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# Technical Notes

## Measurement of Flame Transfer Functions in Swirl-Stabilized, Lean-Premixed Combustion

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### Introduction

To MEET increasingly stringent emission standards for nitric oxides, modern gas turbine designs use lean-premixed combustion. While meeting these new environmental standards, lean-premixed combustion systems introduce some substantial operability concerns with increased susceptibility to blowout, flashback, and instabilities. Significant effort is required to overcome these design challenges to allow turbines to operate in an efficient and environmentally friendly manner. This brief communication provides results of ongoing experimental measurements of lean-premixed combustion flame dynamics, necessary to further predictive capabilities of models for combustion instabilities. Measurements were made of linear flame transfer functions for both velocity and equivalence ratio oscillations. The flame transfer functions showed that the flame behaves as a low-pass filter for both types of excitation, but some important differences in the gain and cutoff frequency occurred. Although the gain and cutoff frequency both increased with equivalence ratio for velocity perturbations, they were observed to have no change with operating equivalence ratio for the case of equivalence ratio oscillations.

The types of combustion instabilities most commonly encountered in premixed combustion systems were first characterized by Rayleigh [1]. In this type of instability, a feedback loop is formed between the fluctuations in heat release rate (HRR) of the flame and the combustor/flow train acoustics [2,3]. Under certain operating conditions, the coupled system can become unstable, resulting in high-amplitude pressure fluctuations that can be detrimental to combustor hardware as well as efficiency. The specific coupling mechanisms by which these instabilities may arise are a significant area of research and readers are directed to the literature for a more significant discussion of the phenomenon [3,4].

For the purposes of this study, two possible mechanisms were considered [5,6]: coupling through velocity and equivalence ratio oscillations, as depicted in Fig. 1. Velocity (mass flow) coupling occurs when the acoustics directly cause a fluctuating mass flow upstream of the flame. The mechanism for equivalence ratio oscillations is known to be related to the injector design [7]. When considering a system level model of instabilities, knowledge of the flame and acoustic transfer functions is necessary to yield an understanding of the occurrence of instabilities [3].

Making useful predictions of instabilities using a closed-loop model, like the one described here, ultimately relies on component models to predict the individual transfer function blocks, of which the flame is the most difficult to characterize. The flame transfer function (FTF) represents the dynamics of the flame response to a perturbation as a function of frequency:

$$\mathrm{FTF}(f) = \frac{q'(f)}{u'(f)} \quad \text{or} \quad \frac{q'(f)}{\Phi'(f)}$$

This FTF may be expected to vary with the combustor operating condition and geometry. Previous modeling efforts have used a variety of physical models to attempt to predict these flame dynamics, including well-stirred reactor models [8,9] and, of more recent interest, flame sheet models [10–12]. Experimental measurements of flame dynamics have also been made by several investigators [13–20], though few considered flame response to equivalence ratio oscillations. The measurements made in this study provide an additional basis for the testing of flame dynamics models as well as offering insight into the flame physics.

The existing literature on velocity perturbations suggests that the flame acts as a low-pass filter in responding to excitations. Making accurate predictions of the flame dynamics thus relies on predicting the low-frequency gain and cutoff frequency of the FTF. Models show predictions of the low-frequency gain as tied to the mean energy content of the reacting mixture [8]. The bandwidth of the flame transfer function has been related to the nondimensional Strouhal number based on the flow convective time scales [12,14,19]. In dimensional terms, this corresponds to the hundreds of hertz range.

### Experimental Setup and Procedure

Experiments were carried out on a rig specifically designed for gaseous, premixed, turbulent combustion experiments, as shown in Fig. 2. The rig design was a swirl-stabilized dump combustor with a center body. Swirl was generated by a fixed-vane swirler with vanes at a 30 deg angle to the flow axis. The actual combustion section was a quartz tube that vented to the atmosphere. The combustor section was sufficiently short as to prevent any self-excitation from occurring.

Mean air flow rates were fixed at 25 SCFM (0.0136 kg/s) for all tests in this study. Fuel flows were specified to provide mean equivalence ratios in the range of $\Phi = 0.48$–$0.7$ for both natural gas and propane. The low end of this range was bounded by the lean stabilization limit. The primary fuel/air mixing took place far upstream, eliminating the possibility of undesired equivalence ratio oscillations reaching the flame. Dynamic equivalence ratio oscillations were introduced through a separate fuel stream.

Because the combustor was not self-excited, it was necessary to deliberately introduce perturbations to the upstream flow rate and equivalence ratio. The flame output (i.e., HRR) was measured relative to each of these perturbations, resulting in the FTF. Excitation of each parameter occurred at a single frequency (sine dwell). This was done in 10 Hz intervals in the range of 10–400 Hz. Combining data

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