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Thermal versus acoustic response of velocity sensitive premixed flames

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Abstract

Premixed flames respond to velocity perturbations with fluctuations in heat release rate ("thermal response"), which in turn generate acoustic perturbations ("acoustic response"). The latter may subsequently influence the velocity field in such a manner that feedback leads to self-excited thermoacoustic instability. The present paper investigates interrelations between the thermal and the acoustic responses of premix flames. The analysis is formulated such that it properly represents the underlying causality of acoustics–flow–flame–acoustics interactions. A flame-intrinsic feedback loop is revealed, which is quite independent of the acoustic environment of the flame, i.e. the acoustic impedances of plenum and combustor. The eigenmodes of this flame-intrinsic feedback loop coincide with poles of the acoustic scattering matrix of the flame. The corresponding frequencies, where the acoustic response is maximum, are in general quite different from frequencies where the thermal response is strong, i.e. where the flame transfer function exhibits "excess gain". Even more remarkable, the intrinsic flame modes may result in thermoacoustic instabilities without lock-on to one of the acoustic eigenmodes of the combustor. Experimental results from two combustor test rigs with laminar conical as well as turbulent swirl flames are scrutinized and are found to confirm our analysis. In particular, unstable modes are identified that are strongly related to flame-intrinsic feedback.

Keywords: Thermoacoustic instability; Combustion dynamics; Flame transfer function; Premixed flame; Causality

1. Introduction

Thermoacoustic instabilities are a cause for concern in combustion applications ranging from domestic burners to rocket engines. Such instabilities are understood to result from flame–acoustic feedback: unsteady combustion generates acoustic perturbations, which are reflected by combustor or plenum such that acoustic waves travel back to the flame, where they modulate the heat release rate. This feedback may lead to self-excited oscillations, possibly causing fatigue or structural damage [1]. In order to avoid thermoacoustic instability, careful analysis of the system dynamics

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should be conducted at every stage of the design process.

Thermoacoustic instability is in general conceptualized as a non-local phenomenon, which depends on the combined dynamics of the combustion process and the combustor acoustics, possibly including air or fuel supply. A comprehensive thermoacoustic analysis of a combustion system by experiment or simulation is thus difficult and expensive. Simplified, low-order models for the flame dynamics on the one hand, and the system acoustics on the other hand have often proven useful. The present study also makes use of such tools.

One may distinguish the "thermal response" from the "acoustic response" of a flame to flow perturbations: The former describes fluctuations in heat release rate, the latter acoustic perturbations generated by unsteady heat release rate. Both thermal and acoustic response are of significant interest in combustion dynamics, and both may exhibit substantial magnitude at favorable frequencies. In the present paper, the thermal and acoustic responses of velocity sensitive premixed flames are compared against each other and their interrelations are investigated. Remarkably, it is shown that a significant amplitude in thermal response does not imply a strong acoustic response, and vice versa.

A distinctive feature of the analysis presented in this paper is that the relevant thermoacoustic processes are represented in a manner that properly respects the causality of acoustics–flow–flame–acoustics interactions, i.e. the principle of cause and effect. Non-trivial dynamics with internal feedback are thereby revealed and one finds that flame-intrinsic modes may emerge, which are in a sense quite independent from the system acoustics. Strong acoustic response of a flame is seen to result from near resonance with one of the intrinsic modes.

The existence of flame-intrinsic modes represents an important departure from established thinking, which conceptualizes thermoacoustic instabilities as acoustic modes excited by fluctuating heat release. It is emphasized that flame-intrinsic modes are essentially thermoacoustic in nature and not a consequence of hydrodynamic, thermo-diffusive or parametric acoustic instabilities [2,3]. The study of Hoeijmakers et al. [4,5], who investigated the thermo-acoustic stability of premix flames in configurations with very low acoustic reflection coefficients, provides independent evidence of flame-intrinsic modes.

2. Model formulation

In thermoacoustic stability analysis, one often resorts to a "divide and conquer" strategy: A model of the system acoustics is combined with a suitable model for the flame dynamics in terms of a flame transfer or flame describing function F [6]. So-called low-order "network models" represent a popular implementation of this approach, which makes possible an efficient, physics-based analysis of the various interaction mechanisms and their impact on system stability. In this section, the model formulation used in this study is introduced. Emphasis is put on the concepts of signal flow and causality. Note that the implications of the analysis presented here are not limited to low-order network models, but should be entirely general.

2.1. Acoustic variables and causality

When formulating a linear acoustic model, flow quantities ϕ (i.e. pressure p, velocity $\underline{u}$, etc.) are decomposed into a steady mean field $\overline{\phi}$ and an acoustic perturbation ϕ',

$$\phi(x,t) = \overline{\phi}(x) + \phi'(x,t). \tag{1}$$

The propagation of acoustic waves can be described in terms of characteristic wave amplitudes f and g, which travel in the downstream and upstream direction, respectively:

$$f = \frac{1}{2}\left(\frac{p'}{\overline{\rho}\,\overline{c}} + u'\right), \tag{2}$$

$$g = \frac{1}{2}\left(\frac{p'}{\overline{\rho}\,\overline{c}} - u'\right). \tag{3}$$

Unlike the "primitive acoustic variables" u' and p', a direction of propagation is associated with the characteristic waves, which allows to discriminate between cause and effect (or excitation and response).

Models formulated in terms of variables which properly represent the underlying causality make it easier to visualize and interpret consistently the signal flow, and hence the system dynamics. For example, Polifke and Gentemann have shown that causality may be important for the proper interpretation and identification of (aero-) acoustic effects [7]. Therefore, the present analysis is carried out in such a framework.

2.2. Network models

An acoustic network consists of a number of interconnected two-port elements. When formulated in the frequency domain, the unknowns are the complex-valued amplitudes of fluctuations of velocity u' and pressure p', or characteristic waves f and g (see above) at the ports of the elements comprising the network. Providing boundary conditions and assembling the unknowns in a state vector yields a homogeneous system of equations. Solutions of the characteristic equation ("determinant of the system matrix = 0") yield the eigenvalues $s_m = j\omega_m + \sigma_m, m = 1, 2, \ldots$ of the