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Combustion instability feedback mechanisms in a lean-premixed swirl-stabilized combustor

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ABSTRACT

Constructive interference between heat release rate and acoustic perturbation is responsible for the growth of acoustic pressure amplitudes, leading to high-amplitude combustion instabilities in combustion systems. This is referred to as the Rayleigh criterion. Even though the knowledge of the heat release-acoustic pressure coupling processes is critical in the description of self-excited combustion instabilities, little is known about how the unsteady coupling processes are determined in response to the variation of time and length scales of acoustic and convective waves present in turbulent reacting flow fields. To address this issue, we performed a large number of measurements of self-excited instabilities, using two different tunable gas turbine combustors, over a wide range of operating conditions. The initiation, evolution, and saturation of pressure disturbances in swirl-stabilized combustion systems were systematically investigated by integrated analyses of pressure-heat release-velocity feedback coupling processes. It was found that self-excited combustion instabilities are governed by the Rayleigh criterion over the entire parameter space. We also observed that at certain inlet conditions, high amplitude velocity and heat release fluctuations coexist even without pressure-heat release coupling, meaning that the Rayleigh criterion is not necessarily associated with the onset of the self-excited instability. The Rayleigh criterion, however, does play an essential role in the linear to nonlinear transition that is necessary for the system to evolve toward a final state of stable limit cycles. We also found that the presence of equivalence ratio nonuniformities exerts a profound influence on instability feedback mechanisms, and consequently the Rayleigh criterion becomes a weak necessary condition for the occurrence of self-excited instabilities. A feedback mechanism that controls the relationship between velocity and acoustic pressure fluctuations was investigated to understand the effect of swirl number on limit cycle behavior. Acoustic admittance analysis reveals that at sufficiently high disturbance amplitude, nonlinear gas dynamic processes become so significant that the nonlinear saturation behavior cannot be defined by the acoustic velocity amplitude normalized by mean flow velocity.

1. Introduction

Combustion instabilities result from a feedback process of (i) inlet flow perturbations, (ii) heat release rate oscillations, and (iii) acoustic oscillations. The relationship between inlet flow perturbations and heat release rate oscillation is defined as flame transfer/describing functions (FTF/FDF), which have been the subject of intensive research over the past decades [1]. Experimental and theoretical investigations of the forced flame dynamics have contributed to the fundamental understanding of various instability driving mechanisms, including acoustic velocity fluctuations [2–4], equivalence ratio nonuniformities [5–9], swirl fluctuations [10–13], and entropy wave propagation [14–16].

The presence of multiple disturbances of different forms further complicates the problem [17]. For example, two different flow disturbances are present in a typical swirl-stabilized combustion system, even under completely premixed conditions [12, 18]. Azimuthal vortical disturbances are induced when an acoustic wave propagates through a swirler, and the interaction of those two disturbances plays a central role in the linear/nonlinear flame response [19,20]. The flame dynamics response to transverse acoustic forcing was investigated to elucidate the key physical processes that control the unsteady heat release fluctuations induced by hydrodynamic instabilities and vortical disturbances [21,22]. Measurements obtained from transverse acoustic excitation of swirling flames provided important insights into the flow/flame dynamics

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in an annular combustion chamber [23,24]. More detailed information can be found in comprehensive reviews by Huang and Yang [25] and Gicquel et al. [26].

The coupling of unsteady heat release and acoustic pressure can be described by means of the Rayleigh criterion [27], which states that the constructive interaction between heat release and acoustic fluctuations is responsible for growth of periodic limit cycles. The Rayleigh criterion is one of the most important conditions for the description of the stability of a combustion system, and therefore it has been extensively used to predict combustion dynamics [28–31]. Durox et al. [32] examined the Rayleigh criterion in two cases of self-excited oscillations involving unconfined laminar premixed flames, and they found that the Rayleigh criterion is well fulfilled by the wave field component corresponding to the pressure radiated back by the resonator investigated. Huang and Ratner [33] showed that acoustic forcing can induce shear layer vortices, which in turn cause flame surface modulations, manifested by intense toroidal structures in the Rayleigh index field. Geraedts et al. [34] demonstrated a method to reconstruct a 3D Rayleigh index field using high-repetition-rate OH* chemiluminescence measurements, and showed that a helical velocity disturbance coupled with a precessing vortex core can be identified. The 2-D Rayleigh index was also used by Broda et al. [28], who explored the mutual coupling between heat release fluctuation and acoustic oscillation. The use of the multi-dimensional Rayleigh index field allows visualization of the local reaction zones driving thermoacoustic oscillations. Care should be exercised in the interpretation of the Rayleigh index, however. It is not necessarily related to the fundamental mechanism that either initiates or sustains the instability. A visualization of the current state of a flame at a high amplitude oscillation state obscures the identification of the origin of the instability.

In addition to these experimental investigations, the flame-acoustic coupling has been studied theoretically [30, 35–37], more recently by Nicoud and Poinsot [38]. The theoretical investigation by Nicoud and Poinsot [38] suggests that the Rayleigh term based on the acoustic energy equation is insufficient to describe combustion dynamics driven largely by entropy fluctuations. Based on conservation equations for fluctuation energy in reacting flows, Nicoud and Poinsot [38] proposed a new stability criterion, in which temperature and heat release must be in phase to trigger the instability. Huang et al. [39] studied the influence of heat release on flow dynamics in a turbulent reacting environment using a triple decomposition technique, accounting for the energy transfer mechanisms between mean, periodic and turbulent fluctuations. It was shown from the theoretical investigation that the oscillatory motions can acquire energy through several different pathways, but the energy transfer from chemical reactions to the periodic flow field only takes place when heat release is in phase with pressure oscillation.

Most of the previous studies focused on the first process connecting flow disturbances and heat release oscillations, because the FTF/FDF is the most complicated, essential part of the problem. Instability feedback mechanisms, including heat release-acoustic pressure coupling ($q' - p'_c$) and acoustic pressure-flow disturbance coupling ($p'_c - u'$,$p'_c - \phi'$,$u' - v'_\theta$, or $u' - \phi'$), have received relatively limited attention. The evolution of the coupling process with respect to acoustic and convective wave interactions is already well documented, but it not yet understood to a sufficient extent. In the present paper, we investigate the instability feedback mechanisms, with emphasis on the heat release-acoustic pressure coupling and acoustic pressure-velocity coupling processes.

As explained earlier, the relationship between heat release rate and acoustic perturbation can be described using the Rayleigh criterion, which has been used as a standard tool for the analysis of self-excited instabilities in experiments and numerical simulations. As an example, Fig. 1 presents the dependence of combustor pressure amplitudes ($p'_c/\overline{p_c}$) on the phase difference between heat release rate and combustor pressure oscillations ($\varphi_{p'_c-q'}$). These self-excited instability data were measured in two different tunable gas turbine combustors over a broad range of operating conditions (inlet temperature, mixture velocity, equivalence ratio, fuel injection location, fuel injection pressure, swirler location, swirl number, fuel composition, and oxidizer composition) For a full description of the experimental program, see Ref. [40]. A total of ~15,000 data points is presented in Fig. 1. The data suggest that combustion instabilities occur only if heat release rate and pressure are in phase, that is, $0^\circ \leq |\varphi_{p'_c-q'}| \leq 90^\circ$. Note that the majority of the data points cluster around the origin. Conversely, no self-excited instabilities occur when the oscillations are out of phase, $90^\circ \leq |\varphi_{p'_c-q'}| \leq 180^\circ$. These experimental data clearly demonstrate experimentally the importance of the Rayleigh criterion as a necessary condition for the onset of combustion instabilities. The data also confirm that the Rayleigh criterion does not serve as a sufficient condition for the development of instabilities, given that there are numerous data points with negligible pressure amplitudes, although they satisfy the in-phase interference condition. This is attributed to three primary reasons; (1) the Rayleigh criterion does not include acoustic energy losses, (2) heat release fluctuations associated with entropy and vortical disturbances are not considered in the definition, and (3) the criterion does not include the effects of various instability driving mechanisms. It was shown that the flame dynamics are significantly influenced by the presence of convective waves, like vortical and equivalence ratio fluctuations. Therefore, the interpretation of the stability characteristics of a given system can be difficult, if the combined dynamics of acoustic and convective disturbances is not carefully considered [20].

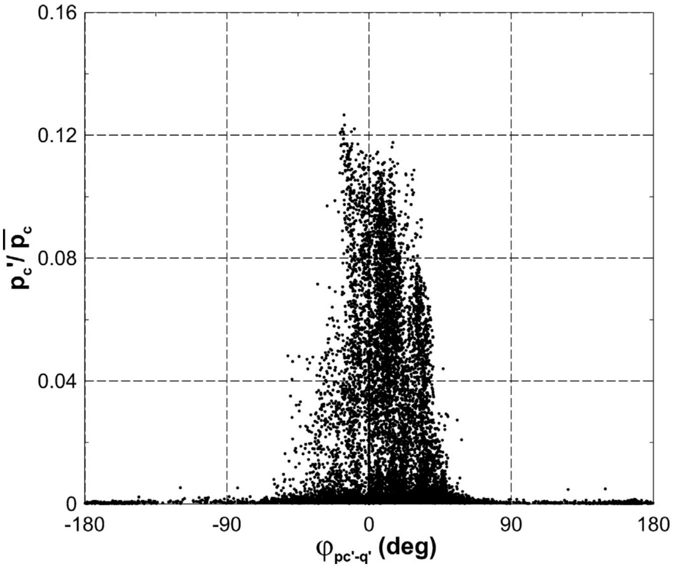

Fig. 1. Normalized combustor pressure amplitude plotted against the phase difference between pressure and heat release rate. Overbar and prime represent time-averaged quantity and Fourier component of oscillation at limit cycle frequency. A full description of the test conditions is shown in [40].

In the present paper we aimed to understand the pattern, evolution, and variability of the acoustic pressure-heat release coupling mechanism by analyzing self-excited instability data. The influence of equivalence ratio nonuniformities on the Rayleigh criterion was evaluated with systematic measurements conducted for variable fuel injection locations and fuel injector impedances. The dynamic response of a typical gas turbine swirl nozzle was analyzed using well-controlled measurements of the acoustic