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Intrinsic thermoacoustic instability of premixed flames

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ABSTRACT

The thermoacoustic stability of velocity sensitive premixed flames is investigated. A causal representation of the flow-flame-acoustic interactions reveals a flame-intrinsic feedback mechanism. The feedback loop may be described as follows: An upstream velocity disturbance induces a modulation of the heat release rate, which in turn generates an acoustic wave traveling in the upstream direction, where it influences the acoustic velocity and thus closes the feedback loop. The resonances of this feedback dynamics, which are identified as *intrinsic eigenmodes* of the flame, have important consequences for the dynamics and stability of the combustion process in general and the flame in particular. It is found that the amplification of acoustic power by flame-acoustic interactions can reach very high levels at frequencies close to the intrinsic eigenvalues due to the flame-internal feedback mechanism. This is shown rigorously by evaluating the "instability potentiality" from a balance of acoustic energy fluxes across the flame. One obtains factors of maximum (as well as minimum) power amplification. Based on the acoustic energy amplification, the small gain theorem is introduced as a stability criterion for the combustion system. It allows to formulate an optimization criterion for the acoustic characteristics of burners or flames without regard of the boundary conditions offered by combustor or plenum. The concepts and methods are exemplified first with a simplistic $n-\tau$ model and then with a flame transfer function that is representative of turbulent swirl burners.

1. Introduction

The dynamics and stability of flames are fascinating and multifaceted phenomena, which have been important and popular topics in combustion research [1,2]. From a fundamental point of view, thermo-diffusive or hydrodynamic flame instabilities might be most interesting [3–5], while phenomena such as blow off or flash back are very relevant for combustion engineering, see e.g. Kröner et al. [6], Aggarwal [7], Cavaliere et al. [8].

The present paper focuses on thermoacoustic instabilities, which result from an interaction between fluctuations of heat release rate and acoustic waves [9]. Starting with the development of rocket engines in the 1930s, thermoacoustic instabilities have impeded severely the development of reliable combustion equipment. The development of lean-premixed, low-emission combustion technology for stationary gas turbines has increased the technological relevance of these instabilities, their prediction and control remains a challenging task with great scientific appeal [10,11].

Thermoacoustic instabilities are usually conceptualized as a coupled feedback loop involving burner, flame, combustion chamber and plenum (possibly also fuel or air supply, etc): Fluctuations of heat release act as a monopole source of sound [12], the resulting acoustic waves are reflected by the combustion chamber or the plenum and in turn modulate the flow conditions at the burner, which successively perturb the flame and thus close the feedback loop [10,13]. If the resulting relative phase between fluctuations of heat release and pressure at the flame are favorable, a self-excited instability may occur [9]. In this well-established framework, thermoacoustic instabilities are considered a result of the *combined* dynamics of the flame and its acoustic environment, i.e. plenum, burner, combustor, supply lines, etc.; a flame placed in a anechoic environment should not be able to develop a thermoacoustic instability.

The present paper develops a different point of view: thermoacoustic interactions at the flame are analyzed in a framework that properly respects the causal relationships between "excitation" and "responses", respectively. With this perspective, it becomes evident that *flame-intrinsic feedback* between acoustics-flow-flame-acoustics may give rise to *intrinsic flame instabilities*, which are distinct from the resonating acoustic eigenmodes of the environment of the flame. Nevertheless, these instabilities are

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Nomenclature

CWA	characteristic wave amplitude
$F(s)$	flame transfer function, –
f	downstream traveling CWA, m s^{-1}
g	upstream traveling CWA, m s^{-1}
$\mathbf{H}$	energy amplification matrix, –
λ_{max}	maximum sound power amplification, –
n	interaction index, –
ω	frequency, rad s^{-1}
Ω	closed loop denominator of flame feedback, –
OLTF	open loop transfer function of flame feedback, –
p'	acoustic pressure fluctuation, Pa
$\vec{\varrho}$	vector of emitted rescaled CWAs, W
s	laplace variable $(= j\omega + \sigma)$, rad s^{-1}
σ	growth rate, rad s^{-1}
$\vec{\varsigma}$	vector of incident rescaled CWAs, W
$\mathbf{S}$	scattering matrix, –
$\mathbf{\Sigma}$	energy scaled scattering matrix, –
τ	time delay, s
θ	relative temperature jump $(= T_d/T_u - 1)$, –
u'	acoustic velocity fluctuation, m s^{-1}
ξ	ratio of specific impedances $(= \rho_u c_u/\rho_d c_d)$, –

Subscript indices

bf	burner and flame
f	flame
u	upstream
d	downstream

thermoacoustic in nature, and thus differ essentially from other types of "intrinsic flame instabilities in premixed and non-premixed combustion", as reviewed by Matalon [5].

In an independent study, Hoeijmakers et al. [14] explored strategies for preventing thermoacoustic instabilities by breaking the aforementioned feedback loop and also observed that a flame can be intrinsically unstable. Experiments were carried out in a setup with significant acoustic losses, induced by acoustic horns. The stability behavior was investigated for three different burners, and a range of operating conditions. It was observed that despite the significant acoustic losses present, thermoacoustic instabilities may still occur [15]. Of course, these results are very closely related to the ideas developed in the present paper. Lending further support to the argument, Bomberg et al. [16] have identified intrinsic flame eigenmodes in experimental setups investigated previously by Noiray et al. [17] and Komarek and Polifke [18], respectively.

The paper is organized as follows: The next chapter introduces first the low-order modeling concepts that are used to formulate ideas. Then the intrinsic thermoacoustic feedback structure of a velocity-sensitive premixed flame is identified. The corresponding spectrum of intrinsic eigenmodes is determined for the simple example of an $n-\tau$ flame transfer function. In the subsequent section, a balance for the flow rates of acoustic energy at a premixed flame is formulated, introducing the "instability potentiality" [19,20]. It is found that frequencies where generation of perturbation energy by fluctuating heat release is maximal correlate with the intrinsic eigenfrequencies of the flame. Invoking the small gain theorem originally deduced by Zames [21], it is then shown how these results are related to a general stability criterion for network models. This leads to an optimization criterion for individual elements in acoustic networks, which might be used to optimize burner designs independently from up- or downstream acoustic conditions at an early stage of combustor development. The tools and concepts developed up to that point are then applied to a more realistic flame transfer function, which is representative of turbulent premixed swirl flames. The analysis in the present paper is formulated in terms of a low-order model for velocity sensitive premixed flames. Nevertheless, implications should go beyond the limitations of the present study and indeed be fairly general, as discussed in the conclusions.

2. Intrinsic thermoacoustic feedback in a velocity-sensitive premixed flame

Our investigation is focused on the dynamics of the coupling between the heat release of the flame and the acoustic waves incident to and emitted from the flame. There is a causal chain of events, consisting of the acoustic waves altering the flow field, which leads to a fluctuation in heat release, which in turn generates acoustic waves. For premixed flames, the heat release fluctuation is typically caused by a velocity perturbation u' upstream of the flame. Thus the flame does not respond directly to incident acoustic waves, but to an upstream flow perturbation. The physical mechanism involved may be flame front kinematics, a convective transport of fuel inhomogeneities or a swirl modulation and possibly other effects.

For example in the case of premixed flames with technical fuel injection, a modulation of air velocity u' at the location of fuel injection results in an equivalence ratio modulation ϕ', which convects downstream. For an acoustically "stiff" injector, positive u' gives a leaner mixture and negative u' a richer mixture, whereas pressure p' has no effect. Once the fuel inhomogeneities arrive at the flame, they cause heat release rate fluctuations.

On the other hand, inside a swirler, in response to a perturbation of velocity, a wave in swirl number (or circulation) is set up, and the flame responds later to the swirl modulation as shown by Straub and Richards [22] as well as Komarek and Polifke [18]. Palies et al. [23] have coined the term "mode conversion" for this effect where an acoustic wave generates a vortical wave. Again, the cause for this generation of swirl modulation is u' at the swirler, p' at the swirler is unimportant.

As a last example, according to the Unit Impulse Response model of the G-equation by Blumenthal et al. [24], the "restoration term" of the flame front kinematics is triggered by movement of the flame at the anchoring point. The physical mechanism for this generic flame model may be vortex shedding at a backward facing step. So again, u' at the anchoring point is important and the flame transfer functions respect this causality as they relate u' to $\dot{Q}'$.

Other than deducing causality from first principles, it is substantially harder to retrieve it from experiments. The reason is, that in frequency domain, no discrimination between causes and consequences is possible and therefore, no causality can be inferred from measured results of harmonic solutions. But there is also numerical evidence for the causal relation between a velocity perturbation and heat release fluctuations of laminar premixed flames. Jaensch et al. [25] have identified and validated causal time domain models for the flame transfer function of such a flame from random time series simulation of a CFD model.

Low-order modeling concepts are used throughout this paper to formulate ideas. The present chapter introduces very briefly pertinent nomenclature and concepts, more details are found, e.g.