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A method to identify thermoacoustic growth rates in combustion chambers from dynamic pressure time series

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Abstract

The stochastic nature of combustion instabilities in practical land-based gas turbines and aeroengines combustors has seldom been investigated. It is shown here that a wealth of information about the constructive acoustic-flame interactions can be gained by scrutinising the effects of the inherent turbulence-induced noise, which forces the nonlinear thermoacoustic dynamics. In particular, one presents a method, based on the Fokker–Planck formalism, to identify from dynamic pressure signals the linear growth rates, the type of flame response nonlinearity and the potential defining the system acoustic energy. It is applied to and validated against experimental data measured in a lab-scale combustion chamber.

Keywords: Combustion instabilities; Stochastic Van der Pol oscillator; Super-critical Hopf bifurcation; Fokker–Planck equation; Output-only system identification

1. Introduction

For decades, thermoacoustic instabilities in practical combustors for aeronautics, aerospace and power generation have been a paramount recurring problem [1]. Due to the lack of cost-effective actuators, passive damping technologies constitute the vast majority of thermoacoustic instability control systems. It has been shown that robust damper design requires the knowledge of the thermoacoustic linear growth rates [2,3]. Up to now, only linear decay rates providing stability margin could be quantified, because the system identification (SI) methods used to process pressure data necessitate linearly stable conditions, e.g. [4]. Recently, it has been shown that one can take advantage of the presence of inherent turbulent combustion noise – whose effect on thermoacoustic dynamics has rarely been investigated, e.g. [5,6] – to extract linear growth rates from limit cycle data [7,8]. One of the methods proposed in [7] is for the first time validated using turbulent combustion experiments. In contrast with input-output SI strategies, widely applied to numerical simulations [9] and laboratory experiments, such output-only SI technique does not require the use of actuators. It therefore provides key data for practical-system thermoacoustic-network-models validation [10].

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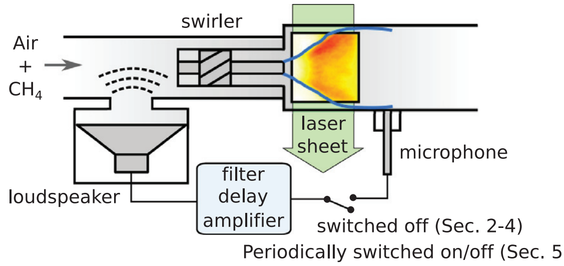

Fig. 1. Cylindrical combustion chamber featuring quartz windows and equipped with an axial-swirler burner. The test rig is operated in a premixed mode at atmospheric pressure (≃ 30 kW). Real-time feedback control using microphone sensing and loudspeaker actuation can be switched on to modulate the upstream flow based on the controller output.

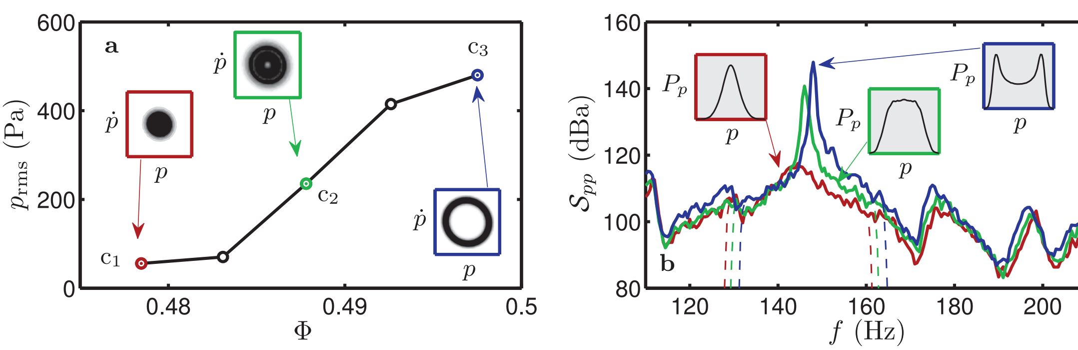

Fig. 2. The control loop is switched off. (a) Acoustic level as function of equivalence ratio Φ and joint probability density functions $P(p, \dot{p})$. (b) Power spectral densities $\mathcal{S}_{pp}$ and acoustic pressure probability density functions $P(p)$ for conditions c_{1-3}.

2. Experimental set-up

A sketch of the experimental set-up used for this study is given in Fig. 1. This cylindrical combustion chamber is operated at atmospheric pressure. The thermal power is approximately 30 kW. Methane is pre-mixed with heated air (573 K) upstream of a flow straightener (not shown on the sketch) in order to avoid acoustically triggered equivalence ratio fluctuations. The turbulent swirled V-type flame [11] is anchored at the rim of the lance equipped with an axial swirler (estimated swirl number 0.5). The bulk flow axial velocity downstream the swirler is 17 m/s. The acoustic pressure in the combustion chamber is measured by using a calibrated water-cooled microphone (Brüel & Kjaer, 4939). When the equivalence ratio Φ is varied from 0.47 to 0.5 by increasing the fuel mass flow, the acoustic level in the combustion chamber sharply increases due to the constructive interaction between the flame and one of the longitudinal acoustic modes. This is shown in Fig. 2a together with the joint probability density functions (PDF) $P(p, \dot{p})$ of the acoustic pressure p and its time derivative $\dot{p}$ at three conditions c_1, c_2 and c_3. Note that the pressure signal taken to compute the $P(p)$ and $P(p, \dot{p})$ has been filtered around the peak at 150 Hz (see dashed lines in Fig. 2b) which corresponds to the self-excited thermoacoustic mode. At condition c_3, $P(p, \dot{p})$ and $P(p)$ respectively exhibit a ring-like and a bimodal distributions, which is typical of stochastic limit cycle oscillation. In contrast, at condition c_1, the PDF has a gaussian like distribution, which is characteristic of randomly excited linearly stable oscillator.

The transition between thermoacoustically "stable" and "unstable" conditions occurs at the same equivalence ratio, whether coming from rich or lean side. In addition to this observation, the identified flame response nonlinearity (presented later in Section 4) indicates that there is no hysteresis behaviour as the ones investigated for instance in [12–15]. Particle image velocimetry (PIV) is performed at condition c_3. The upstream flow is seeded by diverting part of the air through a fluidised bed filled with Al_2O_3 particles (median diameter of 0.8 μm). The frequency-doubled output of the dual-head Nd:YLF laser (Quantronix Darwin Duo) is stretched into a light sheet and passes through the side quartz windows of the combustor. The image pairs are captured with a LaVision HSS6 camera at 1 kHz and processed using LaVision PIV software to obtain the proper orthogonal decomposition (POD) from 2 s data. The time-averaged flow field and line-of-sight

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