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The Effect of Transient Fuel Staging on Self-Excited Instabilities In A Multi-Nozzle Gas Turbine Combustor

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Abstract:

Combustion instability in gas turbines is often mitigated by techniques such as fuel staging. While fuel staging is effective at steady-state conditions, the effect of fuel staging *transients* on self-excited instabilities is not well understood. The goal of this work is to study the effects of fuel-staging transients on combustion instability in a model gas turbine combustor. When the global equivalence ratio is φ = 0.70 and all nozzles are fueled equally, the combustor undergoes self-excited oscillations. These oscillations are suppressed when the center nozzle equivalence ratio is increased to φ = 0.80 or φ = 0.85. Two transient staging schedules that result in transitions from unstable to stable operation, and vice-versa, are studied. We find the characteristic instability decay times are dependent on the amount of fuel staging in the center nozzle, but the characteristic rise times are not. High speed CH* chemiluminescence images and dynamic pressure measurements are used to determine the instantaneous phase difference between the heat release rate fluctuation and the combustor pressure fluctuations in different regions in the combustor.

Experimental Overview

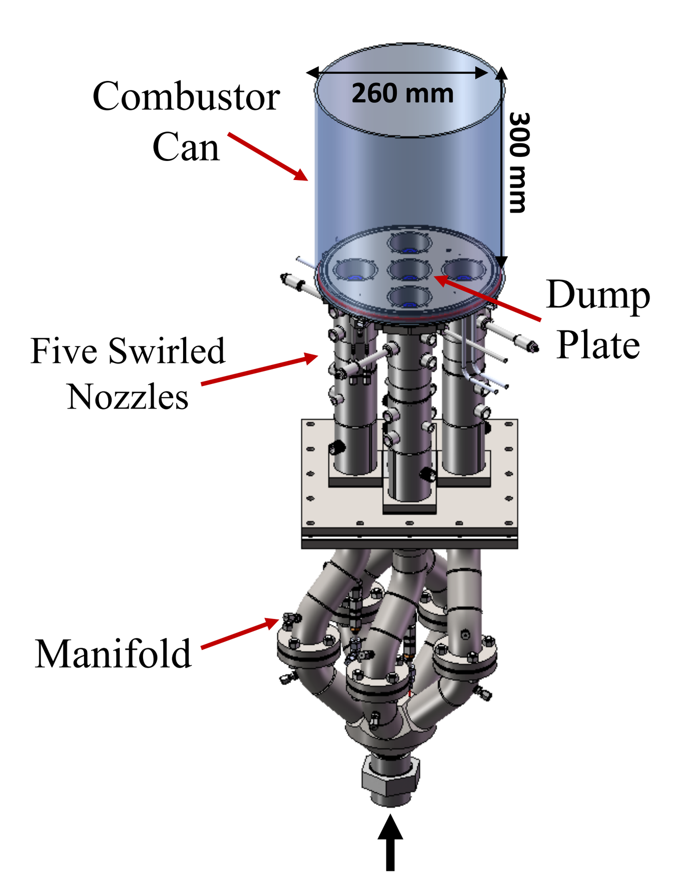

Figure 1: Experimental Apparatus

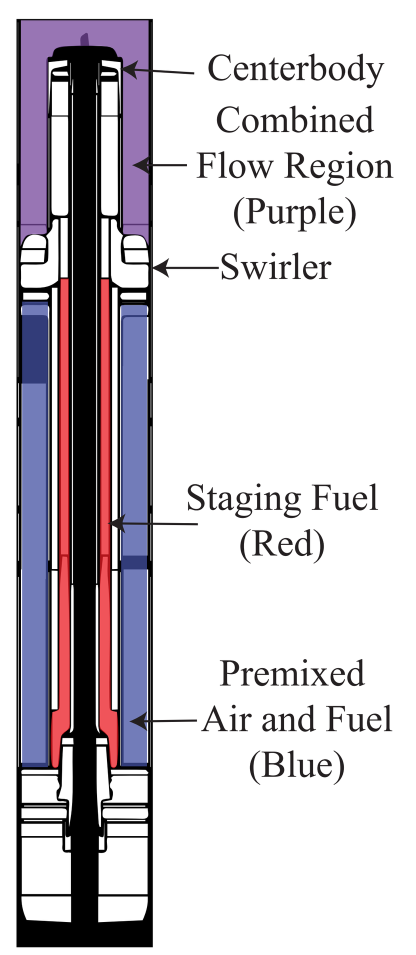

Figure 2: Staging Fuel Flow

The experimental apparatus consists of a lab scale multinozzle combustor as shown in Fig. 1 and descrbed in [1]. The combustor burns a premixed mixture of natural gas and air. Fuel staging is accomplished by injecting a small amount of fuel into the main premixed fuel path in the center nozzle. Each fuel nozzle consists of an annulus, a swirler, and a centerbody, as shown by the cutaway in Fig. 2. Premixed fuel flows through the annulus of the nozzle (blue path), while staging fuel is injected below the swirler (red path). The staging fuel enters the premixed mixture through small holes in the swirler and the combined mixture (purple section) then flows to the flame. The amount of staging fuel represents a small fraction (less than 5%) of the overall fuel flow rate even at the highest staging amount. An electrically actuated proportional solenoid valve is used to control the staging amount and the staging timescale.

Transient Schedule:

Figure 3 shows a diagram of each transient schedule. The lean-to-rich transient (unstable to stable) allows a characteristic decay timescale to be measured while the rich-to-lean transient (stable-to-unstable) allows a characteristic rise timescale to be measured. Note that "lean" and "rich" describes the center nozzle equivalence ratio relative to the outer nozzles. In all cases the overall equivelence ratio remains lean.

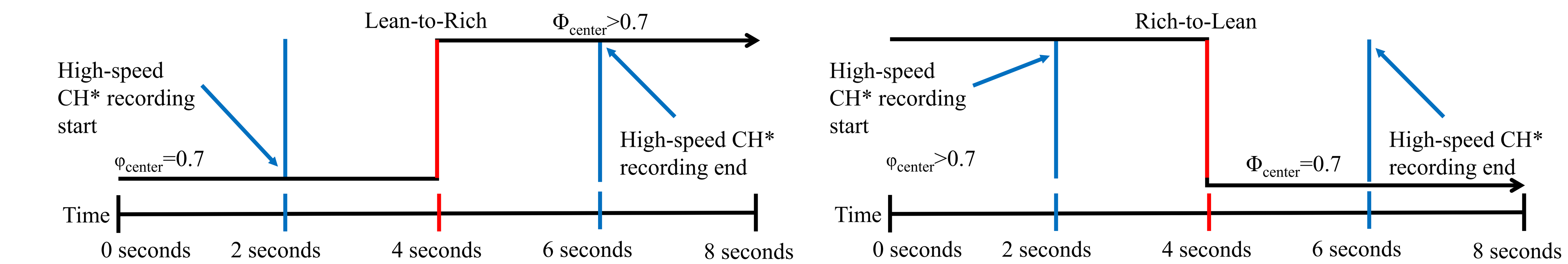

Figure 3: Transient Schedule

Time Series Analysis

Figure 4 shows the combustor pressure fluctuation (blue), the envelope of the pressure (red), and the modeled equation fit (dashed black line). The envelope is obtained from the Hilbert transform of pressure signal and the model fit obtained using nonlinear regression. The fit and time constant equations are below. Figure 5 is a graphical representation of the logistic fit parameters for a decay case, and Fig. 6 shows the ensemble-averaged results of the instability decay and rise times.

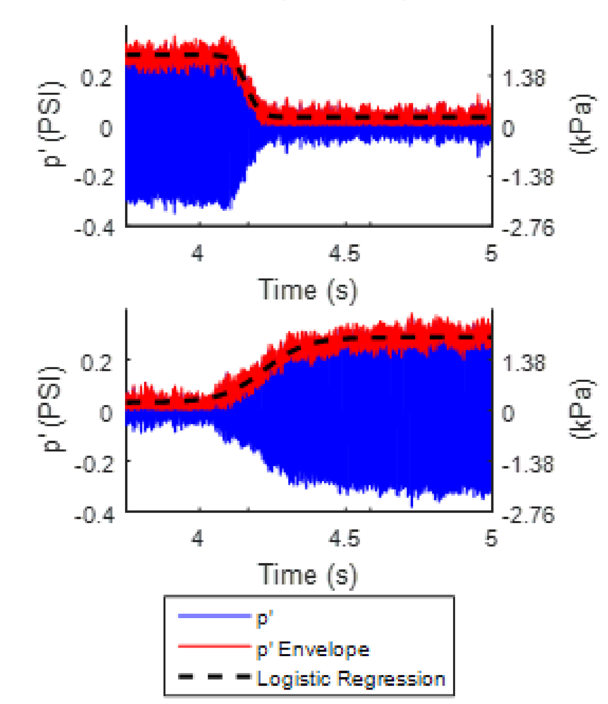

Figure 4: Pressure Envelope and Envelope Regression

$$P'(t)=\frac{(A-B)}{\left((1+e^{k}(t-t_0)\right))}+B$$

$$\tau=\left|\ln\frac{(R-1)}{k}\right|$$

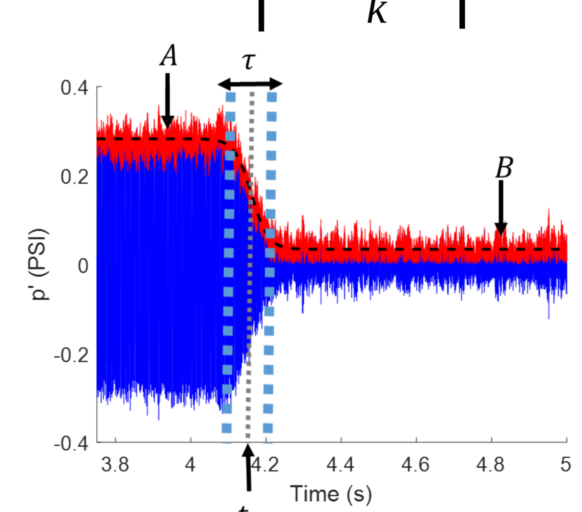

Figure 5: Logistic Fit Parameters

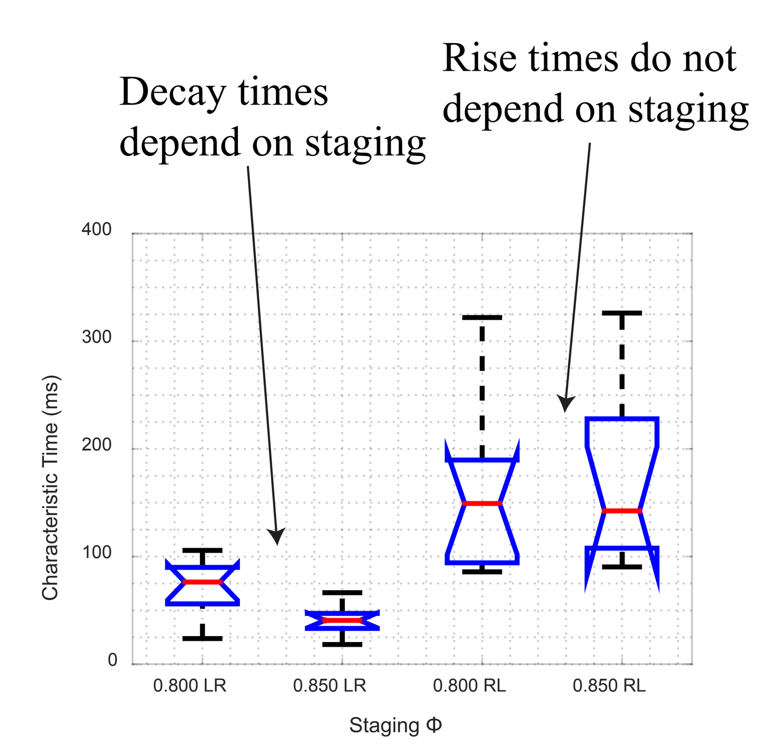

Figure 6: Characteristic Time Boxplots

Image Analysis

Figure 7 shows the instantaneous phase difference between pressure and heat release rate in the combustor at different times throughout the transient. When the combustor is unstable (Fig. 7 a and Fig. 7 h), the center heat release rate and pressure fluctuations are in phase, as indicated by the large, unbroken blue region in the center of the combustor. This coherent structure is much reduced when the combustor is staged stable, as shown in Fig. 7 b and f. During the unstable-to-stable transition, the size of the out-of-phase region decreases in the center flame, (Fig. 7 c and e) and this decrease precedes the the decrease in the outer regions of the combustor. This suggests a phase cancellation between the center region and outer region is responsible for the instability decay. During the stable-to-unstable transition, the size of the in-phase region increases mostly uniformly (Fig. 7 d and f) which differs from the unstable-to-stable transient.

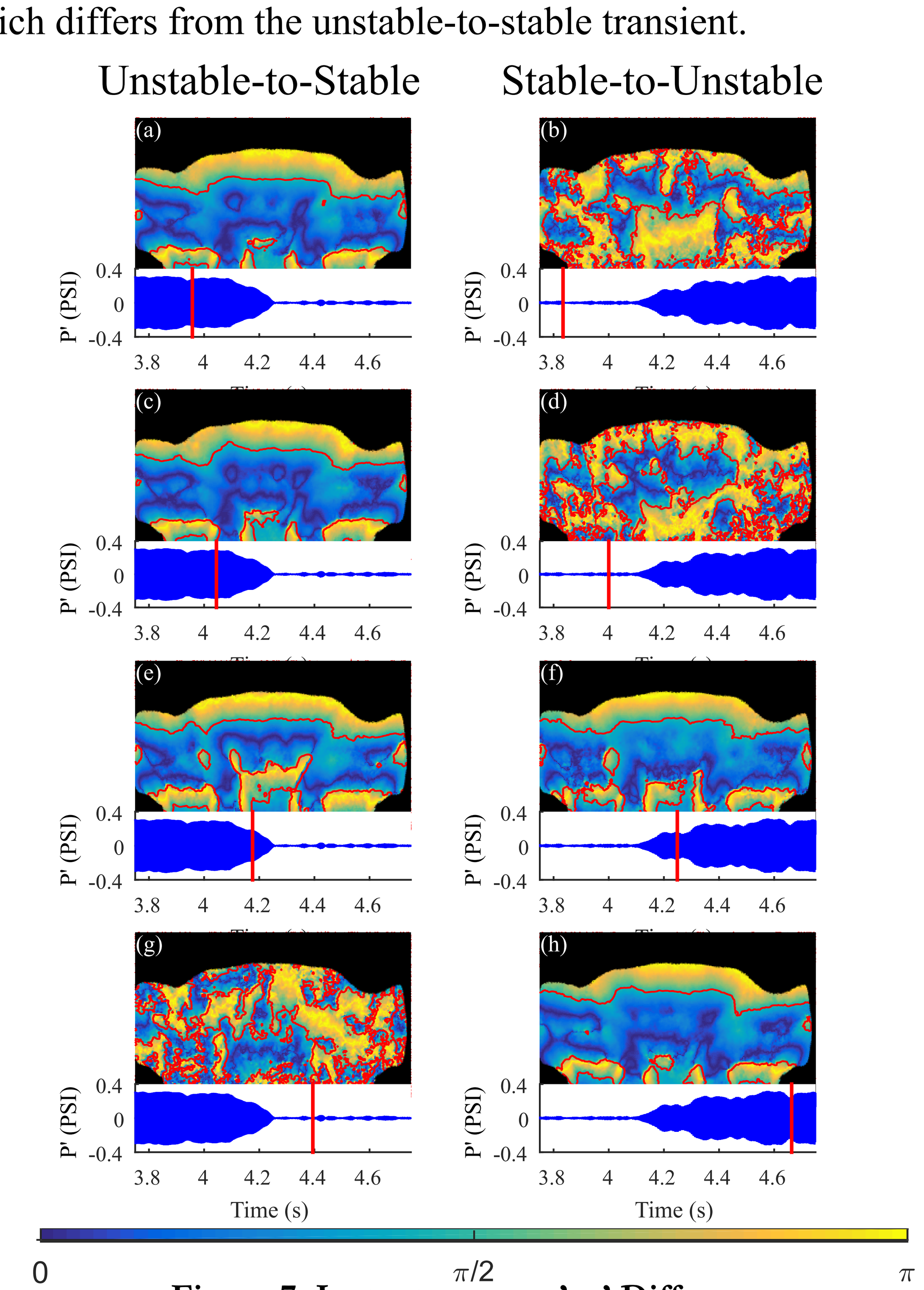

Figure 7: Instantaneous p' q' Difference

Conclusions:

The decay rate of the pressure fluctuations for self-excited instabilities for a step transient depends on the fuel staging amplitude, where larger fuel staging amplitudes result in shorter decay times. It is found that the characteristic rise time tends to be longer than the characteristic decay time for a given staging amplitude. The variation in characteristic decay times also tends to be less than the variation in characteristic rise time, which suggests that the instability growth process is more variable than the instability decay process. The instantaneous phase images suggest a phase cancellation between the center region and the outer region is responsible for the reduction in pressure fluctuation amplitude. While the beginning and end states of the impulse transients are similar, the evolution of the transients differ in which regions of the combutor go out-of-phase or in-phase first. These differences in phase structure likely indicate why the lean-to-rich transients are shorter and less variable in duration than the rich-to-lean transients.

Future Work:

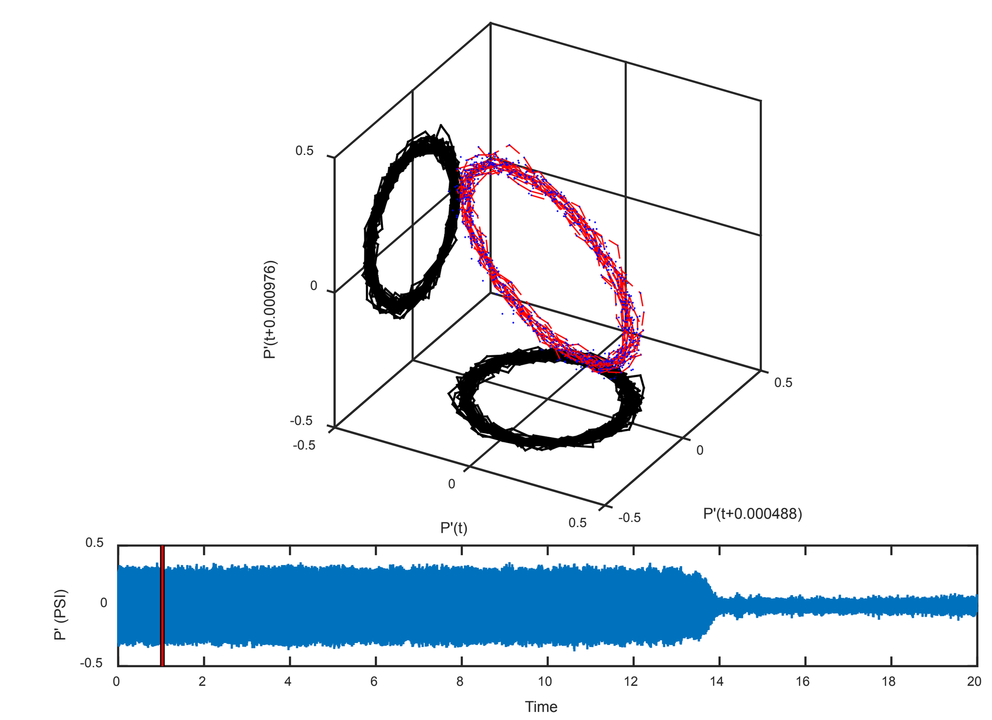

Figure 8: Reconstructed Phase Space Attractor

Future work will focus on analyzing the pressure data in reconstructed phase space, as shown in Fig. 8. Phase space analysis is useful for showing the dynamics of the system and can be conducted using only the pressure signal. We additionally plan to collect OH-LIF images of the flame to better link the behavior of the pressure data to the flame physics.

References

[1] Culler, W. Samarasinghe, J. Quay, B. Santavicca, D. and O'Connor, J., 2017, "The Effect of Transient Fuel Staging on Self-Excited Instabilities in a Multi-Nozzle Model Gas Turbine Combustor", ASME Turbo Expo, ASME, Charlotte, North Carolina.

Acknowledgments

The authors would like to thank Steve Peluso and Xiaoling Chen for their contributions to this work. The authors would also like to thank the U.S. Department of Energy for funding this project under award number DEFE0025495 and contract monitor Mark Freeman.