Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 45 (2014) 1422 – 1431

Energy Procedia

68th Conference of the Italian Thermal Machines Engineering Association, ATI2013

Assessment of Flame Transfer Function Formulations for the Thermoacoustic Analysis of Lean Burn Aero-Engine Combustors

Antonio Andreini[a], Bruno Facchini[a], Andrea Giusti[a,*], Fabio Turrini[b]

[a]*Department of Industrial Engineering, University of Florence, via Santa Marta 3, 50139 Florence, Italy*
[b]*Combustion System Office, AVIO Group S.p.A., via Primo Maggio 56, 10040 Rivalta di Torino (TO), Italy*

Abstract

The numerical analysis of thermoacoustic instability in lean burn aero-engines requires proper Flame Transfer Functions (FTF) able to describe the complex physical phenomena characterizing the coupling between heat release rate fluctuations and the acoustic field which is further complicated by the use of liquid fuel together with advanced injection systems. In this work simple FTF formulations have been applied to the thermoacoustic analysis of a tubular combustor equipped with a PERM (Partially Evaporating and Rapid Mixing) injection system with the main aim of assessing their capabilities in the prediction of thermoacoustic instabilities in lean burn aero-engine combustors.

Keywords: Flame Transfer Function; thermoacoustics; lean burn aero-engine; liquid fueled combustor; airblast injection system.

1. Introduction

In order to reduce NOx emissions, modern gas turbines are often equipped with lean burn combustion systems, where the engine may operate near the lean blow-out limits. One of the most critical issues of lean combustion technology is the onset of combustion instabilities related to a coupling between pressure oscillations and thermal fluctuations excited by the unsteady heat release. The thermoacoustic analysis of lean burn aero-engine combustors suffers from lack of a Flame Transfer Function (FTF) able to completely describe the thermoacoustic driving mechanisms that characterize a liquid fueled combustor especially when advanced injection systems are used.

Besides the typical driving mechanisms of premixed flames that could still be present when rapid evaporation and mixing are achieved, the complex physical phenomena that characterize liquid atomization and droplet evolution could also interact with the acoustic field determining a fluctuation of the local equivalence ratio and thus heat release rate oscillations. More in general, in typical aero-engine lean burn combustors the flame can be classified as a partially premixed one, so typical driving mechanisms of diffusion and premixed flames could be present at the same time.

The flame response to acoustic perturbations has been extensively studied through analytic modeling, detailed computations and experiments in the case of premixed combustors [1] whereas less work could be found in literature

* Corresponding author. Tel.: +39-055-479-6618; fax: +39-055-479-6342.
E-mail address: andrea.giusti@htc.de.unifi.it

doi:10.1016/j.egypro.2014.01.149

on partially premixed or non-premixed systems. However, in the recent years the development of low NOx aero-engines has greatly enhanced the interest on the problem of combustion instability in liquid fueled combustors. Magina et al. [2] studied the dynamics of non-premixed flames excited by bulk velocity fluctuations in comparison with the dynamics of premixed flames. Their work, based on the numerical solution of the Z-equation and G-equation which describe the dynamics of non-premixed and premixed flames respectively, shows that the heat release dynamics in non-premixed flames is dominated by mass burning rate fluctuations whereas premixed flames are mainly affected by flame area fluctuations. Other recent works on non-premixed flames include the study of ducted flame response to axial velocity and mixture fraction oscillations [3] and the investigation of the role of non-normality and nonlinearity in flame-acoustics interaction in a ducted diffusion flame [4].

As discussed above, when liquid fueled combustors are considered, physical processes related to droplet generation and evolution could also be important in driving combustion instabilities. The physical processes involved are very complex and not completely understood (this is for example the case of liquid film primary atomization in prefilming airblast injectors) and very few investigations can be found in literature especially for the interaction between acoustics and droplet primary breakup. As regards the interaction between the acoustic field and the evaporation process, a very interesting approach is the one proposed by Hsiao et al. [5] where the dynamic behaviour of droplet vaporization is quantified using a response function which could be directly exploited in simple models.

Another aspect that should be considered in the FTF modelling is the effect of confinement walls on flame dynamics [6]. The confinement could modify flow and flame structures influencing the coupling between heat release rate and acoustic field. Similar considerations can be extended to combustors characterized by multiple burners; this is the case of annular combustors where the flow field and flames generated by the single burner or injector interact with each other. Even the presence of a swirl in the flow could alter the flame response and several works have been carried out over the years to understand the behaviour of swirling flames especially in the case of premixed flames. In some cases analytical formulations have been developed as in the work of Palies et al. [7] where an analytical model for FTFs of premixed swirling flames subjected to velocity disturbances is derived.

Nomenclature

c	Speed of sound, m/s
d	Droplet diameter, m
f	Frequency, Hz
g	Growth rate, 1/s
K	Parameter in the FTF
L	Flame tube length, m
p	Pressure, Pa
q	Volumetric heat release rate, W/m^3
T	Time period, s
u	Velocity, m/s
U	Mean convection velocity, m/s
V	Volume, m^3
x	Axial coordinate, m

Greeks

γ	Specific heat ratio
$\Delta\tau$	Time spread, s
λ	Eigenvalue = $-i\omega$, rad/s
ξ	Parameter in the FTF
ρ	Density, kg/m^3
τ	Time delay, s
ϕ	Generic quantity
φ	Equivalence ratio
ω	Angular frequency, rad/s

Subscripts

$conv$	Convective
n	Normalized
ref	Reference location

Miscellaneous

$i(\bullet)$	Imaginary number
$\overline{(\bullet)}$	Time averaged quantity
$(\bullet)'$	Fluctuation over the mean quantity
$\widehat{(\bullet)}$	Complex quantity
$\mathrm{Re}(\bullet)$	Real part of a complex quantity
$\mathrm{Im}(\bullet)$	Imaginary part of a complex quantity

Acronyms

CFD	Computational Fluid Dynamics
FEM	Finite Element Method
FTF	Flame Transfer Function
LES	Large Eddy Simulation
PERM	Partially Evaporating and Rapid Mixing
RANS	Reynolds Averaged Navier Stokes

In order to perform reliable thermoacoustic simulations, a more detailed comprehension of the physical phenomena and thermoacoustic driving mechanisms characterizing liquid fueled combustors is necessary, so that more suitable FTF formulations can be developed, without disregarding the computational cost related to such formulations. A good compromise for industrial calculations could be represented by the development of simple FTFs, each of them representing a single driving mechanism, to be applied simultaneously depending on the most important mechanisms influencing the given operating condition. In this work simple FTF formulations have been applied to the thermoacoustic analysis of a tubular combustor equipped with a PERM (Partially Evaporating and Rapid Mixing) injection system developed by AVIO Group S.p.A. with the main aim of assessing their capabilities in the prediction of thermoacoustic instabilities with partially premixed flames.

2. Mathematical model

The solution of a thermoacoustic problem consists in determining the resonant frequencies of the combustor together with the stability properties of the acoustic modes related to such frequencies. Several numerical methods can be used to predict the thermoacoustic properties of a combustor, ranging from one-dimensional network-based tools [8] to fully three-dimensional LES (Large Eddy Simulation) and FEM (Finite Element Method) calculations. In this work the thermoacoustic instability analysis has been performed using a FEM approach consisting in the solution of the Helmholtz equation with an additional source term representing heat release rate fluctuations. Before describing the mathematical model implemented in the FEM solver used in the present study, the so called Rayleigh's criterion for combustion instabilities is presented in order to give a better definition of combustion instabilities and to point out the most important phenomena that have to be taken into account in a thermoacoustic simulation.

2.1. The Rayleigh's criterion

In 1878 Lord Rayleigh described combustion instabilities with these words, also referred to as the Rayleigh's criterion [9]:*"If heat be periodically communicated to, and abstracted from, a mass of air vibrating (for example) in a cylinder bounded by a piston, the effect produced will depend upon the phase of the vibration at which the transfer of heat takes place. If the heat be given to the air at the moment of greatest condensation, or be taken from it at the moment of greatest rarefaction, the vibration is encouraged. On the other hand, if heat be given at the moment of greatest rarefaction, or abstracted at the moment of greatest condensation, the vibration is discouraged"*.

This statement can be summarized using the following mathematical expression which gives a necessary condition for the onset of combustion instabilities [10]:

$$\int_V \int_T p'(x,t)q'(x,t)dtdV \geq \int_V \int_T \sum_i \mathcal{L}_i(x,t)dtdV \tag{1}$$

where $p'(x,t)$, $q'(x,t)$ and $\mathcal{L}_i$ are the combustor pressure oscillations, periodic heat addition process, and i-th acoustic energy loss process, respectively. Eq. 1 allows us to highlight two important aspects. First of all, in order to have combustion instabilities it is necessary a coupling between the acoustic field and heat release fluctuations in such a way that energy is added to the acoustic field. Furthermore, in order to make the combustor unstable, the net rate of energy addition to the acoustic field should exceed the net rate of damping provided by inherent dissipation processes, for example the acoustic energy dissipation due to the multi-perforated liners, usually employed in modern aero-engine combustors [11,12]. The first aspect is strictly connected to the Flame Transfer Function modeling and will be deeply analysed in this paper. As far as dissipation mechanisms are concerned, in reference [12] a detailed analysis of some numerical models [13–15] for the acoustic impedance of multi-perforated liners can be found whereas in reference [16] the effects of the mean flow on the dissipation process are taken into account.

2.2. The eigenvalue problem

The mathematical model that is generally used to describe the thermoacoustic problem is based on the following inhomogeneous wave equation [17]:

$$\frac{1}{\overline{c}^2}\frac{\partial^2 p'}{\partial t^2} - \overline{\rho}\nabla\cdot\left(\frac{1}{\overline{\rho}}\nabla p'\right) = \frac{\gamma-1}{\overline{c}^2}\frac{\partial q'}{\partial t} \tag{2}$$

where q' is the fluctuation of the heat input per unit volume, p is the pressure, ρ is the density whereas t and c denote respectively the time and the sound velocity. The prime indicates a perturbation over the time averaged mean value and the overbar denotes mean values. This equation holds under the assumptions of negligible mean flow velocity, absence of viscous losses and heat conduction and fluid treated as an ideal gas with constant specific heat ratio [17].

In some regions the mean flow velocity could not be negligible in comparison with the sound velocity: in this case, such regions could be treated as separated elements modelled by means of particular transfer function matrices [17,18] or specific boundary conditions [19]. The latter is for example the case of the initial section of the diffuser at the inlet of a combustion chamber which can be replaced with a proper impedance.

Eq. 2 is solved in the frequency domain. The generic fluctuating quantity ϕ' is written as:

$$\phi' = \mathrm{Re}(\widehat{\phi}\exp(i\omega t)) \tag{3}$$

where ω is a complex quantity. Its real part gives the frequency of oscillations whereas its imaginary part gives the growth rate of oscillations and allows the characterization of unstable modes. In particular, the growth rate g can be defined as:

$$g = -\mathrm{Im}(\omega) \tag{4}$$

thus an acoustic mode is unstable if g is positive since it means that the amplitude of the fluctuation grows with time. Once harmonic fluctuations are introduced, Eq. 2 becomes [17]:

$$\frac{\lambda^2}{\overline{c}^2}\widehat{p} - \overline{\rho}\nabla \cdot \left(\frac{1}{\overline{\rho}}\nabla\widehat{p}\right) = -\frac{\gamma - 1}{\overline{c}^2}\lambda\widehat{q} \tag{5}$$

where $\lambda = -i\omega$. Eq. 5 is a quadratic eigenvalue problem that is solved by means of the FEM solver. Heat release fluctuations are usually expressed as a function of acoustic variables through the so called Flame Transfer Function which, as described in the following, directly describes the coupling between the acoustic field and the flame dynamics.

The finite element code used in this work is COMSOL Multiphysics which solves the eigenvalue problem using a variant of the Arnoldi algorithm called the implicitly restarted Arnoldi method. An iterative procedure based on a quadratic approximation around an eigenvalue linearization point λ_0 was adopted. The solver reformulates the quadratic eigenvalue problem as a linear eigenvalue problem of the conventional form $Ax = \lambda Bx$, and iteratively updates the linearization point until convergence is reached. The code and the procedure were validated by Camporeale et al. [17] by analysing simple cases [20] representing combustor thermoacoustic problems and comparing numerical results with analytical solutions.

3. Flame Transfer Function

The dynamic response of a flame to a perturbation can be represented by the Flame Transfer Function (FTF) which relates the heat release rate fluctuations to the velocity oscillations at a reference location upstream of the flame (for example at the exit of the injection system). The fluctuations are typically normalized with their mean values leading to the following expression[1]:

$$FTF(\omega) = \frac{\widehat{q}/\overline{q}}{\widehat{u}_{ref}/\overline{u}_{ref}} \tag{6}$$

The flame transfer function is maybe the most important modelling aspect in a thermoacoustic simulation since it directly describes the coupling between the acoustic field and the flame heat release rate fluctuations determining the presence of unstable modes. Thus, in order to perform reliable thermoacoustic simulations, proper FTF formulations have to be used. Flame transfer functions can be directly obtained through experiments, for example using velocity or pressure sensors in combination with chemioluminescence as an indicator of heat release in the flame, or time resolved CFD simulations together with system identification techniques [21]. The experimental determination of

[1] In the linear response analysis the FTF is generally a function of the sole frequency whereas if non-linear analysis is considered explicit dependence on fluctuating velocity is introduced leading to the so called Flame Describing Function.

FTFs in typical industrial configurations is usually difficult and very costly. As far as the the numerical computation of FTFs is concerned, it appears a very promising tool but still far from an extensive industrial application since, as shown in reference [22], an accurate prediction of the flame dynamics can only be obtained using computationally expensive tools based on LES approach. As a consequence, from an industrial point of view it would be desirable to have a set of ready-to-use FTF formulations that can be used at different operating conditions.

Over the years, several simple FTFs have been proposed starting from experimental measurements or theoretical considerations. In general, the derivation of such formulations requires the identification of the so called driving mechanism, that is a physical process that is influenced by the acoustic field and directly determines the oscillation of heat release rate [23] determining the coupling between acoustic field and heat release rate fluctuations. The choice of the most important driving mechanisms depends on the flame structure, type of fuel (for example in liquid fuel combustors the acoustic field could also interact with the atomization and evaporation processes) and, in general, on the operating conditions. Typical mechanisms include equivalence ratio oscillations, flame surface variations, oscillatory liquid fuel atomization and evaporation [23,24]. Different driving mechanisms could be present at the same time; furthermore they could interact with each other making the development of simple FTFs a real challenge, and a calibration process is sometimes needed especially when the physics regulating the acoustic coupling is so complex to be described by simple models. In the following, three different FTFs will be considered and applied to the prediction of thermoacoustic instabilities in a tubular combustor equipped with an injection system typically used in advanced lean burn aero-engines.

3.1. FTF-1

The first FTF that will be presented considers equivalence ratio oscillations as the key driving mechanism. This FTF is commonly used to investigate thermoacoustic instabilities in lean premixed gas turbines [25,26] where equivalence rate oscillations are one of the most important driving mechanisms. Proving that equivalence ratio fluctuations are basically proportional to the acoustic velocity fluctuations [23], a simple FTF can be written as [10,17,23]:

$$\frac{\widehat{q}}{\overline{q}} \propto \frac{\widehat{\varphi}_{ref}}{\overline{\varphi}_{ref}} \propto -\frac{\widehat{u}_{ref}}{\overline{u}_{ref}} \longrightarrow FTF = -K\exp(-i\omega\tau) \tag{7}$$

where K is a proportionality constant and τ is the time delay between the initial perturbation and the heat release fluctuation. According to [10], the time delay should consider all the physical processes involved in the transport mechanism, ranging from convection time to chemical delay time. However, it is usually represented only by the convection time, i.e. the time required by velocity oscillations at the injection plane to be convected in the flame region. Obviously the convection time depends on the point considered in the flame region, the farther the point is, the greater the time delay will be. Thus, considering a single injection plane, a simplified relation for the convective time can be defined as follows:

$$\tau_{conv}(x) = \frac{x}{U} \tag{8}$$

where x is the axial coordinate and U is a mean convection velocity taken equal for all points of the flame. Different FTF formulations which include other driven mechanisms can also be found in literature. For example in the work of Dowling and Hubbard [20], a FTF which accounts for both flame surface variations and equivalence ratio oscillations is presented. However this formulation, as well as the one presented in Eq. 7, does not directly take into account the role of liquid vaporization in the coupling between heat release fluctuations and acoustic field.

3.2. FTF-2

The previous FTF has an amplitude independent of frequency. However, experimental data (see for example references [6,21,26]) showed that the magnitude of FTF usually decays as the frequency of the perturbation is increased. Thus, following the work by Sattelmayer [27] who suggested that the response is better fitted by a model in which the time delay is taken to vary uniformly from $\tau - \Delta\tau$ to $\tau + \Delta\tau$, the following FTF is proposed [26]:

$$FTF = -K\Theta\exp(-i\omega\tau) \tag{9}$$

where Θ is a function that describes the influence of time delay variation due to flow dispersion (the time spread $\Delta\tau$ is a measure of non-uniformity of the flow and the strength of the encountered dispersion):

$$\Theta = \frac{\sin(\omega\Delta\tau)}{\omega\Delta\tau} \tag{10}$$

3.3. FTF-3

The third FTF formulation considered in this work was derived by Eckstein and Sattelmayer [28] for diffusion flames generated by an airblast injection system. In this case the most important driving mechanism is the fluctuation of droplet diameter caused by the fluctuation of air velocity. Assuming a negligible pre-vaporization [28,29], the heat release rate is directly proportional to droplet evaporation rate and thus a relation between heat release fluctuations and droplet diameter can easily be found. Eckstein et al. [30] proved that for low-frequency combustion oscillations a quasi-steady description of the airblast atomizer is appropriate and droplet diameter fluctuations can be directly related to air velocity fluctuations at the injection plane. The following FTF formulation was proposed [28]:

$$\frac{\widehat{q}}{\overline{q}} \propto -\frac{\widehat{d_{ref}}}{\overline{d}_{ref}} \propto \frac{\widehat{u_{ref}}}{\overline{u}_{ref}} \longrightarrow FTF = 2\xi\Theta\exp(-i\omega\tau) \tag{11}$$

where ξ is a constant derived from experimental correlations for the Sauter mean diameter of droplet population generated by the airblast system. Eckstein [29] for his injection system obtained a value of $\xi = 1.6$; however recent correlations [31] suggest that this constant could be less than 1. Comparing Eq. 7 with Eq. 11 it is possible to note a basic difference between FTF-1 and FTF-3 determined by the different driving mechanisms (equivalence ratio oscillations and droplet mean diameter fluctuations) considered in each formulation. In FTF-3 a positive air velocity fluctuation leads to a positive oscillation of the heat release rate because a higher velocity causes a reduction of droplet mean diameter and so a greater heat release rate (an airblast injector is considered and under the assumption of quasi-steady behaviour of the atomization an increase of air velocity usually leads to a reduction of droplet diameter [32]). Exactly the opposite happens for FTF-1 because a higher air velocity means a smaller equivalence ratio and thus a reduction of the heat release rate (remember that a combustor operating in the lean region is considered).

4. Assessment of FTF formulations

The capabilities of the FTFs formulations presented in the previous section in reproducing the complex phenomena characterizing the coupling between heat release rate and acoustic field in lean burn aero-engine combustors have been assessed by performing a thermoacoustic analysis of a tubular combustor equipped with a PERM injection system. Experiments were also performed in this configuration and an extended set of experimental data is available with combustor resonant frequencies measured at several operating conditions characterized by different mean pressure, air inlet temperature (T_{in}), fuel-air ratio (FAR) and pilot to total fuel mass flow rate ratio (P/T). Before presenting the results obtained in such investigation, the geometry of the combustor and the numerical setup will be described.

4.1. The tubular combustor

The tubular combustor considered for the assessment of flame transfer functions basically consists in a cylindrical flame tube connected to an upstream duct used for air supply. The flame tube terminates with a nozzle allowing a chocked outlet condition to be established. The injector, based on the PERM concept (see Fig. 1), is basically a double swirler airblast atomizer developed in order to achieve partial evaporation inside the inner duct and rapid mixing within the combustor, optimising the location and the stability of the flame. A film of fuel is generated over the lip that separates the two swirled flows. As the film reaches the edge of the lip, primary atomization occurs: fine droplets and rapid mixing are promoted by the two co-rotating swirled flows generated by the double swirler configuration. Furthermore a hollow cone pressure atomizer (pilot injector) is located at the centre of the primary swirler which, depending on the operating condition, could generate a pilot flame to stabilize the combustion. Generally speaking, the flame generated by the PERM injection system can be classified as a partially premixed flame. As said before,

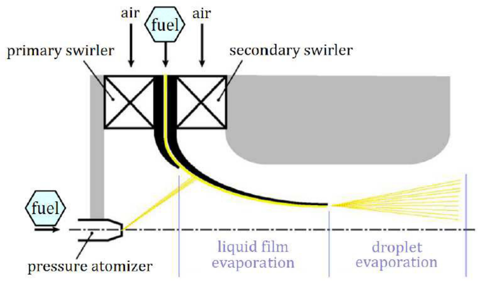
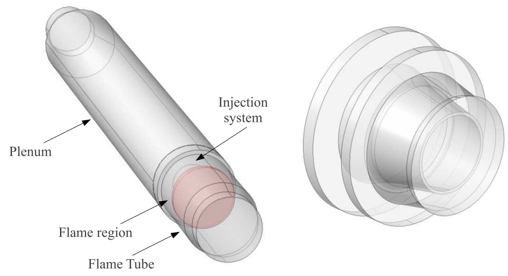


Fig. 1. PERM functioning concept (taken from http://www.newac.eu).



(a) Computational domain. (b) Simplified swirler.

Fig. 2. Tubular combustor geometry.

the presence of a liquid fuel makes the description of the coupling between the acoustic field and the heat release fluctuations a real challenge because all the physical processes related to liquid fuel preparation and evolution, such as primary atomization and evaporation, could have an important role in driving combustion instabilities. Furthermore the flame structure is strictly dependent on the operating condition: for example at high loads all droplets evaporate near the atomizing edge and, as rapid mixing is promoted, a highly homogeneous mixture is generated. On the other hand, when the operating pressure in very low or a large amount of fuel is injected through the pilot injector, typical structures of diffusion flames appear and the thermoacoustic behaviour could be strongly affected by droplet dynamics.

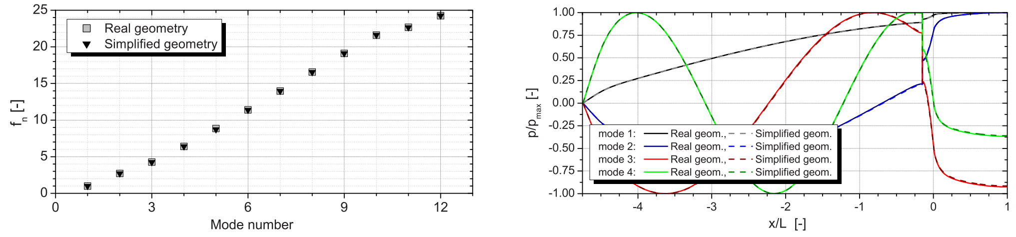
4.2. Numerical setup

The computational domain, showed in Fig. 2, exactly reproduces the real geometry excepting the double swirler injector which was modelled by substituting the swirling channels with equivalent annular inlets. As shown in a previous work [33], this configuration allows us to reduce the computational cost (the real injector system is characterized by a very complex geometry and a lot of small elements, much smaller than the maximum element size imposed by frequency resolution, are required for a correct discretization) without significantly altering the acoustic behavior of the combustor. The flame region, i.e. the region where combustion occurs and the FTF has to be activated, was modeled with a cylindrical shape; a plenum condition ($p' = 0$) was imposed at the inlet whereas the outlet was modeled using a chocking condition ($u' = 0$). As regards thermodynamic mean properties, two different operating conditions have been considered. The first one, which will be referred to as Case A, is a low pressure case (representative of idle conditions) in which about 20% of fuel is supplied through the pilot injector whereas in the second one (Case B) a high pressure condition is considered. In both cases a one-dimensional axial temperature profile derived from a RANS simulation of the combustor was imposed inside the flame tube.

Before presenting the results of thermoacoustic instability analysis and the comparison between the different FTFs, the results of a passive simulation, that is a thermoacoustic simulation without flame, are presented in Fig. 3 in order to show that the simplifications made to the injector geometry have a negligible effect on the computation of both eigenfrequencies and eigenmodes. The values of resonant frequencies have been normalized using the value of the first resonant frequency of the simplified geometry ($f_n = f/f_1$).

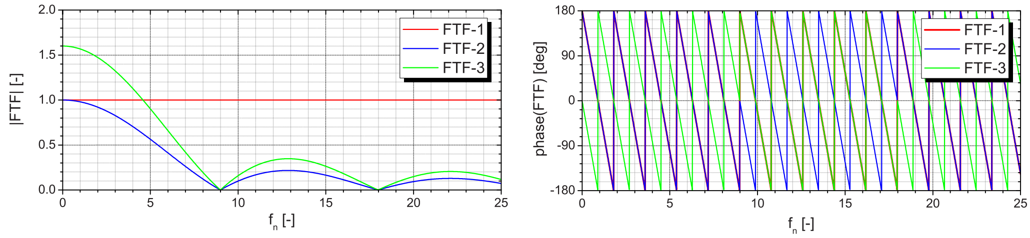
4.3. Results and discussion

The magnitude and phase of the flame transfer functions used in the present analysis are shown in Fig. 4. K and ξ were taken equal to 1.0 and 0.8 respectively whereas the time delay was computed as the mean convection time from the injection location to the flame (see Eq. 8, taken equal for all points of the flame) and a value of 0.1τ was assigned to the time spread $\Delta\tau$. As explained in Section 3, the magnitude of FTF-1 does not vary with frequency whereas the other formulations exhibit an amplitude which decays as the frequency is increased. As far as the phase is concerned, the three formulations are characterized by different values with a shift of 180 degrees between the phase of FTF-2



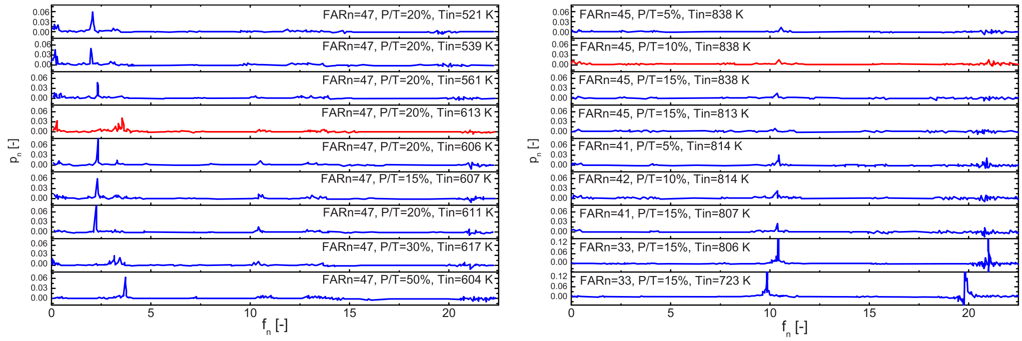
(a) Eigenfrequencies. (b) Eigenmodes.

Fig. 3. Results of the passive simulation (Case A).



(a) Magnitude. (b) Phase.

Fig. 4. Comparison between the FTFs analysed in this work (Case A).



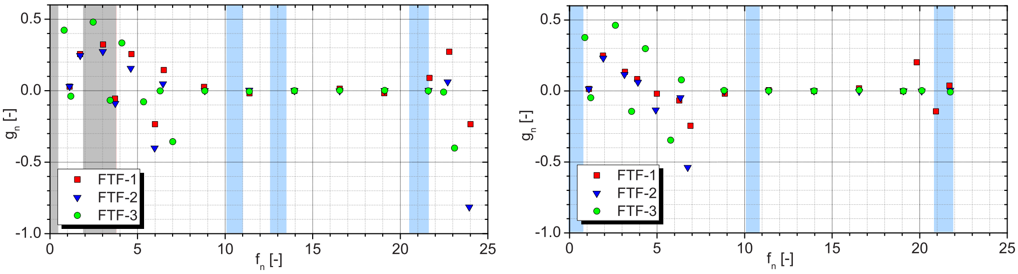
(a) $\overline{p} = 5.4$ bar (— Case A). (b) $\overline{p} = 22.0$ bar (— Case B).

Fig. 5. Experimental pressure spectra.

and FTF-3. It is important to note that the phase is an important characteristic of the FTF since it directly determines whether the interaction between heat release rate fluctuations and acoustic field is constructive or not.

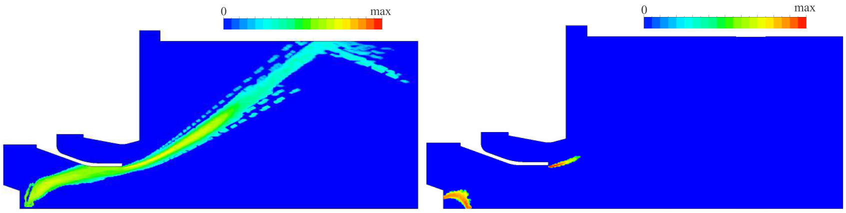
The pressure spectra measured in experiments for both cases are reported with red lines in Fig. 5 together with other measurements performed at different conditions. In Case A, experiments showed high pressure peaks in the low frequency range which could be related to the presence of unstable modes. On the contrary, in Case B no significant pressure peak appears excepting the small amplitude oscillations near $f_n = 10$ and $f_n = 20$ which clearly become unstable when the FAR is decreased.

In Fig. 6 the eigenfrequencies predicted by the different FTFs are compared with each other. Coloured areas denote the frequency ranges where pressure oscillations are observed in experiments: the grey colour has been used to indicate the regions with the highest pressure peaks whereas the light blue colour indicates the regions with small peaks. Results are presented in terms of normalized resonant frequency f_n and growth rate g_n computed using the value of the first resonant frequency of the passive simulation as the reference value. In Case A (Fig. 6(a)) the most



(a) Case A. (b) Case B.

Fig. 6. Comparison between eigenfrequencies predicted by the different FTFs.



(a) Case A. (b) Case B.

Fig. 7. Droplet evaporation rate [kg/(m^{3}s)] predicted by RANS simulations.

interesting results have been obtained using the FTF-3 which seems to be able to properly predict instabilities in the low frequency range. It should be noted that at the operating condition of Case A the combustion retains most of the characteristics of diffusion flames. Fig. 7(a) shows the droplet evaporation rate predicted by RANS simulations and it is possible to note that in this case droplets completely evaporate far away from the injection system and a highly inhomogeneous mixture is burned. As discussed in Section 3, FTF-3 was specifically devised for the study of low-frequency instabilities in airblast swirl diffusion burners. Thus the driving mechanism accounted for in FTF-3 could actually be the physical process that determines low-frequency instabilities also in the system under investigation. As regards Case B (Fig. 6(b)), all the proposed formulations completely fail to reproduce the experimental results: unstable modes are predicted in the low frequency range which however are not detected by the experiments. In this case, as shown in Fig. 7(b), all the fuel evaporates close to the injection location promoting the formation of a more homogeneous mixture than Case A which moves the combustion process towards premixed flames. However the mechanism which drives combustion instabilities could not be the one described by FTF-1 and FTF-2 (these formulations were developed to study premixed combustors with equivalence ratio oscillations as the main driving mechanism; furthermore the fuel is considered to be injected at a single location disregarding the physics of liquid fueled combustors where the evaporation process acts like a distributed fuel injection) and other formulations should be considered.

5. Conclusions

The thermoacoustic behaviour of lean burn aero-engine combustors is strongly dependent on operating conditions and simple FTF formulations seem to be inadequate to the study of the thermoacustic stability in all conditions. This is mainly due to the presence of liquid fuel since the physical processes related to droplet evolution, in particular droplet breakup and evaporation, are highly influenced by the mean properties of the flow field determining different flame structures and thus a different dynamic response of the flame. In order to fulfill the objective of developing simple FTFs to be used in lean burn aero-engines, further investigations are required to understand the basic driving mechanisms that regulate the coupling between heat release rate fluctuations and the acoustic field with great attention to the impact of liquid fuel evolution and droplet dynamics.

References

[1] Lieuwen, T.. Modeling premixed combustion acoustic wave interactions: a review. J Propul Power 2003;19(5):765–781.
[2] Magina, N., Shin, D.H., Acharya, V., Lieuwen, T.. Response of non-premixed flames to bulk flow perturbations. Proceedings of the Combustion Institute 2013;34:963–971.
[3] Tyagi, M., Jamadar, N., Chakravarthy, S.R.. Oscillatory response of an idealized two-dimensional diffusion flame: Analytical and numerical study. Combustion and Flame 2007;149:271–285.
[4] Balasubramanian, K., Sujith, R.I.. Non-normality and nonlinearity in combustion-acoustic interaction in diffusion flames. J Fluid Mech 2008;594:29–57.
[5] Hsiao, G.C., Meng, H., Yang, V.. Pressure-coupled vaporization response of n-pentane fuel droplet at subcritical and supercritical conditions. Proceedings of the Combustion Institute 2011;33:1997–2003.
[6] Cuquel, A., Durox, D., Schuller, T.. Scaling the flame transfer function of confined premixed conical flames. Proceedings of the Combustion Institute 2013;34:1007–1014.
[7] Palies, P., Schuller, T., Durox, D., Candel, S.. Modelling of premixed swirling flames transfer functions. Proceedings of the Combustion Institute 2011;33:2967–2974.
[8] Andreini, A., Facchini, B., Mangani, L., Simonetti, F.. Development and validation of a 1-D tool for thermoacoustic instabilities analysis in gas turbine combustors. Proceedings of the ASME Turbo Expo 2008;(GT2008-51248).
[9] Rayleigh, J.S.W.. The Theory of Sound, Volume II. MacMillan and Co; 1878.
[10] Lieuwen, T.C.. Investigation of combustion instability mechanisms in premixed gas turbines. PhD Thesis; Georgia Inst. of Technology; 1999.
[11] Andreini, A., Facchini, B., Giusti, A., Vitale, I., Turrini, F.. Thermoacoustic Analysis of a Full Annular Lean Burn Aero-engine Combustor. Proceedings of the ASME Turbo Expo 2013;(GT2013-94877).
[12] Andreini, A., Facchini, B., Giusti, A., Turrini, F.. Thermoacoustic Analysis of a Full Annular Aero-engine Lean Combustor with Multi-perforated Liners. Proceedings of the AIAA-CEAS Aeroacoustic Conference 2013;.
[13] Howe, M.S.. On the theory of unsteady high Reynolds number flow through a circular aperture. In: Proceedings of the Royal Society of London; vol. 366 of *Series A, Mathematical and Physical Sciences*. The Royal Society; 1979, p. 205–223.
[14] Bauer, A.B.. Impedance Theory and Measurements on Porous Acoustic Liners. J Aircraft 1977;14(8):720–728.
[15] Mendez, S., Eldredge, J.D.. Acoustic modeling of perforated plates with bias flow for Large-Eddy-Simulations. Journal of Computational Physics 2009;228:4757–4772.
[16] Gikadi, J., Ullrich, W.C., Sattelmayer, T., Turrini, F.. Prediction of the acoustic losses of a swirl atomizer nozzle under non-reactive conditions. Proceedings of the ASME Turbo Expo 2013;(GT2013-95449).
[17] Camporeale, S.M., Fortunato, B., Campa, G.. A Finite Element Method for Three-Dimensional Analysis of Thermo-acoustic Combustion Instability. Journal of Engineering for Gas Turbines and Power 2011;133.
[18] Campa, G., Camporeale, S.M., Cosatto, E., Mori, G.. Thermoacoustic analysis of combustion instability through a distributed flame response function. Proceedings of the ASME Turbo Expo 2012;(GT2012-68243).
[19] Myrczik, M.. Determination of inlet impedances for acoustic eigenmode computation in combustion chambers. Student research project WN/CFD/06/58; CERFACS; 2006.
[20] Dowling, A.P., Hubbard, S.. Instability in lean premixed combustors. Proc Instn Mech Engrs 2000;214.
[21] Tai-Wo-Chong, L., Komarek, T., Kaess, R., Föller, S., Polifke, W.. Identification of Flame Transfer Functions from LES of a premixed swirl burner. Proceedings of the ASME Turbo Expo 2010;(GT2010-22769).
[22] Tai-Wo-Chong, L., Bomberg, S., Ulhaq, A., Komarek, T., Polifke, W.. Comparative Validation Study on Identification of Premixed Flame Transfer Function. Proceedings of the ASME Turbo Expo 2011;(GT2011-46342).
[23] You, D.. A three-dimensional linear acoustic analysis of gas-turbine combustion instability. PhD Thesis; The Pennsylvania State University; 2004.
[24] Huang, Y., Yang, V.. Dynamics and stability of lean-premixed swirl-stabilized combustion. Progress in Energy and Combustion Science 2009;35:293–364.
[25] Lieuwen, T., Zinn, B.T.. The role of equivalence ratio oscillations in driving combustion instabilities in low NOx gas turbines. Proceedings of the 27th Symposium (International) on Combustion 1998;:1809–1816.
[26] Dowling, A.P.. Modeling and control of combustion oscillations. Proceedings of the ASME Turbo Expo 2005;(GT2005-68452).
[27] Sattelmayer, T.. Influence of the Combustor Aerodynamics on Combustion Instabilities from Equivalence Ratio Fluctuations. Journal of Engineering for Gas Turbines and Power 2003;125(1):11–19.
[28] Eckstein, J., Sattelmayer, T.. Low-Order Modeling of Low-Frequency Combustion Instabilities in Aeroengines. Journal of Propulsion and Power 2006;22(2).
[29] Eckstein, J.. On the Mechanisms of Combustion Driven Low-Frequency Oscillations in Aero-Engines. PhD Thesis; Technische Universität München; 2004.
[30] Eckstein, J., Freitag, E., Hirsch, C., Sattelmayer, T., von der Bank, R., Schilling, T.. Forced Low-Frequency Spray Characteristics of a Generic Airblast Swirl Diffusion Burner. Journal of Engineering for Gas Turbines and Power 2005;127:301–306.
[31] Gepperth, S., Koch, R., Bauer, H.J.. Analysis and comparison of primary droplet characteristics in the near field of a prefilming airblast atomizer. Proceedings of the ASME Turbo Expo 2013;(GT2013-94033).
[32] Lefebvre, A.H.. Atomization and sprays. Taylor and Francis; 1989.
[33] Andreini, A., Facchini, B., Giusti, A., Turrini, F., Vitale, I.. Thermo-Acoustic Analysis of an Advanced Lean Injection System in a Tubular Combustor Configuration. In: Proceedings of the COMSOL European Conference. 2012,.