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Acoustic and intrinsic thermoacoustic modes of a premixed combustor

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Abstract

Premixed flames are velocity sensitive, i.e., they react to a velocity perturbation at the burner mouth, say, with fluctuations in heat release rate. Unsteady heat release generates acoustic waves that travel back from the flame to the burner mouth, where they modulate the velocity and thereby close an *intrinsic thermoacoustic* (ITA) feedback loop. The present paper demonstrates that corresponding ITA eigenmodes are in general important for the dynamics and stability of premixed combustion systems. It is shown that the complete set of eigenmodes of a combustor test rig should be interpreted as the sum of acoustic and ITA eigenmodes. A procedure is presented which allows to distinguish between eigenmodes that may be considered as acoustic modes driven by the flame, versus those resulting from ITA feedback (but influenced by the acoustic properties of the combustor). This procedure is based on a factorization of the dispersion relation of the thermoacoustic model. Differences between the acoustic and intrinsic eigenmodes of a combustor test rig, in particular the corresponding mode shapes, are discussed. The paradoxical observation that increased acoustic losses at the boundaries may destabilize a combustion system is explained as an instability of the dominant ITA mode.

Keywords: Intrinsic thermoacoustic feedback; Premixed flame; Thermoacoustics; Combustion dynamics

1. Introduction

Thermoacoustic stability of combustion systems as diverse as gas turbines and domestic burners is important for emissions, noise and wear. Such devices possess acoustic modes (also known as "cavity modes"), which may be attenuated or amplified by the unsteady heat release. According to Rayleigh [1], the amplification is driven by heat release fluctuations in phase with pressure oscillations. The common perception is that instability occurs due to acoustic eigenmodes becoming unstable if the driving by the flame exceeds the damping by acoustic losses inside the device and at the boundaries [2].

Recently it was discovered that premixed flames can exhibit thermoacoustic instability even if non-reflective boundary conditions enforce that

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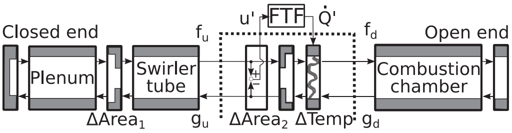

Fig. 1. Scheme of the premixed combustion test rig network model, flow from left to right.

resonant acoustic modes cannot exist [3–5]. Bomberg et al. [6] identified the mechanism causing such instabilities as an intrinsic thermoacoustic (ITA) feedback. This mechanism may be summarized as follows: Premixed flames are *velocity sensitive*, i.e., they react with fluctuations in heat release to a perturbation of velocity at an upstream location, say at the burner mouth. Heat release fluctuations act as a volume source and generate upstream traveling acoustic waves, which in turn cause upstream velocity perturbations. Even if the ITA modes caused by the feedback are stable, they are associated with the amplification of acoustic power scattered by burner and flame of a system [7]. Therefore, ITA modes may be distinguished from the acoustic modes of the system. Note that they should not be confused with thermo-diffusive intrinsic instabilities of premixed flames.

Corroborating experimental work by Hoeijmakers et al. [8], we demonstrate in this paper that unstable ITA modes are encountered not only in idealized configurations with non-reflecting boundaries [3–5], but play in general an important role also in combustor configurations of applied interest. At first the linear acoustic network model of the investigated combustor test rig as depicted in Fig. 1 is introduced. The pure acoustic modes are obtained by removing the flame dynamics from the full combustor model (Fig. 3a). Stripping the upstream and downstream sections of the full combustor results in a pure ITA system (Fig. 3b). Eventually a procedure is presented that shows how the eigenmodes of the full combustor system relate to the pure acoustic and the pure ITA modes, respectively (Fig. 3c). The total number of eigenmodes is equal to the sum of acoustic and ITA modes. The frequency of the dominant ITA mode in the test rig we investigate is between the frequencies of a Helmholtz mode and the quarter wave mode of the combustion chamber. Eventually the paradox that damping of acoustic modes by introducing losses at the boundaries can destabilize a thermoacoustic system—as previously observed in numerical simulation by Silva et al. [5]—is explained as a result of ITA feedback.

2. The premixed combustion test rig network model

Linear, low-order acoustic network models have proven their capability to predict thermoacoustic instabilities in experiment [9–12] and simulation [5]. By construction, such models take into consideration the relevant interactions between velocity, heat release rate and acoustics and thus capture also the effects of ITA feedback. This justifies the use of a low-order network model to demonstrate the existence and impact of ITA modes on the dynamics of a combustion system with reflective boundaries.

Table 1
Parameters of the test rig network model.

Name	Parameters
Closed end	Reflection coefficient $r_C = 1$ Inlet: Ma $= 0.0011$, $c = 343\text{ms}^{-1}$ $\rho = 1.2\text{kgm}^{-3}$
Plenum	Duct, $l_P = 0.17$m
Δ Area 1	Area ratio $\alpha_1 = A_u/A_d\|_1 = 29.76$
Swirler tube	Duct, $l_S = 0.18$m
Δ Area 2	Area ratio $\alpha_2 = A_u/A_d\|_2 = 0.13$
Δ Temperature	Linearized energy equation, $\theta = (T_d - T_u)/T_u = 5.59$ Ratio of specific impedances $\xi = \rho_u c_u/\rho_d c_d = 2.57$
Combustion chamber	Duct, $l_C = 0.70$m
Open end	Reflection coefficient $r_O = [-1, 0]$
FTF	Identified from LES [12], see Fig. 2

The configuration investigated in the present study is depicted in Fig. 1, with model parameters specified in Table 1. It represents a turbulent, perfectly premixed, swirl stabilized single burner test rig that was experimentally investigated by Komarek and Polifke [13]. Tay-Wo-Chong et al. [12] analyzed a similar model of the test rig with a length of the combustion chamber $l_C = 0.7$m. Whereas the model of Tay-Wo-Chong et al. [12] was a classical frequency domain low order network model, here linear state space models are used, as described by Emmert et al. [14]. Propagation of acoustic waves is modeled by 1D linearized Euler equations, which are spatially discretized using a third order upwind scheme. The frequency range of interest extends to 500 Hz, which is below the cut on frequency of the plenum $f_{co} = 1.84\, c/(2\pi r) \approx 1000$ Hz, with $r = 0.10$m. All area changes are modeled as acoustically compact elements without losses or correction factors. The axial swirler is assumed to be acoustically transparent. The flame is modeled as an acoustically compact temperature discontinuity with superposed heat release fluctuations. According to the different temperature levels in plenum and combustion chamber, there are different densities and speeds of sound upstream and downstream of the flame.

As illustrated in Fig. 1, the network model can be divided into four parts: the upstream and downstream sections (u,d), the acoustic part of the burner mouth and flame (b), and the unsteady heat release of the flame (f).

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