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Non-stationary local thermoacoustic phase relationships in a gas turbine combustor

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Abstract

A framework is presented for analyzing the local instantaneous phase difference between non-stationary heat release rate and pressure oscillations that is appropriate for use in high-pressure liquid-fueled combustors. High-speed OH* chemiluminescence images were used as a qualitative marker of the heat release rate, from which the local phase shift relative to the pressure was calculated using the Hilbert transform technique. Two types of behavior were observed during time sequences with constant amplitude pressure oscillations. For the first behavior, a region with out-of-phase pressure and heat release rate oscillations moved upstream along the nozzle shear layer towards the nozzle. For the second behavior, transitions occurred between out-of-phase oscillations in a region along the centerline and a toroidal region close to the nozzle. For time periods with increasing amplitude pressure fluctuations, in-phase heat release rate and pressure oscillations developed throughout the upstream portion of the combustor. These in-phase oscillations could extend along the burner centerline and towards the downstream portion of the combustor. This behavior is reversed during time periods with decreasing amplitude pressure oscillations; the upstream portion of the combustor transitions to featuring regions with out-of-phase oscillations.

Keywords: Thermoacoustic oscillations; Gas turbine combustion; Hilbert transform

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1. Introduction

This paper presents a method of experimentally analyzing non-stationary (temporally evolving) thermoacoustic oscillations that can be applied in high-pressure, liquid-fueled gas turbine combustors. Whether pressure (p) and heat release rate ($\dot{q}$) oscillation amplitudes increase, decrease, or remain stationary is determined by the balance between thermoacoustic driving and damping [1–3]. Given quasi-harmonic oscillations, this is controlled by the local phase shift between the pressure and heat release rate oscillations, along

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with the oscillation amplitudes. Coupled local heat release rate and pressure oscillations are a source (sink) of acoustic energy if they are less than (greater than) 90° out of phase. Hence, the nature of the coupling can be deduced from the phase shift field. The present investigation focuses on the local phase relationships between the pressure and heat release rate oscillations in a high-pressure liquid fueled gas turbine combustor.

An underlying challenge in the study of thermoacoustic oscillations is interpretation of experimentally-accessible $\dot{q}$ metrics at the relevant conditions, which are elevated-pressure multi-phase flows with large spatio-temporal variations in equivalence ratio. Quantification of planar laser induced fluorescence (PLIF)-based heat release rate through, e.g. OH/CH_2O PLIF or HCO PLIF, currently is not possible due to the need for composition-dependent quenching corrections, signal reduction due to pressure-induced line broadening, and signal trapping (self-absorption) through the high pressure gas [4–6]. Chemiluminescence-based $\dot{q}$ measurements are not quantitative in flows with strong equivalence ratio variations, are line-of-sight integrated, and also suffer from background CO_2^* chemiluminescence as well as signal trapping at high pressure [6,7].

These challenges are accentuated for non-stationary oscillations, which may occur during transition between operating conditions or during nominally stationary operation due to chaotic triggering of a quasi-deterministic large-scale dynamic process [8–14]. For example, Dawson and Worth [8] observed time-varying pressure oscillation amplitudes, as well as time-varying phase between pressure signals recorded at different azimuthal locations in an annular combustor. Studies in a single-element [11–13] combustor have reported time varying oscillation amplitudes as the flame chaotically transitioned between attached (V-shaped) and detached (M-shaped) flames. These transitions were associated with local flame based extinction, formation/attenuation of a precessing vortex core, and upstream flame propagation.

The majority of studies on self-excited thermoacoustically oscillating flames have been performed at stationary limit-cycle oscillations, e.g. [15–19]. Spatial heat release rate distribution has been quantified using phase-conditioned flame surface density (derived from OH PLIF) and/or line-of-sight integrated phase-conditioned chemiluminescence measurements [15,20–22]. The latter commonly are Abel inverted to produce pseudo two-dimensional phase-conditioned mean fields from the line-of-sight integrated measurements in axisymmetric flows [20,23]. Recently, phase-conditioned chemiluminescence tomography has been used to produce three-dimensional images in swirl flames with coherent asymmetries due to precessing vortex cores [23,24]. However, phase-conditioning cannot be applied to non-stationary data and, as described above, these methods of heat release rate measurement have high uncertainties at practical gas turbine conditions.

The objective of this work is to extend the experimental analysis of internal thermoacoustic oscillations to non-stationary behavior in high-pressure liquid-fueled flames that are relevant for aeronautical applications. Specifically, we aim to identify transient regions in which oscillations are being driven or damped based on the instantaneous phase shift between a heat release rate marker (OH* chemiluminescence) and the pressure. This framework does not require knowledge of the absolute heat release rate magnitude, and hence is robust to uncertainty in its measurement. Thus, in addition to this motive, the presented framework provides a potential means for comparison with numerical simulations based on the temporally evolving spatial distribution of in-phase and out-of-phase oscillation regions.

2. Experimental methodology

The analysis presented here utilizes data from a liquid-fueled gas turbine combustor configuration. A schematic of the experimental setup is presented in Fig. 1(a). The combustion chamber was installed inside a high pressure vessel that was equipped with fused silica windows for optical access. The chamber itself, shown in Fig. 1(b), was comprised of a single-piece of fused silica, having a square cross-section with a side length of $L = 125$ mm. The nozzle studied here had dual co-annular air swirlers and multi-point fuel injection, similar to that described in Ref. [25]. In the present study, fuel was only supplied to the inner air feed. As shown in the figure, the flow direction is from left to right. Also shown are the mean OH* chemiluminescence field and the extents of the measurement domain (described below).

An operating condition that exhibited non-stationary thermoacoustic oscillations at stationary inflow conditions is discussed here. Air was provided to the nozzle at pressure and temperature of $p/p_{\mathrm{crit}} = 0.42$ and $T/T_{\mathrm{crit}} = 0.84$, respectively, where the critical pressure and temperature are those of a typical single hydrocarbon surrogate fuel. The combustor was operated with the Jet A fuel at a total power of 600 kW.

Simultaneous OH* chemiluminescence and pressure measurements were performed in the present study. The chemiluminescence imaging suffers from line-of-sight integration and is only considered to provide a qualitative metric for the distribution of the heat release rate. This line-of-sight integrated nature of the measurements must be kept in mind during interpretation of the results. Because we are interested in instantaneous heat release dynamics, the data cannot be Abel inverted to

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