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Measurements of triggering and transient growth in a model lean-premixed gas turbine combustor

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ABSTRACT

Instability triggering and transient growth of thermoacoustic oscillations were experimentally investigated in combination with linear/nonlinear flame transfer function (FTF) methodology in a model lean-premixed gas turbine combustor operated with CH_4 and air at atmospheric pressure. A fully premixed flame with 10 kW thermal power and an equivalence ratio of 0.60 was chosen for detailed characterization of the nonlinear transient behaviors. Flame transfer functions were experimentally determined by simultaneous measurements of inlet velocity fluctuations and heat release rate oscillations using a constant temperature anemometer and OH^*/CH^* chemiluminescence emissions, respectively. The phase-resolved variation of the local flame structure at a limit cycle was measured by planar laser-induced fluorescence of OH. Simultaneous measurements of inlet velocity, OH^*/CH^* emission, and acoustic pressure were performed to investigate the temporal evolution of the system from a stable to a limit cycle operation. This measurement allows us to describe an unsteady instability triggering event in terms of several distinct stages: (i) initiation of a small perturbation, (ii) exponential amplification, (iii) saturation, (iv) nonlinear evolution of the perturbations towards a new unstable periodic state, (v) quasi-steady low-amplitude periodic oscillation, and (vi) fully-developed high-amplitude limit cycle oscillation. Phase-plane portraits of instantaneous inlet velocity and heat release rate clearly show the presence of two different attractors. Depending on its initial position in phase space at infinitesimally small amplitude, the system evolves towards either a high-amplitude oscillatory state or a low-amplitude oscillatory state. This transient phenomenon was analyzed using frequency- and amplitude-dependent damping mechanisms, and compared to subcritical and supercritical bifurcation theories. The results presented in this paper experimentally demonstrate the hypothesis proposed by Preetham et al. based on analytical and computational solutions of the nonlinear *G*-equation [J. Propul. Power 24 (2008) 1390–1402]. Good quantitative agreement was obtained between measurements and predictions in terms of the conditions for the onset of triggering and the amplitude of triggered combustion instabilities.

1. Introduction

Unstable combustion oscillations can be initiated and sustained in a linearly stable system with disturbances of sufficiently large amplitude. These instabilities can be generated by even low-amplitude disturbances, which are of the same order of magnitude as the background noise level [1,2]. This is known as triggering, and it is one of the most important nonlinear phenomena in a combustion system. In light of the fact that self-sustained oscillations generated by triggering could reach very high amplitudes, the instability triggering phenomenon is physically and practically significant. Most previous studies on this unsteady phenomenon have been theoretical [3–7]. These investigations, which account for nonlinear gas dynamic processes, provide a theoretical background to explain the nonlinear saturation phenomenon observed in solid-propellant rocket engines. In lean-premixed gas turbine combustors, however, the gas dynamics generally remains in the linear regime, even under limit cycles, while the nonlinear combustion dynamics plays a critical role in saturation mechanisms [8]. This hypothesis has been confirmed by a series of experimental studies [9–14]. Recently, Balasubramanian and Sujith [15,16] showed that non-normality causes transient growth in a thermoacoustic system and Juniper [17] showed how this leads to triggering. Using the latter analysis, Waugh et al. [18] showed how triggering can be caused by low levels of noise.

Most previous studies on triggering have been performed using theoretical methods, due primarily to the difficulty of developing

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well-controlled systematic experiments. The crucial work by Noiray et al. [19] revealed that several nonlinear features of a premixed combustion system, including limit cycle amplitudes, hysteresis, mode switching, and finite-amplitude triggering, can be suitably predicted using a flame describing function (FDF) framework in combination with linear acoustic theory. Using this novel method, they are able to anticipate whether a given system will be susceptible to triggering, based on the position of an unstable periodic solution [20]. Lieuwen [21] showed from an analysis of steady state time series data that inherent noise in the system can strongly affect the combustor's transition from stable to unstable operation, but the transient dynamics of the system were not examined thoroughly in that study.

While the above-mentioned studies have contributed to an improved understanding of the transient triggering phenomena, the fundamental mechanisms of the occurrence of triggering and the relationship between triggering and the nonlinear heat release response are still unclear. The present paper describes triggering and transient growth in a model gas turbine combustor using linear/nonlinear transfer functions and amplitude-dependent system damping energy. Before the measurement data are presented, the amplitude response of heat release, $H(A)$, for the flame subjected to harmonic acoustic forcing with varying frequency, f, and amplitude A is discussed, because the evolution of the heat release response correlates strongly with the occurrence of triggering.

In recent studies on the response of premixed and partially premixed flames, it was found that the heat release response $H(A)$ exhibits drastically different amplitude dependence depending on inlet conditions [22]. As an example, Fig. 1 presents hypothetical driving and damping processes with respect to perturbation amplitude. At small perturbation amplitude, the heat release response $H_1(A)$ is larger than the damping term $D(A)$, here assumed to be linear with amplitude A, which leads to positive initial growth rate of inherent disturbances in the combustor, meaning that the combustion system is linearly unstable. The nonlinear heat release saturation of $H_1(A)$ gives rise to limit cycle oscillations at high amplitude when $H_1(A) = D(A)$. The evolution pattern of $H_2(A)$ with respect to perturbation amplitude is more interesting. At small amplitude, the system is stable. With a sufficiently large impulse, the thermoacoustic system can "trigger" self-induced oscillations. The system is linearly stable but can support sustained oscillations at sufficient input amplitude. Nonlinear combustion processes, such as the instability triggering phenomenon, cannot be explained from a linear point of view. The third amplitude-dependent driving curve, $H_3(A)$, exhibits two distinct saturation points. The first saturation point occurs at low amplitude. The flame response levels off beyond the first saturation point, and gradually increases with amplitude. The heat release response levels off again at sufficiently large amplitude. Irrespective of the nonlinearity, the heat release response does not exceed the damping energy of a given system. Therefore, a stable limit cycle cannot be achieved. The last example, $H_4(A)$, has the unique dynamic characteristic that the flame response remains in the linear regime even at sufficiently high amplitude [11]. Similar observations on the evolution of flame describing functions were reported by Thumuluru and Lieuwen [23], Balachandran et al. [9], Bellows et al. [10,24], and Lieuwen and Neumeier [25].

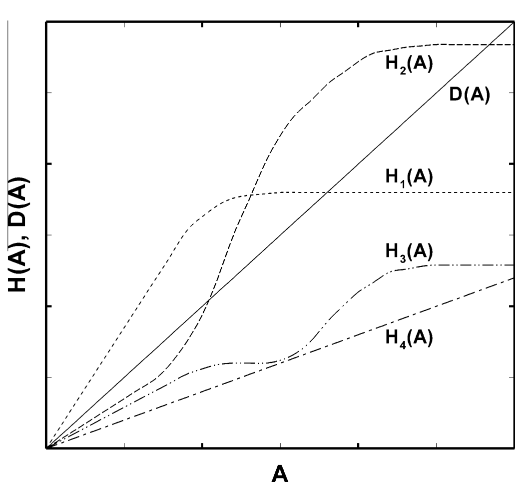

Fig. 1. Hypothetical driving $H(A)$ and damping $D(A)$ processes (adapted from Preetham et al. [26]). The four driving processes, $H_i(A)$, represent typical flame describing functions in response to harmonic acoustic forcing, measured in the swirl burner.

A typical example of unsteady flame front evolution in the face of triggered thermoacoustic oscillations is presented in Fig. 2, showing instantaneous OH PLIF distributions of a premixed flame at six different phase angles during a period of limit cycle oscillation. These OH PLIF images were taken in a swirl burner (see Fig. 3). The frequency and the intensity of the triggered instability are $f = 186$ Hz and $u'/U = 0.75$, respectively. This is the strongest instability mode in all operating conditions investigated in the present study. The phase-synchronized OH PLIF distributions clearly show that the combustion zone oscillates back and forth significantly. The variations in flame angle are remarkable. At $\theta = 120°$, in particular, the flame position is nearly vertical. When the reaction zone moves downstream at $\theta = 240–300°$, the flame surface is affected by the interaction between the flame and counter-rotating large-scale flow structures. During the limit cycle oscillation, the local flame fronts are strongly wrinkled, due to the strong turbulence-flame interactions. Isolated regions often appear to emerge in the single-pulse OH PLIF images, presumably due to local extinction/ignition events or 3D flame structures. The flame front oscillation generates strong fluctuations of volumetric gas expansion, which in turn produces an intense sound emission in the combustion chamber. If the frequency of this oscillation coincides with one of the eigenmodes of a given system, an acoustic-combustion resonant interaction occurs.

The present experimental investigation shows that the high-amplitude triggered instability shown in Fig. 2 is observed only when the trajectories of the driving and damping processes follow the relationship between $H_2(A)$ and $D(A)$. Note that the $H_2(A)$ curve has an inflection point at a certain amplitude. Using an analytical approach which accounts for flame sheet kinematics, Preetham et al. [26] found that under certain inlet conditions, the nonlinear heat release response exhibits an inflection point, and such a system will manifest nonlinear characteristics such as hysteresis and triggering. This scenario, proposed based on a theoretical investigation, is explored here in a well-controlled experimental configuration. The objectives of the present paper are: (i) to explain the relationship between the nonlinear onset of a triggering and FTF/FDF, (ii) to identify detailed processes of transient growth leading to saturation, (iii) to give an explanation for measured triggering phenomena using subcritical and supercritical bifurcations, and (iv) to propose a methodology for predicting conditions in which instability triggering phenomena may be developed in a system.

2. Experimental methods

2.1. Swirl burner

An axisymmetric, laboratory-scale, lean-premixed burner was used in this investigation. It is illustrated schematically in Fig. 3A. This burner consists of an air inlet section, a siren, a mixing section, an optically-accessible quartz combustor section, and an exhaust section. Air is introduced and mixed with the fuel (meth-