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A theoretical study of mean azimuthal flow and asymmetry effects on thermo-acoustic modes in annular combustors

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Abstract

The objective of this paper is to develop an analytical model to capture two symmetry breaking effects controlling the frequency and nature (spinning, standing or mixed) of azimuthal modes appearing in annular chambers: (1) Using two different burner types distributed along the chamber (2) Considering the mean azimuthal flow due to the swirlers or to effusion cooling. The ATACAMAC (Analytical Tool to Analyze and Control Azimuthal Modes in Annular Chambers) methodology is applied using the linearized acoustic equations with a steady and uniform azimuthal mean flow. It provides an analytical implicit dispersion relation which can be solved numerically. A fully analytical resolution is possible when the annular chamber is weakly coupled to the burners. Results show that symmetry breaking, either by mixing burners types or with a mean azimuthal flow, splits the azimuthal modes into two waves with different frequencies and structures. Breaking symmetry promotes standing modes but adding even a low azimuthal mean flow fosters spinning modes so that the azimuthal mean flow must be taken into account to study azimuthal modes.

Keywords: Azimuthal; Theoretical; Instabilities; Mean flow; Symmetry

1. Introduction

Thermoacoustic unstable modes are a major problem in combustion systems and they take a specific form in annular chambers. In modern gas turbines, azimuthal modes can develop in a frequency range which coincides with longitudinal modes [1–4]. The nature of these azimuthal modes has been the topic of multiple past studies since the pioneering works of companies like Siemens [1] or Alstom [5] who showed that both spinning or standing azimuthal modes could be observed in an annular gas turbine. Five years ago, the development of powerful LES techniques applied to full annular combustors [6,7] showed that

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azimuthal modes could change nature randomly, evolving from spinning to standing structure at random instants. Experiments have also been developed [8,9], confirming LES results but also raising additional questions, for example linked to the effect of outlet conditions on the development of modes. Various theories have been proposed [5,10–13], focusing on two questions: (1) what controls the nature and the occurrence of azimuthal modes? and (2) is it possible to suppress them? Most solutions focus on breaking symmetry, for example by mixing burners with different unsteady responses in a given chamber.

A major limitation of both experimental and LES studies in this field is cost. To understand azimuthal modes, simpler tools which allow to explore their basic nature in idealized configurations, are needed. Such tools can be built using network approaches and fully analytical methods [14–16]. Recently, analytical studies have progressed in two directions: (1) Linear theories based on network models [15–17] where the acoustic-flame behavior is assumed linear and modeled by a Flame Transfer Function (FTF) while major features of the configuration are retained such as complex burners, both annular plenum and chamber, mean flow etc. These studies are usually performed to determine the stability of the configuration but can also predict linear effects on mode structure. (2) Non-linear theories based on linearized Galerkin methods [5,13] where the configuration is usually reduced to a simple annulus with zero or an infinite number of burners and no plenum but the acoustic-flame behavior is non-linear and modeled using a Flame Describing Function (FDF). Non-linear approaches are especially designed to study limit cycles and mode structures but they require simplifications. Both linear and non-linear analytical tools, as well as Helmholtz solvers, can only investigate the nature of the two components A and B of the azimuthal modes but fail to estimate their respective amplitudes. Especially, the ratio A/B is ignored and the final structure cannot be fully determined analytically: it requires experiments or high fidelity simulations.

This paper develops a linear approach to investigate two linear mechanisms controlling azimuthal modes by breaking symmetry: (1) Geometrical symmetry (GS) breaking by mixing burners with different responses and (2) Flow symmetry breaking by introducing a mean swirling motion (SM) in the annular chamber. The SM mechanism is shown to play a strong role: it makes the period of the two modes (co-rotating with the mean swirl and counter rotating) different because propagating at $c + w$ or $c - w$ (where w is the swirl velocity and c the sound speed in the chamber). This 'splits' azimuthal modes (which are usually degenerate at zero Mach number) into two distinct modes. This effect is dominant compared to GS breaking and results suggest that the nature of azimuthal modes in annular chambers cannot be analyzed in the zero Mach number limit but must incorporate the effects of a mean azimuthal velocity. All applications are performed for a chamber containing 4 burners but conclusions are expected to be valid for real chambers (N $\simeq$10–30).

2. The analytical model

2.1. Model description

Consider a configuration where N burners feed a 1D annular chamber (Fig. 1). The length and section of the i^{th} burner are noted L_i and S_i while the perimeter and the cross-section of the annular chamber are $2L_c = 2\pi R_c$ and S_c respectively. Points in the burners are located using the axial coordinate z where $z = 0$ designates the upstream end and $z = L_i$ the burner/chamber junction. The i^{th} compact flame location is given by the normalized abscissa $\alpha = z_{f,i}/L_i$. The position in the annular cavity is identified by the angle θ defining the azimuthal coordinate $x = R_c\theta$. An impedance Z is imposed at the upstream end of each burner ($z = 0$).

This model is limited to purely azimuthal modes where acoustic fluctuations in the chamber depend only on the azimuthal coordinate (θ or $x = R_c\theta$): it does not apply to academical setups open to the atmosphere [8,9,18] but corresponds well to real chambers terminated by a choked nozzle ($w' = 0$). Mean density and sound speed are noted ρ^0 and c^0 in the annular chamber and in the hot part of the burners ($\alpha L_i < z < L_i$) and ρ_u^0 and c_u^0 in the cold part of the burners ($0 < z < \alpha L_i$).

Different types of burners are used to study GS breaking (Section 3.4) and a mean azimuthal flow is imposed in the chamber to study SM breaking (Section 3.3). This mean flow field is supposed to be one dimensional, steady and uniform:

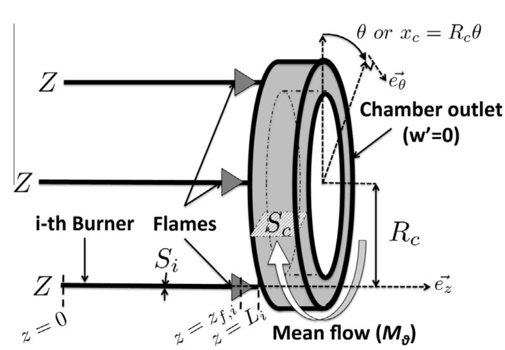

Fig. 1. Configuration to study unstable modes in annular chambers with a steady and uniform azimuthal flow (constant Mach number M_θ).