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Numerical study on intrinsic thermoacoustic instability of a laminar premixed flame

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ABSTRACT

A study on the velocity sensitivity and intrinsic thermoacoustic stability of a laminar, premixed, Bunsen-type flame is carried out. Direct numerical simulation (DNS) of the flame, placed in an acoustically anechoic environment and subjected to broad-band, low-amplitude acoustic forcing, generates time series of fluctuating heat release rate, velocities and pressure. The time series data is post-processed with system identification to estimate the impulse response and transfer function of the flame. The associated frequency response is validated against experiment with good accuracy. DNS results obtained with acoustic excitation from the inlet or outlet boundary, respectively, confirm that the flame responds predominantly to perturbations of velocity. The stability of eigenmodes related to intrinsic thermoacoustic feedback is investigated with a network model. Both stable and unstable intrinsic thermoacoustic modes are predicted, depending on details of the configuration. The predicted modes are directly observed in direct numerical simulations, with good agreement in frequencies and stability.

1. Introduction

Thermoacoustic combustion instabilities have been an important subject of combustion research for many decades, originating from the enormous problems encountered during the design and test of rocket engines [1,2]. The increased interest in recent years is due to the occurrence of thermoacoustic instabilities in gas turbine power-plants, aero engines and other low emission combustion systems, which often operate under lean premixed conditions [3,4].

The established understanding of self-excited thermoacoustic instabilities involves feedback between unsteady heat release by the flame and acoustic waves in fuel and air supply and the combustion chamber: The unsteady flame acts as a monopole source of sound and generates acoustic waves, which are reflected by the combustion system back towards the flame, where they perturb in turn the heat release rate. This feedback loop may go unstable provided phase lags are favorable [5] and the loss of perturbation energy not excessive.

In the simplest case, premix flames are described as *velocity sensitive*: the global heat release rate $\dot{Q}'$ responds to perturbations u' of velocity upstream of the flame. The link between these two quantities is commonly given in terms of the *flame frequency response* or *flame transfer function* $\mathcal{F}(\omega)$, such that

$$\frac{\hat{\dot{Q}}(\omega)}{\bar{\dot{Q}}} = \mathcal{F}(\omega)\ \frac{\hat{u}(\omega)}{\bar{u}}, \tag{1}$$

or the corresponding flame impulse response $h(t)$

$$\frac{\dot{Q}'(t)}{\bar{\dot{Q}}} = \frac{1}{\bar{u}} \int_0^T h(\tau)\ u'(t-\tau)\ \mathrm{d}\tau. \tag{2}$$

In these equations, ($'$) denotes the deviation of a quantity from its mean value ($\bar{\ }$) and the ($\hat{\ }$) stands for the Fourier transform. The symbols ω and τ represent angular frequency and time delay, respectively. T accounts here for the duration of the impulse response $h(t)$.

The flame transfer function (FTF) as defined in Eq. (1) has been used extensively in the study of thermoacoustic instabilities of laminar and turbulent flames. Experimentally, the FTF is typically evaluated by imposing a sinusoidal excitation of the flow upstream of the flame and by measuring the corresponding response in heat release $\hat{\dot{Q}}(\omega)$ [6–11]. Sinusoidal excitation also gives satisfactory results in numerical studies of flame dynamics [12,13], but only at considerable computational cost. The identification of the flame response through the corresponding impulse response $h(\tau)$ – see Eq. (2) – offers an alternative, which is computationally more efficient. This method was introduced in the work of Polifke et al. [14],

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Zhu et al. [15] and Gentemann et al. [16], and subsequently used and refined in a number of studies [17–20]. Once the flame transfer function is known, it can be implemented in analytical dispersion relations [21–23], network models [21,24,25] or Helmholtz solvers [26–28] to study the thermoacoustic stability of combustion systems.

The present paper originated from an attempt to estimate the dynamics of a laminar premix flame by direct numerical simulation (DNS) combined with system identification (see the Ref. [29] for a description of the approach and previous applications in aero- and thermoacoustics). A computational model (case B in Section 4.2) with acoustically non-reflecting boundary conditions was set up, because it is understood that low reflection coefficients foster accurate identification [30]. However, it was observed that this computational model responded to low amplitude broad-band excitation with very strong, resonant, low-frequency oscillations in flame shape and heat release rate, such that identification of the flame dynamics in the limit of linear behavior was not possible. This was not expected, since acoustically non-reflecting boundaries imply a significant loss of acoustic energy. Furthermore, the low frequencies of the exhibited thermoacoustic instability could not be explained. Due to the small size of the domain, any acoustic cavity resonances would occur at frequencies much higher than that of the combustion dynamics.

Hoeijmakers et al. [31] observed in an independent study that low-order acoustic network models of a combustion system with zero acoustic reflection coefficients can indeed possess unstable eigenmodes. This might appear unphysical at first sight, because non-reflecting boundaries should break the feedback between the flame and the system acoustics introduced above. However, Hoeijmakers et al. [31] demonstrated analytically with a simple n-τ model for the flame dynamics that under some conditions the flame scattering matrix may indeed be an "intrinsically unstable element". An interpretation of the physics of the instability was not developed, but instabilities observed in a combustion test rig with low acoustic reflection coefficients [32] lend some support to the argument that flame-acoustic coupling may be intrinsically unstable.

A physics-based explanation of Intrinsic Thermo-Acoustic (ITA) modes in terms of flow – flame – acoustic interactions was developed by Bomberg et al. [33]. The interactions were analyzed in a representation that respects causality, i.e. a formulation that allows to distinguish input from output signals and thus cause from effect. In this framework a thermoacoustic feedback loop intrinsic to the thermo-acoustic coupling was identified, which may go unstable, or exhibit resonant amplification. As a result, the generation of acoustic energy by a perturbed flame may exhibit very strong peaks, which can be associated with poles of the flame scattering matrix ([34,31]).

The ITA feedback loop was detailed by Bomberg et al. [33] and Emmert et al. [34] as follows: a flow perturbation u' just upstream of the flame causes perturbations that are convected along the length of the flame and cause in turn a fluctuation in heat release rate $\dot{Q}'$, see Eq. (1). The fluctuation $\dot{Q}'$ then generates acoustic waves that propagate away from the flame. The acoustic wave propagating in the upstream direction modulates the upstream velocity u', thus closing the feedback loop. A more detailed analysis of the "physics" of ITA feedback and the structure of the corresponding modes is given by Courtine et al. [35].

In the light of these findings, it was understood that the unexpected behavior of the laminar premix flame DNS described above should be interpreted as a result of resonance of the external excitation with the ITA feedback loop. Without persistent excitation, the DNS develops a strong instability, which can be identified as an unstable ITA mode (see Section 4.2). Further analysis of the case with low-order models helped to identify a configuration where the intrinsic mode is stable, such that identification of flame dynamics is possible.

Before completion of the present study, several questions, which indeed are strongly related to each other, were pending. It was questioned whether the thermoacoustic intrinsic instability is a real physical phenomenon or merely a spurious result of simplistic network models. Furthermore, it was debated whether the response of a compact premixed flame is actually velocity sensitive, or whether flame dynamics should be described as a response also to pressure. In addition, more direct evidence for the validity of the ITA feedback as described by Bomberg et al. [33] was sought. Accordingly, the present study has the following objectives: First, to demonstrate, by Direct Numerical Simulation, that the ITA feedback is an authentic physical phenomenon that is present in premixed combustion systems. Second, to give evidence, by an adequate identification of the FTF, that compact laminar premixed flames indeed respond predominantly to perturbations of upstream velocity and thus may be treated as velocity sensitive elements. Furthermore, we confirm that thermoacoustic network models in conjunction with the identified FTF are indeed capable of analyzing the stability of ITA modes.

This article is organized as follows. In the next section, a brief overview of system identification is given. In the third section the flame transfer function of the laminar flame under study is estimated with DNS/SI, by imposing upstream as well as downstream broadband acoustic forcing, and validated against experimental and computational results published previously [36,12]. Results are analyzed under the description of a laminar premix flame considered as a velocity sensitive element. In the fourth section, low-order models of a burner-stabilized laminar flame are developed to compute the frequencies and growth rates of acoustic modes for various acoustic reflection coefficients of the inlet–outlet boundaries, including the limiting cases of zero reflection coefficients. Stable as well as unstable intrinsic modes are found, depending on the details of the configuration. Corresponding results from DNS of laminar premix flame corroborate the results of the low order models, and some properties of the ITA mode are studied.

In concluding this study, the reader is cautioned that intrinsic thermoacoustic instabilities are not to be mistaken for intrinsic thermo-diffusive or hydrodynamic instabilities of premix flames, as reviewed e.g., by Clavin [37].

2. Overview of system identification

In order to infer a model of the relation between inputs and outputs of a system, system identification uses the information contained in corresponding time series data [38]. If a Single Input Single Output (SISO) system, considered as a *black box*, is assumed to be Linear Time Invariant (LTI), it is then completely characterized by its Impulse Response (IR). Be aware that the IR is a property of a such a system, not a model. When the system does not exhibit internal feedback, i.e. when the outputs of the system can be assumed to be related to the input by merely time delays, a model for the system can be written as

$$r_t = b_0 s_t + b_1 s_{t-1} + \cdots + b_{n_b} s_{t-n_b}, \tag{3}$$

where r_t and s_t denote the output and the input of the system at discrete time t, respectively. In this case, the IR of the system can be modeled as a polynomial

$$G(q) = b_0 + b_1 q^{-1} + \cdots + b_{n_b} q^{-n_b}, \tag{4}$$

where the shift operator is defined by the property $q^{-k} s_t = s_{t-k}$. The coefficients b_k describe the response of the system to a unit impulse