# Coupling a Helmholtz solver with a Distributed Flame Transfer Function (DFTF) to study combustion instability of a longitudinal combustor equipped with a full-scale burner

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## Abstract

Lean premixed combustion chambers used in modern gas turbines for power generation are often affected by thermo-acoustic combustion instabilities. Previous experiments as well as theoretical and numerical investigations indicate that the modes involved in this process may develop in the longitudinal direction and the azimuthal direction depending on the geometry of the combustor. The present article reports a numerical analysis of instability coupled by longitudinal modes. This corresponds to experiments carried out in the LRIA (Longitudinal Rig for Instability Analysis) test facility equipped with a single full-scale industrial burner for power generation. The dynamic response of the flame is described by means of a distributed n-$\tau(\mathbf{x})$ flame transfer function (FTF) model, where the space distribution of the time delays is derived directly from Reynold averaged Navier-Stokes (RANS) simulations. Coupling this model with an acoustic Helmholtz solver results in a linear stability problem from which frequency and growth rate ($\alpha$) of the thermo-acoustic modes of the system are analyzed. The influence on the stability analysis of the length of the combustion chamber is investigated in a second step. The numerical results are compared with experiments showing a good correspondence in the stability ranges and wave shapes of the unstable modes.

## Introduction

Modern gas turbines for power generation equipped with lean premixed dry low NOx combustion systems suffer the problem of thermo-acoustic combustion instability. This phenomenon is characterized by self-sustained pressure oscillations, which arise from the loop coupling between unsteady heat release produced by the flame and the acoustic waves of the system [1]. The pressure oscillations may become so large to cause loss of combustion efficiency, an increase of pollutant emissions and, if prolonged over time, deterioration of combustion chamber. Over the years, different approaches have been developed aiming to study this phenomenon. Computational fluid dynamics (CFD) simulations, particularly Large Eddy Simulation (LES), have been demonstrated to be able to reproduce numerically the main effects of the phenomenon but large numerical resources are required[2]. The

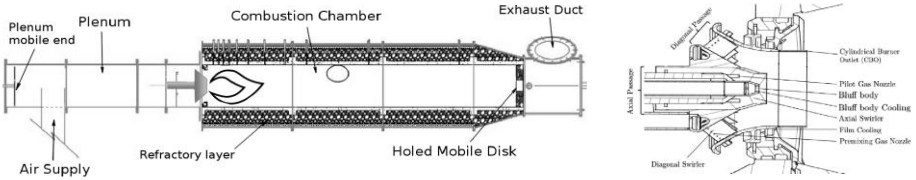
Helmholtz solver approach performs an eigenmode analysis focusing on the coupling mechanism between acoustic waves and heat release rate fluctuations. In premixed flames, it is generally recognized that heat release fluctuations are coupled to velocity oscillations occurring at a reference upstream section after a time lag [1] and are treated as a source term into the acoustic equation. In the frequency domain the differential equation problem is converted into a eigenvalue problem and solved by means of a Finite Element Method (FEM) acoustic code [3]. From the eigenvalues of the system, it is possible to ascertain if one mode is stable or unstable, within the limits of the linear stability analysis [4]. In order to validate the analytical and numerical models, experimental data are required. In this context, the CCA (Centro Combustione e Ambiente) and Ansaldo Energia have developed the Longitudinal Rig for Instability Analysis (LRIA) test facility to test full-scale burner [5]. In this article, the thermo-acoustic behavior of this combustor is examined with a Helmholtz solver approach [6, 7]. The mean reactive flow is calculated by means of CFD simulations. The linear stability analysis is performed coupling the wave equation with a distributed - flame transfer function with the distribution of time delays computed from the RANS simulations [8]. The analysis is performed for several configurations with different lengths of the combustion chamber. The numerical stability limits are compared with the experimental results showing a good agreement both in frequency and in wave shape of the unstable modes.

## The Experimental Setup

The LRIA test facility consists of an atmospheric longitudinal combustor equipped with a single full-scale industrial burner for energy generation [5]. The length of the combustion chamber can be varied continuously during tests by means of a multi-holed perforated disk with a flow passage area of equivalent diameter equal to 150 mm. The area ratio of the disk is the 7.4% designed in order to have an acoustic behavior as closest as possible to an ideal wall , differently from previous works where an anechoic condition was searched [6, 7]. The maximum achievable length variation is equal to 2 m. *Figures 1(A)* shows a schematic picture of the system. In *Figure 1 (B)* is shown the burner that equipped the examined configuration of the system. The combustion air is flows through two different coaxial swirlers, diagonal and axial, with the main air flow passing through the diagonal passage. The premixed mixture is formed in the diagonal passage by mixing with natural gas that is injected through gas nozzles located in the swirling vanes. Only the premixed line is operated when base load condition is reached. In the configuration examined in this article, the total air mass flow rate is 1.3 kg/s pre-heated at 600 K before reaching the plenum. The global fuel/air equivalent ratio is equal to 0.51 corresponding to a lean condition slightly above the flammability limit for premixed combustion of methane [9]. In these conditions, the generated total mean heat power is almost 2 MW.

## Reynold Average Simulations of the Reactive Flow

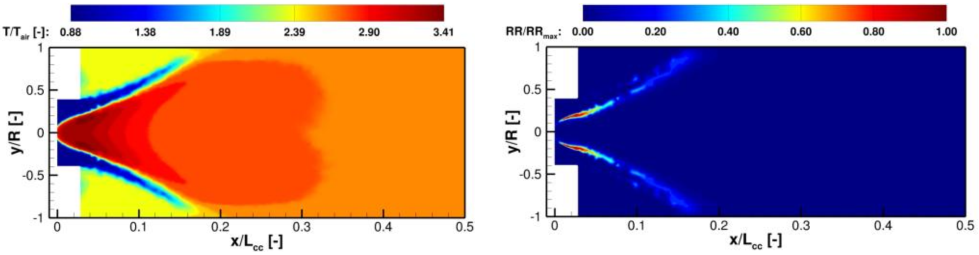
Reynolds Average Navier Stokes (RANS) simulations are performed in order calculate the three-dimensional fields of the thermodynamics quantities of the mean flow.



(A) (B)

**Figure 1.** (A) The schematic of the LRIA combustor. (B) The schematic of the full-scale burner equipped in the analysed configuration.

A classical three-step methane oxidation mechanism has been used to simulate the combustion process. Figure 2 reports the contour plots of the fields of temperature (Figure 2 (A)) and rate of reaction of the $CH_4$ oxidation (Figure 2 (B)) taken on a slice of the combustion chamber. Further details of these RANS simulations and a comparison between results from LES simulation can be found in *Ref.* [5].



(A) (B)

**Figure 2.** Contour plot of the mean field of the (A) temperature and (B) reaction rate of the CH4 oxidation.

## The Thermo-acoustic Model

The derivation of the mathematical model used for thermo-acoustic studies is briefly discussed hereafter. The complete formulation can be found in *Refs. [10, 11]*.

Equation (*1*) shows the equation of pressure perturbations for reactive flows derived from the Euler equations with the hypothesis of treating the fluid as an ideal gas and neglecting the mean flow, the viscous losses and the heat conduction

(1)

is the fluctuations of the heat release rate per unit volume, is the mean density, *t* and *c* are, respectively, the time and the sound velocity. In the frequency domain, *equation (1)* becomes

—— —— —— (2)

with - where *i* is the imaginary unit and is the complex angular frequency. *Equation (2)* is referred to as the non-homogeneous Helmholtz equation. A relation to correlate the unsteady heat release rate oscillations with the pressure fluctuations is needed. Following *Ref.* [12], a time delay - flame transfer function is assumed, where *n* is the acoustic-combustion interaction index that control the amplitude of the flame response and is the time delay between the acoustic perturbation measured at reference point and the heat release oscillations measured at the flame front. From the RANS simulations, this time delay is computed at each point on the flame front. In the frequency domain, this model results

—— – ( 3 )

The mean heat release is defined as where RR(x) is the reaction rate reported in *Figure 2 (B)* and is the lower heating value of methane. In this study, *n* is assumed equal to unity for all frequency. *Figure 3* shows the contour plot of time delay reported on the flame front.

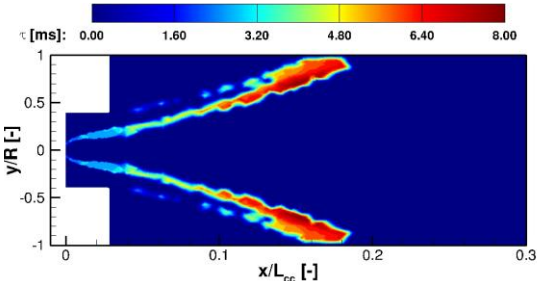


**Figure 3.** Contour plot of the time delays on the flame front

*Equation (2)* coupled with *equation ( 3 )* results in a quadratic eigenvalue problem that is solved around an eigenvalue linearization point with an Arnoldi algorithm. Given the complex angular frequency solution of the study, its real part gives the frequency of the thermo-acoustic mode, while its imaginary part can be used to define the growth rate, - . If is positive the mode is unstable, i.e., the amplitude of fluctuations grow exponentially in time; otherwise, if is negative the mode is stable and perturbations decay.

## Experimental and Numerical Results

The conditions of combustion instability have been found by varying the length of the combustion chamber. Correspondingly, the linear stability curve of the system colored with respect to the value of the combustion chamber length has been evaluated numerically (*Figure 4*). Each point of the curve corresponds to a stability analysis of the system in terms of frequency and growth rate . The ranges of frequencies around which instability has been registered experimentally are highlighted in the pink zones. The model is proved to be able to predict the stability margins of the system. *Figure* 5 shows a good comparison of the numerical and experimental wave shape of the unstable mode in the configuration with both in the plenum and in the combustion chamber The experimental wave shape has been reconstructed by means of the Multi-Microphone-Method starting from the pressure transducers measurements. Comparisons for the other configurations can be found in *Refs*. [6, 8]

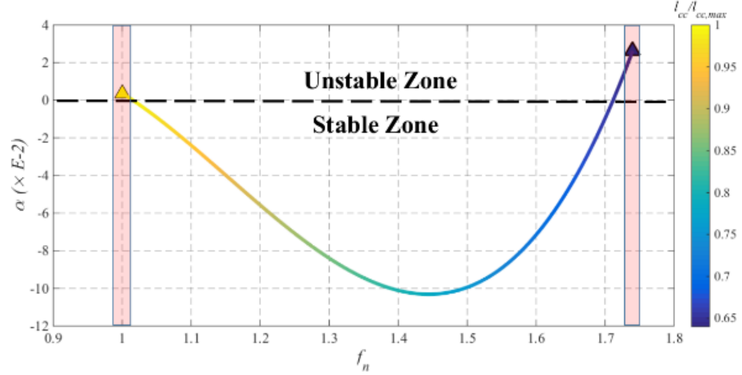
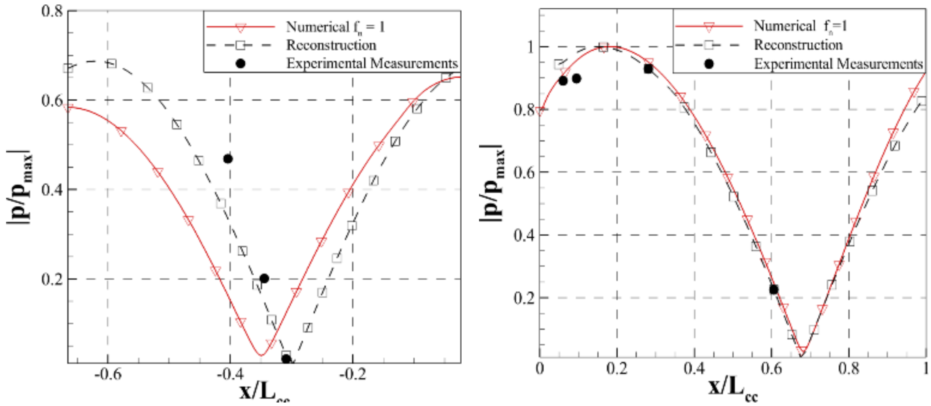


**Figure 4**. Numerical analysis: stability trajectory of the test rig colored with respect to the length of the combustion chamber. The frequency is shown in non-dimensional form:



(A) (B)

**Figure 5.** Normalized absolute pressure of the unstable mode in the configuration with in the plenum (A) and combustion chamber (B). Numerical results (red continuous lines); reconstruction (black dashed lines) performed from the experimental measurements (black dots).

## Conclusions

In the present article, a numerical analysis of instability coupled by longitudinal modes has been presented. This corresponds to experiments carried out in the LRIA (Longitudinal Rig for Instability Analysis) test facility equipped with a single full-scale Ansaldo Energia burner. At first RANS simulations have been performed in order to calculate the mean fields of the thermodynamics quantities. Afterwards, a linear stability analysis is performed by means of a Helmholtz solver coupled with a distributed - flame transfer function. The analysis has been conducted for different configurations characterized by different lengths of the combustion chamber. Comparing the results with experiments, the model has been proved suitable to predict the stability range of the system and the wave shape of the unstable modes.

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doi: 10.4405/38proci2015.X5