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Proceedings of the Combustion Institute 000 (2016) 1–11
Proceedings of the Combustion Institute
www.elsevier.com/locate/proci

Extracting flame describing functions in the presence of self-excited thermoacoustic oscillations

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Received 3 December 2015; accepted 7 June 2016
Available online xxx

Abstract

One of the key elements in the prediction of thermoacoustic oscillations is the determination of the acoustic response of flames as an element in an acoustic network, in the form of a flame describing function (FDF). In order to obtain a response, flames often have to be confined into a system with its own acoustic response. Separating the pure flame response and that of the system can be complicated by the non-linear effects that the flame can have on the overall system response. In this paper, we investigate whether it is possible to obtain a flame response via the usual methods of dynamic chemiluminescence and pressure measurements, starting from an unforced system with incipient self-excitations at a given frequency f_s, in the form of a stabilized flame at atmospheric pressure with a 700 mm tube as a combustor. The flame is forced at discrete frequencies from 20 to 400 Hz, away from the self-excitation, and the response of the flame is measured using OH* chemiluminescence. This response was compared to a flame response measured in a short tube with no other excitations.

The results show that both the gain and phase can be entirely dominated by the behavior of the self-excitation, so that in general it is not possible to extract reliable gain and phase information as if the forced and self-excited modes acted independently and linearly. Although the gain in this particular case was not significantly affected, the phase information of the original flame became dominated by the triggered self-excitation.

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http://dx.doi.org/10.1016/j.proci.2016.06.050

Please cite this article as: S. Balusamy et al., Extracting flame describing functions in the presence of self-excited thermoacoustic oscillations, Proceedings of the Combustion Institute (2016), http://dx.doi.org/10.1016/j.proci.2016.06.050

Boundary conditions and systems used for flame acoustic forcing therefore need to be carefully controlled whenever there is a possibility of self-excitation.

Keywords: Thermoacoustics; Nonlinear dynamics; Combustion instability; Turbulent premixed flames; Self-excited oscillations

1. Introduction

The principles that give rise to thermoacoustic oscillations in combustors have been known for over a century [1], but the methods of prediction of both the frequency and amplitude of such oscillations continue to be developed. Over the past twenty years, significant advances have been made in the use of nonlinear methods for quantitative prediction [2–6]. The overall behavior of the system has been shown to be reasonably accurately captured by a combination of acoustic network modeling, nonlinear flame describing functions (FDFs), and in some cases, entropy describing functions [7]. These functions are the gain and phase in heat release rate or entropy, respectively, due to the change in another scalar, typically the acoustic velocity perturbation.

Significant work has therefore been devoted to developing methods for measuring FDFs in a variety of flames. Most experimental rigs involve a method for forcing the input, typically via a loudspeaker or siren, while the flame response is measured via chemiluminescence of OH^* or CH^*, which have been shown to correlate linearly with the rate of heat release in premixed flames [8,9]. Experiments by Ćosić et al. [6] and earlier by Schuermans et al. [10] showed that it is also possible to experimentally obtain FDFs by measuring the transfer functions of acoustic waves across a flame via use of the multiple microphone method (MMM). These results were shown to approximate well the flame transfer functions (FTFs) measured using chemiluminescence under premixed conditions. Although the method requires an estimate of the post-flame temperatures, the key advantage is that it enables the measurement of FTFs under partially premixed conditions, where chemiluminescence measurements may be unreliable. The method demonstrated by Ćosić et al. [6] was deployed in a well controlled experiment at atmospheric conditions, with variable length sections both upstream and downstream of the flame. Previous work by Schuermans et al. [10] also used the same method in a high pressure combustor with a nearly anechoic (non-reflecting) downstream boundary. In many practical situations, however, such ideal conditions may not be produced, as it is often laborious and expensive to invest in large facilities with controlled boundaries at high pressure, or with long extensible moving sections.

In those situations, self-excited oscillations at a particular frequency may develop naturally at selected operating conditions, as a result of the nonlinear combination of boundary and operating conditions, and the very FDFs one wishes to measure. Such FDFs have in the past been extracted using high pressure facilities [11,12], even though a self-excited instability was present in the system at a particular frequency range. Previous work by Balusamy et al. [13] showed how forced oscillations under these conditions can excite or suppress natural self-excited oscillations. Experiments by Balachandran et al. [14] showed nonlinear interactions between two forcing frequencies, and the work by Schimek et al. [15] demonstrated the effect of forcing a system off its natural frequencies, but neither group compared their results to that of a system that was not self-excited. Finally, work by Moeck and Paschereit [16] and Bothien et al. [17] offered a comprehensive analysis of nonlinear interactions of multiple modes based on existing models of system nonlinear dynamics and control, offering a number of explanations for the findings in [14,15], and demonstrated the use of active changes in boundary conditions to control the onset of oscillations. In the present experiments, we consider the question of whether and how the response of a flame at the forcing frequency is affected by the presence of low level self-excited oscillations, to understand how these may affect measurements of flame response function in realistic systems.

2. Experimental setup

Experiments are performed on an axisymmetric swirl-stabilized burner (Fig. 1), which has been used before to study the forced response of stratified flames [18] and the interaction between forcing and self-excitation in premixed flames [13,19,20].

For this paper, premixed flames are created by mixing air and methane, both metered with mass flow controllers (Alicat MCR series, ± 0.2% FS). This reactant mixture is split into two streams that enter the mixing plenum via either a graduated bypass valve, or via a siren. The siren consists of a stator and a rotor, whose rotational speed determines

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