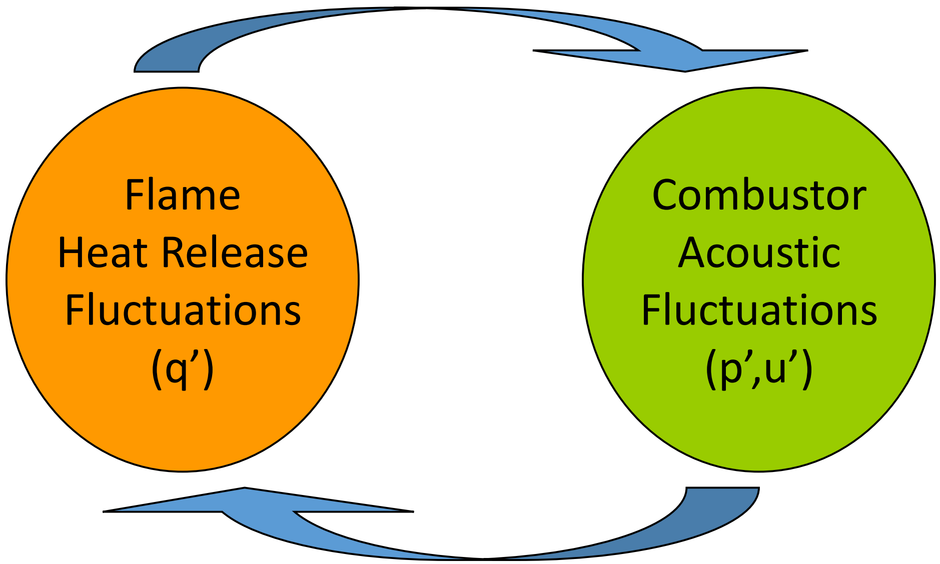
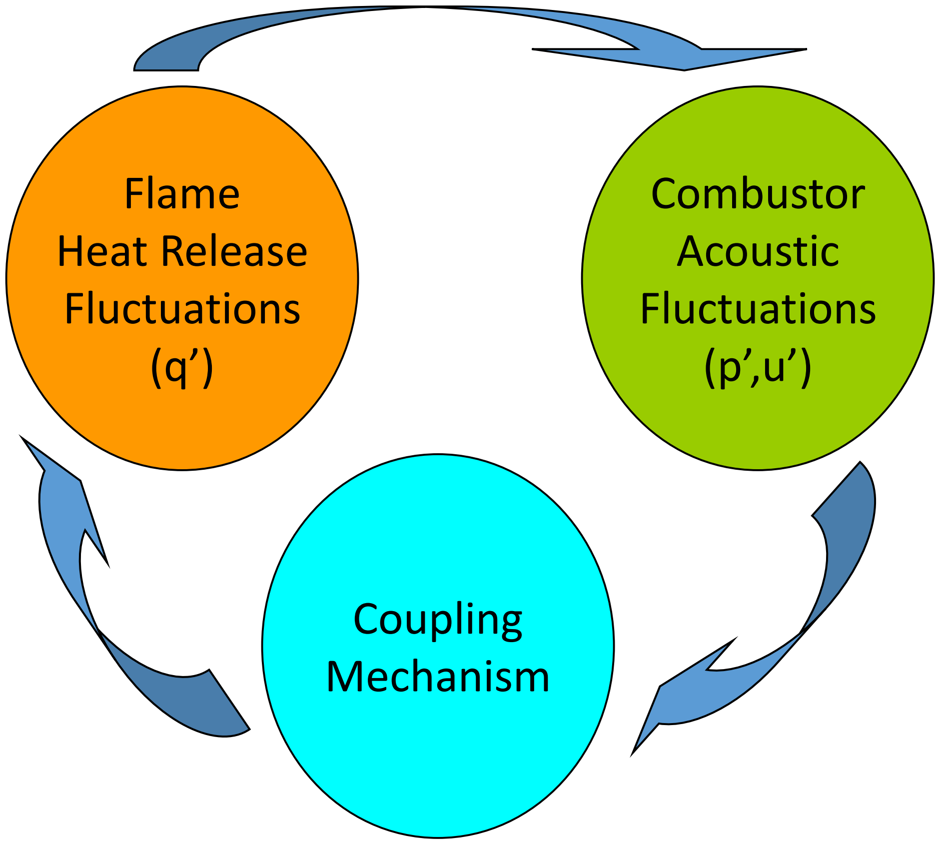
Combustion Instability: Mechanisms and Suppression

Jacqueline O'Connor, Ph.D.
Mechanical and Nuclear Engineering
Pennsylvania State University
sites.psu.edu/ccpp/



PennState

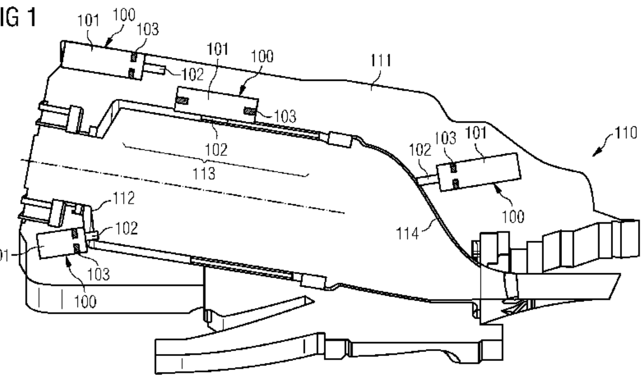
Combustion instability is the feedback between combustor acoustics and the flame through a coupling mechanism



In real devices, combustion instability suppression takes a number of forms

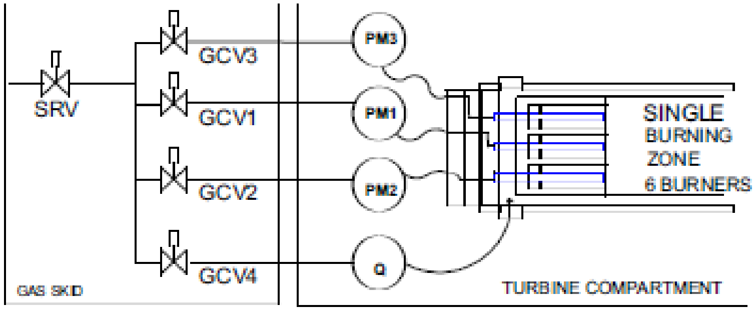
Acoustic Damping

FIG 1



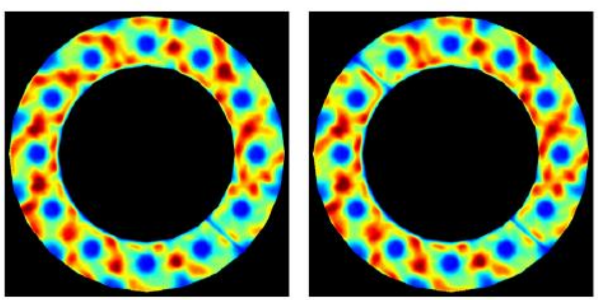
Bulat, Ghenadie. "Helmholtz resonator for a gas turbine combustion chamber." U.S. Patent No. 8,689,933. 8 Apr. 2014.

Fuel Splitting



Davis and Black, "Dry Low NO_x Combustion Systems for GE Heavy-Duty Gas Turbines"

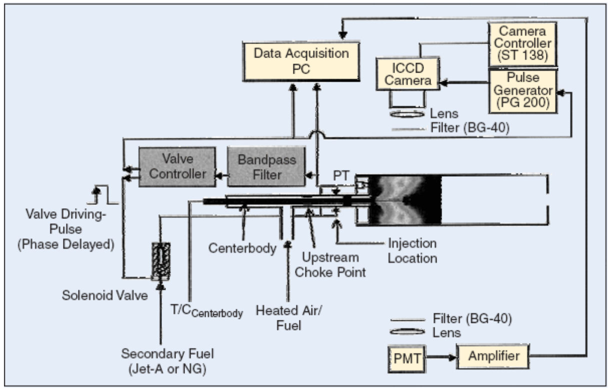
Symmetry breaking



(a) $N_b = 1$ (b) $N_b = 2(s)$

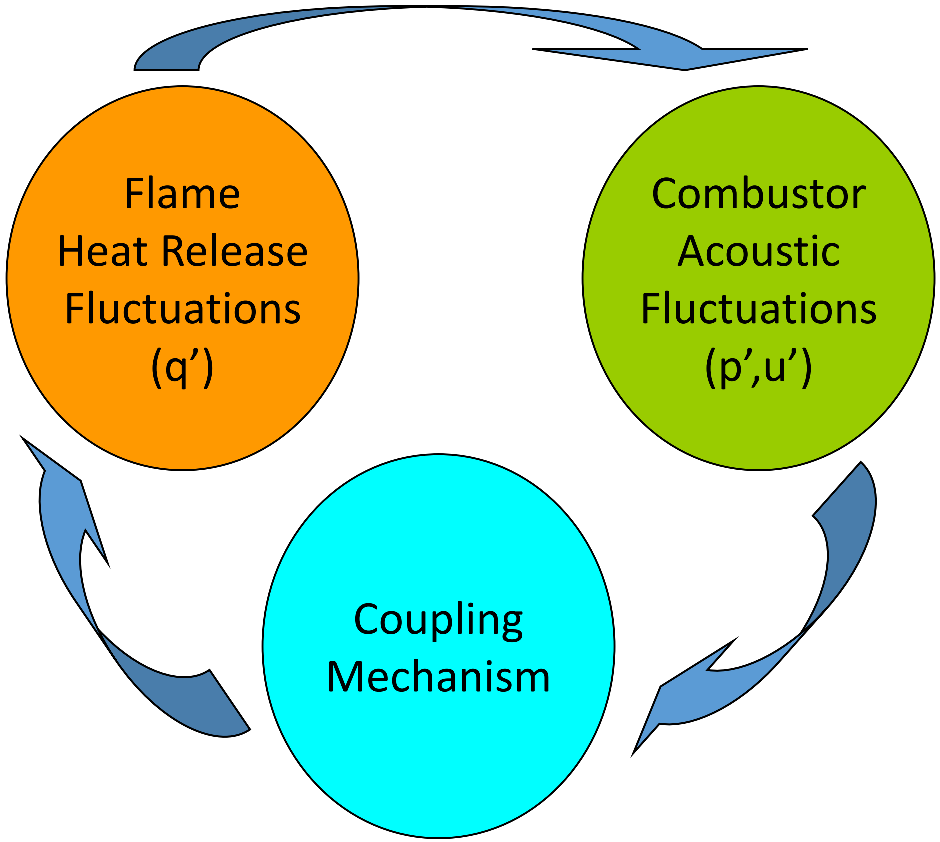
Dawson, J. R., & Worth, N. A. (2015). The effect of baffles on self-excited azimuthal modes in an annular combustor. *Proceedings of the Combustion Institute*, *35*(3), 3283-3290.

Active control

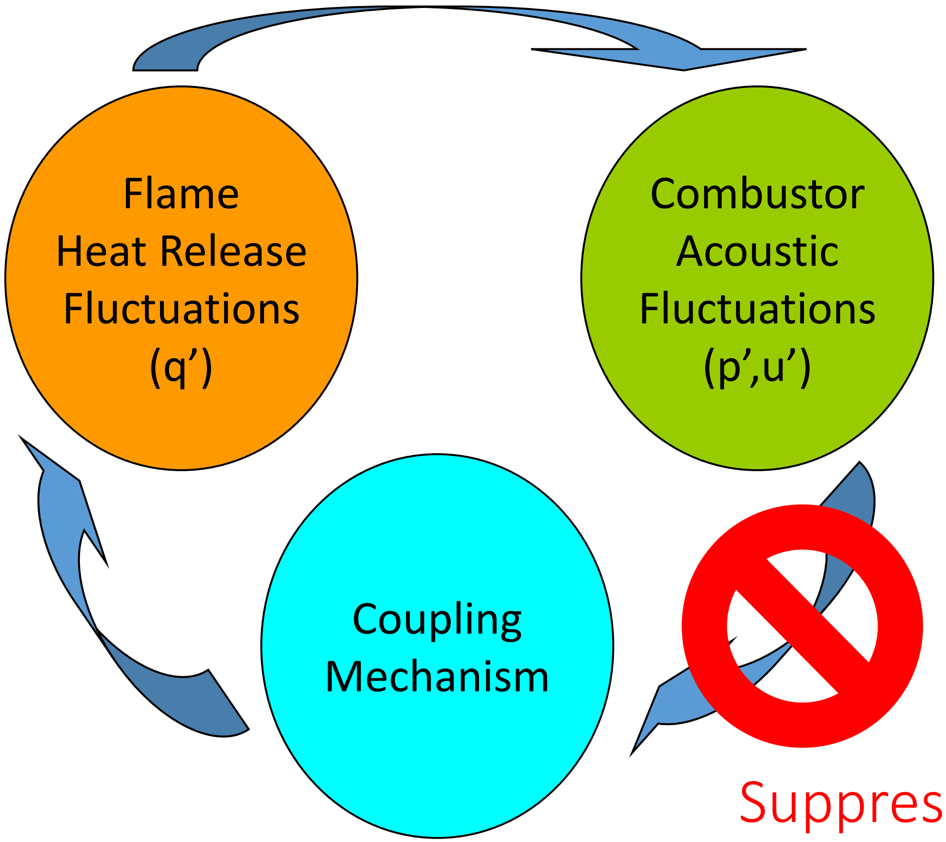


Annaswamy, A. M., & Ghoniem, A. F. (2002). Active control of combustion instability: Theory and practice. *IEEE control systems*, *22*(6), 37-54.

Combustion instability suppression can also achievable by "breaking" any part of this feedback loop



The focus of this talk is suppression of the feedback loop through suppression of shear layer receptivity

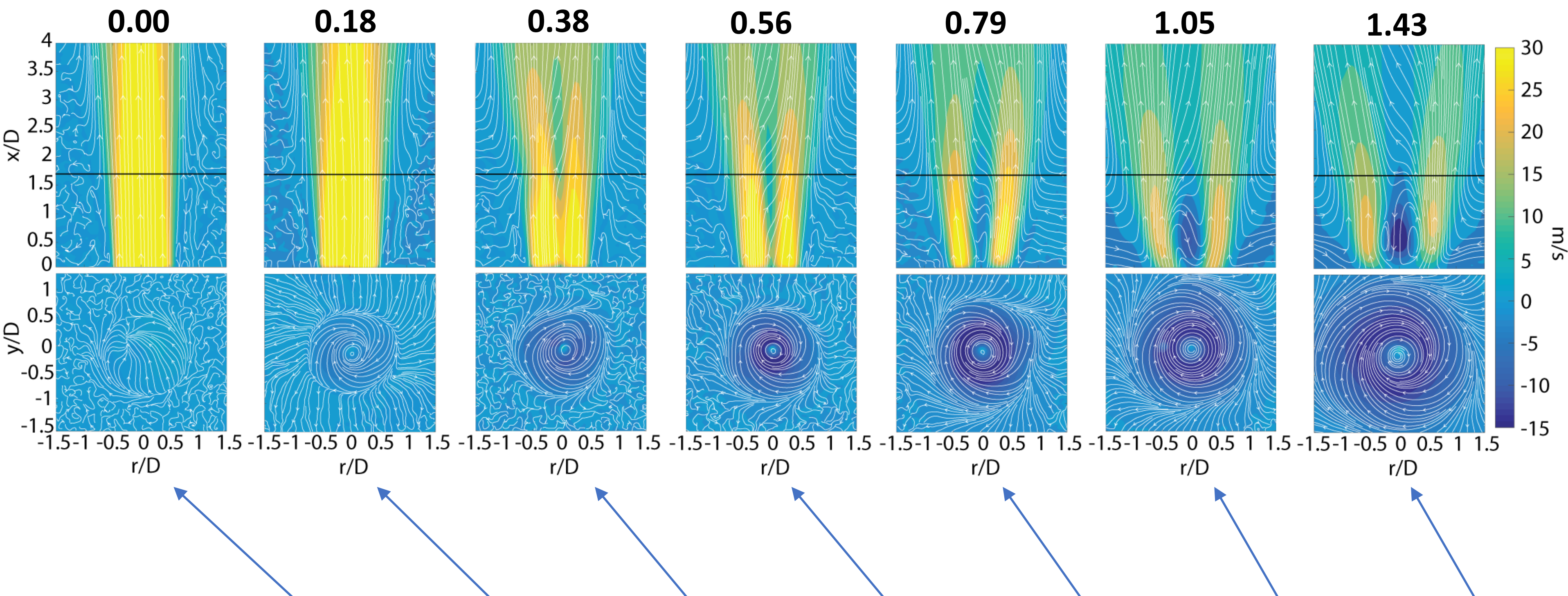


Suppression through changes in shear layer receptivity

Goals of the talk:

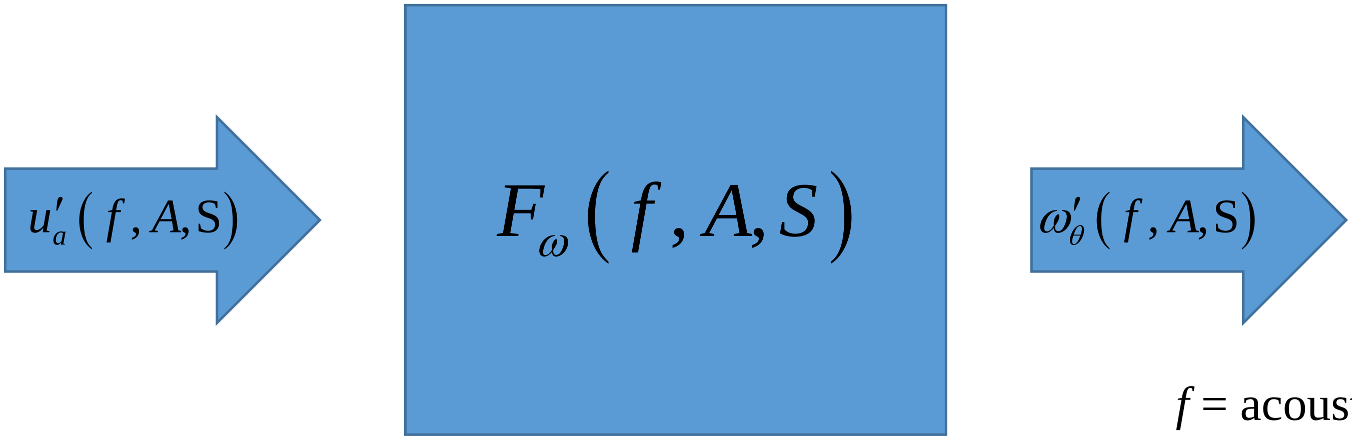
- Demonstrate flow receptivity and its role in the thermoacoustic feedback loop
- Discuss methodologies to quantify flow receptivity
- Propose method for suppressing combustion instability through suppression of flow receptivity

Structure of swirling flows change significantly with swirl number, inducing vortex breakdown and PVC



Swirl Number	0.00	0.18	0.38	0.56	0.79	1.05	1.43
Flow State	No VB	No VB	No VB	Intermittent VB	Weak PVC	PVC	Strong PVC
PVC Frequency	-	-	-	-	770–815 Hz	840 Hz	1060 Hz

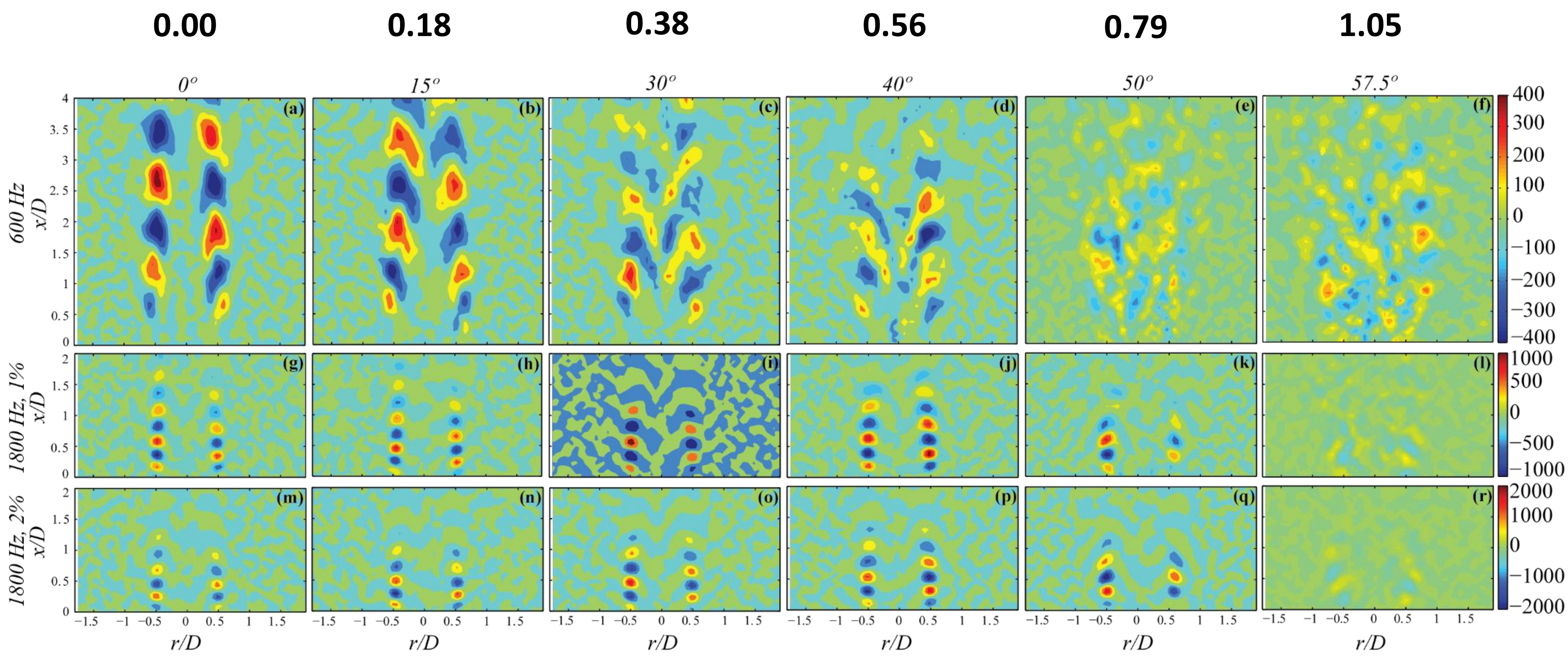
As the structure of the flow changes, its receptivity to acoustic forcing changes, as does its preferred frequency



f = acoustic frequency
A = acoustic amplitude
S = swirl number

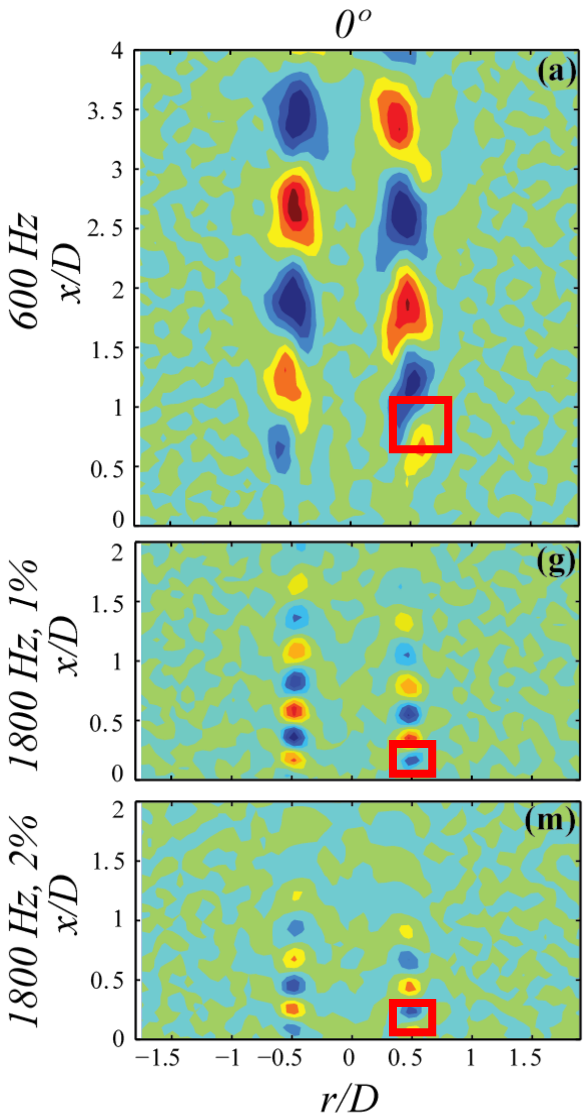
$$F_\omega(f, A, S) = \frac{\omega'_\theta(f, A, S) / \bar{\omega}(S)}{u'_a(f, A, S) / \bar{u}(S)}$$

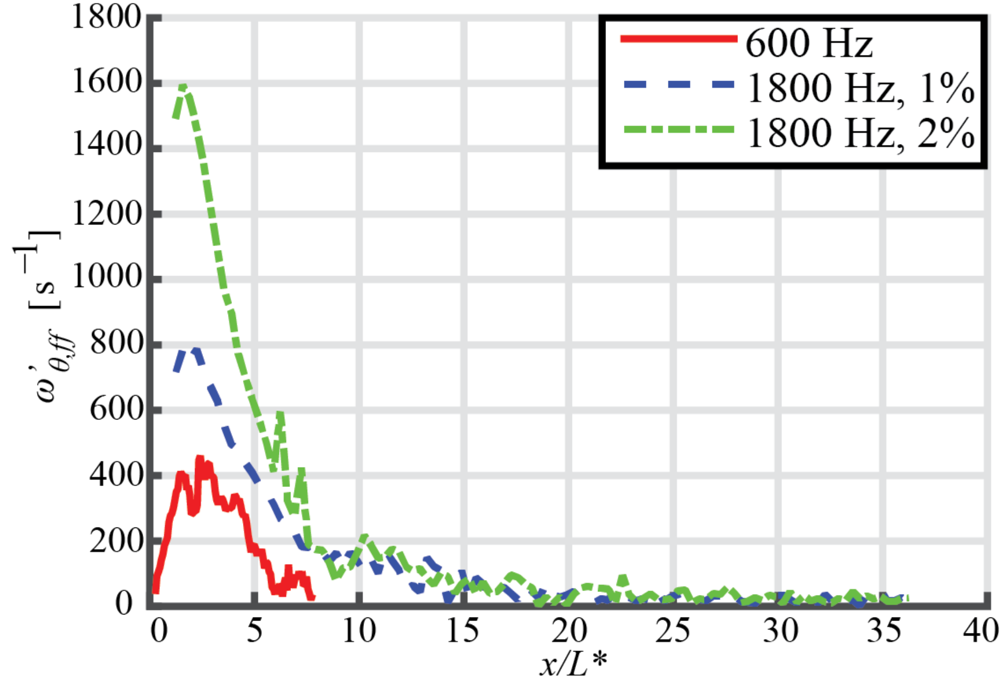
Harmonic reconstruction of forced response indicates variation in shear layer receptivity with swirl number, frequency



Swirl number

To quantify magnitude of vorticity fluctuation, we measured at the end of the vortex development length

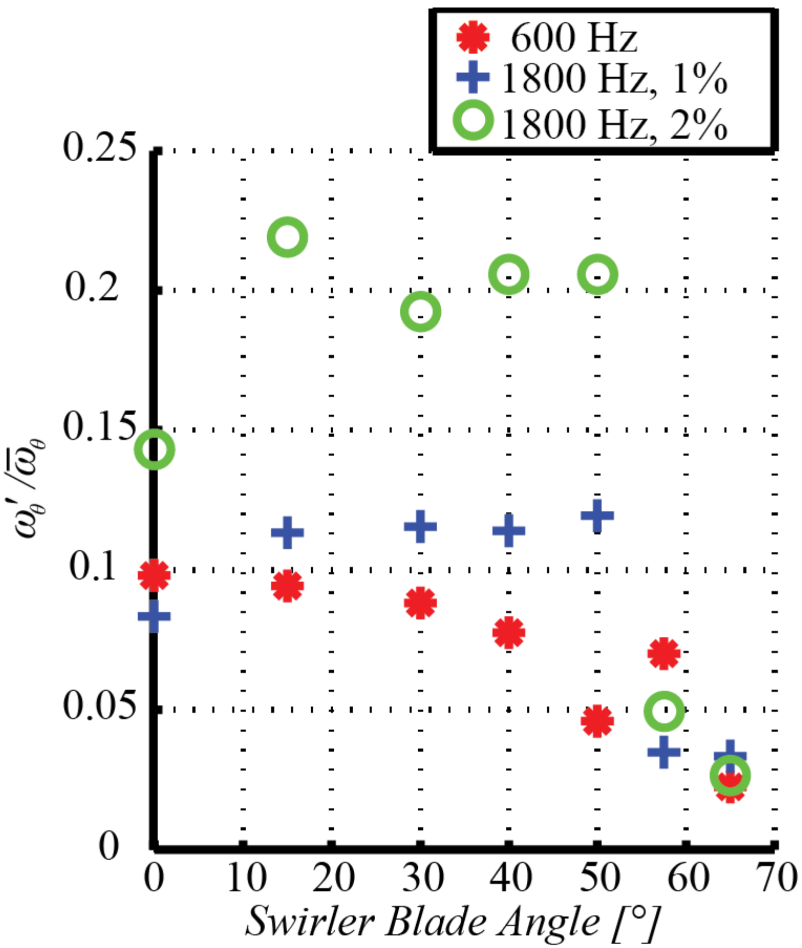




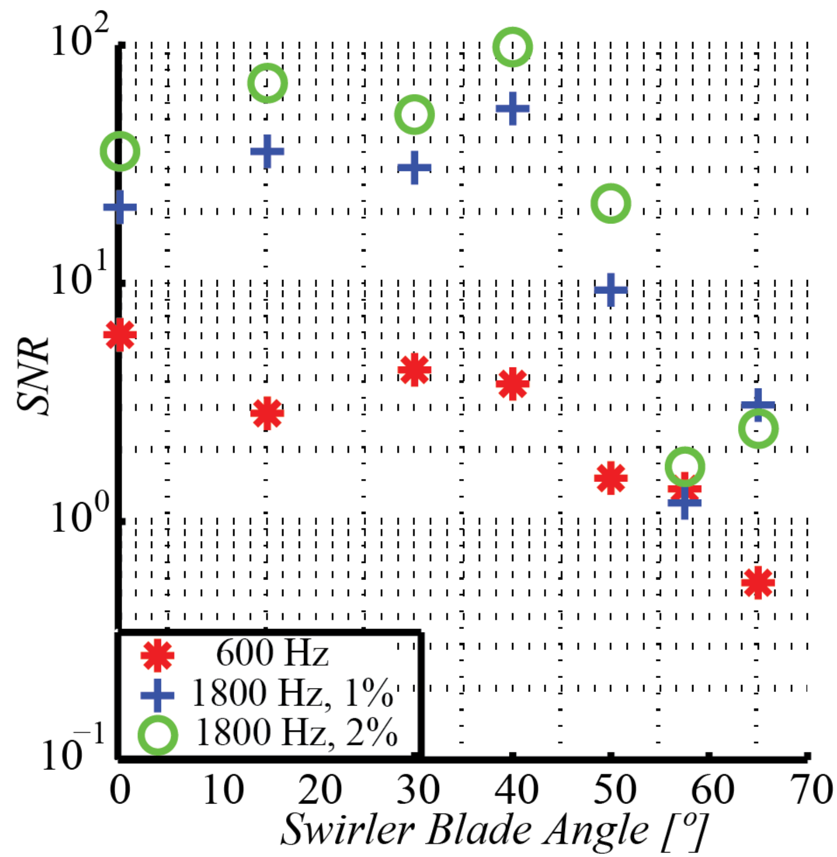
$$L^* = \bar{u}/f$$

Normalized vorticity fluctuation amplitude vary with swirl number, low frequencies are less coherent at high swirl

Normalized Vorticity Fluctuation

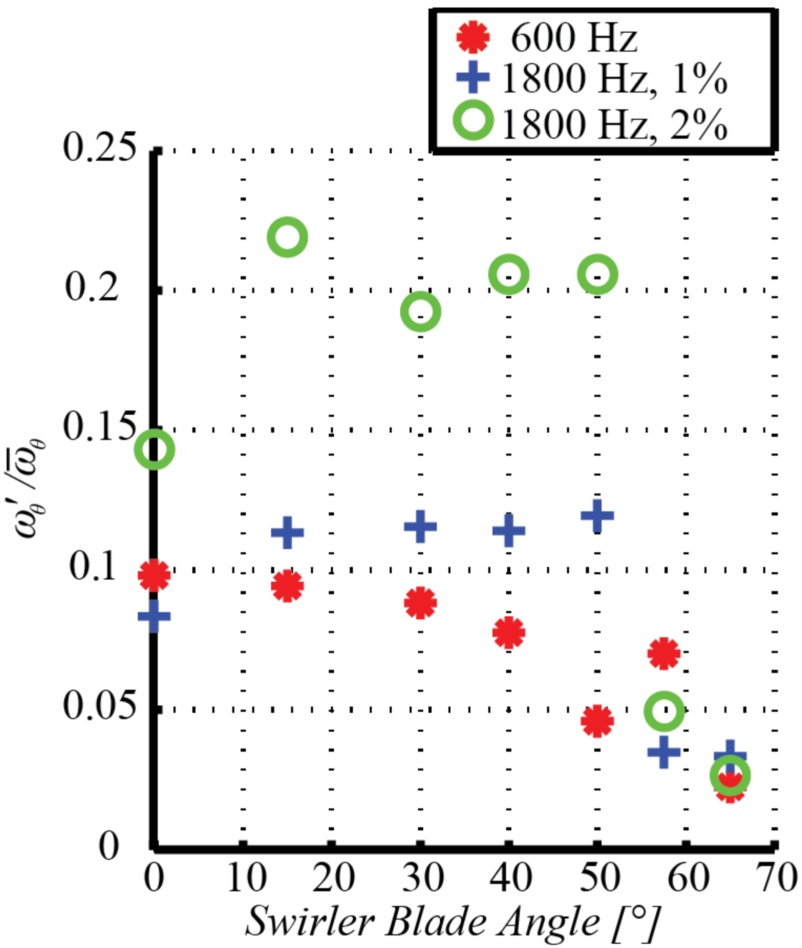


Vorticity SNR

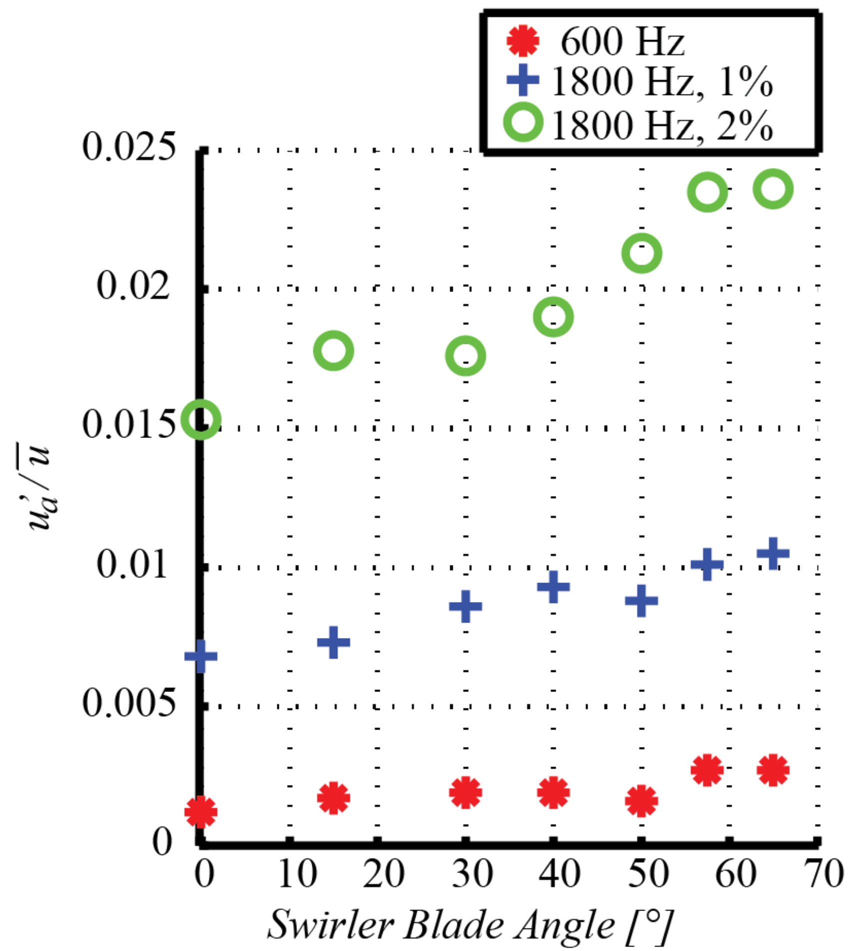


Variations in acoustic forcing amplitude with swirl number likely stem from variation in impedance at swirler

<u>Normalized Vorticity Fluctuation</u>

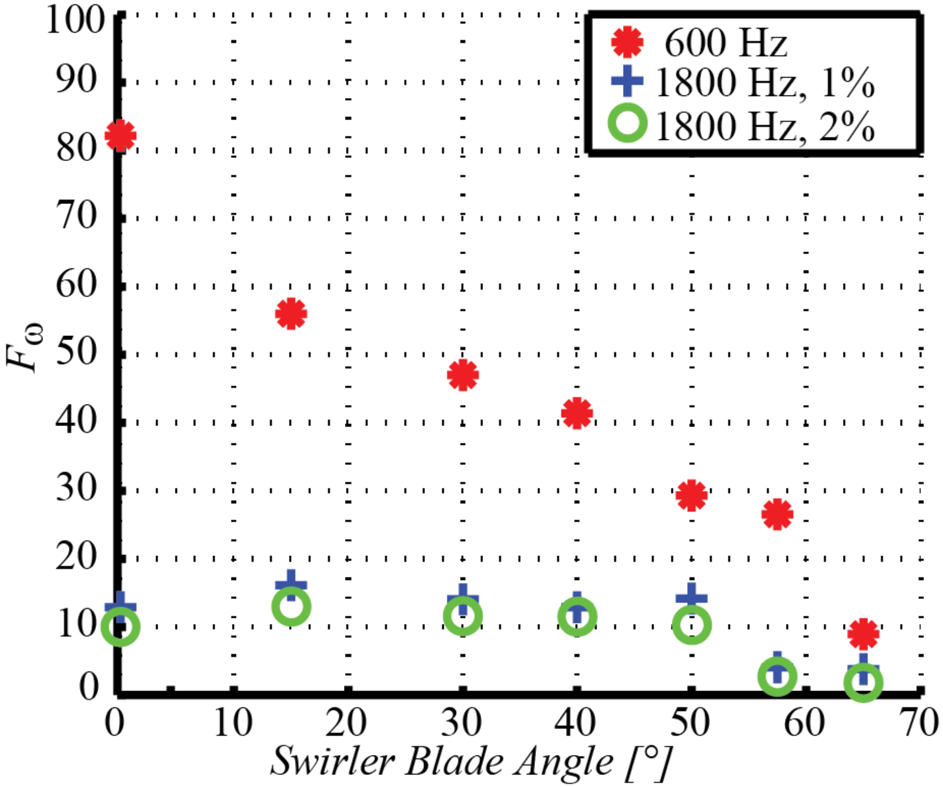


<u>Normalized Axial Velocity Fluctuation</u>

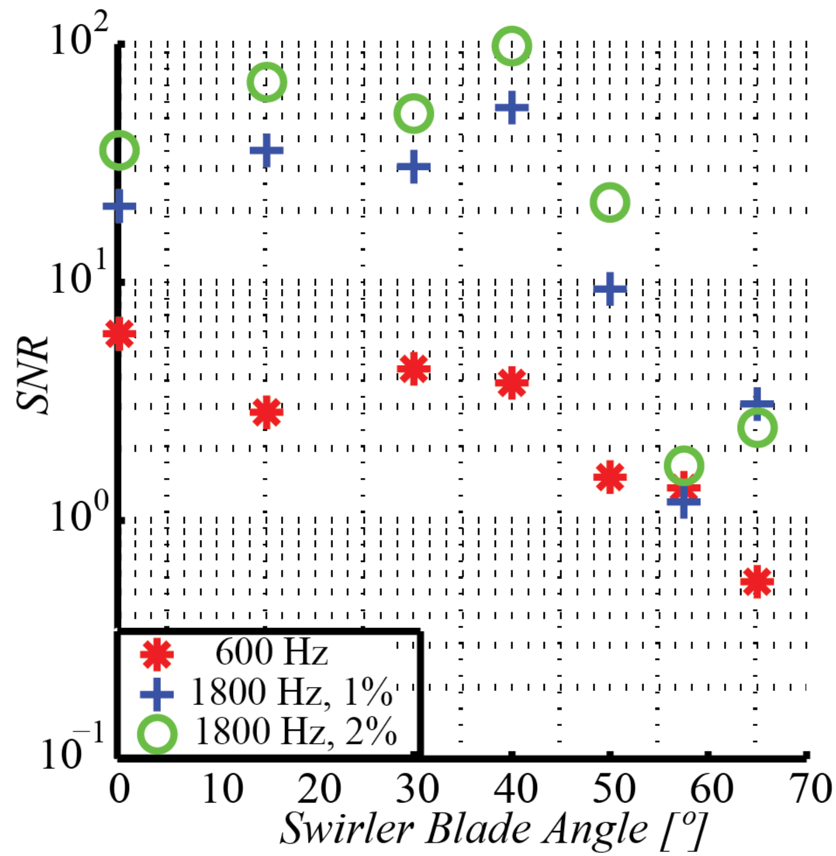


Acoustic to vortical transfer function shows significant amplification of disturbances except at high swirl number

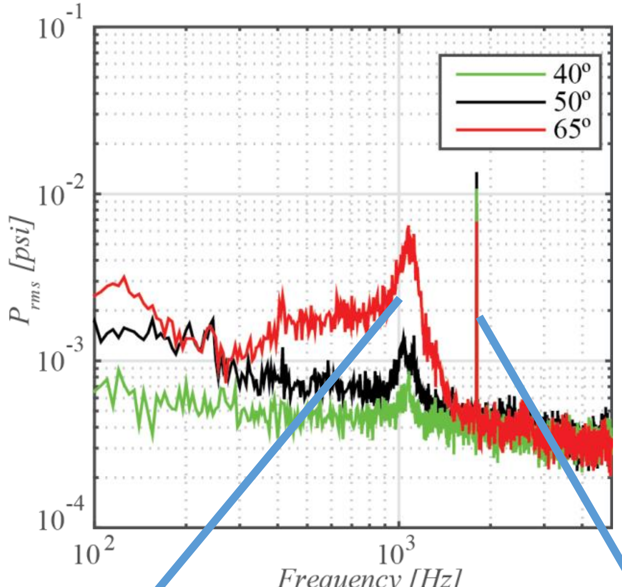
Acoustic to Vortical TF

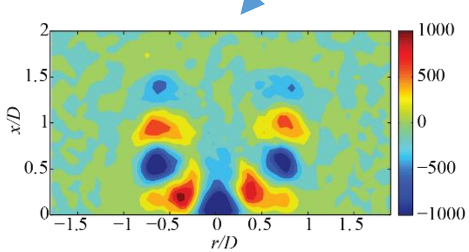


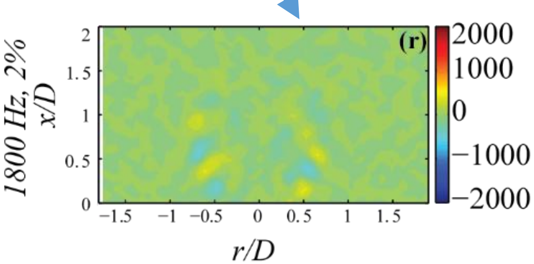
Vorticity SNR

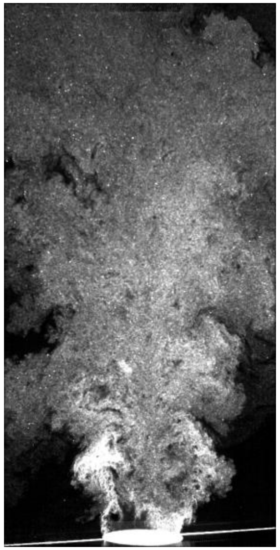


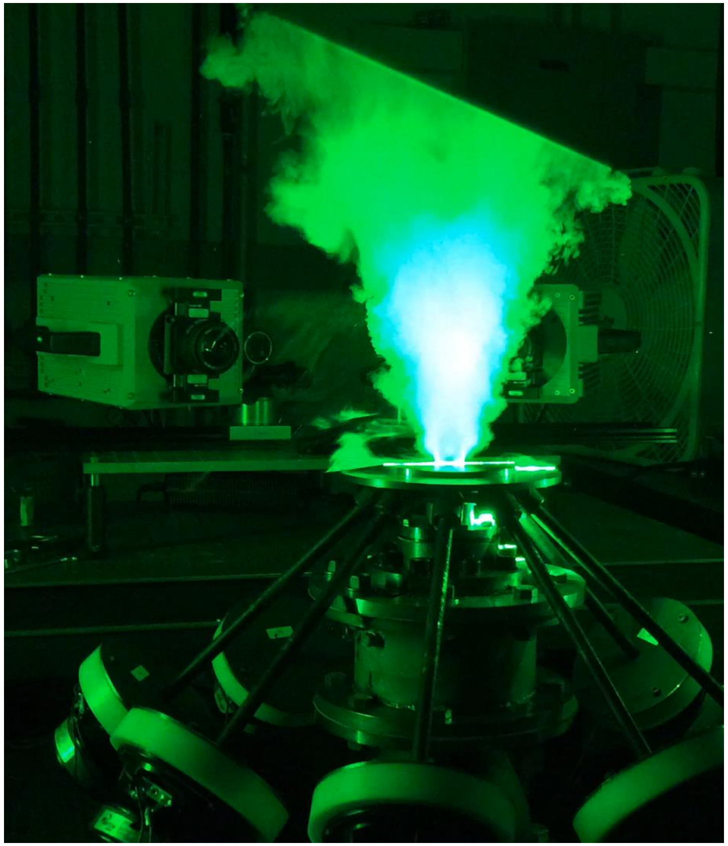
PVC is present in the flowfield at the three highest swirl numbers; PVC is has significant turbulent kinetic energy





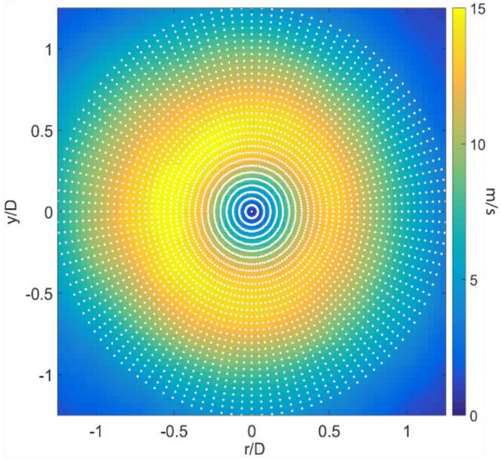






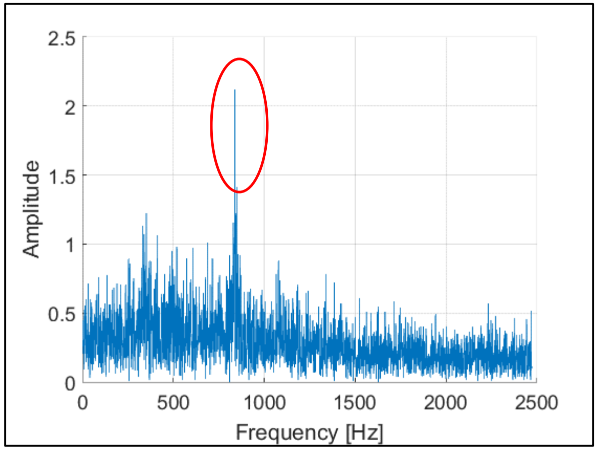
Analysis of the dynamical features of the flow field includes both POD and azimuthal decomposition

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



Fourier Transform

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



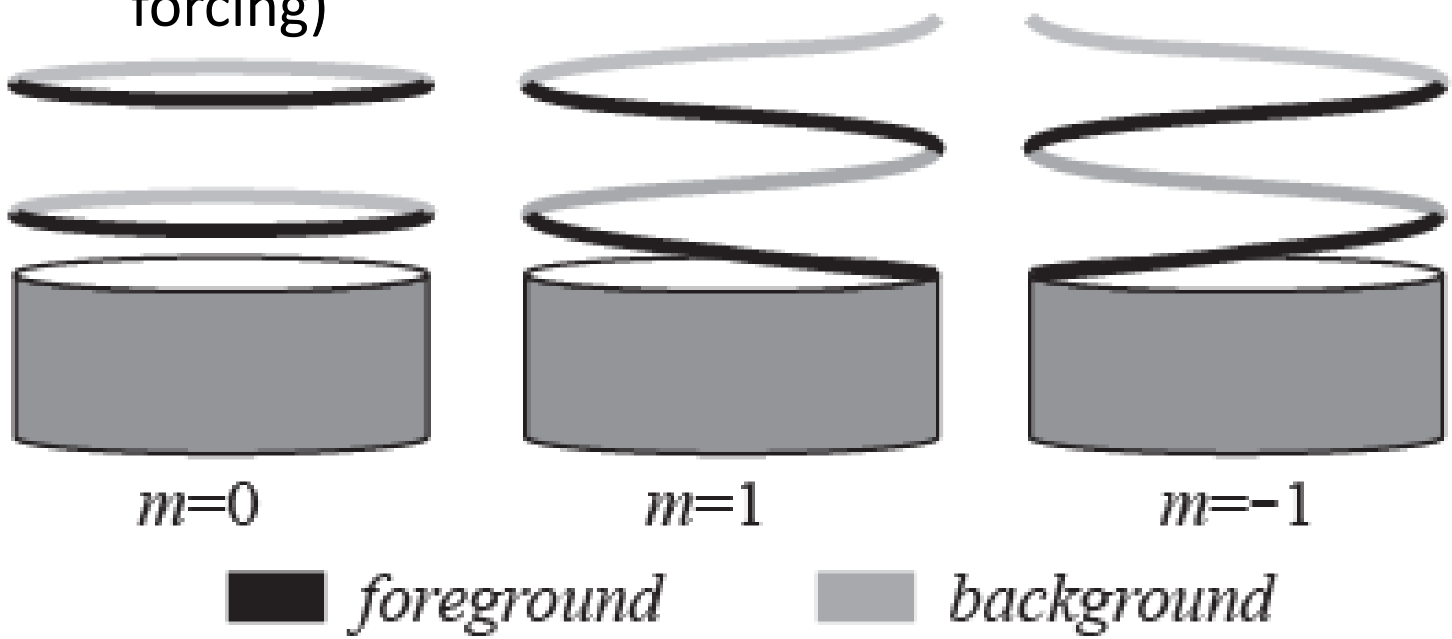
$$\hat{B}_{i,m}(r,x,\omega)=\frac{1}{2\pi}\int_0^{2\pi}\hat{u}_i'(r,x,\theta,\omega)e^{-im\theta}d\theta$$

M-modes provide information about the symmetry of the disturbance field

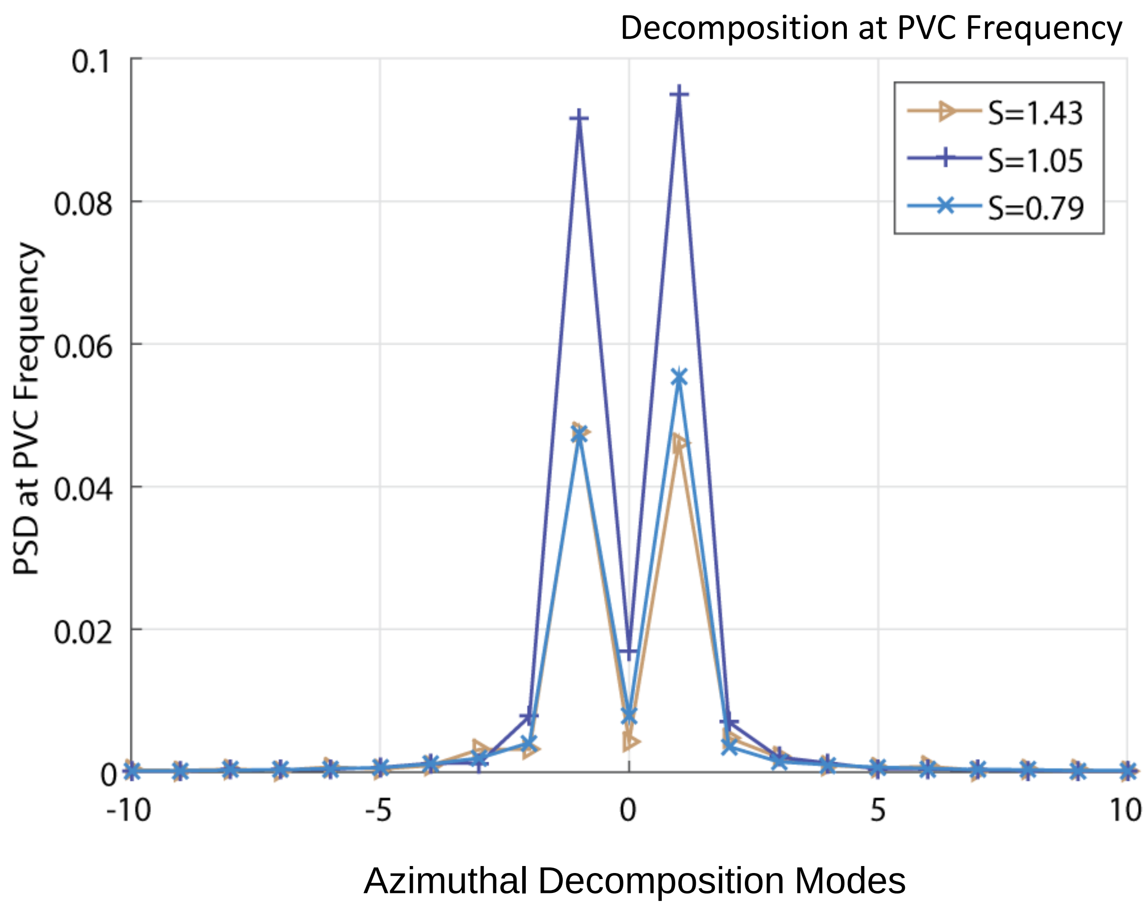
<u>Axisymmetric</u>
(like response to acoustic forcing)

<u>Non-axisymmetric</u>
(like PVC)

<u>Non-axisymmetric</u>
(like PVC)

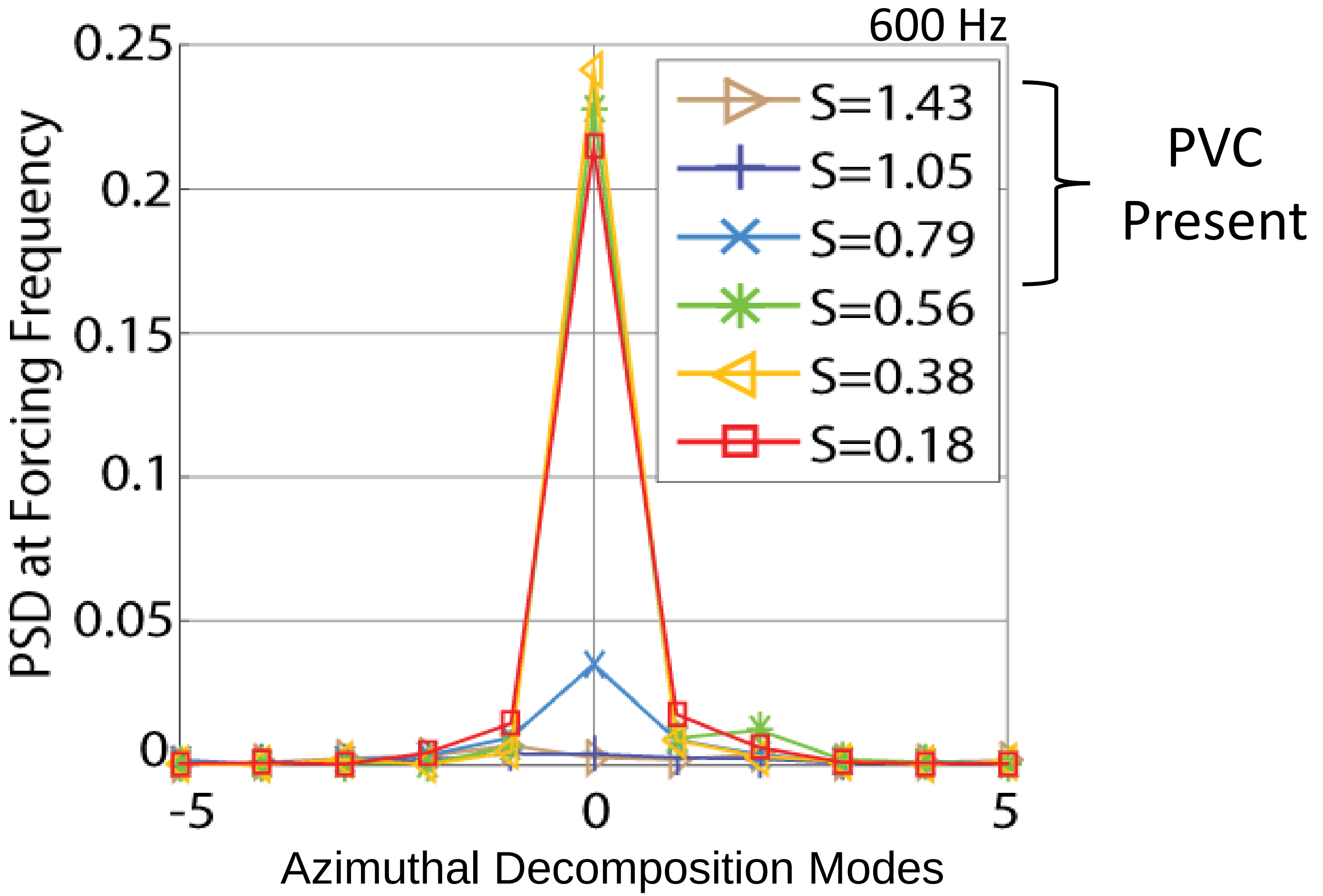


A PVC manifests itself predominantly in m=1 and m=-1 motions with a very small response at mode m=0



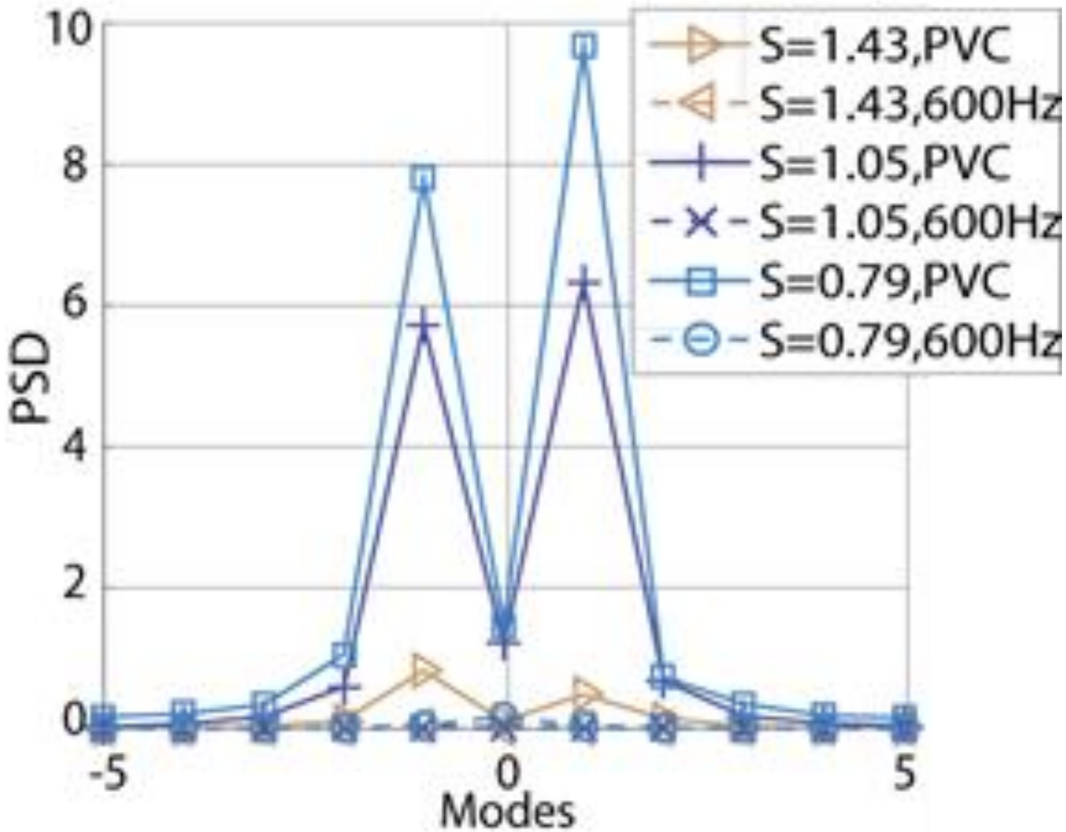
Decomposition performed at *r/D = 0.7*

Mode m=0 does not show a response to a forcing frequency of 600 Hz at swirl numbers that produce a PVC



Decomposition performed at *r/D = 0.5*

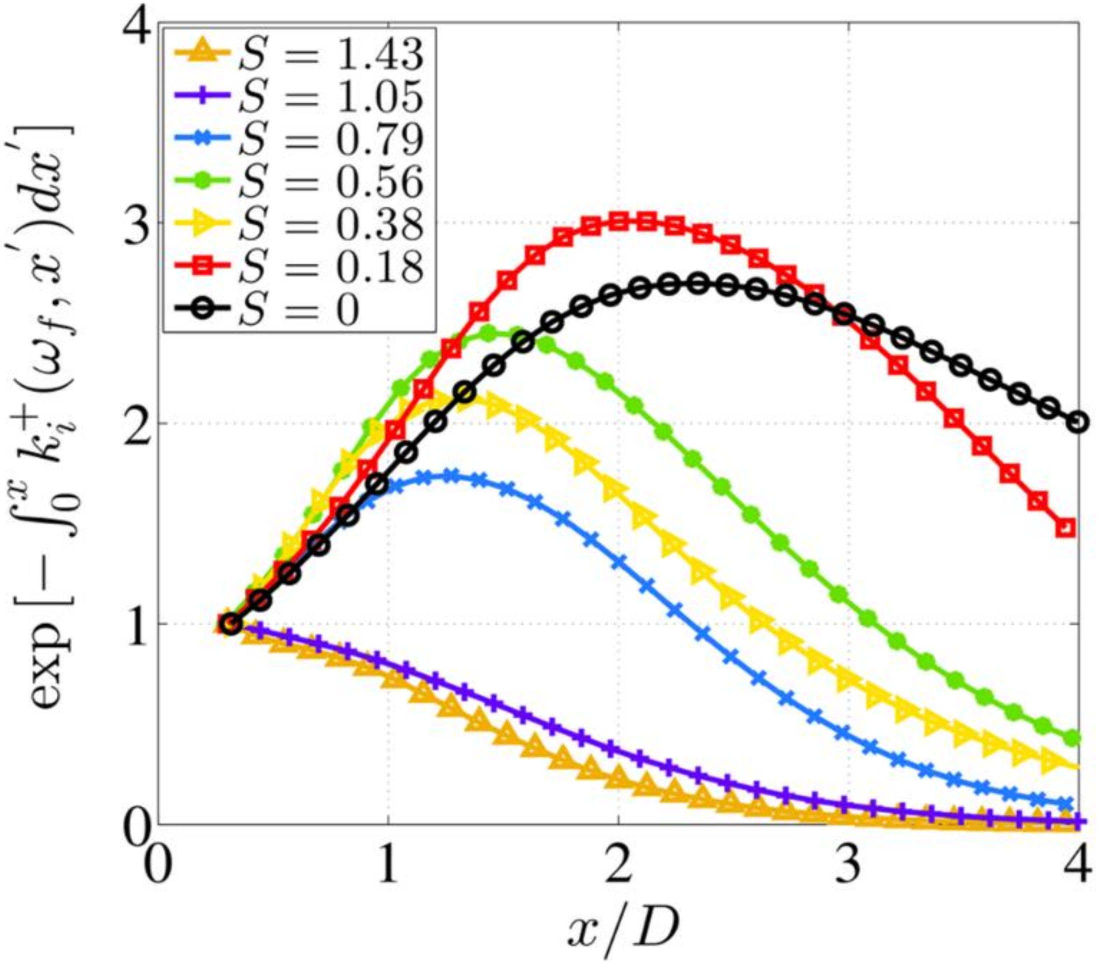
When forcing at 600 Hz, only the PVC frequency shows a response at m=1 and m=-1



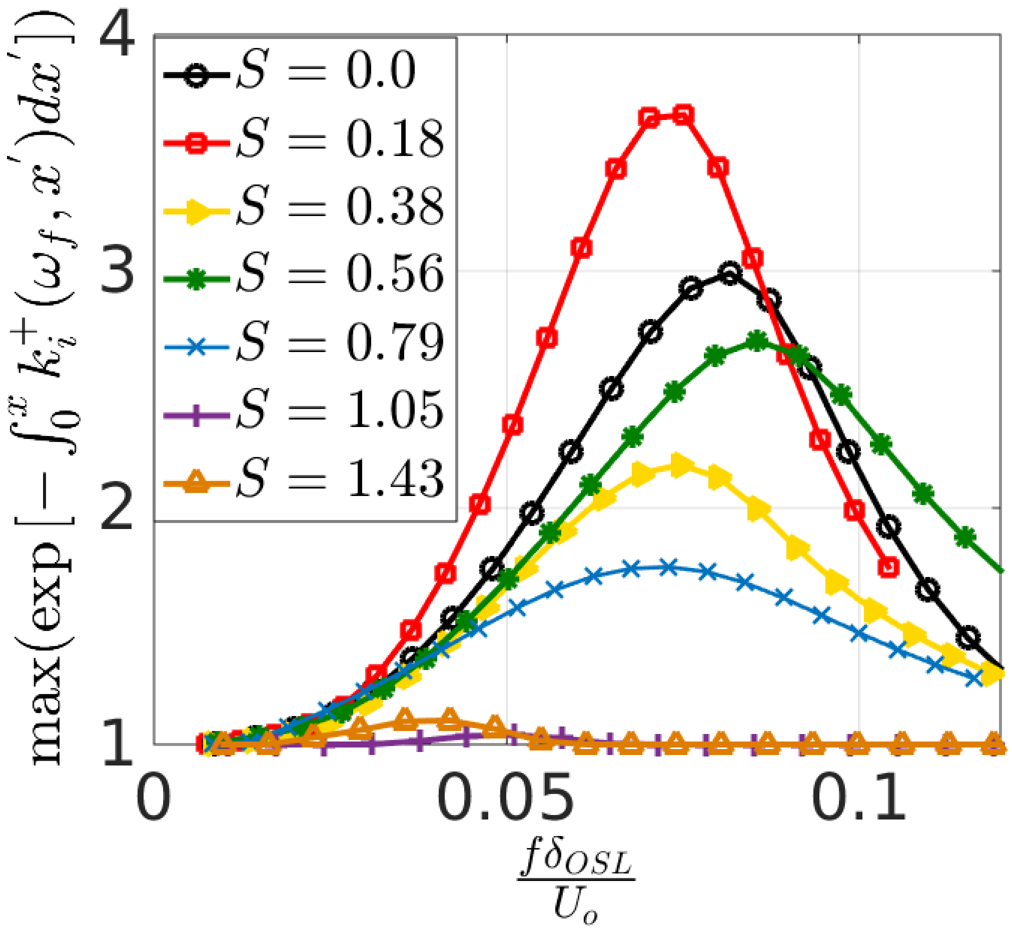
Decomposition performed at *r/D = 0.5*

Shear layer disturbance growth rates are negative for cases with PVC, indicating response suppression

Disturbance Growth Rate – 700 Hz

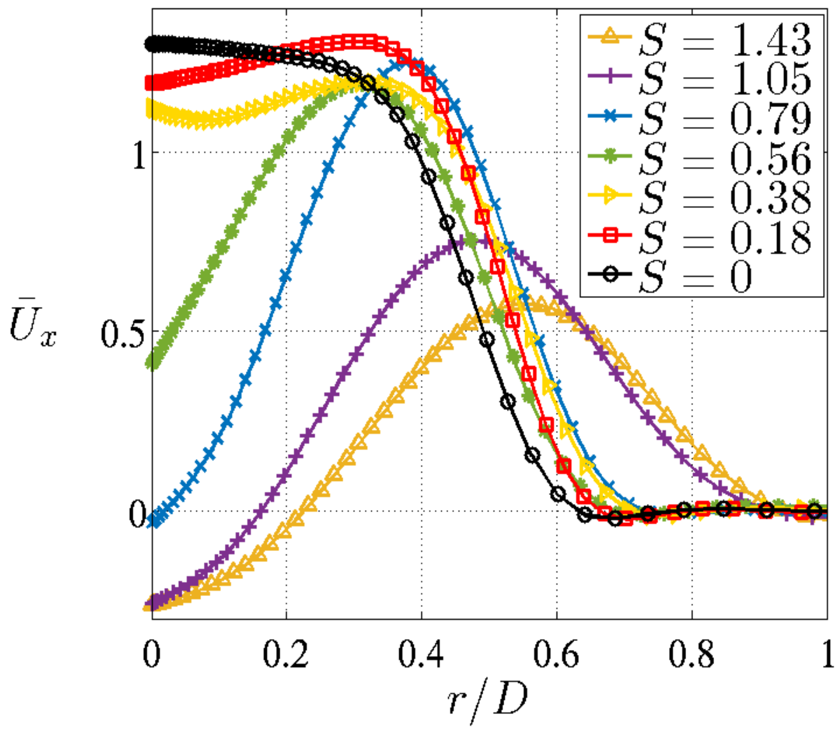


Shear layer disturbances do not grow or only minimally grow over a large range of frequencies

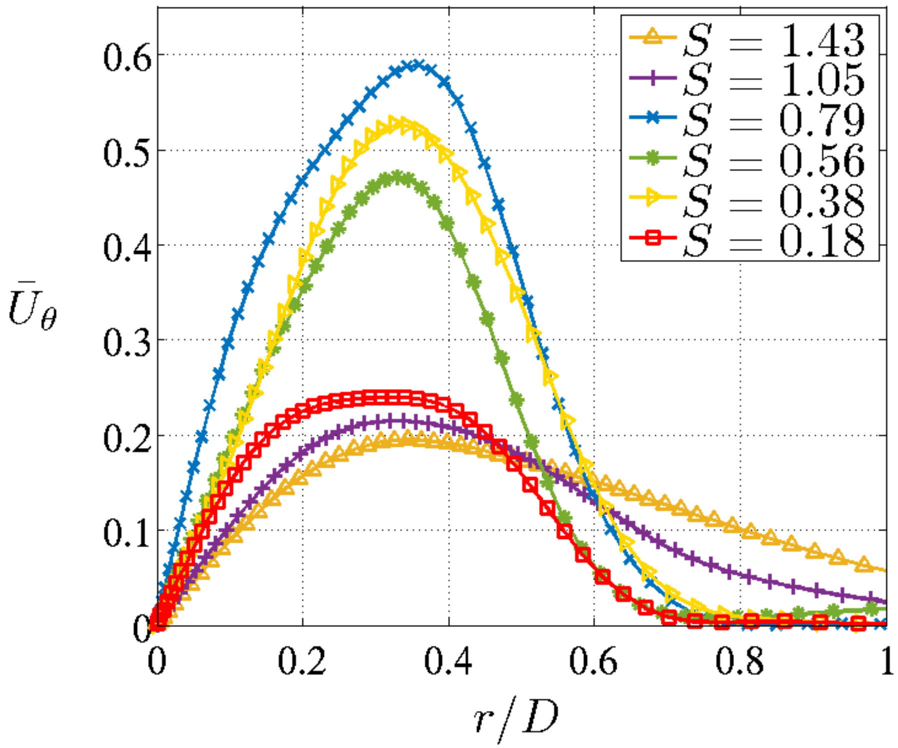


Shear layers become less sensitive to acoustics with PVC due to shear layer thickening. Streamwise location: x/D = 0.3

Streamwise Velocity

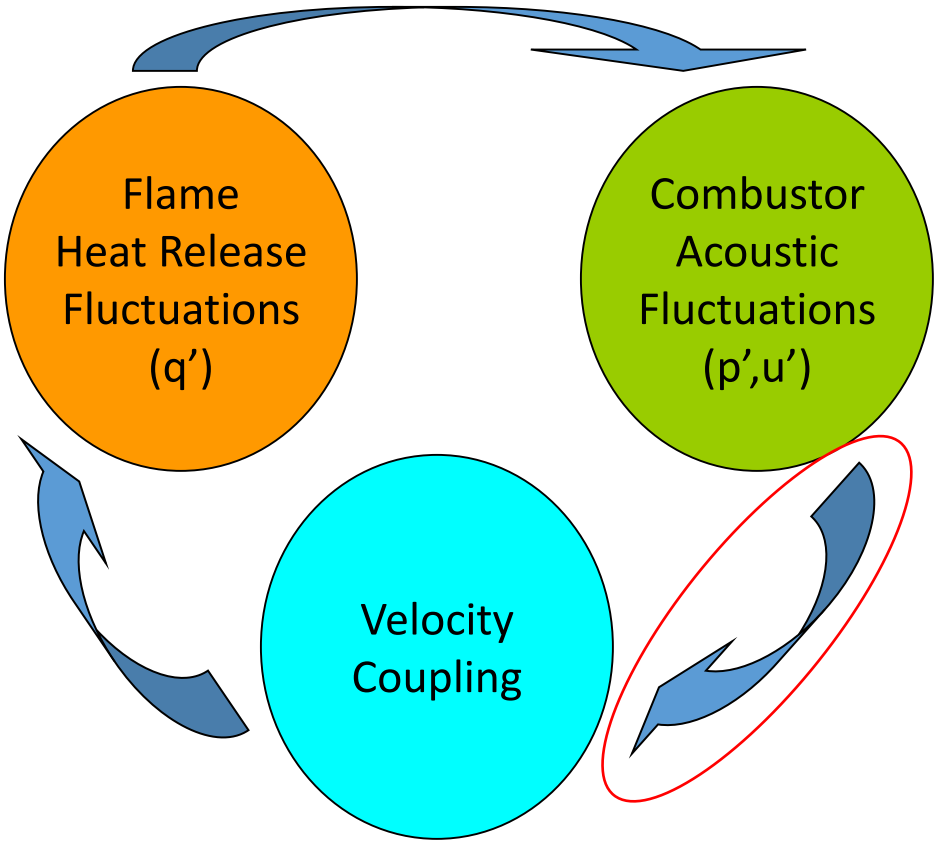


Swirling Velocity



Study demonstrates how a PVC can suppress the receptivity of a swirling flow field to longitudinal acoustic forcing

- Receptivity of the shear layers was analyzed using both experiment and linear stability analysis
- Shear layer receptivity is suppressed by a PVC as a result of shear layer thickening, which alters the growth rate of external disturbances in the flow field



Acknowledgements

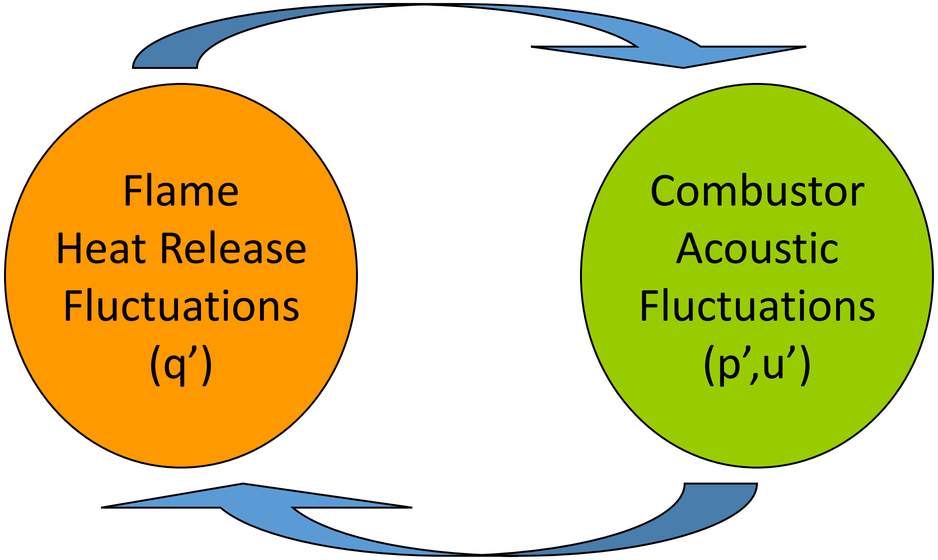
- Mark Frederick (UG), Sean Clees (UG), Ben Mathews (UG), Sam Hansford (MS)
  - Penn State Erickson Discovery Grant

- Kiran Manoharan (PhD) and Dr. Santosh Hemchandra – IISc-Bangalore

Questions?

Combustion Instability: Mechanisms and Suppression

Jacqueline O'Connor, Ph.D.
Mechanical and Nuclear Engineering
Pennsylvania State University
sites.psu.edu/ccpp/



PennState