Development and Evaluation of a Novel Fuel Injector Design Method using Hybrid-Additive Manufacturing

Project DE-FE12806463, Oct. 2019 – Sept. 2022
Program Monitor: Mark Freeman

Project Review – November 7, 2019

PI: Jacqueline O'Connor
Co-PIs: Guha Manogharan, Yuan Xuan

Mechanical Engineering
Pennsylvania State University

Industry Partner: Solar Turbines Incorporated
Hanjie Lee, Dave Voss

PennState

Overview of presentation

- Background
- Technical approach
- Project objectives
- Project structure
- Next steps

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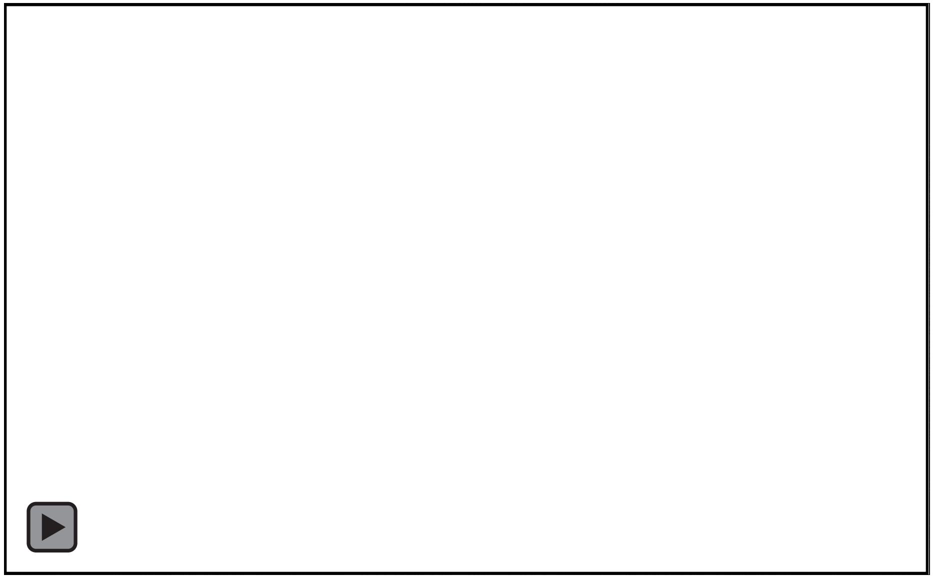
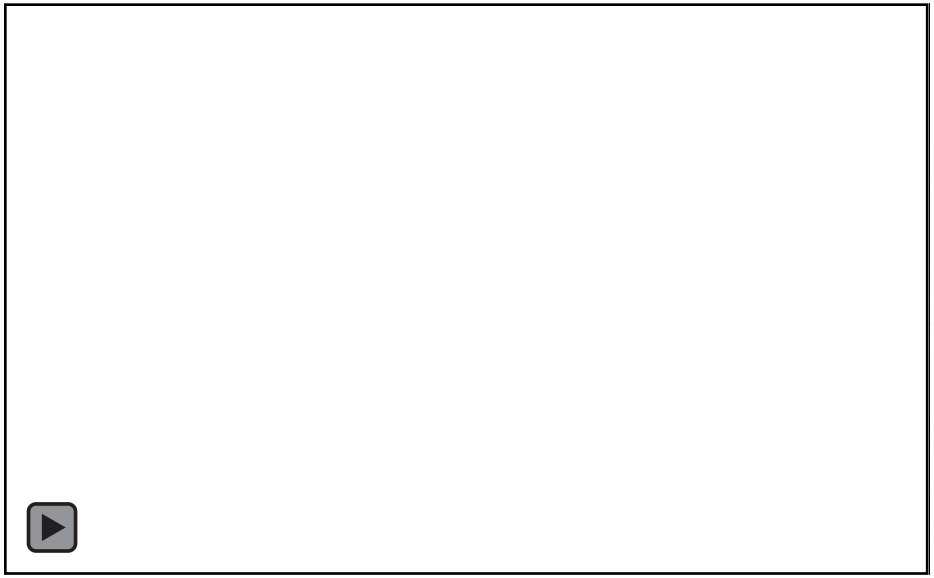
Project origin: Discussions with industry about issues related to combustion operability and fuel injector manufacturing

"Why do fuel injectors have to look like fuel injectors?"

Current fuel injector designs do well at flame stabilization for a moderate range of fuel compositions, operating conditions



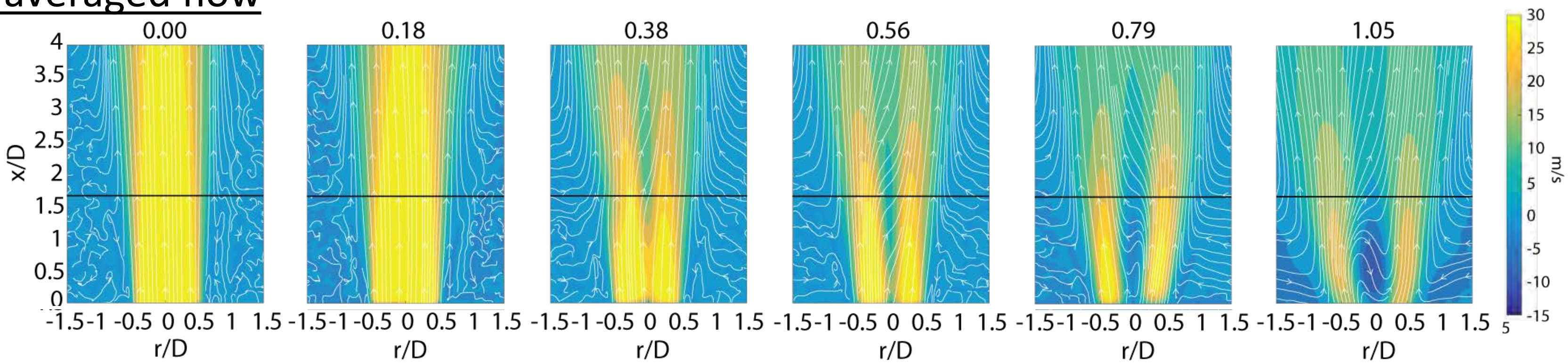
Off-design operation



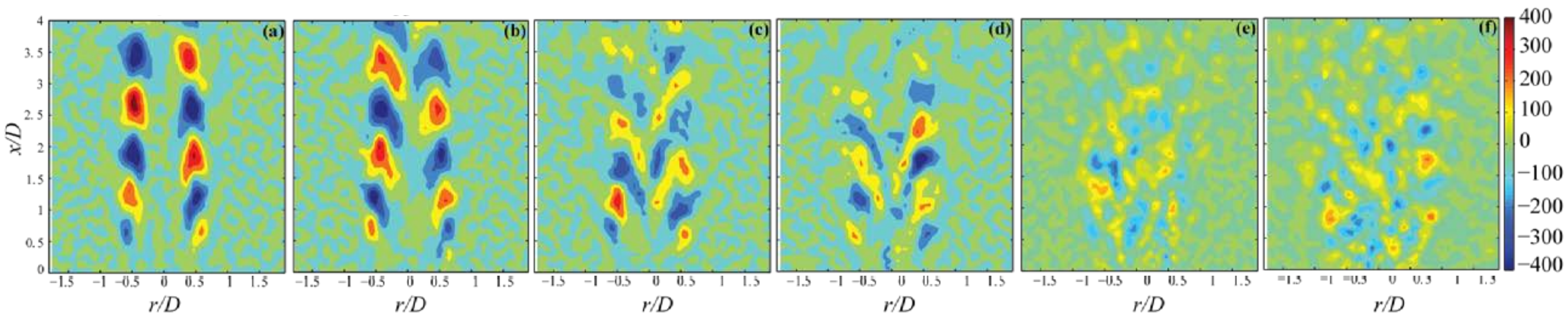
DOE University Turbine Systems Research Program, Mark Freeman (contract monitor), Grant DE-FE0025495

Recent work by PI and collaborators has showed that a stable flow can be “designed” using hydrodynamic stability analysis

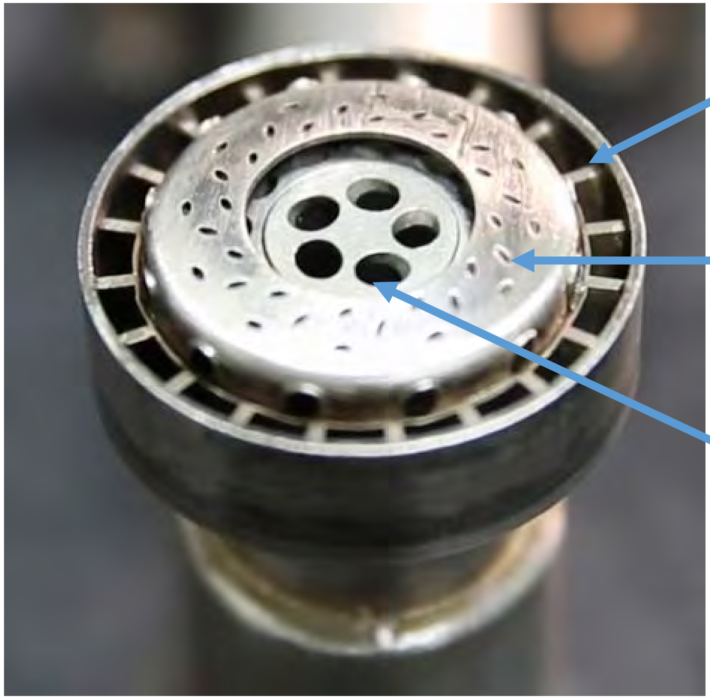
Time-averaged flow



Coherent response



Fuel injectors are notoriously difficult to manufacture and can be comprised of dozens of components, assembled by hand

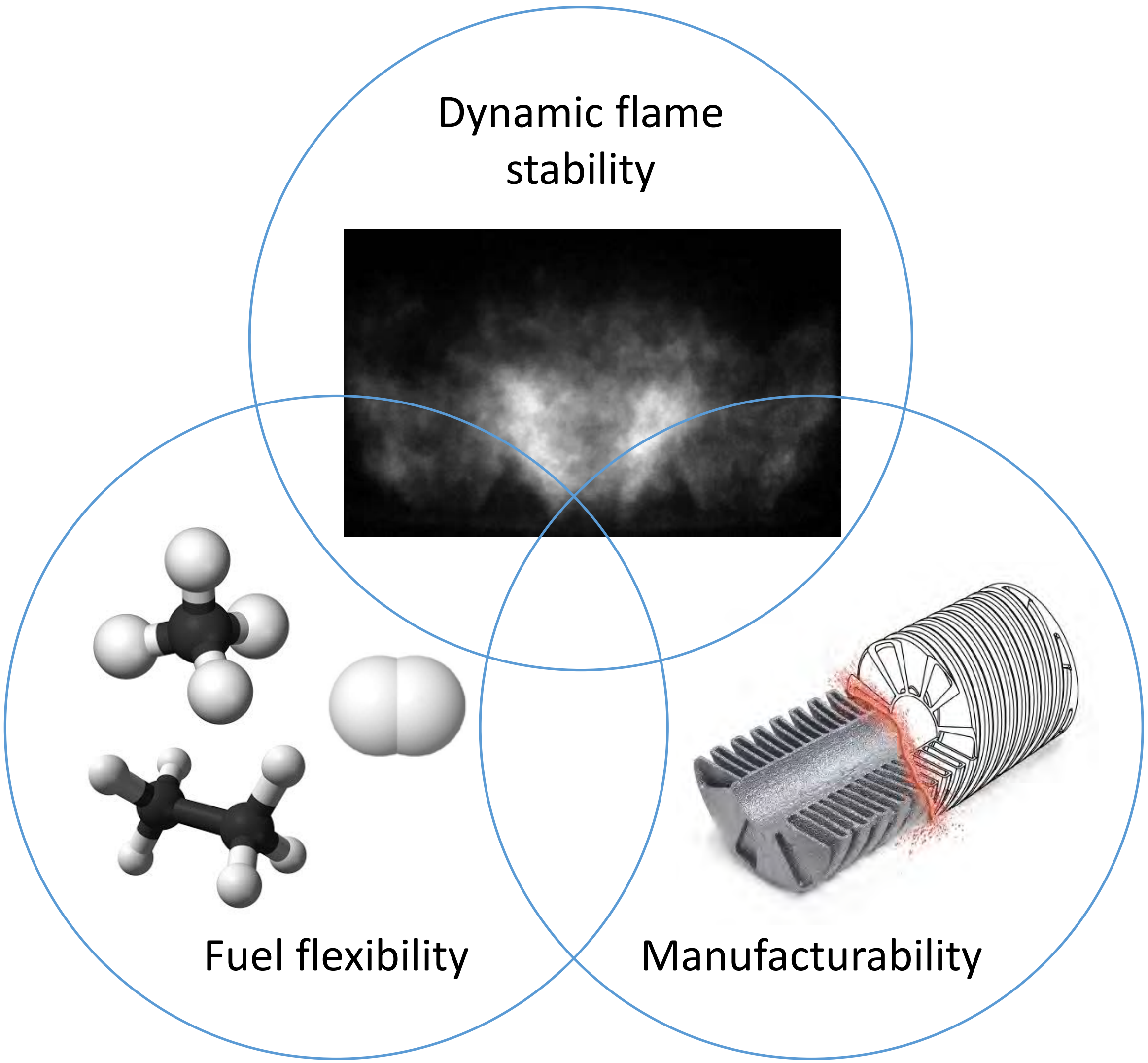


Complex aerodynamic surfaces

Small orifices with specified surface finish

Internal flow passages

Goal of this project is to create a design optimization paradigm that marries combustion physics and manufacturing



The team is comprised of three PIs and two grad students from Penn State and industrial partners Solar Turbines

PI: Jacqueline O'Connor
Associate Professor of ME
Combustion/Gas Turbines

Co-PI: Guha Manogharan
Assistant Professor of ME
Design +Hybrid-Additive Manufacturing

Co-PI: Yuan Xuan
Assistant Professor of ME
Combustion simulation

Solar® Turbines
A Caterpillar Company

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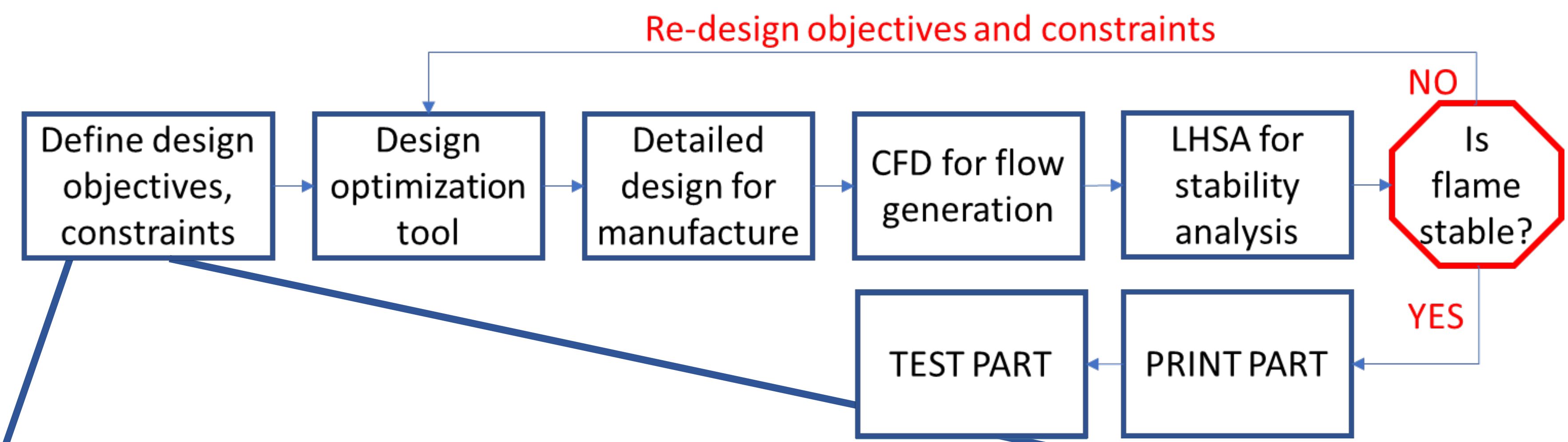
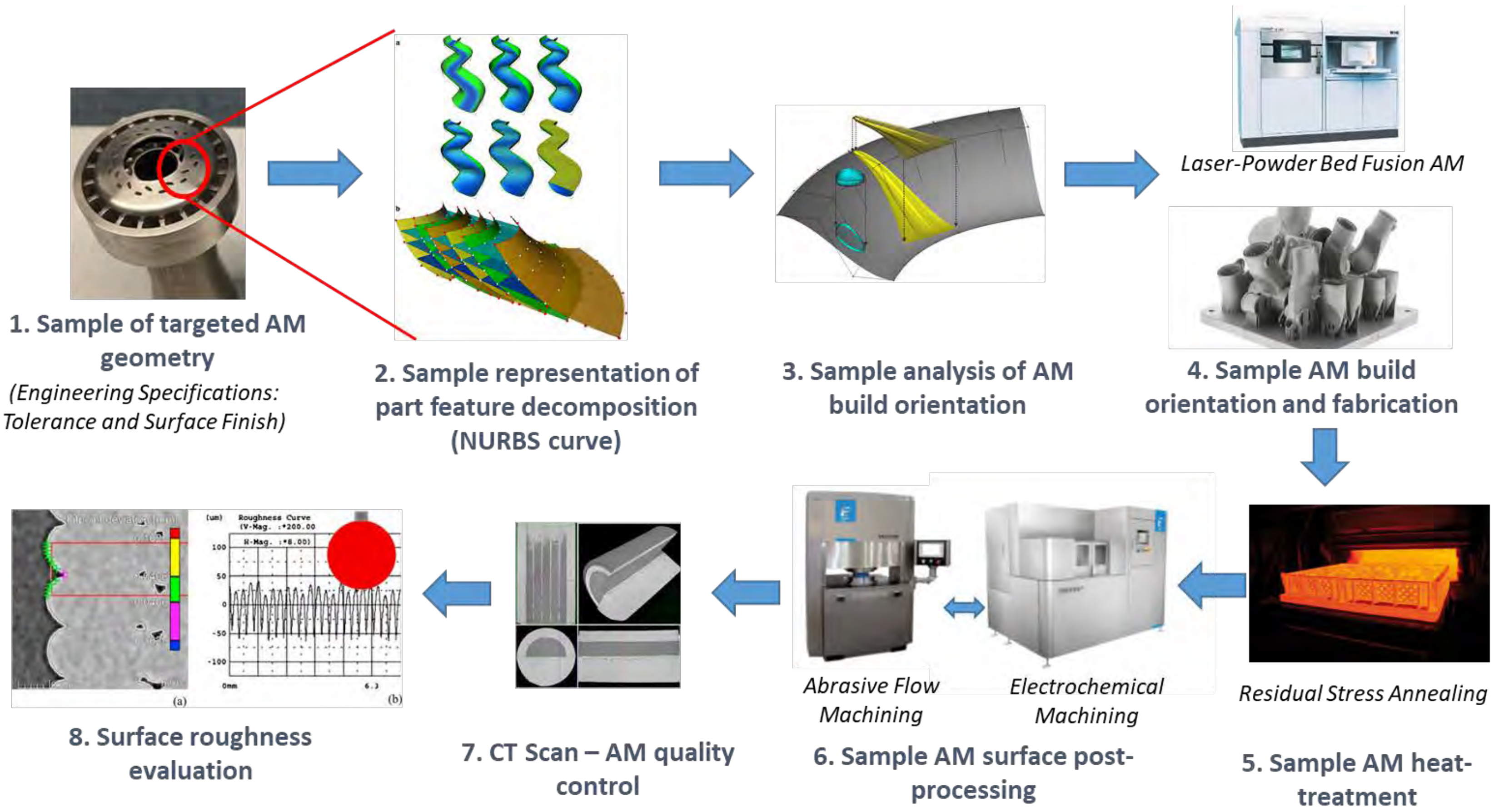
Technical approach uses an optimization framework for incorporating combustion and manufacturing constraints



1. Flame dynamic stability through flow response modeling
2. Flame static stability through computational fluid dynamics
3. Fuel flexibility through computational fluid dynamics
4. Additive manufacturing considerations for laser powder bed fusion
5. Surface finishing considerations for abrasive flow machining

Parametric design-process planning advanced manufacturing approach is proposed for fuel-injector applications



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Project objectives center around four gaps in the fuel injector design process to help industry

- Integrate issues related to flame static and dynamic stability more seamlessly into the design process

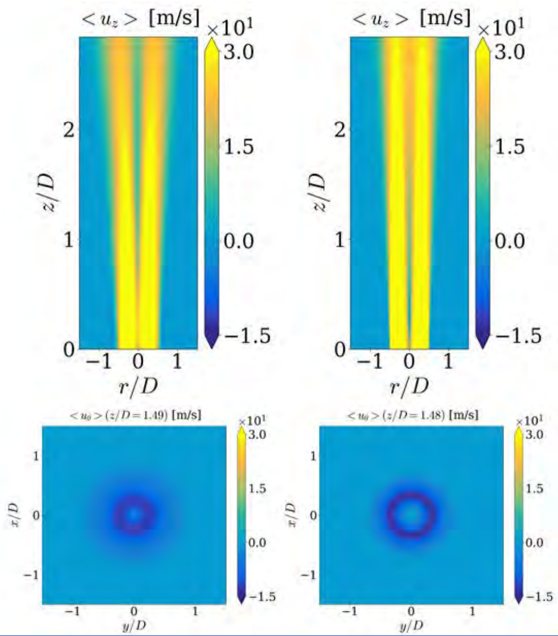
- Incorporate the use of hydrodynamic stability analysis for prediction of dynamic stability issues for efficient computational prediction

- Incorporate high-fidelity, multi-physics modeling into optimization processes

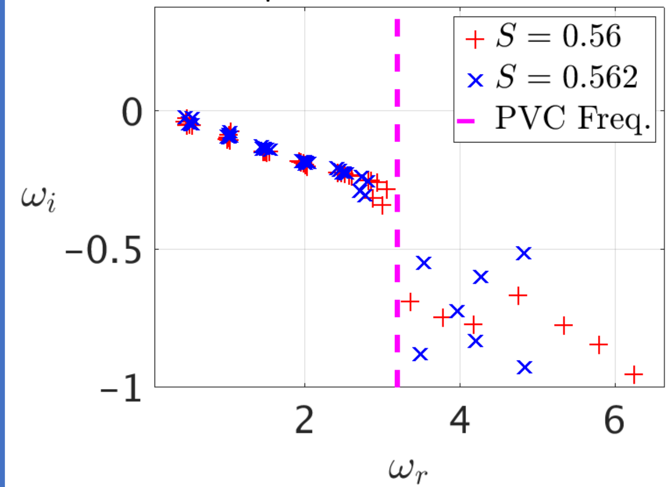
- Link post-processing steps of the AM component into the design optimization process

An initial proof of concept exercise showed that hydrodynamic stability + CFD could be used for optimization

Step 1: CFD captures experimental trends



Step 2: LHSA results from CFD and experiment match



Step 3: Optimization of flow stability (ω_i) on parameter S

$$L(S,\lambda) = \omega_i(S) - \lambda(\omega_i(S) - \epsilon)$$

$$\frac{\partial L}{\partial S} = 0 \rightarrow \frac{\partial \omega_i}{\partial S}(1-\lambda) = 0 \rightarrow \lambda = 1$$

$$\lambda \omega_i(S) = \epsilon$$

Result: Optimizer stepped towards stability condition

Iteration	S	ω_r	ω_i
1	0.56	3.40	-0.68
2	0.57	3.38	-0.69
3	0.6	3.03	-0.28
4	0.65	3.03	-0.27

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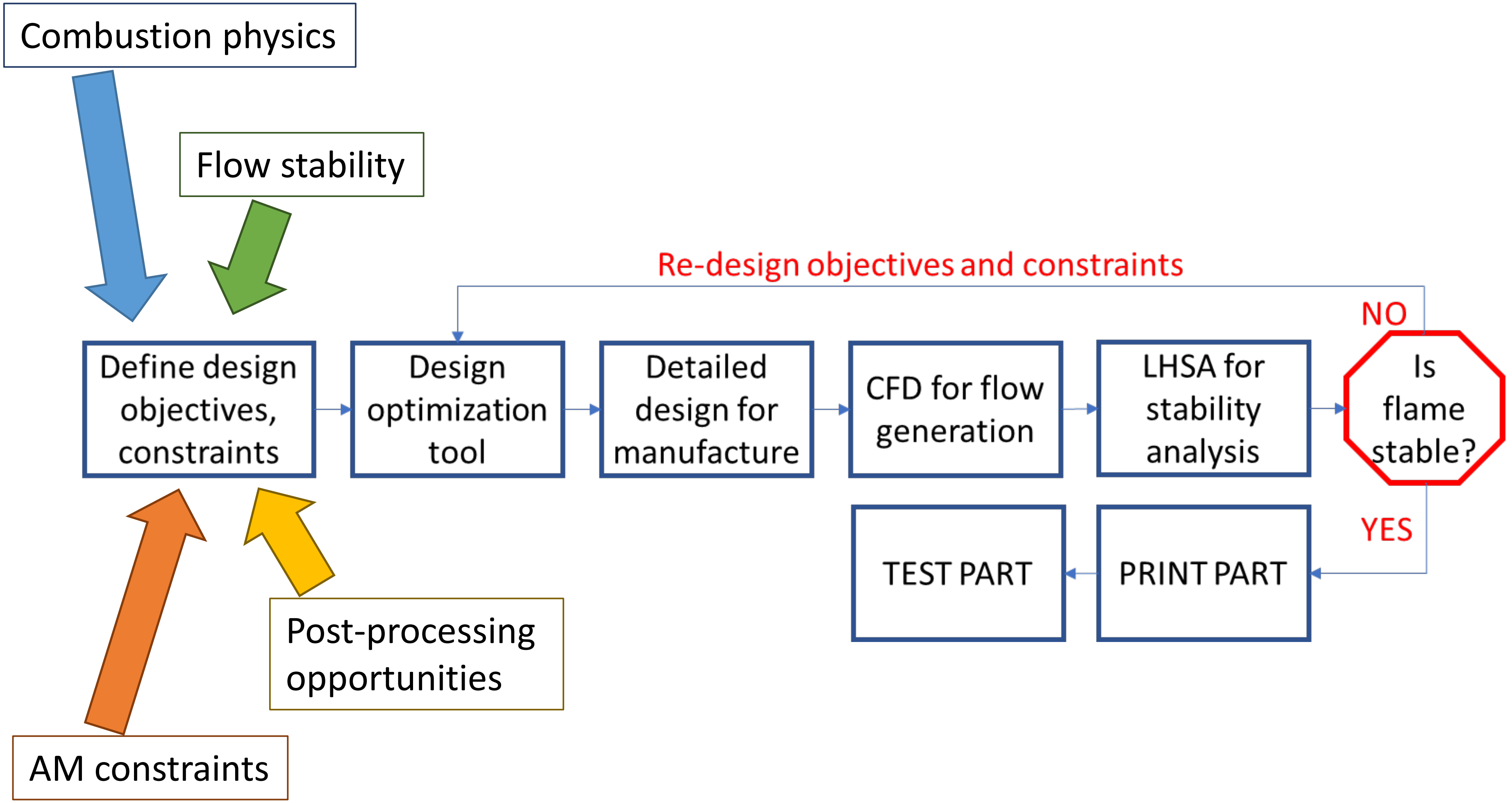
Project objectives center around four gaps in the fuel injector design process to help industry

- Task 1: Project management and planning
- Task 2: Establish baseline
- Task 3: Develop design optimization tool
- Task 4: Implement optimization process on baseline configuration
- Task 5: Design process improvement
- Task 6: Integration of improved design process
- Task 7: Final process testing and technology transfer

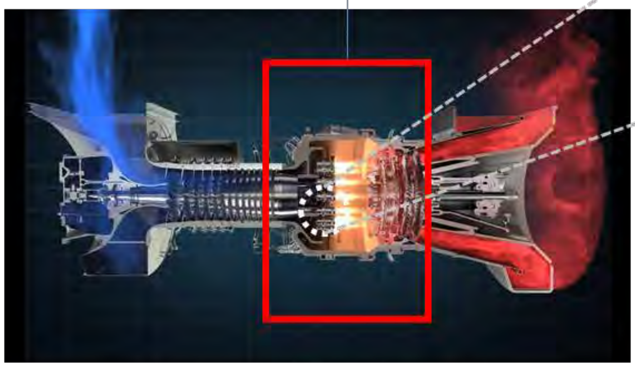
Novel contribution: Design optimization tool that will incorporate physics-based constraints



Novel contribution: Integrated Design-AM-Post Processing Framework

Hot-section

Gas Turbine



(Source: www.solarturbines.com)

(Source: Solar Turbines (2011))

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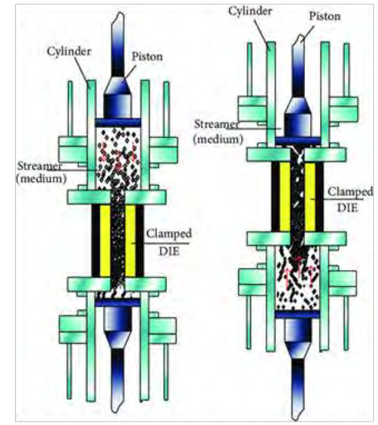
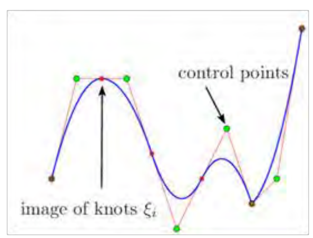
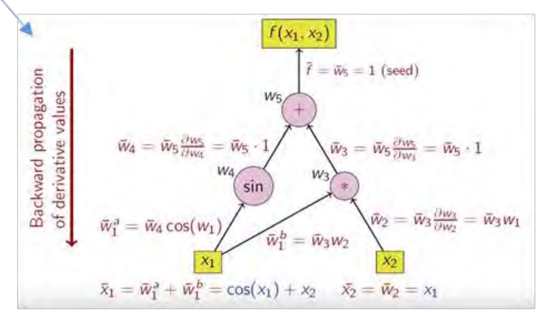


(Source: Li Junye, et. al. (2015))

NURBS curves

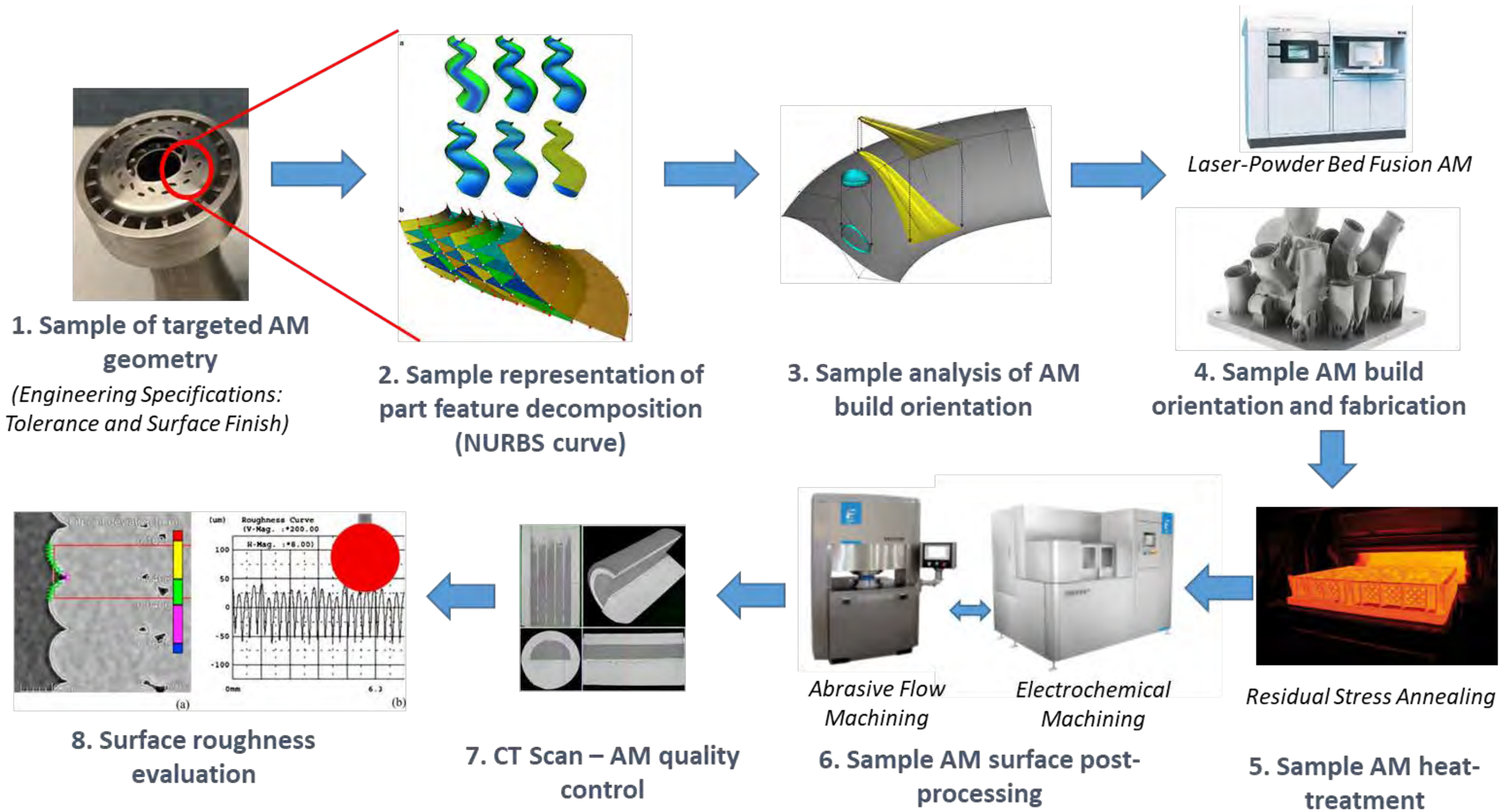


(Source: Vin Phu Nyugen, et. al. (2013))



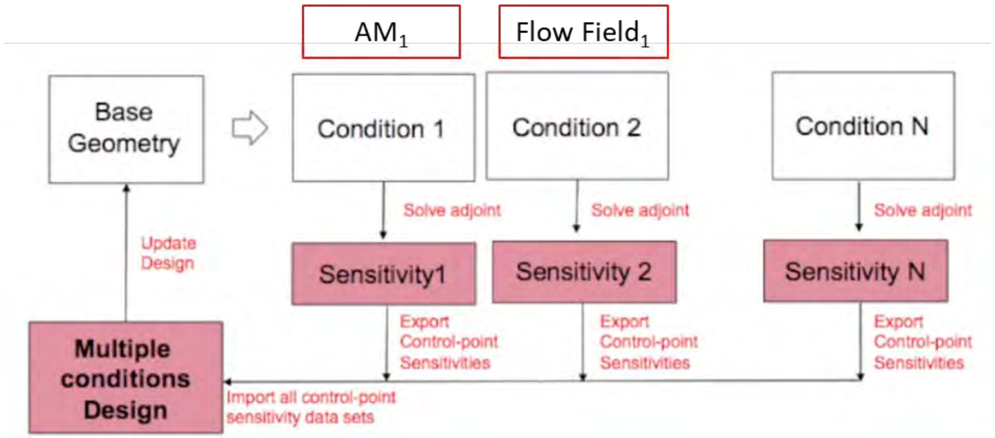
Adjoint based design

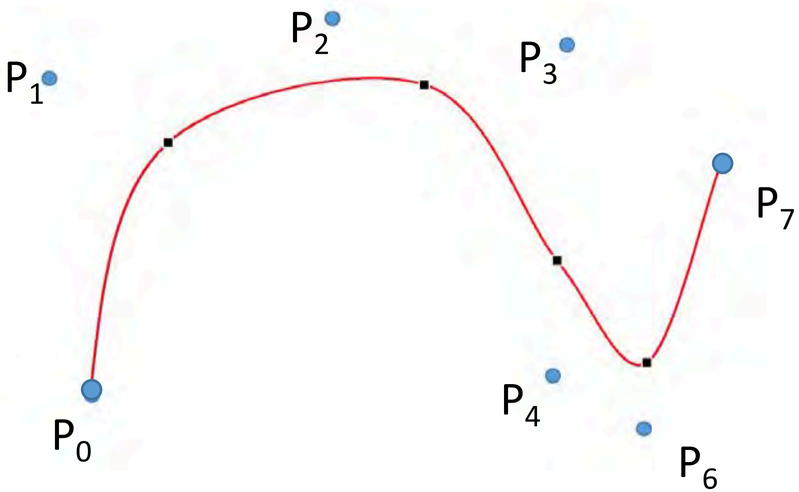
Parametric design-process planning advanced manufacturing approach is proposed for fuel-injector applications



Novel contribution: NURBS based design approach

- Non-Uniform Rational Basis Splines
- Super set of all curves
- Advantages
  - Can approximate most curves and surfaces mathematically
  - Flexibility
  - Computational efficiency
  - Local propagation (segments)
  - Maintains continuity requirements (slope and curvature)





Project impact stems from multi-disciplinary team and technology transfer to industry partner for future designs

PennState



- Gas turbine operability
- Combustion simulation
- Hybrid manufacturing
- Material post-processing
- Design optimization

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- Combustor design
- Manufacturing at scale
- Process integration

Questions?

Development and Evaluation of a Novel Fuel Injector Design Method using Hybrid-Additive Manufacturing

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Backup slides

Combustion dynamics is one of the most expensive problems in the gas turbine industry

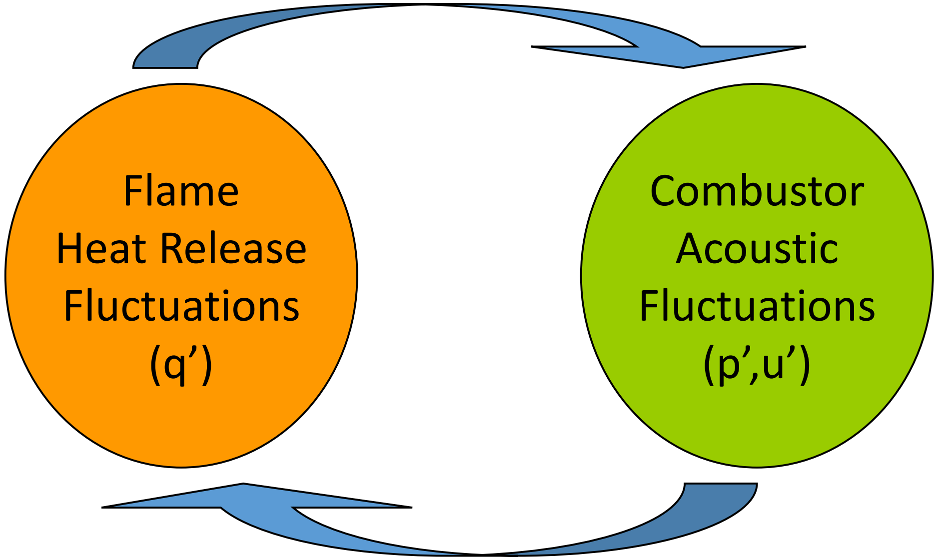
— Damages expensive hardware

— Reduces operability

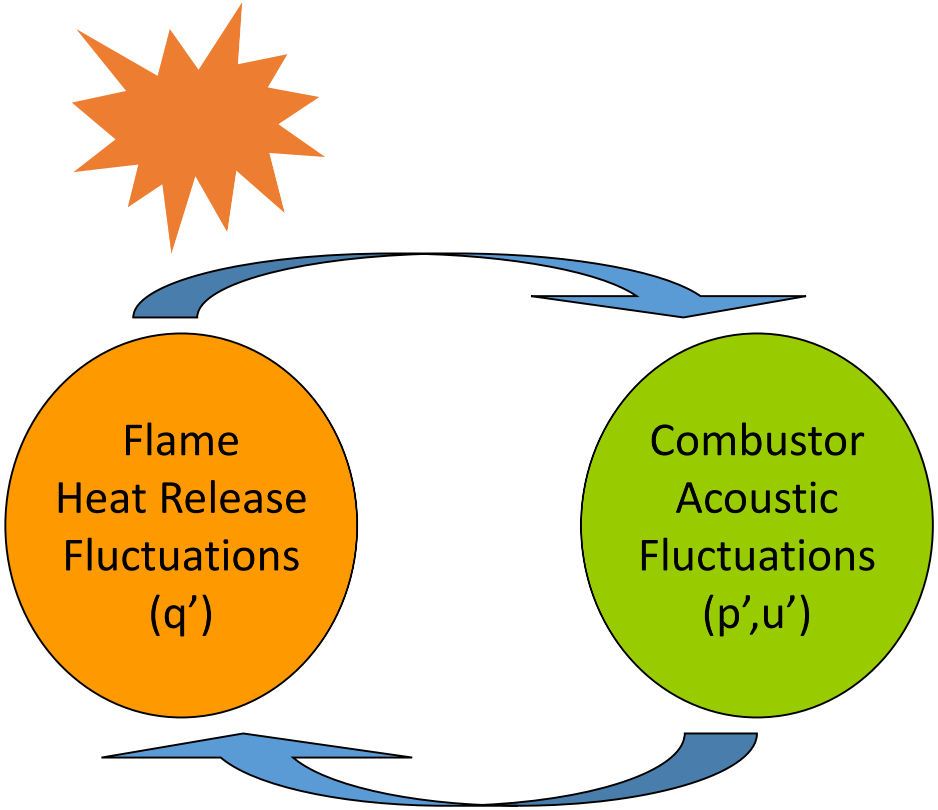
— Increases emissions (NO_x, CO)

Goy *et al.,* in *Combustion instabilities in gas turbine engines: operational experience, fundamental mechanisms, and modeling*, T. Lieuwen and V. Yang, Editors. 2005. p. 163-175.

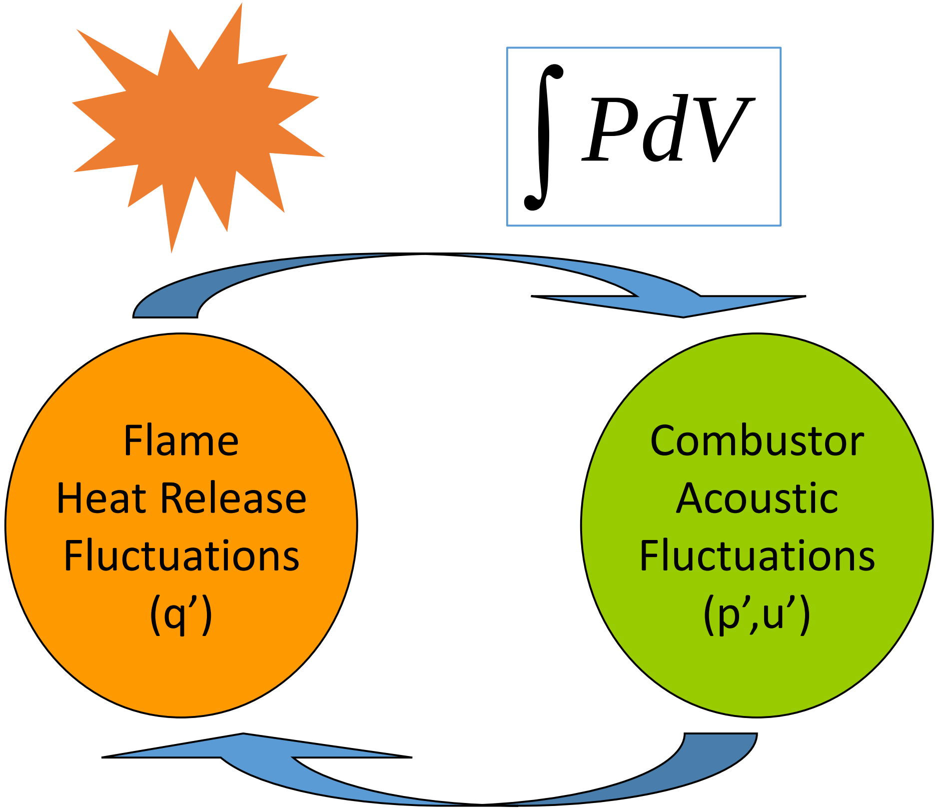
Combustion dynamics is a coupling between combustor acoustics and flame heat release rate fluctuations



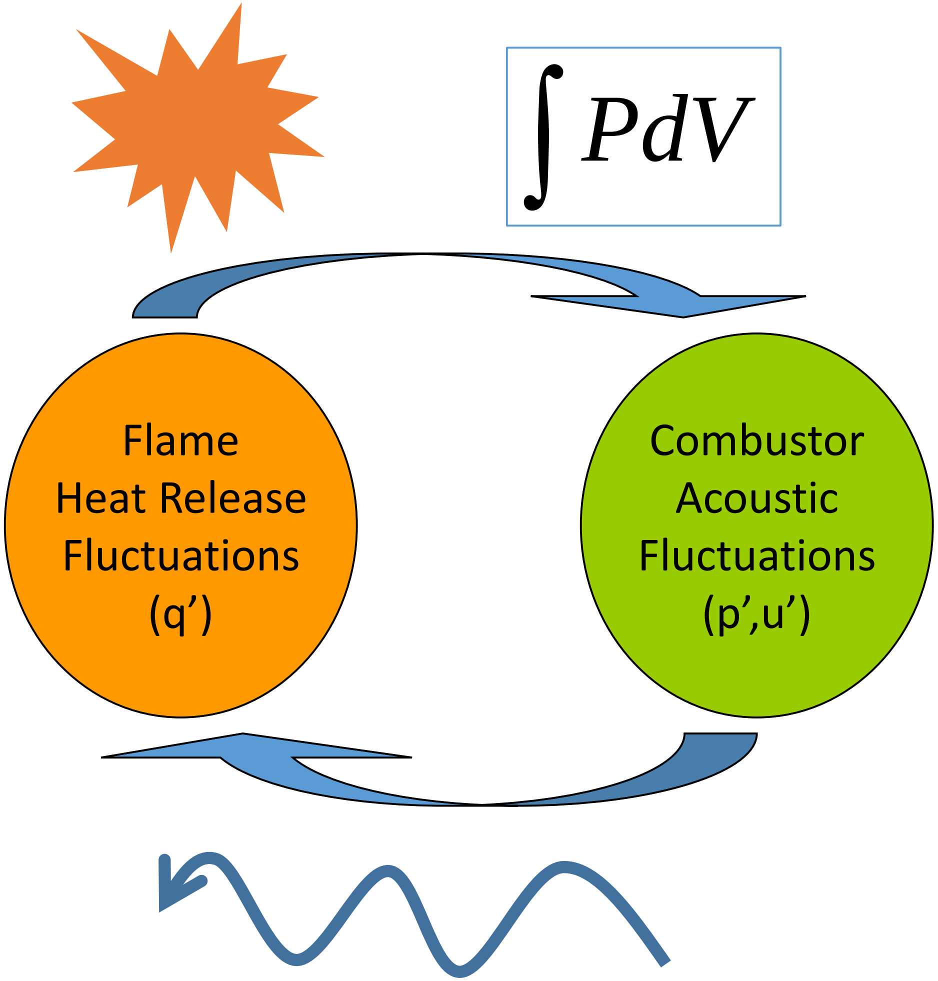
Initially, some perturbation in heat release rate causes *gas expansion* from the flame



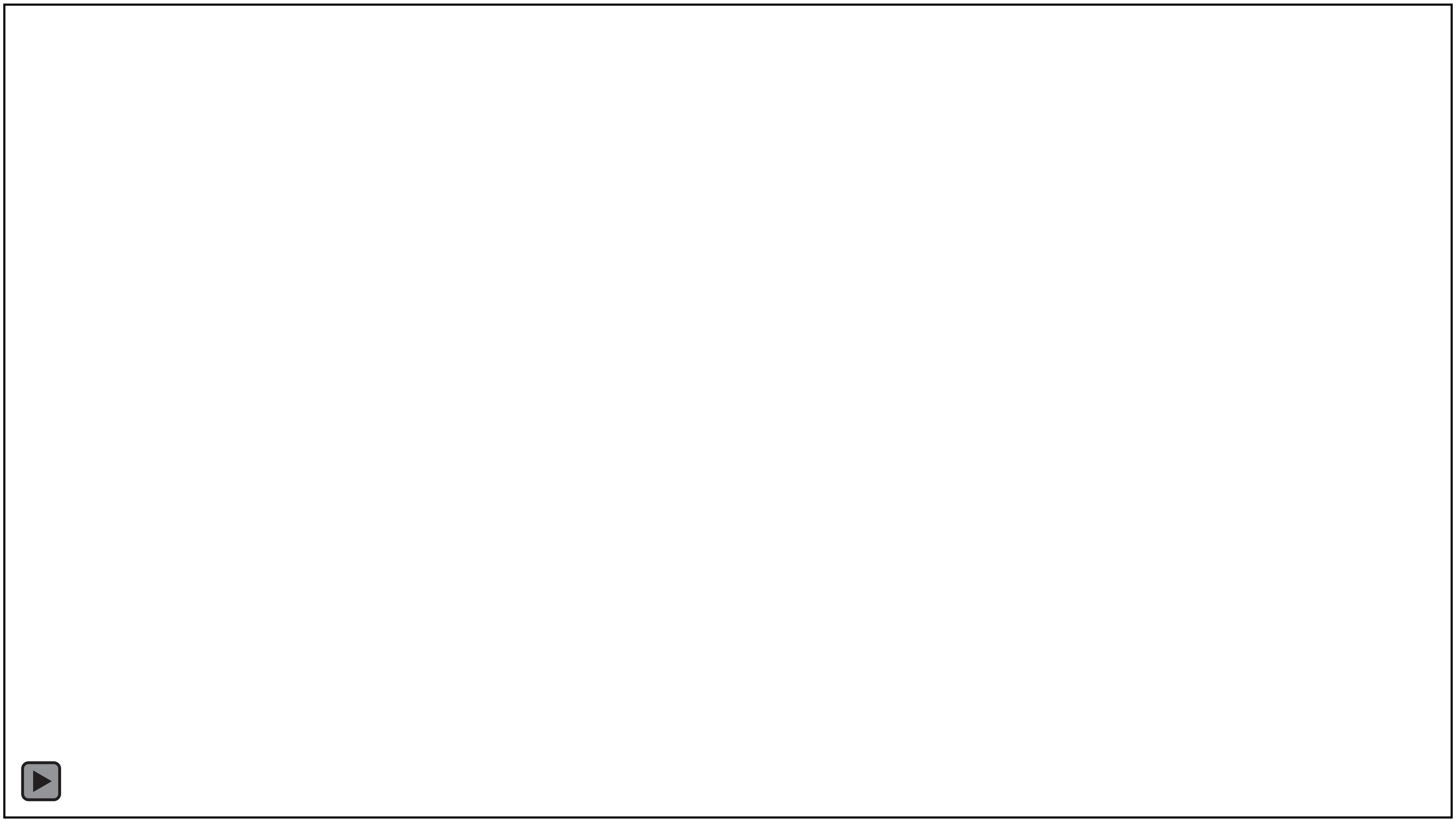
The gas expansion does compression work, locally adding energy to the acoustic field (a pressure anti-node)



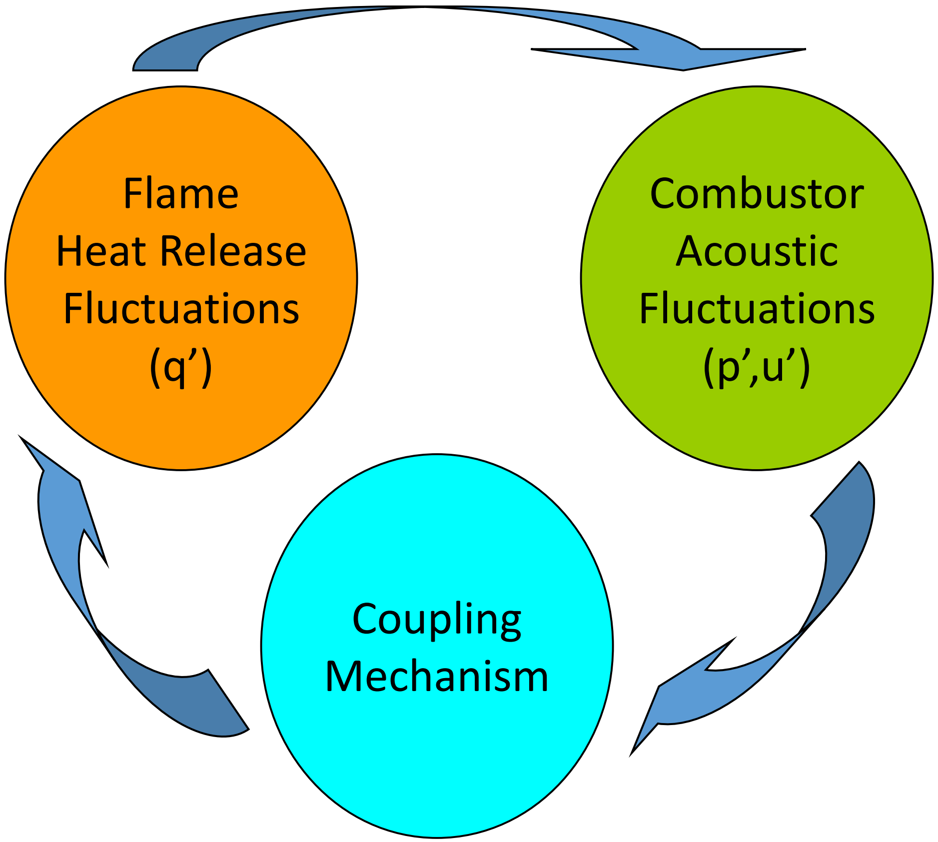
The energized acoustic field then produces a disturbance, which can excite further heat release rate oscillations



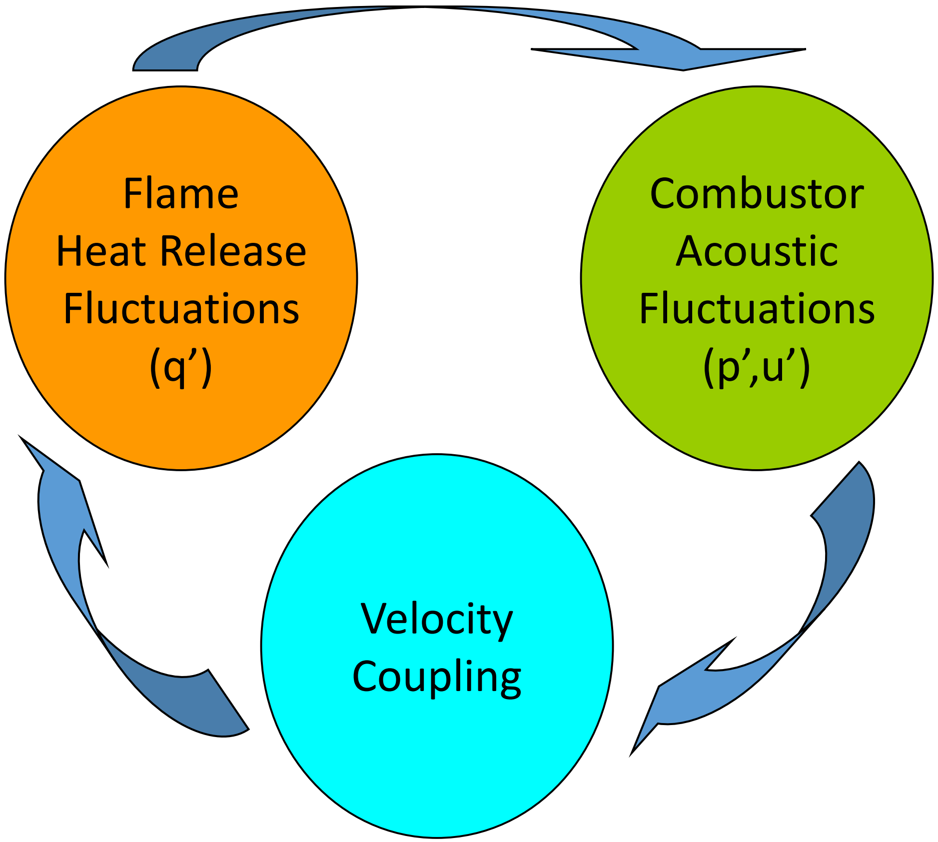
Combustion instability is a phenomena better heard or "felt" than analyzed for better understanding



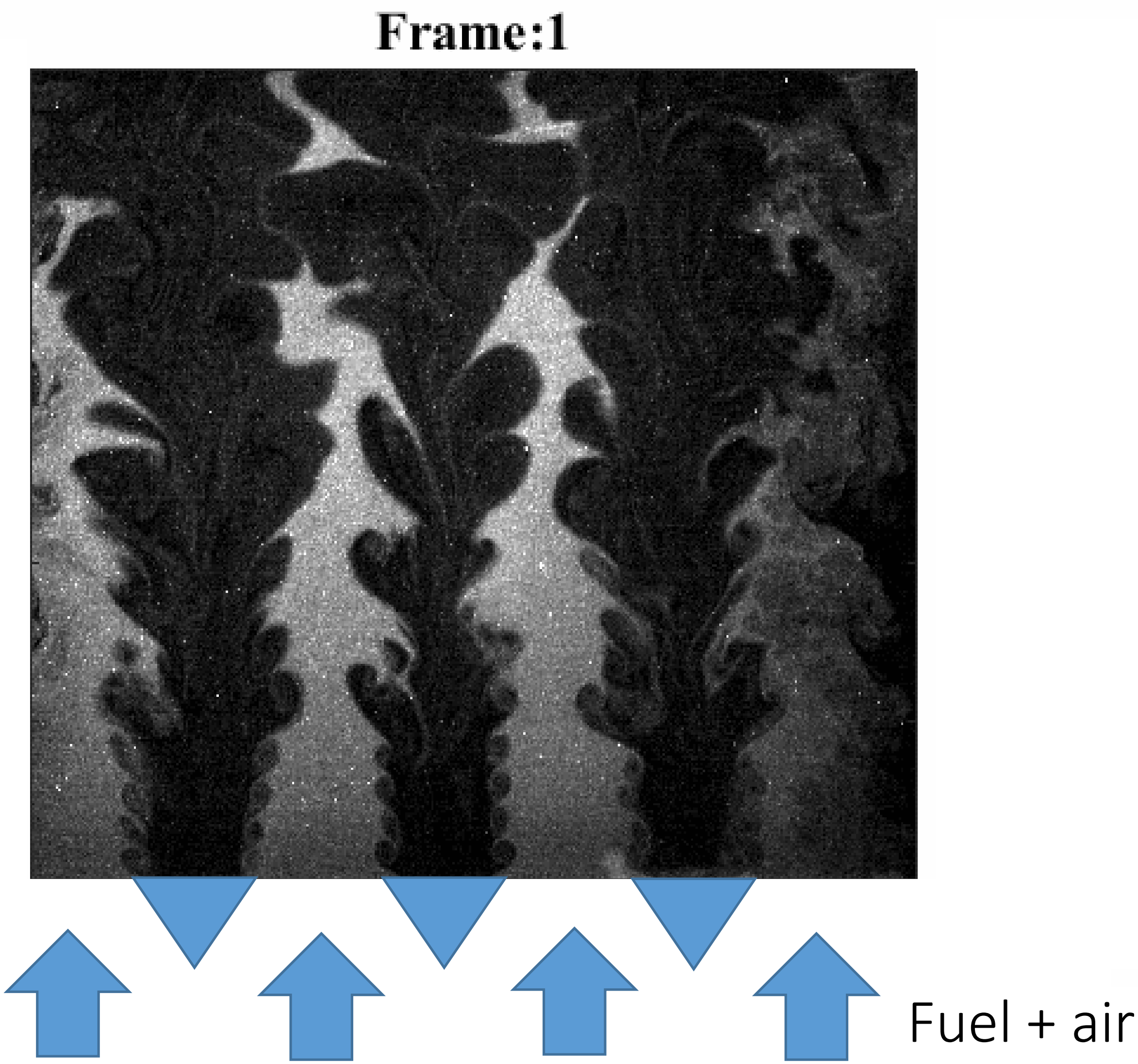
In real devices the feedback from acoustics to the flame typically includes a “coupling mechanism”



Velocity coupling: acoustic fluctuations produce vortex roll-up in the flowfield, resulting in flame disturbances



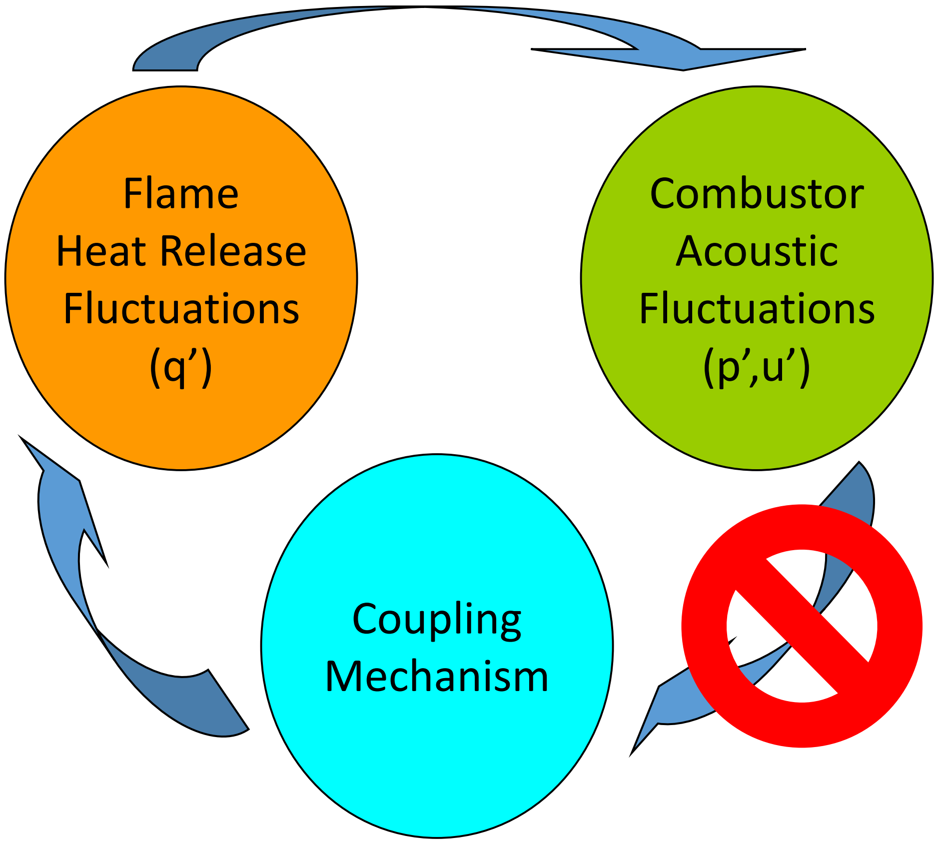
Velocity coupling: acoustic fluctuations produce vortex roll-up in the flowfield, resulting in flame disturbances



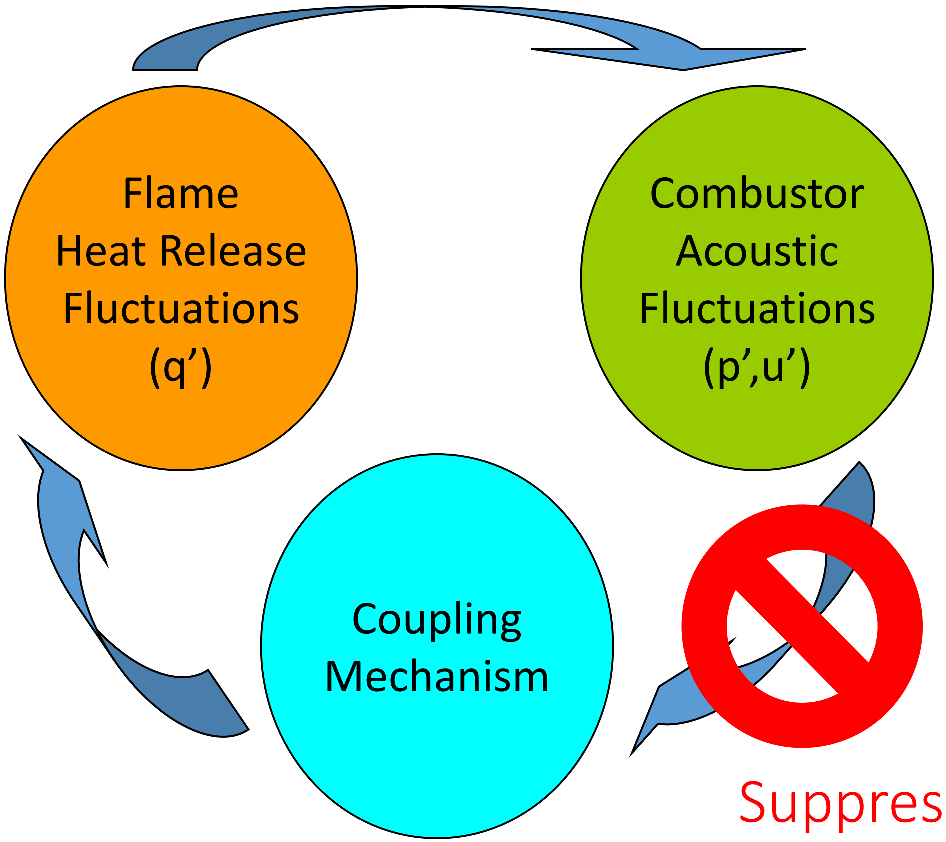
Velocity coupling: acoustic fluctuations produce vortex roll-up in the flowfield, resulting in flame disturbances

Samarasinghe, J., Culler, W., Quay, B., Santavicca, D. A., O'Connor, J. (2017) "The effect of fuel staging on the structure and instability characteristics of swirl-stabilized flames in a lean premixed multi-nozzle can combustor." *Journal of Engineering for Gas Turbines and Power*, **139**(12), 121504.

What if we could stop the feedback loop not by changing the flame or acoustics, but changing the flow?

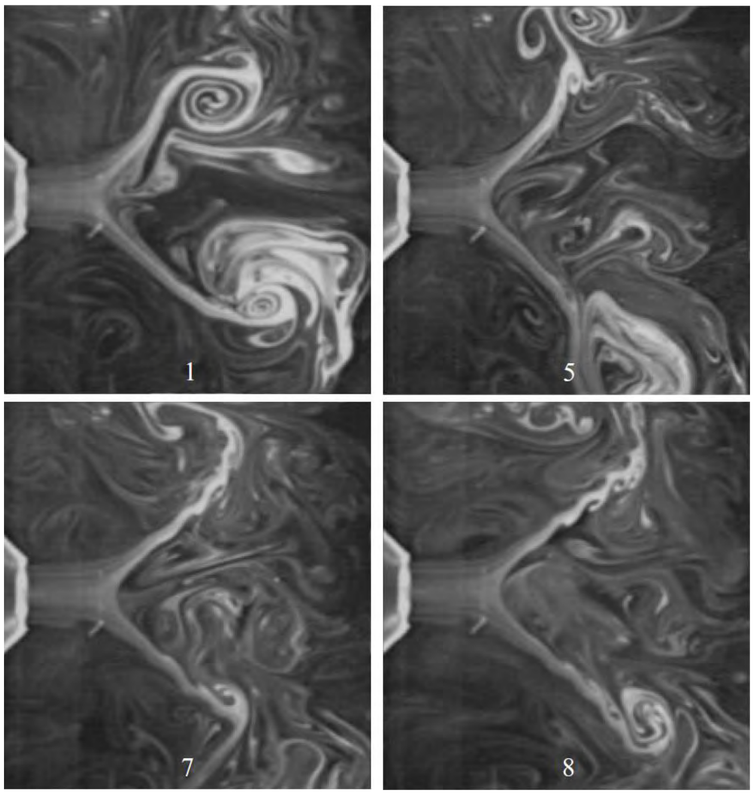


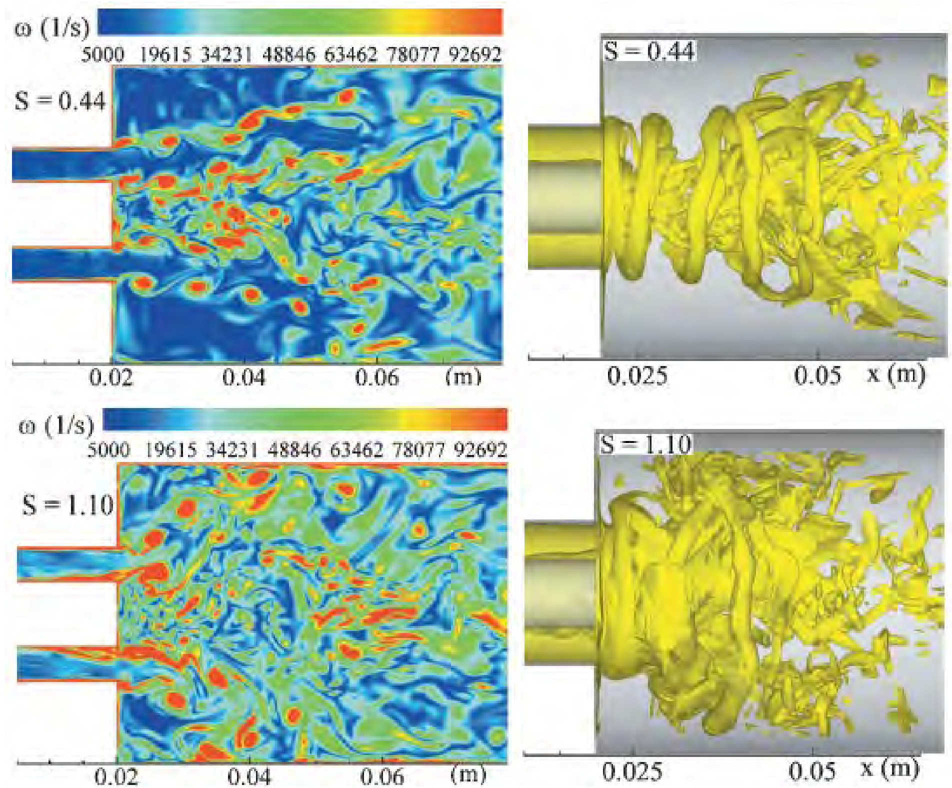
What if we could stop the feedback loop not by changing the flame or acoustics, but changing the flow?



Suppression through changes in *shear layer receptivity*

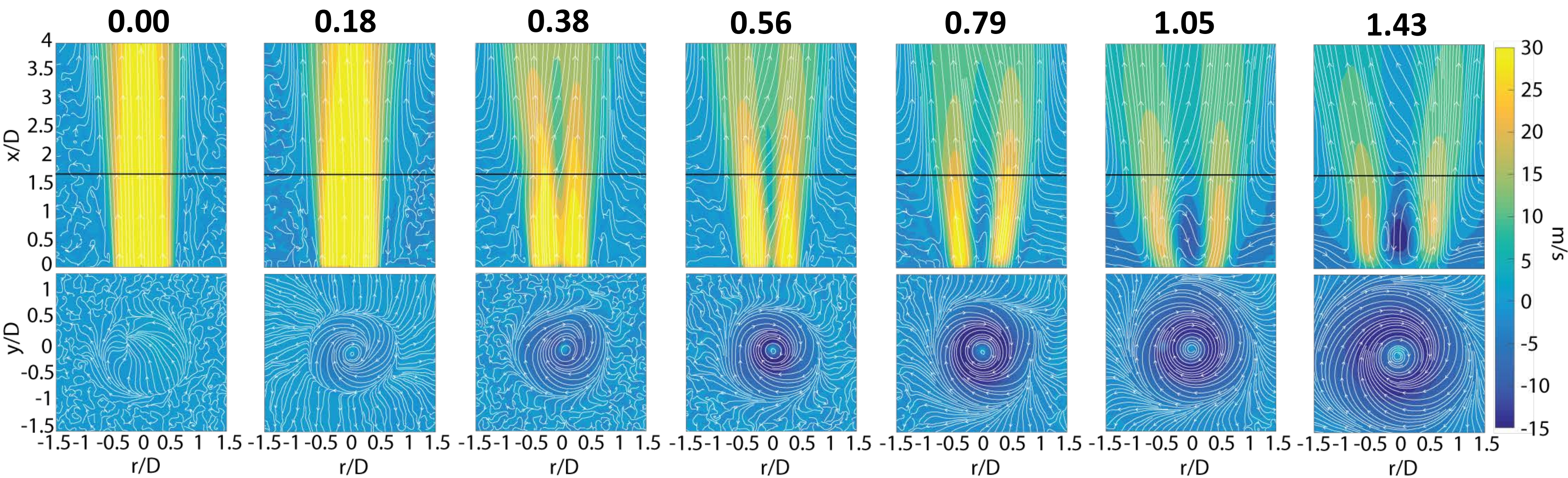
Swirling flows are hydrodynamically unstable and susceptible to acoustic forcing in different ways throughout the flow





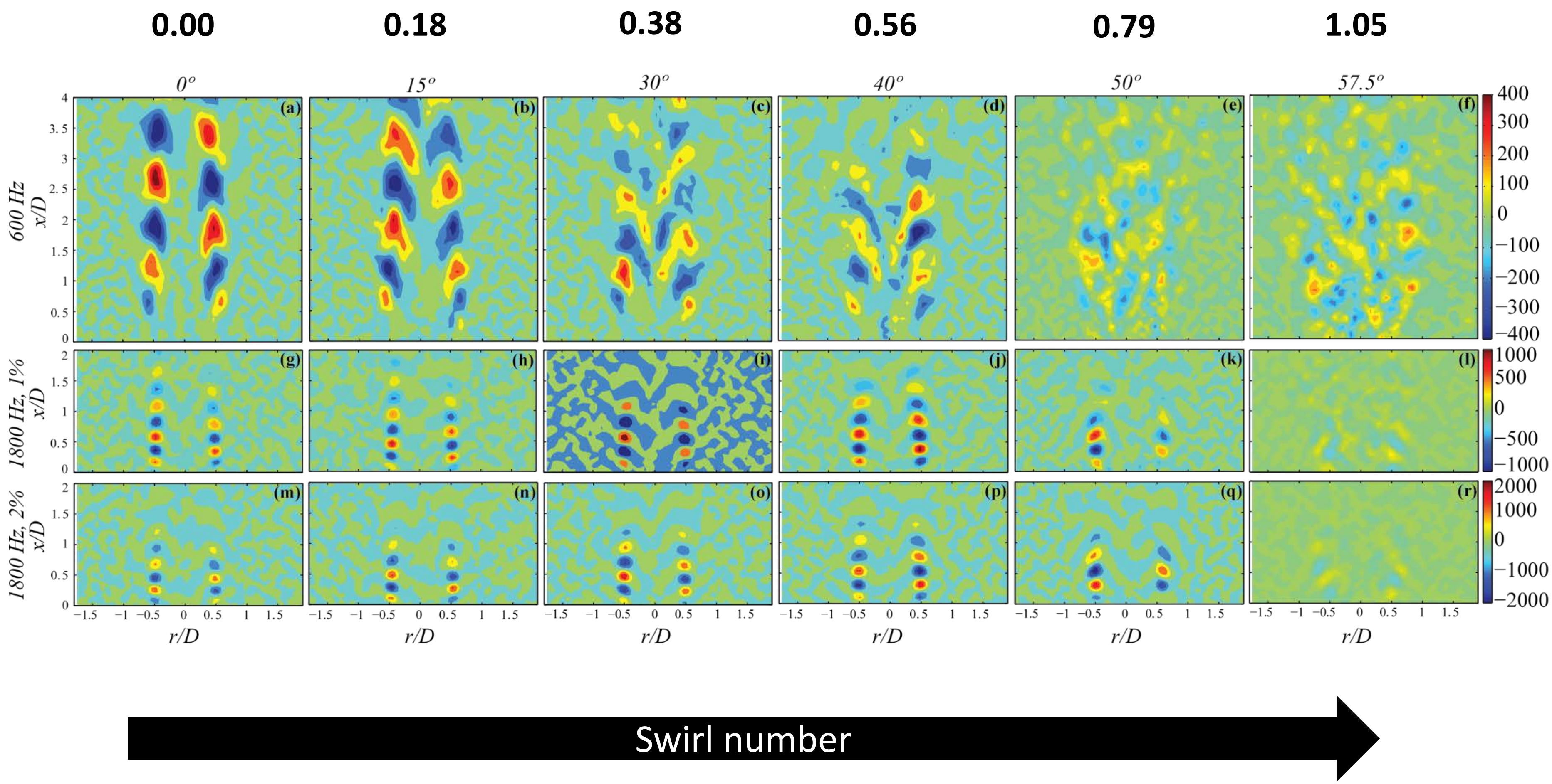
Billant et al., JFM, 1998, Huang et al., AIAA J., 2006

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



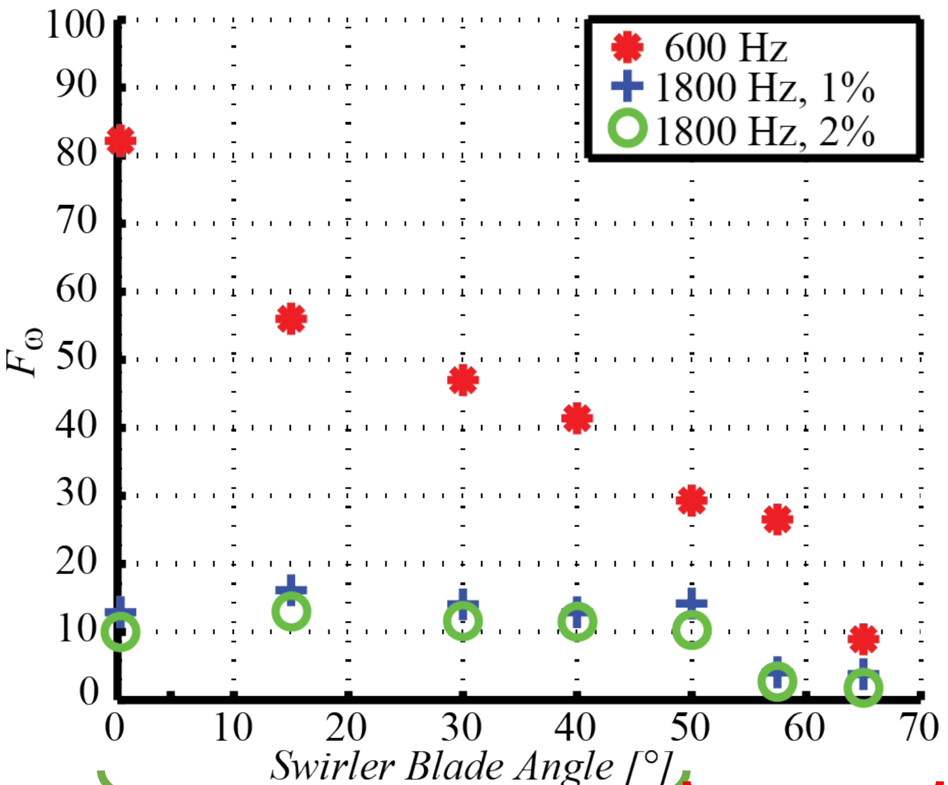
Swirl Number	0.00	0.18	0.38	0.56	0.79	1.05	1.43
Flow State	No VB	No VB	No VB	Intermittent VB	Weak PVC	PVC	Strong PVC
PVC Frequency	-	-	-	-	770–815 Hz	840 Hz	1060 Hz

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



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

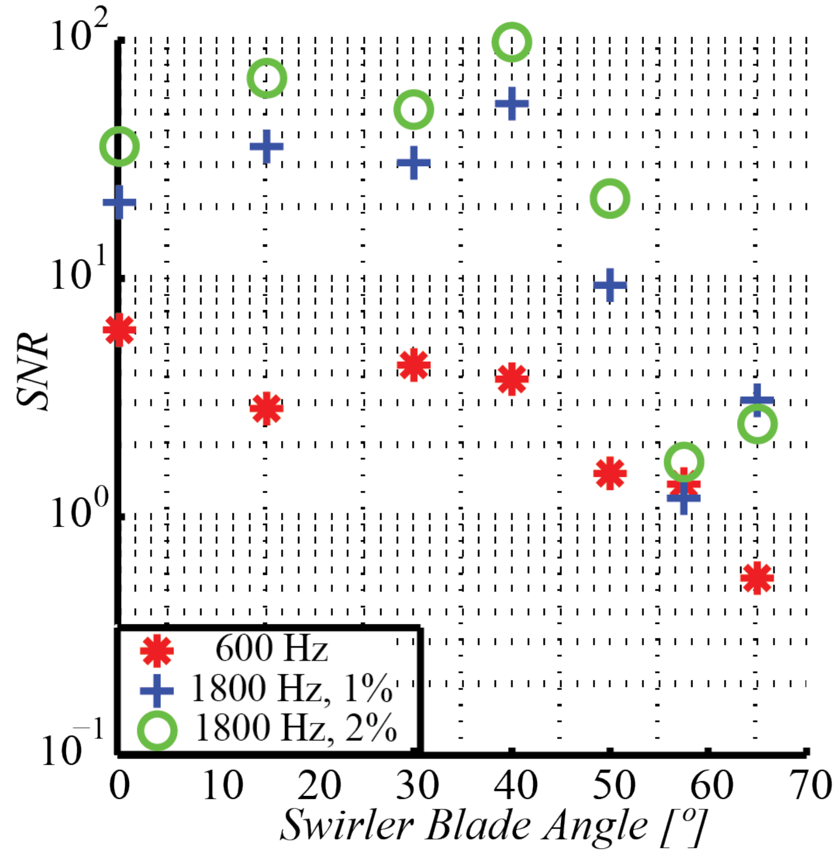
Acoustic to Vortical TF



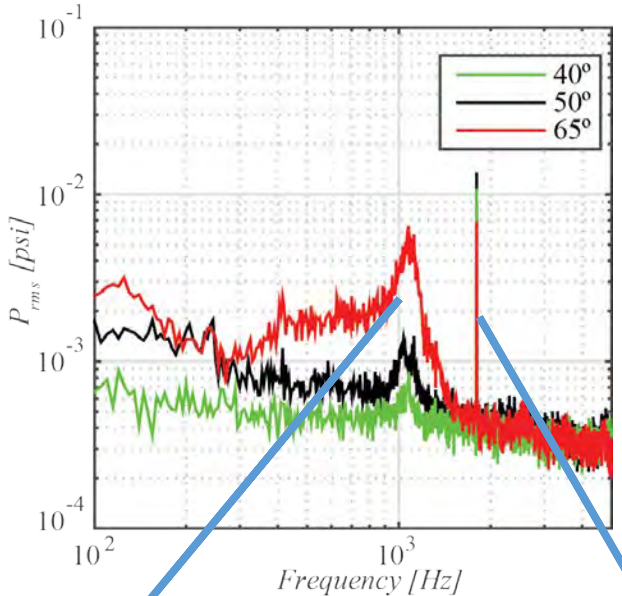
Velocity coupling possible

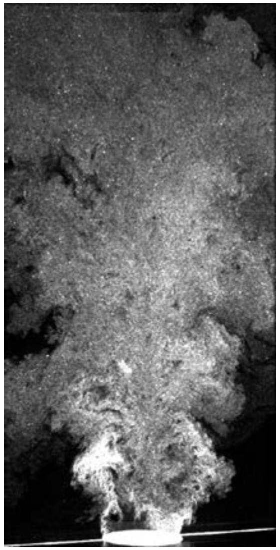
No velocity coupling

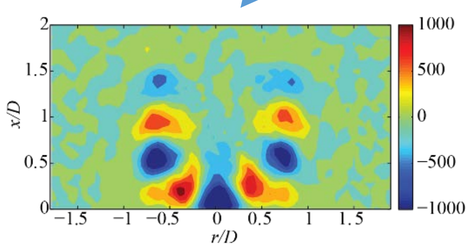
Vorticity SNR

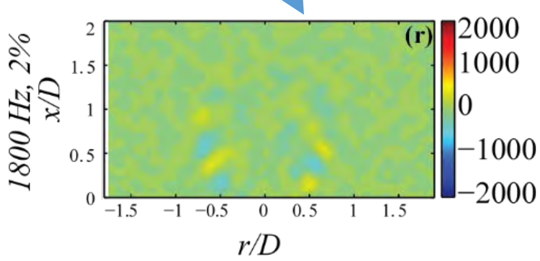


PVC is present in the flowfield at the three highest swirl numbers; PVC is has significant turbulent kinetic energy

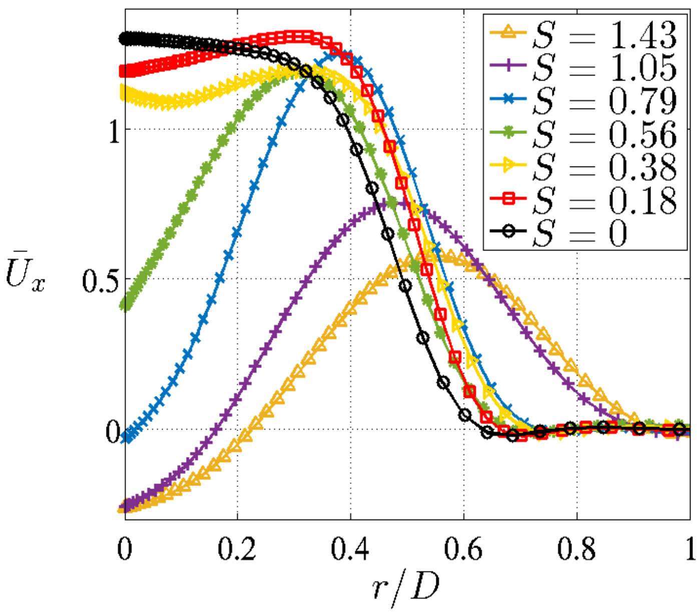


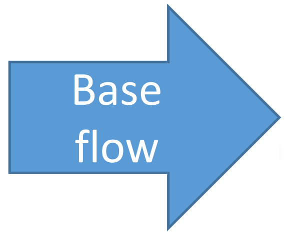






Stable design through flow design – use of hydrodynamic instability tools to tune flowfield receptivity



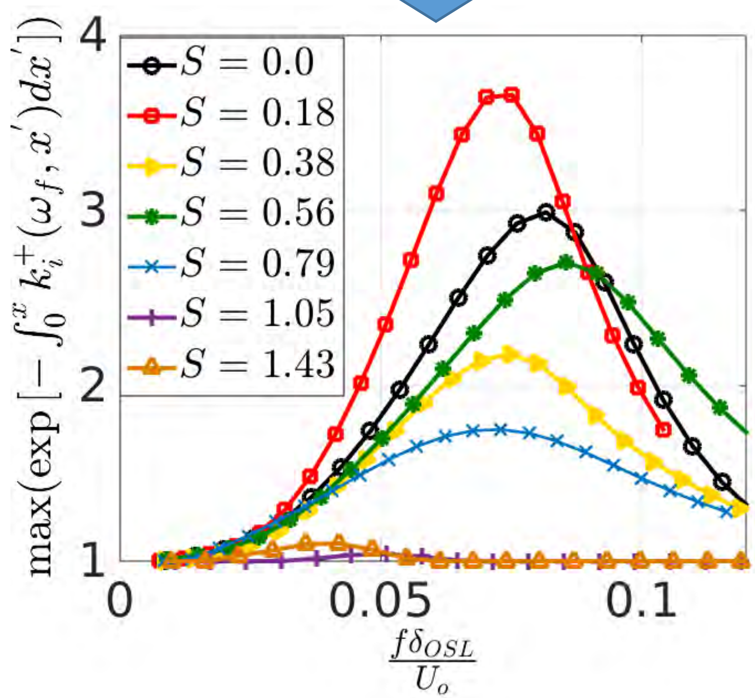


Collaborators: Santosh Hemchandra and Kiran Manoharan, IISc-Bangalore

<u>Weakly non-linear stability calculation</u>

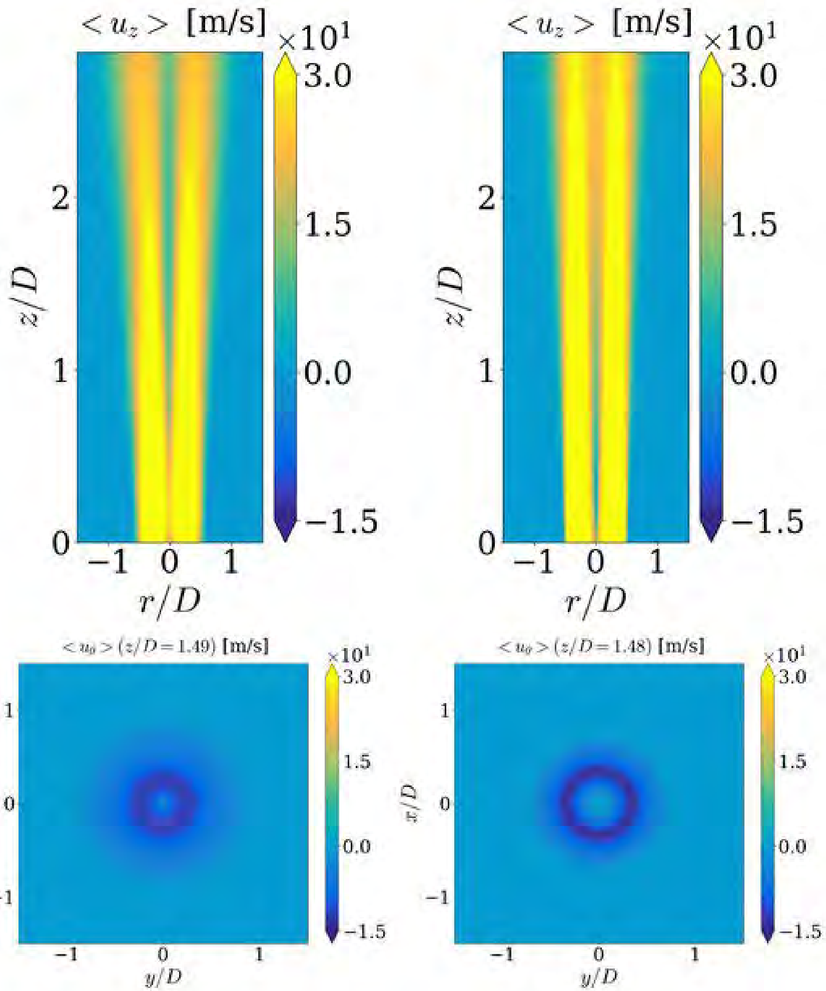
$$\mathbf{q}(r,z,\theta,t) = \bar{\mathbf{q}}(r,z) + \mathbf{q}'_c(r,z,\theta,t) + \mathbf{q}''(r,z,\theta,t)$$

$$\mathscr{B}\frac{\partial \mathbf{q}}{\partial t} + \mathscr{N}\{\mathbf{q}\}\mathbf{q} + \mathbf{S}\mathscr{N}^{s}\{\mathbf{q}\}\mathbf{q} + \mathbf{S}^2\mathscr{N}^{ss}\{\mathbf{q}\}\mathbf{q} = \mathscr{L}_{\mathrm{v}}\mathbf{q} + \mathbf{S}\mathscr{L}_{\mathrm{v}}^{s}\mathbf{q}$$



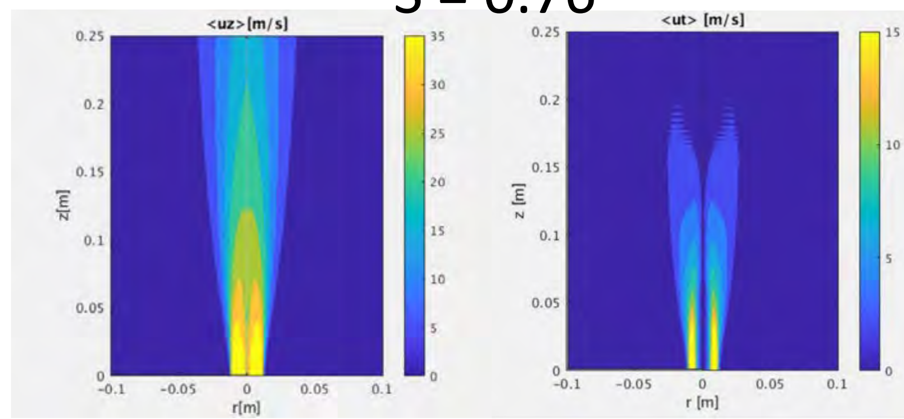
LES results of turbulent swirling flows

Comparison with measurements for S = 0.56

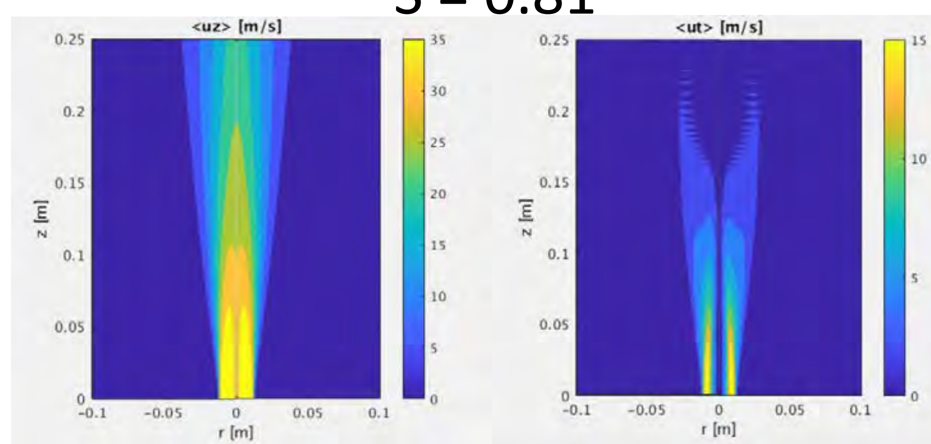


Other simulation results with higher Swirl numbers

S = 0.76



S = 0.81



Hydrodynamic stability analysis – proof of concept

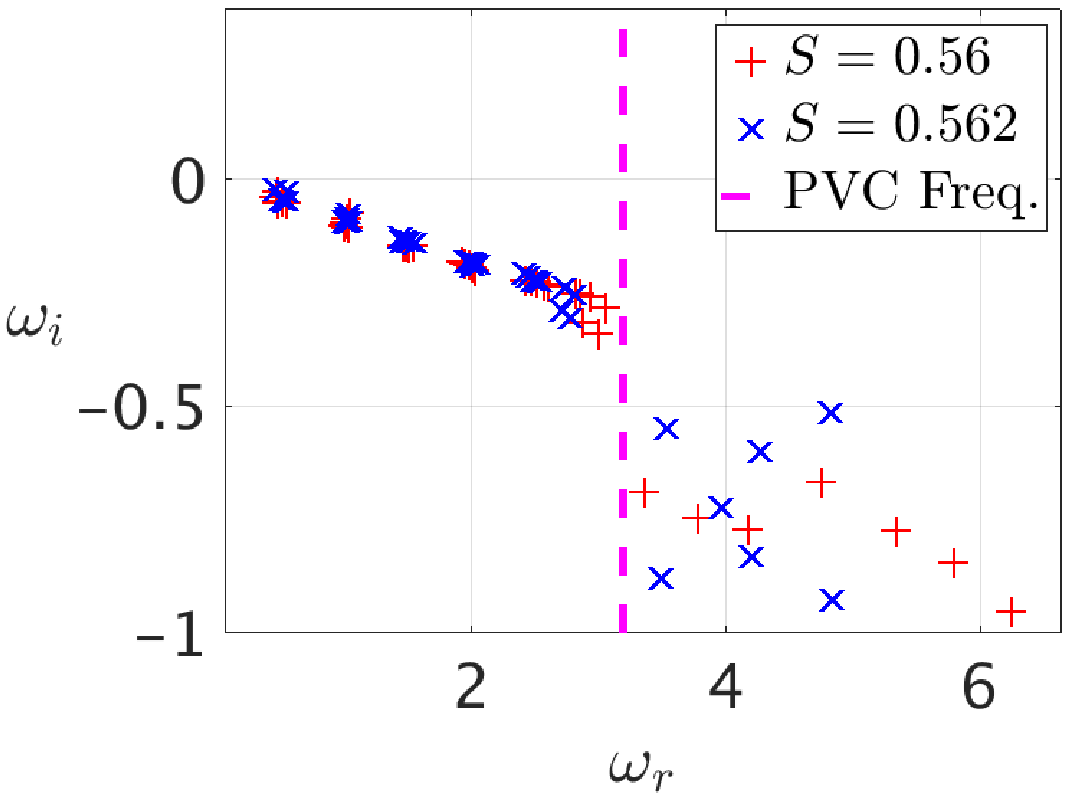


Table 2. Results of proof-of-concept optimization study.

S	ω_r	ω_i
0.56	3.40	-0.68
0.57	3.38	-0.69
0.6	3.03	-0.28
0.65	3.03	-0.27