PENNSTATE
Center for Advanced Power Generation

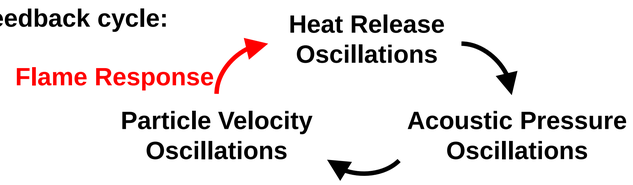
Comparison between Self-excited and Forced Flame Response of an Industrial Lean Premixed Gas Turbine Injector

Stephen Peluso, Bryan D. Quay, Jong Guen Lee, Domenic A. Santavicca

Turbulent Combustion Lab, Center for Advanced Power Generation, Penn State University

Combustion Instability Background

- Combustion instabilities are large amplitude oscillations sustained by coupling between heat release and system acoustics
- In a completely premixed flame, flame response refers to the relationship between velocity oscillations into the flame and heat release oscillations from the flame during an instability cycle
- Instability feedback cycle:



Objective

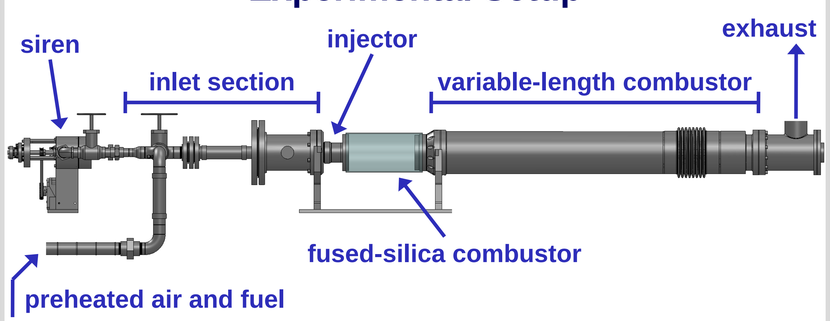
- Measure and compare the flame response of self-excited and forced turbulent lean premixed flames to velocity oscillations
  - Self-excited flame: velocity oscillations result from positive coupling between pressure, heat release, and velocity
  - Forced flame: velocity oscillations generated with siren
  - Flame response is characterized using the Flame Transfer Function (FTF), which relates normalized velocity oscillations (*v'*) to heat release oscillations (*q'*):

$$FTF(f,A)=\frac{\dot{q}'(f)/\dot{q}_{MEAN}}{v'(f)/v_{MEAN}}$$

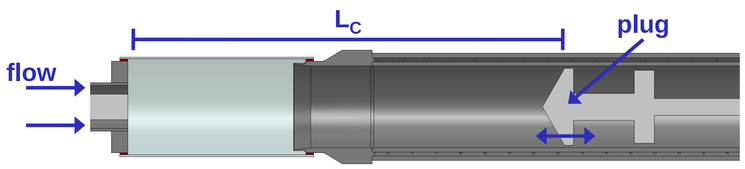
Measurement Techniques / Data Acquisition

- Measurement Techniques
  - Heat release oscillations were measured using a PMT filtered with a 430 nm narrowband filter to capture CH* chemiluminescence emission
  - Velocity oscillations were measured using two pressure transducers in the injector and the two-microphone method
- Data Acquisition / Processing
  - F_s = 8192 samples/sec
  - N = 262,244 samples (T = 32 sec)
  - Each 32 second record was divided into 32 one second long records yielding a final frequency resolution of ΔF = 1 Hz

Experimental Setup



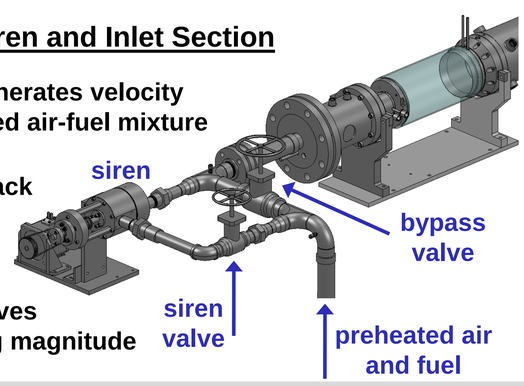
Variable-length Combustor Cross-Section



- Plug used to vary overall combustor length (L_C)
- Self-excited measurements: Varied L_C to find lengths with positive coupling between q', p', v'
- Forced measurements: Fixed L_C at a stable flame location

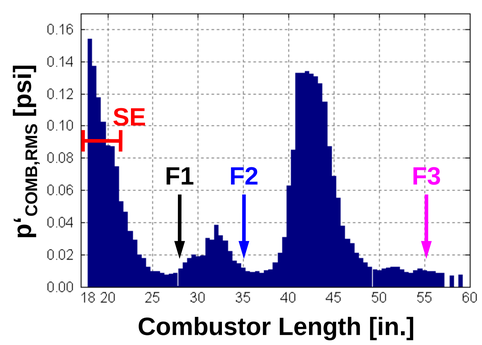
Siren and Inlet Section

- Rotor-stator siren generates velocity fluctuations in premixed air-fuel mixture
- DC motor with feedback controls oscillation frequency within ¼ Hz
- Siren and bypass valves used to control forcing magnitude



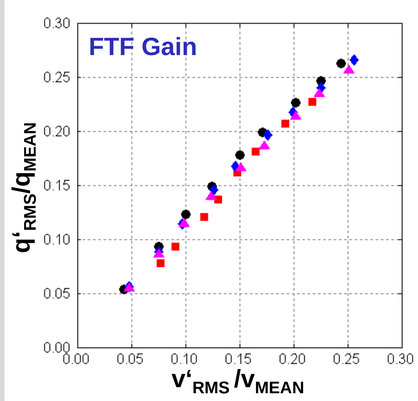
Results

Combustor Pressure Stability Map



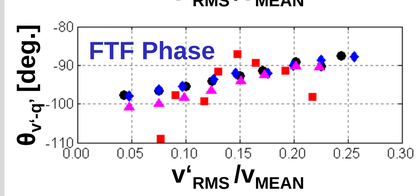
- Stability map was produced to locate combustor lengths for both self-excited unstable (SE) and stable flames
- Peaks in combustor pressure denote regions of unstable flames
- Three stable combustor lengths were chosen for forced flame experiments (L_C = 27", 35", and 55") and forced measurements were completed at the same freq. and v'_{RMS} as the SE instability

Comparison between SE and Forced Response



- FTF Gain = slope of linear fit through each data set
- All values of gain agree within uncertainty

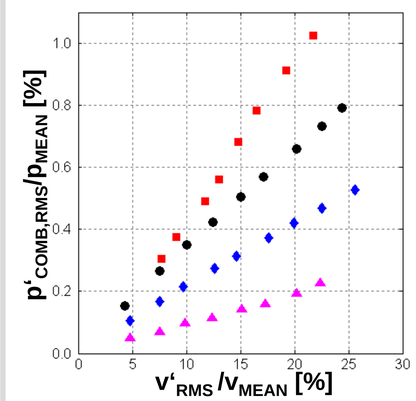
		Gain		Range
●	F1	1.13	4.6%	1.08 – 1.18
◆	F2	1.09	4.2%	1.04 – 1.14
▲	F3	1.06	2.7%	1.03 – 1.09
■	SE	1.07	3.2%	1.04 – 1.10



- FTF Phase = phase difference between velocity and heat release oscillations
- Max. phase disagreement: 12° (~3% of one cycle)

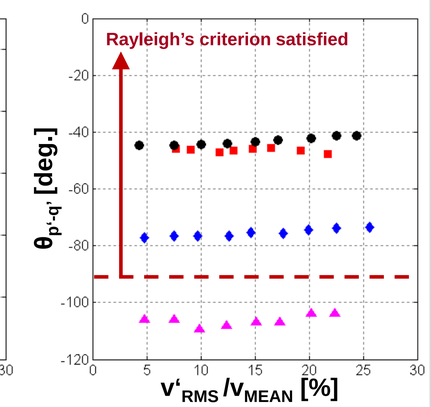
Results

Combustor Pressure



- The relationship between *p'* and *v'* changes with L_C
- Normalized *p'* was typically an order of magnitude less than *v'*

p' – q' Phase Difference

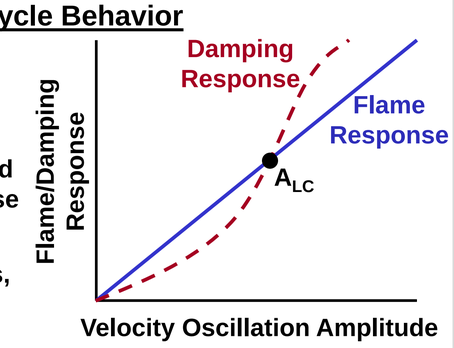


- SE, F1, F2: Rayleigh's criteria $|\theta_{p'-q'} < 90°|$ is satisfied, indicating *q'* is adding energy to the *p'* field
- F3: *q'* is out of phase with *p'*, indicating *q'* is damping *p'*

- Despite differences in *p' – q'* and *p' – v'* relationships, flame response is identical for self-excited and forced measurements

Limit Cycle Behavior

- A_{LC} = limit-cycle oscillation amplitude
- Self-excited limit cycle behavior is typically attributed to nonlinear flame heat release
- As flame response remains linear in these measurements, nonlinearities in system damping determine A_{LC}



Funding for this research was provided by Solar Turbines Inc.