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Numerical Identification of a Premixed Flame Transfer Function and Stability Analysis of a Lean Burn Combustor

Alessandro Innocenti[a,*] , Antonio Andreini[a], Bruno Facchini[a]

[a] Department of Industrial Engineering - University of Florence, Via S Marta 3, Florence 50139, Italy

Abstract

Combustion instabilities represent a long known problem in combustion technology. The environment-friendly lean premixed gas turbines exhibit an increased risk of occurrence of thermo-acoustically induced combustion oscillations. In the present work the stability of a lean premixed swirl-stabilized combustor, experimentally studied at Technische Universität of Munich, has been investigated. The complex interaction between the system acoustics and the turbulent swirling flame is studied using unsteady CFD simulations with Flamelet-Generated Manifolds combustion model. Results were validated against experimental data. Perturbations are introduced in the system imposing a broadband excitation as inlet boundary condition. The flame response to the perturbation is then computed and described exploiting system identification techniques. The identified Flame Transfer Function (FTF) shows quantitative agreement with experiment for amplitude and phase, especially for the low frequency range. At higher frequencies the phase prediction slightly deteriorates while the gain is still well described. The obtained results are implemented into a finite element model of the combustor in order to analyze the stability of the system. Results are compared with available experimental data showing a satisfactory agreement. The advantage introduced by a more sophisticated model for FTF is further evidenced comparing the results with those obtained with analytical formulation found in literature.

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Keywords: Flame Transfer Function, System Identification, Thermoacosutic stability.

1. Introduction

Lean premixed combustion technology can be considered the most effective solution to meet the stringent regulations on pollutant emissions, in particular NOx. One of the most critical issues of lean combustion technology is the occurrence of combustion instabilities related to the coupling between

* Corresponding author. Tel.: +39 055 2758771
E-mail address: alessandro.innocenti@htc.de.unifi.it.

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pressure oscillations and thermal fluctuations excited by unsteady heat release. Such instabilities may damage combustor's components and limit the range of stable operating conditions so that the prediction of the thermoacoustic behaviour of the system becomes of crucial importance.

Among the methods used to predict the thermoacoustic instabilities of a combustor, such as the solution of full three-dimensional unsteady Navier-Stokes equations or low-order models as 1D-acoustic elements networks, Finite Element Methods (FEM) may be used to solve for the complete 3D problem. The set of linear transport equations for the perturbations of velocity, temperature and density can be derived by linearizing the Navier-Stokes equations. It is often assumed that the mean flow is at rest so that a wave equation for the acoustic perturbations can be derived, where the local unsteady heat release appears as a forcing term. To model the latter an accurate description of the flame dynamics is necessary and it is usually expressed in terms of Flame Transfer Function (FTF).

The FTF may be obtained experimentally, e.g. using chemiluminescence to evaluate heat release combined with velocity or pressure sensors [1]. However, the experimental determination of FTFs can be difficult, very expensive and requires very careful experimental work – especially in the presence of turbulent flow or combustion – sophisticated post-processing, and long test runs [2].

An attractive way to determine the FTF is its computation from computational time series data generated with unsteady CFD simulations where the flame dynamics is reproduced. A simulation is performed exciting the system with a carefully designed broadband signal while recording the time series of both velocity and heat release fluctuations. The FTF is then reconstructed from these data, using methods from system identification.

Otherwise, analytical models have been proposed which are derived under simplifying assumptions.

In this work the dynamic response of a perfectly premixed swirled flame, well studied in literature [1], [3-6], is investigated with numerical simulations, with the main aim of assessing and verifying the procedure described above. In the following sections the test case and the numerical setup are presented together with the obtained FTF. Finally, the results obtained from FEM simulations with both the classical n-τ model and the computed FTF are compared.

2. Dynamic behavior of a perfectly premixed combustion system

The dynamic response of a combustion system can be described, in linear regime, in terms of heat release fluctuations which are influenced by several factors. Among these, the most important two are the mass flow rate and the equivalence ratio fluctuations.

In a perfectly premixed system, as the one studied in the present work, no equivalence ratio fluctuations are present: the main mechanism inducing a heat release perturbation is a modulation of the flow upstream the flame, the axial velocity fluctuation at the burner exit. A perturbation comes from the burner and propagates from this section downstream the flame causing a variation of the flame area and position. The local turbulent field and the turbulent flame speed can be also modified with a direct effect on the reaction speed. The strength of the disturbance is directly related to that of the velocity fluctuation at the burner.

The dynamic response of a flame to a perturbation can be represented in the frequency domain by its Flame Transfer Function:

$$FTF(\omega) = \frac{\frac{\hat{q}(\omega)}{\bar{q}}}{\frac{\hat{u}(\omega)}{\bar{u}}} \Longrightarrow \frac{\hat{q}(\omega)}{\bar{q}} = FTF(\omega)\frac{\hat{u}(\omega)}{\bar{u}} \quad (1)$$

Where ω is the frequency and where the velocity fluctuations at the burner exit ($\hat{u}(\omega)$) and the heat release ones ($\hat{q}(\omega)$) are normalized with their respective mean values $\bar{q}$ and $\bar{u}$.

The previous expression identifies a single-input single-output system: a black-box with a single variable as input (velocity fluctuations just upstream the flame) and a single output (heat release fluctuations) as shown in Fig. 1. Considering a linear time-invariant single-input single-output system, from theory of systems it is well known that its behaviour is completely determined once that its response to the unit impulse, or equivalently its frequency response (the FTF), is known.

From the time series of the input excitation and of its response, it is possible to calculate the unit impulse response using System Identification (SI) techniques. In particular, a well-established procedure (see i.e. [7]) based on a linear least square optimization and exploiting correlation functions is considered (Wiener-Hopf method). The computed unit impulse response is then Z-transformed to obtain the FTF.

More details on the System Identification method and its application to thermoacoustics may be found i.e. in [1], [3]–[6]).

Fig. 1 Scheme of the Single-Input Single-Output model used for the flame

In the present work the time series for the SI comes from an unsteady-CFD simulation: the system is excited at the inlet and the time series of both the velocity fluctuations at a specific section upstream the flame, and of the global heat release fluctuations on the whole domain, are recorded.

A key point of the procedure is the input signal choice. In general, the frequency spectrum is to be excited in the range of interest. Therefore, a broadband signal that allows doing it in a single CFD simulation should be chosen. Alternatively, with a much more computationally expensive procedure, the FTF for one particular frequency can be computed at a time. An input signal with low intensity can lead to poor results, especially in presence of noise [6]. On the other hand, the signal must be limited in amplitude to respect the linearity hypothesis lying behind the identification procedure (e.g. below the 20% of the mean velocity). Comparing several signal used in literature (random binary signal, random noise etc.) a specific signal has been designed. This is basically a square wave with random variable amplitude that allows the direct control of the cut-off frequency and signal intensity without deteriorating its quality. For further detail refer to [8].

3. Test case and numerical setup

The identification strategy described is applied to the BRS combustion, experimentally and numerically studied at the TUM University in Munchen. In particular, experimental measurement [3] [4] of FTF are available for two operating conditions, at 30kW and 50kW, while velocity profiles at three axial locations are available only for the latter.

The BRS combustor is operated at ambient pressure with a perfectly-premixed lean mixture of air and methane (ϕ = 0.77). It has an axial swirler for the generation of the vortex breakdown and flame anchoring. The swirler is mounted on a centre-body at 30 mm upstream of the burner exit, an annular section with an inner diameter of 16 mm and an outer diameter of 40 mm. The combustor has a square section (90mmx90mm) combustion chamber and a total length of 300mm.

The geometry (in Fig.2) is then reconstructed from sketches and schemes of the test rig in [3].

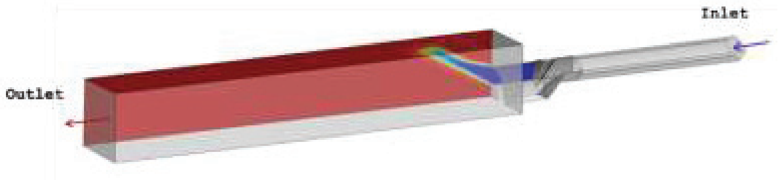

Fig.2 BRS combustor: numerical domain

The flame is simulated using Unsteady-RANS and the commercial software ANSYS Fluent 15.0

Exploiting the domain periodicity just one quarter of the domain has been simulated. Adiabatic non-slip condition is applied at the mixing tube walls while at the combustor wall a temperature of 600K has been assigned. At the outlet a Non Reflecting Boundary Condition is adopted to avoid that flame dynamic behavior and the identification procedure being influenced by wave reflected at the boundary.

Standard k – ε model is used as turbulence model.

In order to choose a combustion model, a comparison between the Perfectly Premixed model with the classical Turbulent Flame Speed closure proposed by Zimont [9] and the Flamelet Generated Manifolds (FGM) model [10] has been carried out.

As far as the former is concerned, an equation for the reaction progress variable c is solved, which completely describes the reaction in case of a premixed adiabatic (heat-loss effect not taken into account) flame. The progress variable source term is set proportional to a turbulent flame speed ST that depends on the physical-chemical characteristics of the fuel mixture through its laminar flame speed SL and on the local turbulence level:

$$S_T = A\, G\, u'^{3/4} S_l^{1/2} \chi_u^{-1/4} L_T^{1/4} \tag{2}$$

Being u' the RMS of velocity fluctuations, L_T the integral scale, χ_u the thermal diffusivity. The model constant A is empirical and the suggested value is 0.52 for most hydrocarbon fuels and G the stretch factor [9].

The FGM chemistry reduction technique, instead, combines the advantages of chemistry reduction and flamelet models. The approach shares with the latter the idea that a multi-dimensional flame can be considered as an ensemble of one-dimensional flames, while a low-dimensional manifold is constructed solving one-dimensional flamelets [10]. As other manifolds, the number of independent control variables (manifold dimension) can be increased (i.e. progress variable c, heat loss, turbulence etc.) thus improving the description of the combustion process. In the present work, non-adiabatic premixed flamelet configuration and GRI-Mech 3.0 mechanism is used to generate laminar flamelets database for the FGM. All the variables are defined as a function of both mixture fraction Z and reaction progress variable c. The latter dimension makes FGM model sensitive to finite chemistry effects due to a reaction in progress and not instantaneously completed. The final manifold includes turbulence effects, after a PDF integration routine, and has four input parameters: Z, reaction progress variable c and their respective variances. The progress variable definition, used in the flamelet parametrization, is based on CO and CO2 mass fractions. The Fluent Finite Rate/Turbulent Flame Speed, where the minimum between the source term coming from the flamelet manifold and the Turbulent Flame Speed closure one is used to model the c-equation source term.

A computational mesh of around 1.3E6 elements is chosen after a mesh sensitivity analysis.

After a first stabilization period, necessary for the intrinsic non-stationary phenomena to rise and propagate through the domain, the mean values are computed. Successively, the broadband excitation is superimposed at the inlet velocity and both the velocity at the reference section and the heat release are recorded.

The results obtained with the two models against experimental profiles of velocity at three axial locations, available for the 50kW configuration [1], are shown in Fig. 3.

At all the three planes (30, 60 and 80 mm downstream the burner exit) the FGM catches better the flow-field inside the combustor: position of the high speed jet, velocity peak and recirculation region.

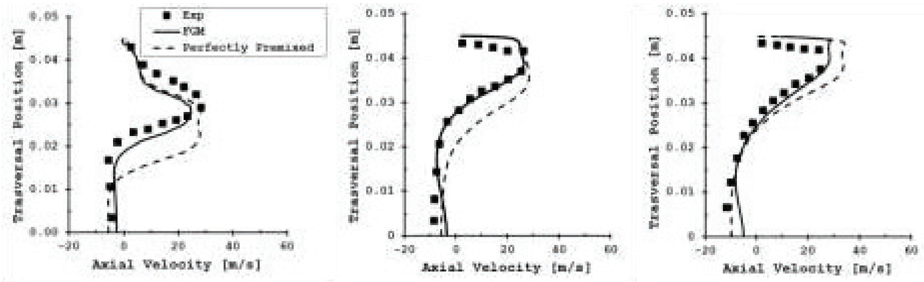

Fig. 3 Velocity profiles at three axial locations obtained with the tested combustion models

The inclusion of finite-rate effect in the FGM model allows a better reproduction of the flame and is therefore adopted for the following analysis.

4. Results

For the Flame Transfer Function the 30kW case has been simulated. The computed FTF is depicted in Fig. 4 in terms of gain and phase as function of the frequency.

The obtained response shows the typical features of a perfectly premixed flame response.

The theoretical limits for a premixed Flame Transfer Function are, in fact, observed: for zero frequency the gain tends to 1 while the phase correctly approaches to 0. This is due to the quasi-steady response of the flame so that any fluctuation in the mixture flow is translated into an equal fluctuation of heat release [11].

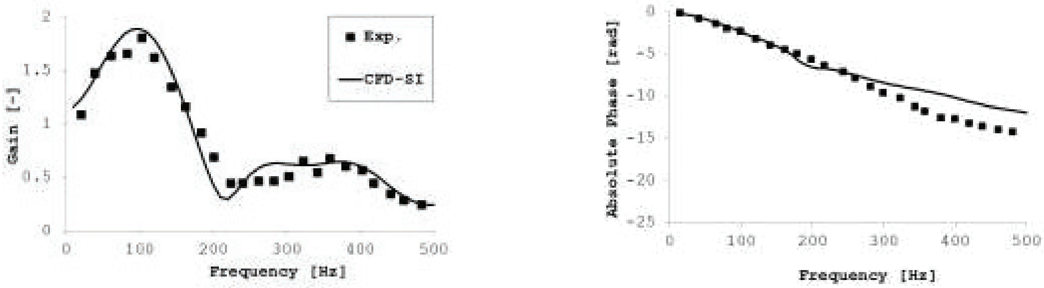

Fig. 4 Computed (CFD-SI) and experimental (Exp.) FTFs

At the other limit for $\omega \to \infty$, the dispersion of the perturbation is large, so that the flame does not follow the perturbation any more, and the gain of the FTF tends to 0: The flame is acting as a low-pass filter.

Comparing the results with experimental data it is possible to observe a good agreement for the amplitude all over the range. The peak location is caught by the model as well as the corresponding value.

A minimum gain is predicted at around 200Hz, then the curve follows the experimental plateau.

The phase matches the experimental data up to a frequency of 200 Hz. After that a small discontinuity is evident and the slope of the numerical curve is changed. In this second part of the frequency range experimental results are not perfectly matched and higher values are predicted for the phase.

Looking at Fig. 5 where the normalized heat release is plotted against experiments (proportional to OH concentration), it is possible to see that the simulation predicts the maximum heat release location with reasonable accuracy even if the predicted flame seems to be slightly shorter and moved upstream. This could be due to the fact that the flame stabilizes in both the inner and outer shear layers, while experimentally only in the inner one. The predicted phase is therefore smaller as the time lag that is, response of the flame to the perturbation reduces with the flame length.

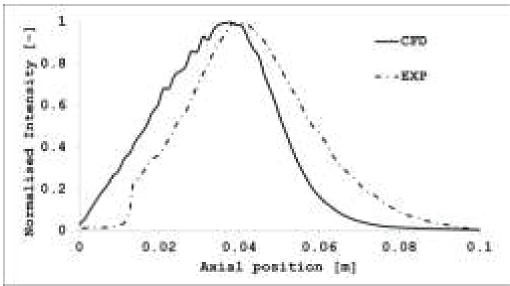

Fig. 5 Area normalizes heat release distribution

4.1. Stability analysis

The computed FTF is then used to perform a linear stability analysis. Simulations are also performed with the analytical n-τ model [12] so that a comparison can be made between the two flame models.

When using the flame n-τ model, the interaction index n is set to a constant value of 1, while the time lag τ assumes local values equal to the convective time from the burner outlet to the flame point considered. It should be noted that the described flame response described in Section 4, the gain above unity for the low frequency range as well as the low-pass filter behaviour is neglected when considering the $n = 1$.

In order to compare the results with experiments [4], where a longer combustor was used so that unstable modes exhibit, the combustor length is changed to 700 mm, in this case. A FEM model of the combustor is generated in COMSOL Multyphysics [13]. The Helmholtz equation (Eq. 3) is solved in the frequency domain with an additional source term representing heat release rate fluctuations:

$$\frac{\lambda^2}{c^2}\hat{p} - \nabla^2\hat{p} = -\frac{\gamma-1}{c^2}\lambda\hat{q} \tag{3}$$

Where $\hat{q}$ is the heat release fluctuation, $\hat{p}$ is the pressure fluctuation, c the sound velocity, γ the specific heat ratio. $\lambda = -i\omega$. ω is a complex quantity whose real part represents the frequency of oscillations and the imaginary one the growth rate which characterize the stability of a mode.

The swirler is replaced in the model by its transfer matrix, computed following the procedure described in [14]. The burner transfer matrix obtained in this way includes the effects of the mean flow in the swirler section on the local acoustics. Temperature profile and flame volume are imported in the FEM model from CFD data. In Fig. 6 it is possible to observe the flame region, where the source term of Eq. 2 is applied. No pressure fluctuations are imposed at both inlet and outlet section ($\hat{p} = 0$).

To solve for the problem the COMSOL Pressure Acoustic module is employed and the domain is discretized with a computational mesh able to detect acoustic modes up to 2kHz.

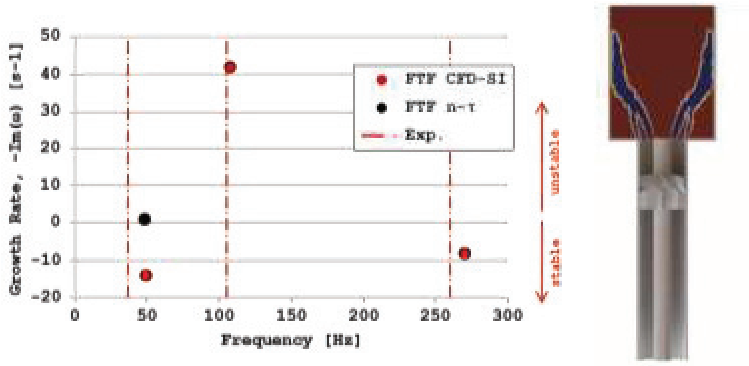

Fig. 6 Predicted eigenvalues using n- τ model and the computed FTF

When the computed FTF is used, three modes are detected in the range 0-300 Hz where the measurements were available (see Fig. 6). In particular, one unstable mode is predicted at 107,3 Hz (experimentally found at 103.3 Hz) and two other stable modes, experimentally found at 35 and 260 Hz. The model is then able to identify the main modes as well as their stability.

In case of using the n-τ model only the first mode at 48.2 Hz was found as convergence issues arose when looking for the other modes.

The adoption of a more refined model as the Flame Transfer Function computed from CFD data leads to improved results and seem to introduce also a stabilisation in the solution procedure of the FEM code.

5. Conclusions

The dynamic response of a perfectly premixed flame has been characterized in terms of Flame Transfer Fucntion exploiting numerical simulations and system identification technique. A combustion model sensitivity has been carried out showing that when finite-rate effects are taken into account a better agreement is obtained with experiments.

Comparisons with measured FTF allow the validation of the procedure for FTF identification from CFD simulations. Good agreement is obtained for the identified Flame Transfer Function in terms of both gain and phase. The predicted FTF shows the classical premixed-like shape and the theoretical limits are well respected. A stability analisys of the combustor has been carried out with a FEM simulation comparing the results obtained with the computed FTF with those where the n- τ model is implemented and with experiments, showing the model ability to identify the main modes as well as their stability. Improved results and easier convergence are obtained with the computed FTF.

The validated procedure will be applied in future works to industrial configurations of gas turbine combustors. An upgrade will be necessary to take into account equivalence ratio fluctuations effects on the flame response, related to the technically-premixed nature of practical burners, that is, modelling the flame as a multi-input single-output.

6. Copyright

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Biography

Alessandro Innocenti is a Ph.D. student at the Industrial Engineering Department of Florence (DIEF), University of Florence. His research activity is mainly focused on thermos-acoustics and reactive simulations in aero-engine and heavy-duty gas turbines.