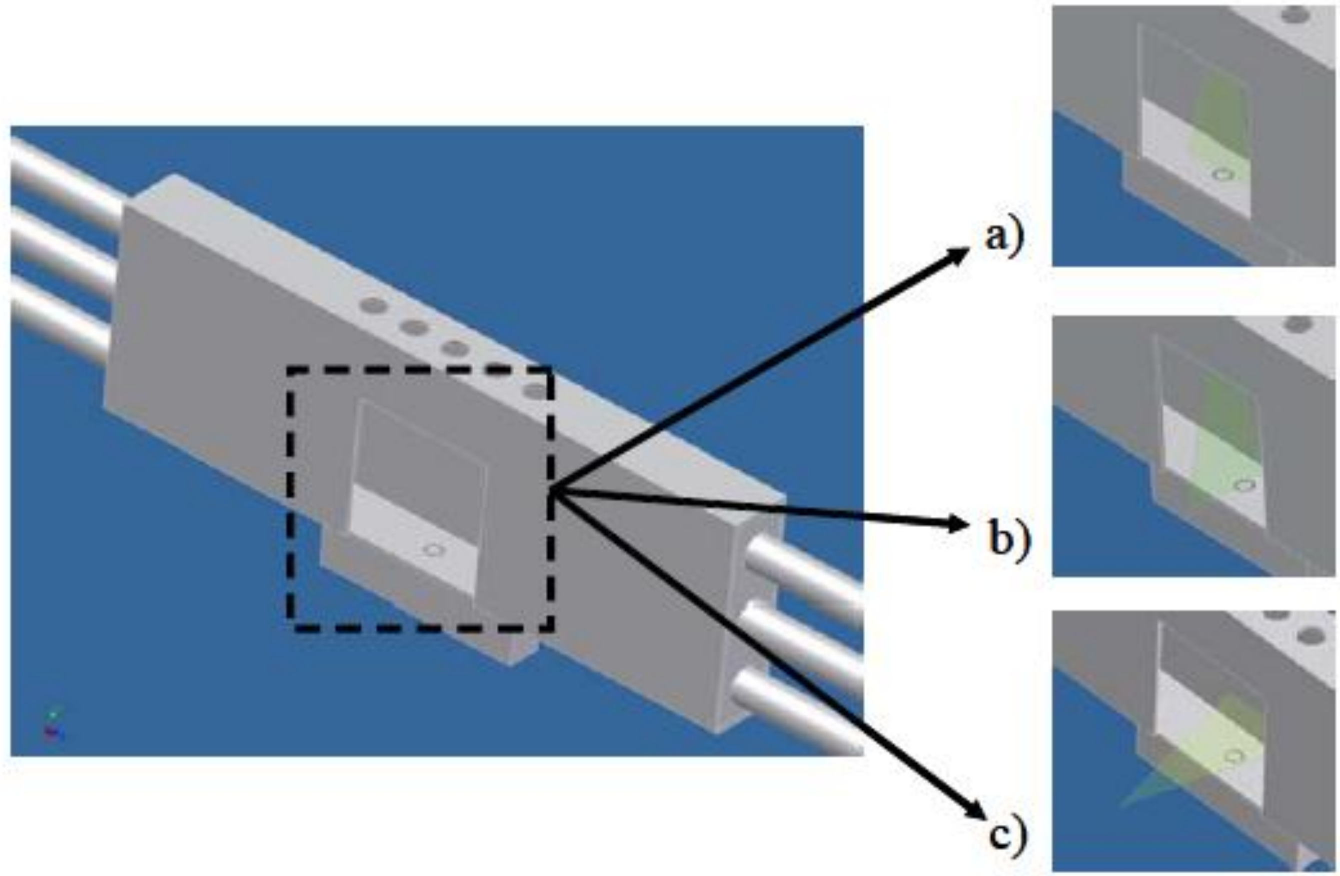


Time-average vorticity



Swirling Flow Instability

• We can more closely examine the symmetry of the disturbances by looking in the r-ϑ plane



Swirling Flow Instability

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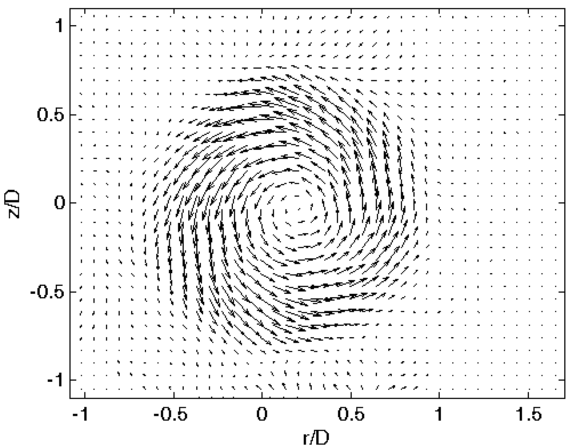
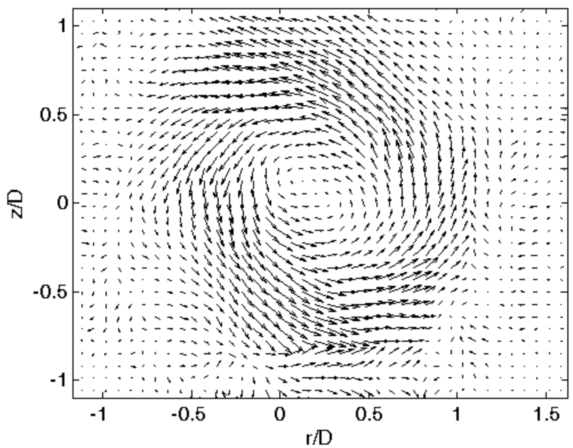
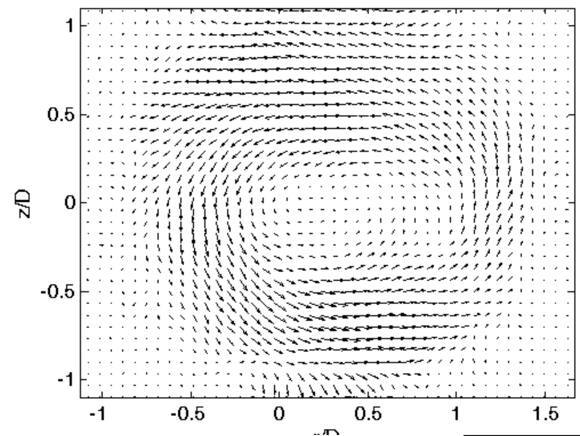
x/D = 0

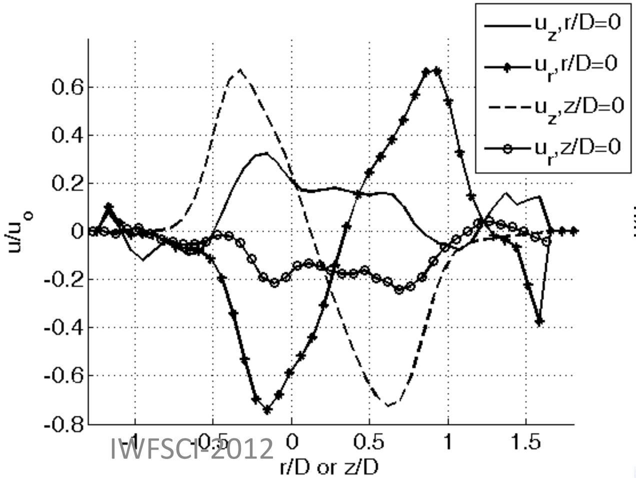
x/D = 1

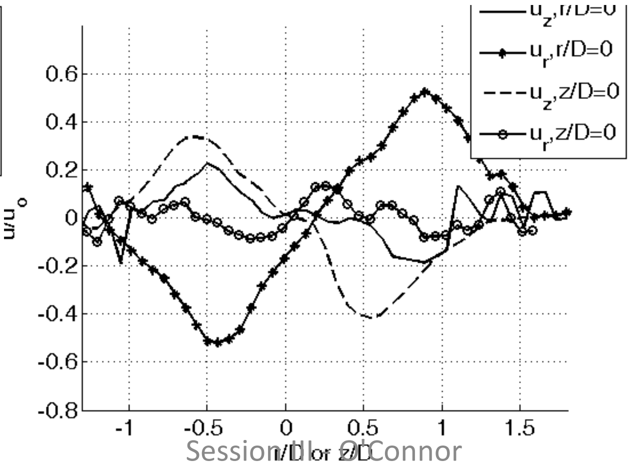
x/D = 2

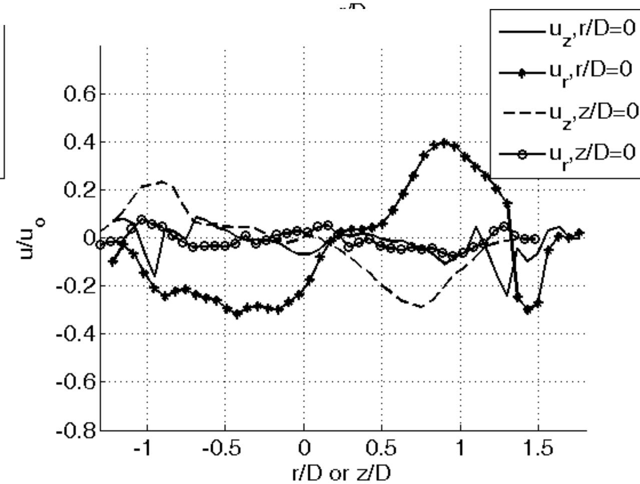








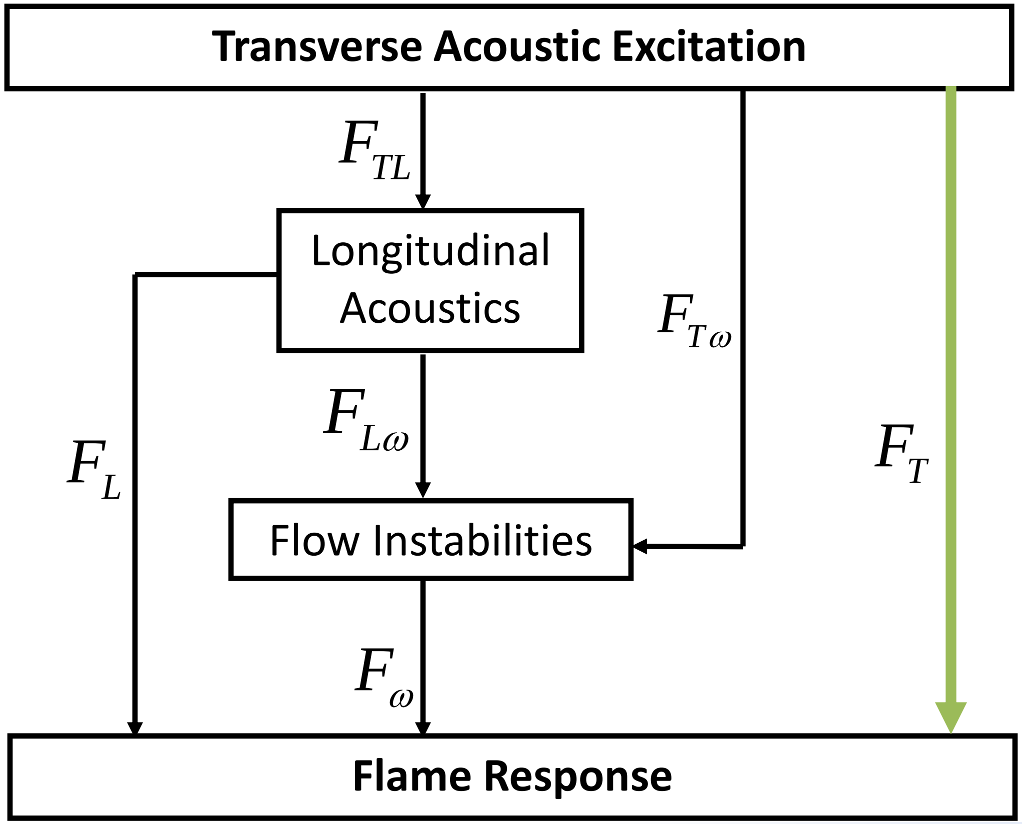




QUESTION: What are key physical processes controlling flame response during transverse instabilities?

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

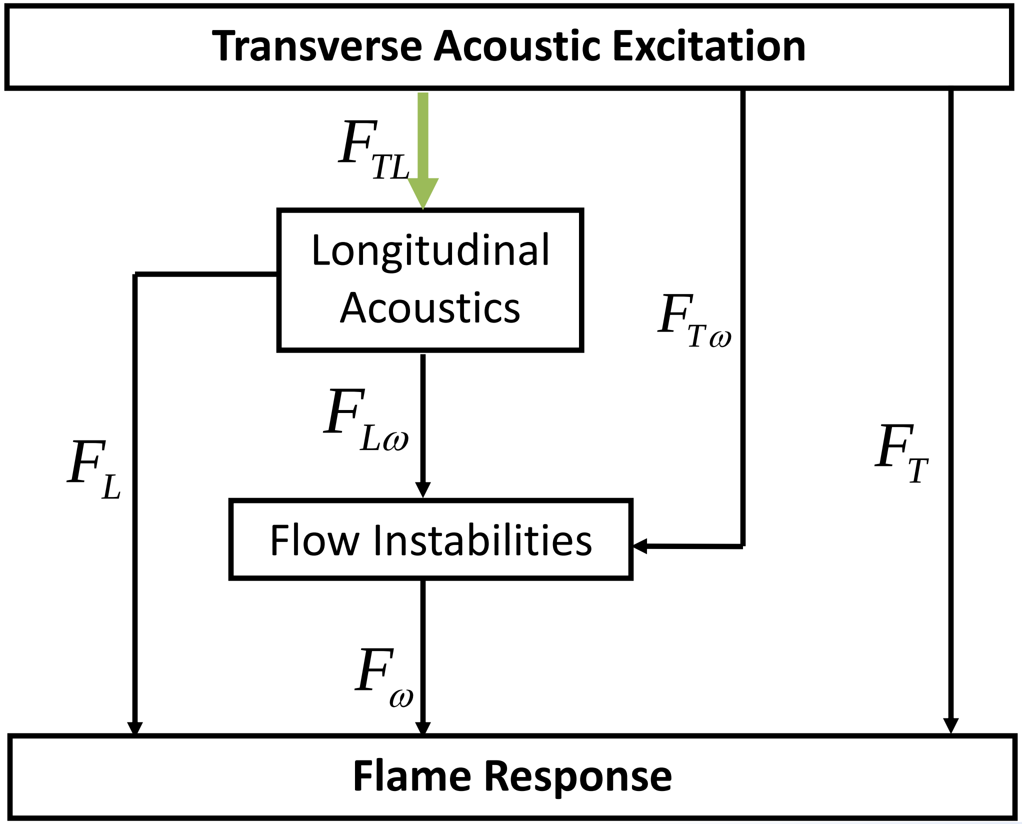
- **Minimal effect on flame response at most frequencies of interest**
  - No net mass flow through flame over acoustic cycle



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

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

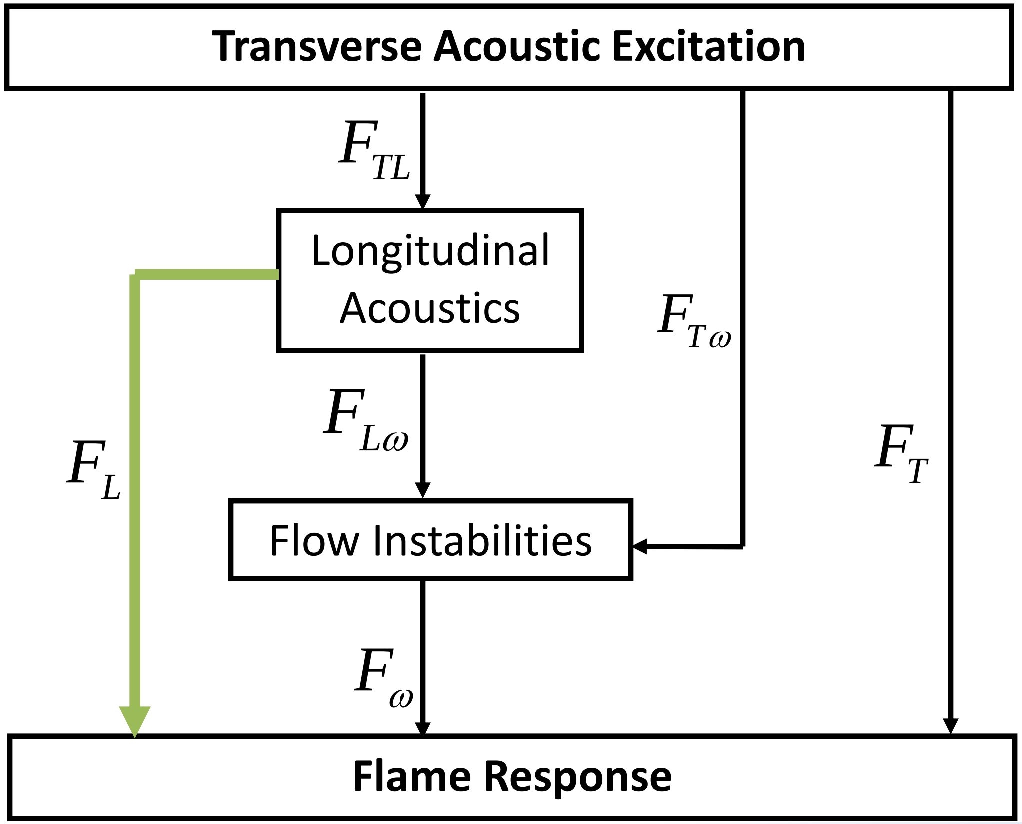
- **Describes acoustic coupling between combustor and swirler nozzle cavity**
- **Key coupling mechanism that determines the relative role of transverse vs. longitudinal motion**
  - Suggests proper reference velocity for flame transfer functions



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

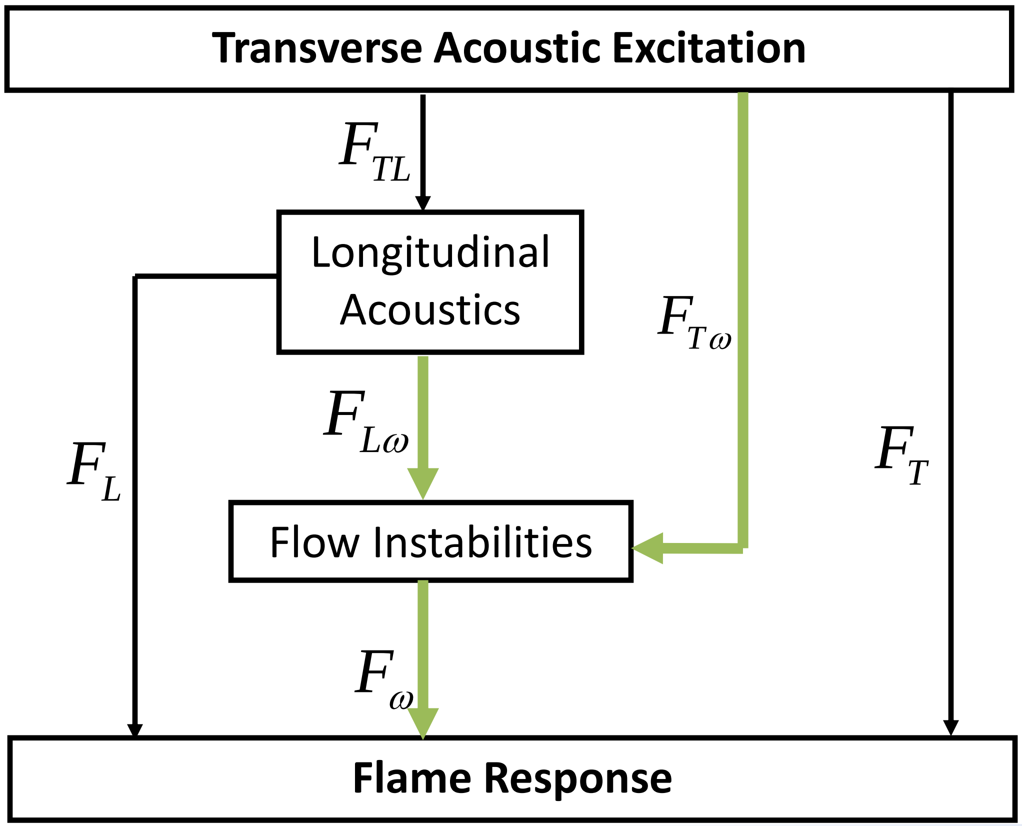


QUESTION: What are key physical processes controlling flame response during transverse instabilities?

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

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

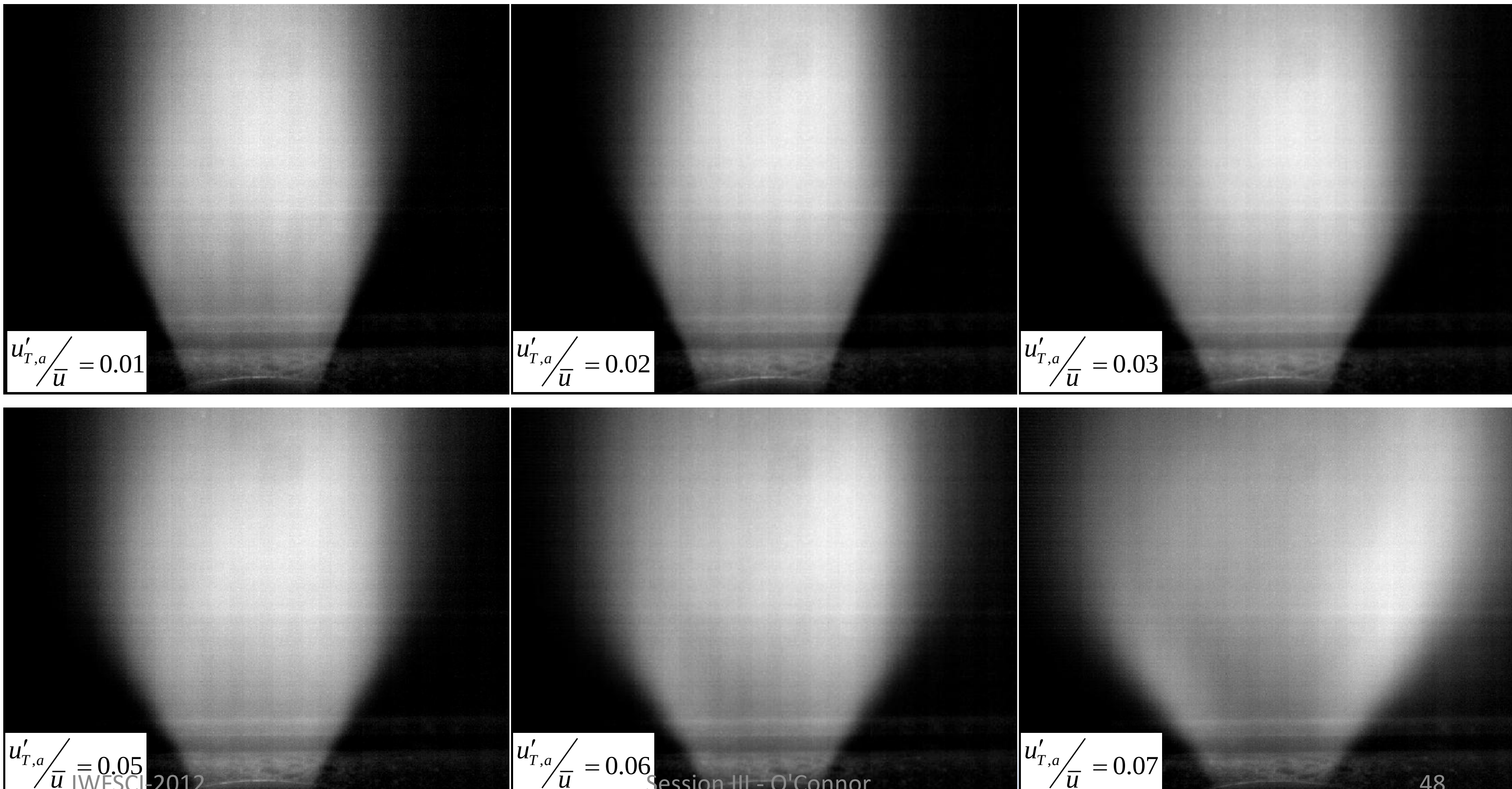
$$F_{\omega}(f) = \frac{q'(f)/\bar{q}}{u'_{\omega}(f)/\bar{u}}$$



Effect of Forcing on Time-Average Flow

- The progression of the flow field shape as the amplitude of forcing increases is due to changes in the vortex breakdown bubble

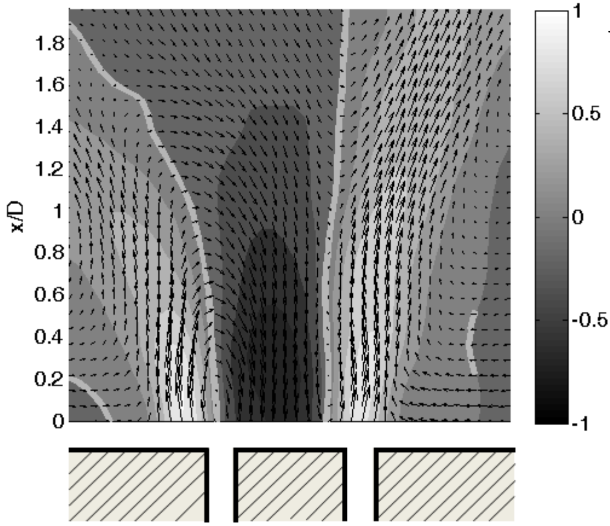
1800 Hz in-phase



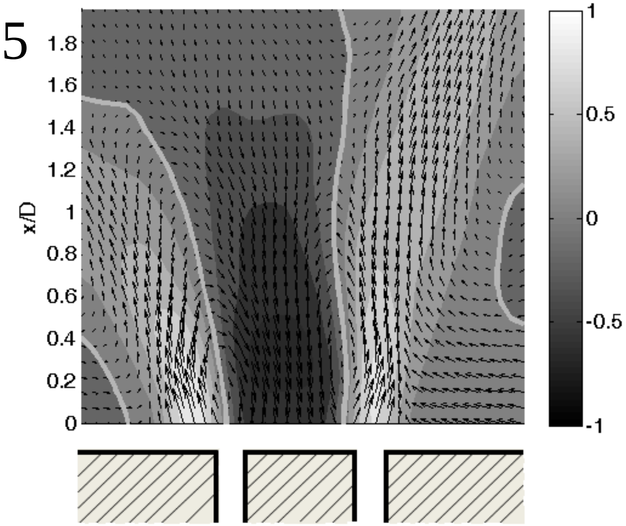
Effect of Forcing on Time-Average Flow

- This behavior is reflected in changes in the structure of the vortex breakdown bubble at high amplitudes

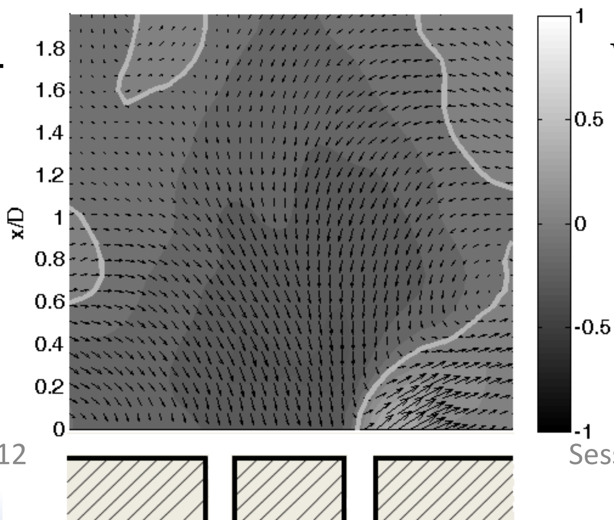
$v'/u_o = 0.3$



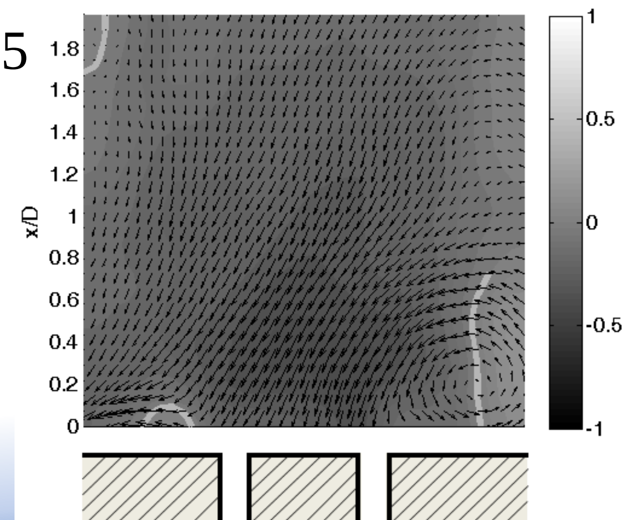
$v'/u_o = 0.35$



$v'/u_o = 0.4$

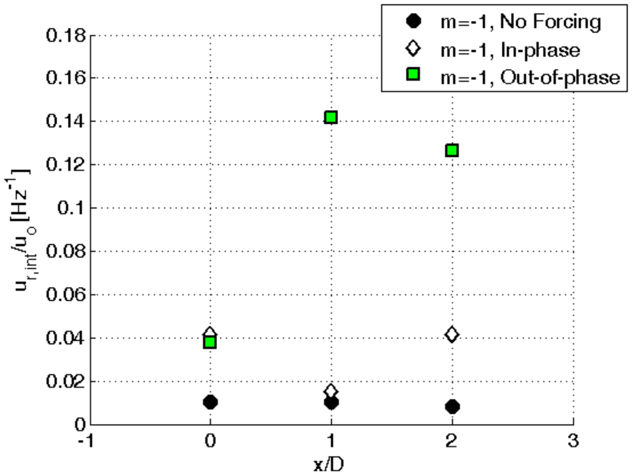


$v'/u_o = 0.45$

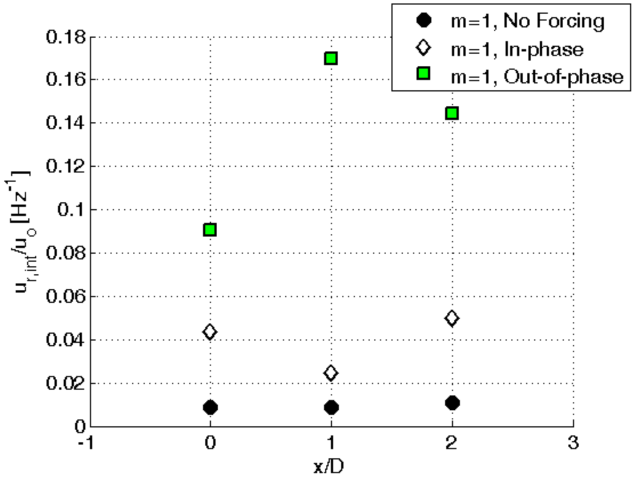


Flow Field Topology – Downstream Development

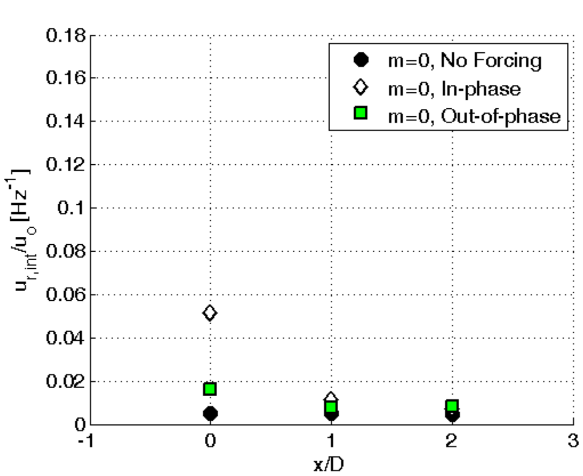
Mode *m*=-1



Mode *m*=1

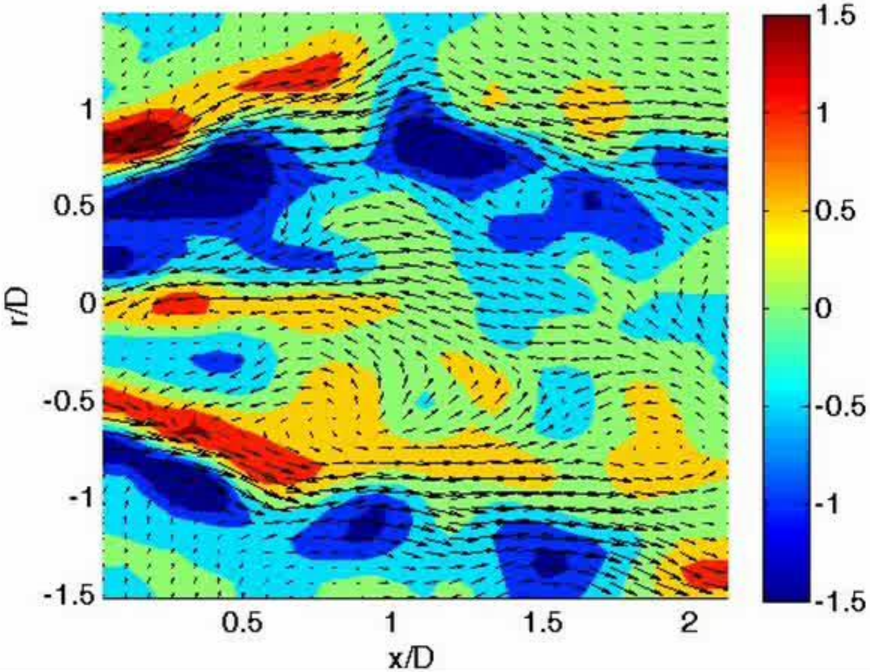


Mode *m*=0



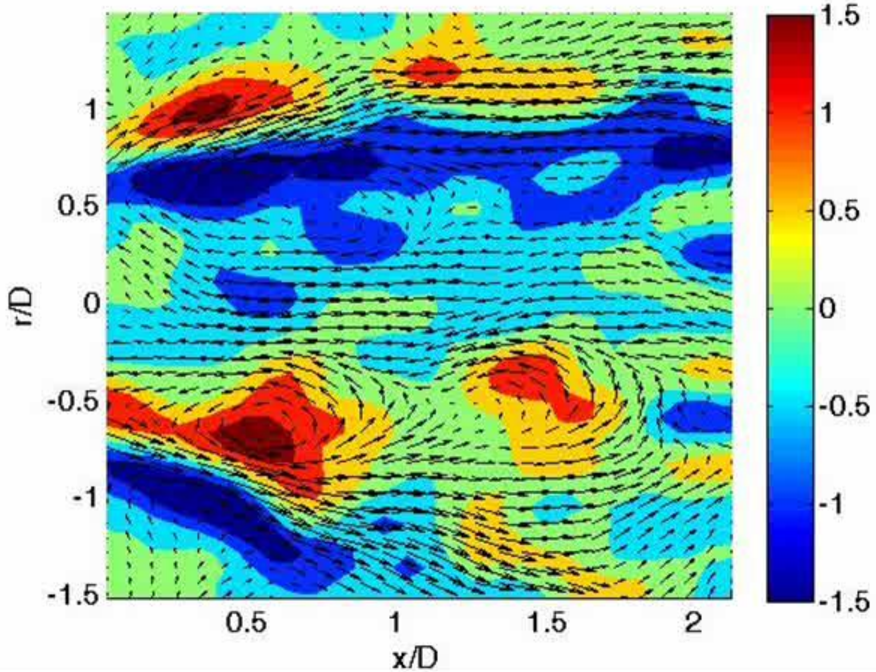
Flow Field Topology – Instantaneous Velocity

In-phase Forcing



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

Out-of-phase Forcing



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

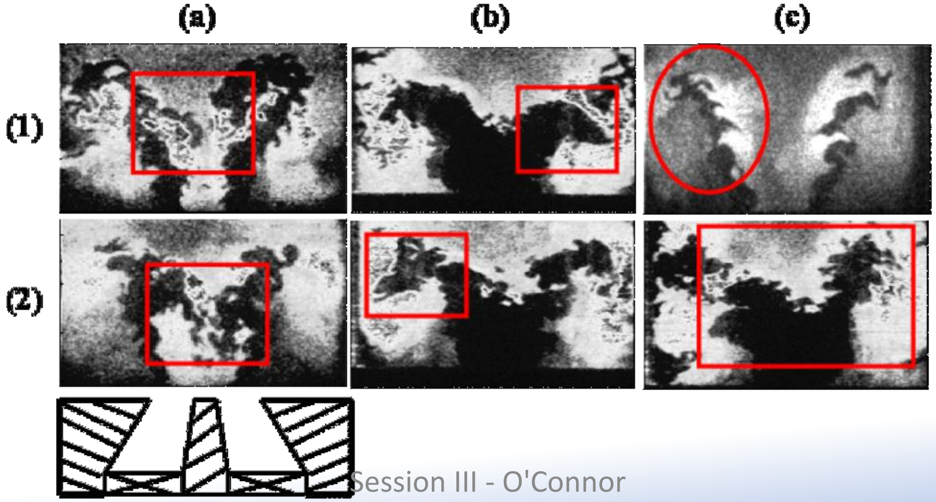
Swirling Flow Instability and Flame Response

- Flame response in velocity-coupled combustion instabilities is dictated by these two levels of instability

- The “base state” governs the flame shape and, in part, the magnitude of the flame response

$$\frac{\partial G}{\partial t} + (\vec{u} \cdot \vec{n} - S_L) |\nabla G| = 0$$

- The shear layer instabilities drive the oscillating heat release

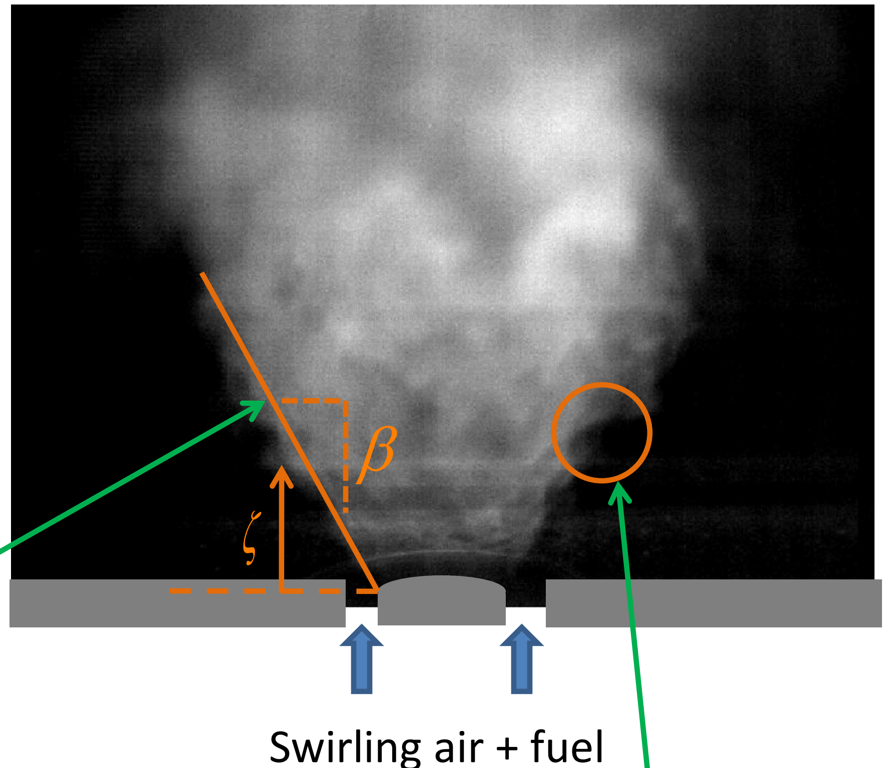


Reproduced from Thumuluru and Lieuwen, Proceedings of the Comb. Inst., 2009

Swirling Flow Instability and Flame Response

Time-average behavior (base state)

Fluctuating behavior (flame wrinkling)



$$\bar{u} - \beta\bar{v}\bar{\zeta}_r - S_L(r)\sqrt{1+\beta\bar{\zeta}_r^2}$$

$$\frac{\partial\zeta'}{\partial t} = u' - \beta\bar{v}\zeta_r' - \beta v'\bar{\zeta}_r - \frac{\beta^2 S_L\bar{\zeta}_r\zeta_r'}{\sqrt{1+\beta^2\bar{\zeta}_r^2}}$$

High-Speed Data Database

- **Velocity data: 462 cases**
  - Non-reacting and reacting
  - S=0.85, S=0.5
  - R-x and R-ϑ views
  - u_o=10, 15, 20, 40 m/s
  - f_f = 400-1800 Hz, variety of amplitudes, symmetries

- **PLIF data: 38 cases**
  - S=0.5, u_o = 10 m/s
  - f_f = 400-1800 Hz, variety of amplitudes, symmetries

- **Flame luminescence data: 64 cases**
- **Smoke visualization data: 276 cases**
- **Flame transfer function data: 224 cases**