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Proceedings of the Combustion Institute xxx (2014) xxx–xxx

Proceedings of the Combustion Institute

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Nonlinear dynamics of a self-excited thermoacoustic system subjected to acoustic forcing

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Abstract

We experimentally study the nonlinear dynamics of a self-excited thermoacoustic system subjected to acoustic forcing. Our aim is to relate these dynamics to the behavior of universal model oscillators subjected to external forcing.

The self-excited system under study consists of a swirl-stabilized turbulent premixed flame (equivalence ratio of 0.8 and thermal power of 13.6 kW) enclosed in a quartz tube with an open-ended exit. We acoustically force this system at different amplitudes and frequencies, and measure its response with pressure transducers and OH^* chemiluminescence from the flame. By analyzing the data with the power spectral density and the Poincaré map, we find a range of nonlinear dynamics, including (i) a shifting of the self-excited frequency towards or away from the forcing frequency as the forcing amplitude increases; (ii) an accompanying transition from periodicity to two-frequency quasiperiodicity; and (iii) an eventual suppression of the self-excited amplitude, indicating synchronization of the self-excited mode with the forced mode. By further analyzing the data with the Hilbert transform, we find evidence of phase trapping, a partially synchronous state characterized by frequency locking without phase locking.

All of these dynamics can be found in universal model oscillators subjected to external forcing. This suggests that such oscillators can be used to accurately represent thermoacoustically self-excited combusting systems subjected to similar forcing. It also suggests that the analytical solutions to such oscillators can be used to guide the reduction and analysis of experimental or numerical data obtained from real thermoacoustic systems, and to identify effective methods for open-loop control of their dynamics.

Keywords: Thermoacoustics; Nonlinear dynamics; Combustion instability; Turbulent premixed flames; Low-order modeling

1. Introduction

Despite decades of research, thermoacoustic instability remains one of the biggest challenges facing manufacturers of gas turbines. In these devices, the acoustics is usually linear,[1] but the flame's heat-release response to incident perturbations is highly nonlinear [1]. The overall thermoa-

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[1] This is because the perturbation Mach number remains small even when the acoustic velocity fluctuation is large.

http://dx.doi.org/10.1016/j.proci.2014.05.029
1540-7489/

coustic system is therefore expected to behave like a coupled nonlinear dynamical system.

In a linear analysis, the flame response to perturbations at different frequencies is assumed to be the sum of the flame response at each of those frequencies. However, studies have shown that this is an oversimplification because significant energy can be transferred between frequencies, for example between a self-excited mode and a forced mode [2,3]. Crucially, in both simple and complex thermoacoustic systems [4,5], the oscillations are not necessarily periodic, but can be quasiperiodic, frequency-locked, chaotic, or synchronized with external forcing. Such systems can also exhibit mode switching as a result of the coexistence of two or more stable attractors. For a rigorous analysis, therefore, it is necessary to consider the system's response (i) in state space and/or (ii) at all frequencies, even when it is externally forced at only one.

In this paper, we take a dynamical systems approach to studying the nonlinear interaction between self-excited oscillations and forced oscillations in a combustor containing a swirl-stabilized turbulent premixed flame. Recent studies have shown that the forced response of hydrodynamically self-excited jets and flames at low Reynolds numbers can be explained by the forced response of simple (low-dimensional) model oscillators with weak nonlinearity [6–8]. Our aim is to see whether this also applies to a thermoacoustically self-excited system at a higher Reynolds number.

2. Experimental setup

Experiments are performed on an axisymmetric swirl-stabilized burner (Fig. 1). This burner has been used before to study the forced response of stratified flames [9] and the triggering of a premixed thermoacoustic system [10].

For this paper, a premixed flame is 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: (i) one that enters a mixing plenum via a graduated bypass valve, and (ii) one that enters the same mixing plenum via a siren. The siren is used to generate acoustic velocity perturbations. It consists of a stator and a rotor, whose rotational speed determines the forcing frequency and is controlled by a variable-speed motor (EZ motor Model 55EZB500). The forcing amplitude is independently controlled by varying the opening of the graduated bypass valve.

The mixing plenum is 1000 mm long and consists of two concentric tubes (diameters: 15.05 and 27.75 mm) and an axisymmetric centerbody (diameter: 6.35 mm). The downstream ends of both tubes are aligned flush with the end of the

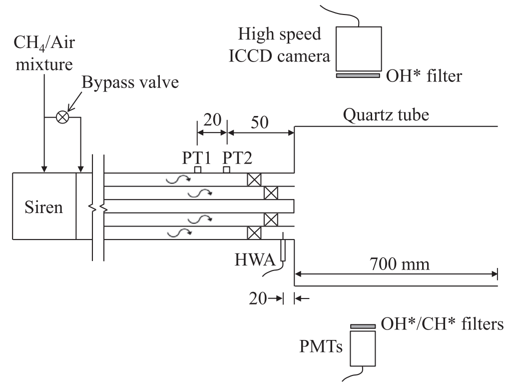

Fig. 1. Schematic of the swirl-stabilized turbulent premixed burner.

centerbody to form a well-defined burner exit. For flame stability, two axial swirlers are mounted in each annular section. Each swirler has six swirl vanes, of thickness 0.5 mm, aligned at 45° to the flow. For this geometry, the swirl number (i.e. the ratio of tangential to axial momentum) is estimated to be 0.55. Downstream of the burner exit is the combustor, which consists of a stainless steel dump plane and an optically accessible fused-silica tube with an inner diameter of 94 mm and a length of 700 mm. The exit of this tube is at ambient conditions. For certain flame conditions (Section 3.1), this combustor geometry supports thermoacoustically self-excited oscillations at the fundamental (longitudinal) mode of the tube.

These oscillations are examined by measuring the dynamic pressure in the mixing plenum with two pressure transducers (Model 40BP GRAS), one mounted 70 mm (PT1) and the other 50 mm (PT2) upstream of the dump plane. From these, the acoustic velocity fluctuation is calculated using the two-microphone technique [11] and the results are validated against hot-wire measurements taken 20 mm upstream of the dump plane in cold-flow conditions. The normalized pressure fluctuations from PT1 and PT2 are almost identical, so only the PT1 data will be used for characterizing the system's pressure response.

As an additional indicator, the global OH^* (308 ± 10 nm) and CH^* (430 ± 10 nm) chemiluminescence from the flame is measured using two photomultiplier tubes (Thorlabs model PMM01) fitted with bandpass filters. As is typical for premixed flames, the chemiluminescence emission is assumed to be proportional to the total heat-release rate. The normalized chemiluminescence intensities of OH^* and CH^* are almost identical, so only the OH^* data will be used for characterizing the system's heat-release response.

At each test point, the data are sampled at a frequency of 8192 Hz for 4 s on a data acquisition system (National Instruments, BNC-2111), resulting in a spectral resolution of 0.25 Hz and a

Please cite this article in press as: S. Balusamy et al., *Proc. Combust. Inst.* (2014), http://dx.doi.org/10.1016/j.proci.2014.05.029