Thermo-Acoustic Analysis of an Advanced Lean Injection System in a Tubular Combustor Configuration

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Abstract: In this work a thermoacoustic analysis of a tubular combustor with an advanced lean injection system is presented. The performed analysis is based on the resolution of the eigenvalue problem related to an inhomogeneous wave equation which includes a source term representing heat release fluctuations (the so called Flame Transfer Function, FTF) in the flame region. The effect of the mean flow is neglected whereas the effect of temperature variations on pressure waves is included by considering the temperature profile in the combustion chamber obtained from CFD (Computational Fluid Dynamics) computations. Numerical results were compared with both experimental data and results obtained with a monodimensional network-based solver. Comparisons with available experimental data showed the necessity of an improved FTF, more suitable for liquid fueled gas turbines where the evaporation process could play an important role in the flame heat release fluctuations. Furthermore, a criterion to simplify the geometry of the double swirler injector was defined allowing us to reduce the number of elements necessary to model this component.

Keywords: thermo-acoustics, Flame Transfer Function, combustion instabilities, tubular combustor.

1. Introduction

In order to reduce pollutant emissions, modern gas turbines are often equipped with lean low emission combustion systems, where the engine operates near the lean blow-out limits. One of the most critical issues of lean premixed technology is the onset of combustion instabilities related to a coupling between pressure oscillations and thermal fluctuations excited by the unsteady heat release of the flame. Such instabilities may reduce the life of combustor components, thus, the prediction of the thermoacoustic behavior of a combustion system is a fundamental task during the design of low emission gas turbines. As far as aero-engines are concerned, thermoacoustic issues become much more critical since they are directly related to passenger security. Furthermore the use of liquid fuels makes the physical modeling more difficult. Several numerical methods can be used to predict the thermoacoustic properties of a combustor, ranging from monodimensional network-based tools to fully three-dimensional LES (Large Eddy Simulation) and FEM (Finite Element Method) calculations. In this work an advanced AVIO PERM (Partially Evaporated and Rapid Mixing) Injection System has been analyzed using the acoustic module of the FEM code COMSOL Multiphysics.

2. Mathematical model

The solution of a thermoacoustic problem consists in determining the resonant frequencies of the combustor together with stability properties of the acoustic modes related to such frequencies.

The mathematical model that is generally used to describe the acoustic problem in combustors is the following inhomogeneous wave equation [1]:

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

where q' is 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. Moreover, the prime indicates a perturbation over the time averaged mean value and the overbar denotes mean values. This equation holds under the hypotheses of negligible mean flow velocity, absence of viscous losses and heat conduction and fluid treated as an ideal gas with constant specific heat ratio.

In some regions the mean flow velocity could not be negligible in comparison with the sound velocity: in this case such regions can be treated as separated elements modeled by means of particular transfer function matrices [1,2] or specific boundary conditions [3]. 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. (1) is solved in the frequency domain. The generic fluctuating quantity ϕ' is written as:

$$\phi' = \mathrm{Re}(\hat{\phi}\exp(i\omega t)) \tag{2}$$

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 an acoustic mode is unstable if the imaginary part is negative since it means that the amplitude of the fluctuation grows with time. Once harmonic fluctuations are introduced, Eq. (1) becomes:

$$\frac{\lambda^2}{\bar{c}^2}\hat{p} - \bar{\rho}\nabla\cdot\left(\frac{1}{\bar{\rho}}\nabla\hat{p}\right) = -\frac{\gamma-1}{\bar{c}^2}\lambda\hat{q} \tag{3}$$

where $\lambda = -i\omega$. This is the quadratic eigenvalue problem that is solved by means of the acoustic module of COMSOL Multiphysics.

Heat release fluctuations $\hat{q}$ are usually expressed as a function of acoustic variables through the so called Flame Transfer Function (FTF). The following expression is often adopted:

$$\hat{q} = Kf(\hat{u}_i, \hat{p}_i)\exp(\lambda\tau_{tot}) \tag{4}$$

K is a proportionality constant and τ_{tot} is the time delay between the initial perturbation and the heat release fluctuation; the subscript i denotes the injection location. According to [4], the time delay should consider all the physical processes involved in the transport mechanism, ranging from convection time to chemical delay time. It should be noted that in case of liquid fueled combustors, the droplet evaporation time could also be significant. In this work the following FTF was used:

$$\hat{q} = -K\frac{\bar{Q}}{\bar{u}_i}\hat{u}_i\exp(\lambda\tau_{conv}) \tag{5}$$

where $\bar{u}_i$ is the air mean velocity at the fuel injection location, $\bar{Q}$ is the mean heat release rate per unit volume and the time delay constant is computed by only considering the convection time from injection plane to the flame location. This is the typical expression for premixed combustion where heat release fluctuations can be directly related to equivalence ratio oscillations at the fuel injection plane.

3. Use of COMSOL Multiphysics

In this section the problem and the numerical strategies used to solve it will be described in much more detail.

3.1 Geometry and computational domain

In this work, a tubular combustor has been analyzed. The fuel is injected by means of an advanced lean injection system called PERM. It basically consists in an airblast injector with a double swirler setup which helps the evaporation and mixing process. Figure 1 shows the combustor configuration. Air is supplied to the injection system through a circular duct with an inlet diffuser. Fuel and air are partially mixed in the injection system and then discharged in the downstream circular duct where the combustion takes place. At the exit a nozzle is located allowing the flow to be chocked. The upstream duct is approximately 6D long (D is the duct diameter) whereas the combustion zone is roughly 2D long with a slightly smaller diameter.

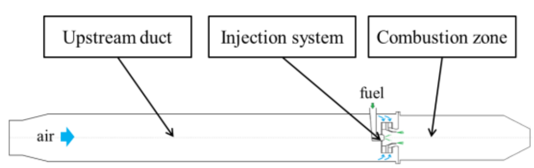

Figure 1: Combustor geometry.

Figure 2 shows the computational domain and the tetrahedral mesh used in FEM simulations. The geometry was built using SolidWorks® while the mesh was directly created using COMSOL. The maximum element size was chosen in order to detect acoustic modes up to 3 kHz. It must be noted that in the computational domain used for the present analysis, the presence of the fuel line was not considered.

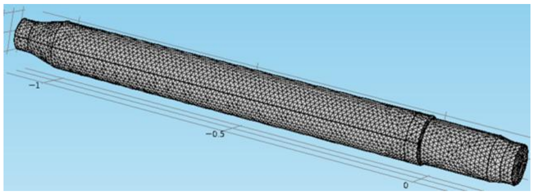

Figure 2: Computational mesh.

3.2 Injection system preliminary analysis

The PERM injection system is characterized by a very complicated geometry (see for example Figure 3a) which enhances the computational cost since a lot of small elements, much smaller than the maximum element size imposed by frequency resolution, are required for a correct discretization. Thus, geometry simplifications could be greatly appreciated.

Before performing the combustor thermo-acoustic analysis, different strategies to model the injection system have been analyzed and compared with each other with the main aim of reducing the geometrical complexity of such system without significantly affecting the acoustic response of the combustor. Figure 3 shows the three different configurations that were considered. The first one is the real geometry, the reference case; the second one was obtained from the real geometry by substituting the inlet channels with an unique annular channel with the same total area; finally the last configuration is similar to the previous one except for the annular channel height which is equal to the real one and the absence of internal separation between the two swirlers.

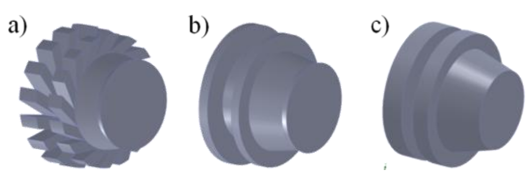

Figure 3: Simplification of swirler geometry; a) real geometry, b) annular inlets, c) annular inlets without internal separation.

First of all, the acoustic behavior of the three different configurations was analyzed without considering the presence of the combustor. Injection system eigenfrenquecies were computed imposing a plenum (p'=0) boundary condition both at the inlet and the outlet and using the same reference conditions (mean pressure and temperature) of the combustor simulation. In particular p=5.38 bar and T = 623 K.

Figure 4 reports the computational mesh and the first eigenmode of each case. The three meshes are characterized by the same maximum element size; however the real geometry necessitates more than twice the elements required by the other configurations to correctly represent all the geometrical features. As regards eigenfrequencies and eigenmodes, first of all it is important to note that the first mode appears at a frequency greater than 4 kHz, far away from the typical range considered in thermoacoustic analysis. Furthermore, case a) and b) present very similar eigenmodes both in terms of frequency and modal shape. On the other hand, in case c) the removal of swirler internal separation causes the acoustic coupling between the two swirlers, significantly affecting modal shapes (compare for example the first mode of case b) and c) represented in Figure 4) and frequencies.

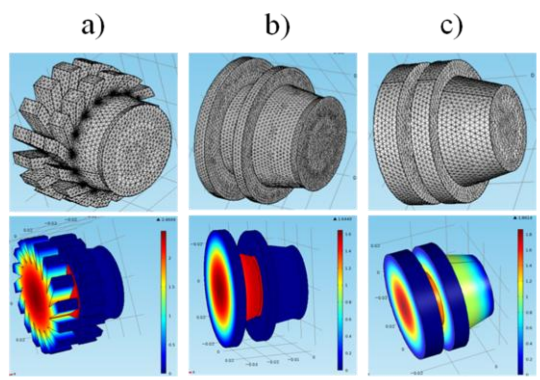

Figure 4: Computational mesh and first eigenmode; a) real geometry, b) annular inlets, c) annular inlets without internal separation.

In order to confirm the observations made in the injection system stand-alone analysis, three different passive (i.e. without the presence of the flame) simulations of the combustor were performed using the three injection system geometries. A plenum condition was imposed at the diffuser inlet, while at the combustor outlet a chocked condition (u'=0) was used. A reference mean pressure equal to 5.38 bar was considered in the entire domain; as regards temperature, a mean reference value equal to 623 K was imposed in the upstream duct and in the swirlers whereas in the combustion chamber a variable temperature was used. Such temperature profile was obtained from a RANS (Reynolds Averaged Navier Stokes) simulation by averaging the temperature field in planes normal to the combustor axis. Figure 5 schematically shows such averaging process.

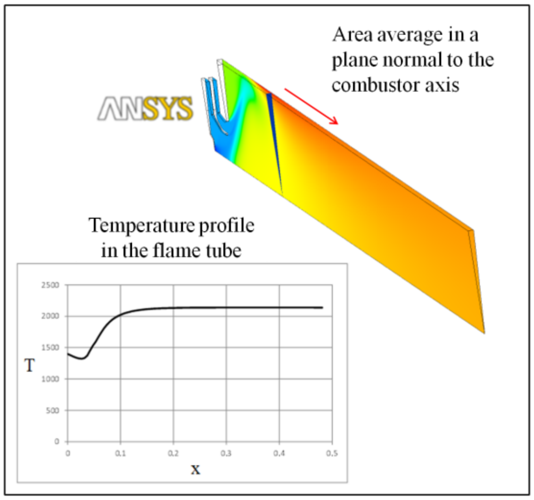

Figure 5: Averaging process to obtain mean temperature profile in the flame tube.

In Figure 6 combustor resonant frequencies obtained in the three cases are compared with each other. Values reported in the graph were obtained as the ratio between a given mode frequency and the frequency of the equivalent mode of case a). Case a) and b) are characterized by the same frequencies whereas in case c) slightly different values can be observed. It is important to note that this analysis was performed up to a maximum frequency close to 2.5 kHz, far away from the first injection system resonant frequency detected in the stand-alone analysis.

Concluding, in order to reduce computational costs, the geometrical simplifications of case b) could be a good choice. However, it is important to point out that all the performed simulations didn't consider the effect of the mean flow on the acoustic propagation. Because of the presence of small sections, in the swirler region, gas flow velocity is usually not negligible in comparison to sound velocity making the simplification of zero mean flow velocity a possible source of errors. From this point of view the approach described in [2], where the injection system is replaced by a transfer function matrix, should be considered in future works since it could allow us to both reduce the computational cost and consider the effect of mean flow.

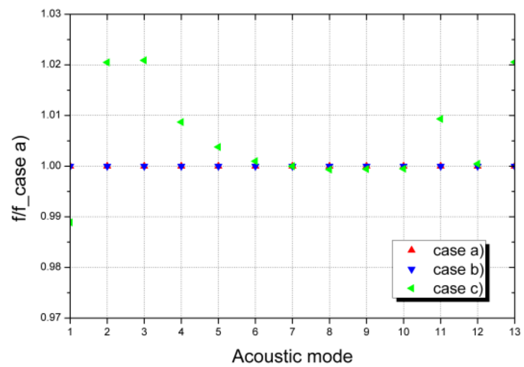

Figure 6: Comparison between resonant frequencies obtained with different injection system configurations

3.3 Tubular combustor computational setup

Starting from the computational setup used for the passive simulations described in the previous section, the numerical model is completed by introducing the flame and the related FTF. First of all a flame region, where the FTF is activated, has to be identified. Two different shapes for the flame region have been proposed and compared with each other. The first one is a conical flame (see Figure 7a) obtained from the CFD simulation by means of a CO (carbon monoxide) iso-contour. The second one is a cylindrical shape characterized by the same volume of the conical flame with the centroid placed at the same location of the cone geometric center (see Figure 7b).

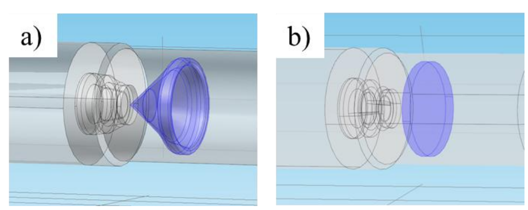

Figure 7: a) Conical flame, b) cylindrical flame.

As regards the FTF, two different strategies were tested. In the simplest approach Eq. (5) was directly used. Velocity fluctuations were sampled at the swirler exit plane, the same location where the mean velocity was computed. Results presented below were obtained by setting K=1and by assigning to τ a constant value computed as the ratio between the mean flow path and the mean velocity.

However, looking at the functioning of the PERM injector, two distinct injection points can be identified: the pilot injector, at the centre of the system, and the edge of the lip that separates the two swirlers where the liquid fuel film undergoes atomization. In order to include the two distinct contributions, considering the linear formulation of the problem, a different FTF formulation, which will be referred to as “double injection” or “dInj”, has been evaluated:

$$\hat{q}_{dInj} = -K_1 \frac{\overline{Q}_1}{\overline{u}_1} \hat{u}_1 \exp(\lambda \tau_1) + - K_2 \frac{\overline{Q}_2}{\overline{u}_2} \hat{u}_2 \exp(\lambda \tau_2) \qquad (6)$$

$\overline{u}_{1/2}$ was set equal to the mean velocity at the injection point whereas $\overline{Q}_{1/2}$ was computed by considering the fuel mass flow rate contribution of each injection. Finally $K_{1/2}$ was taken equal to unity and $\tau_{1/2}$ was computed as the ratio between the mean flow path from injection point to flame region and mean velocity. The model could be further improved by considering τ as a function of the axial distance x between a point in the flame region and the injection location:

$$\tau(x) = \frac{x}{\overline{u}} \qquad (7)$$

3.4 Numerical results

In Figure 8 results obtained with the two different flame region shapes are compared to each other. These simulations were performed using the FTF of Eq. (5) and the injection system simplified as in case b) (see Section 3.2). Acoustic resonances appear to be sensitive to the shape of the flame region only at the lowest frequencies while at high frequencies no important difference arises.

In Figure 9 complex frequencies obtained with different injection system geometries and different FTFs are compared with each other. As observed in Section 3.2 for simulations without flame, geometries a) and b) give the same results also when the presence of the flame is considered. As regards the FTF, the two different models tested in this work give very similar results. Simulations were also repeated assigning to τ the expression of Eq. (7). These results are reported in Figure 10: different eigenfrequencies with different stability properties were found. This clearly shows the importance of the delay time in the combustion instability modeling.

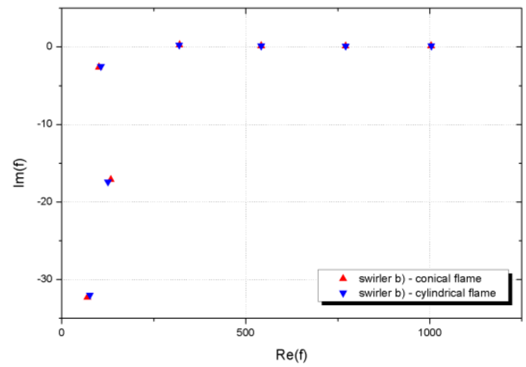

Figure 8: Complex eigenfrequencies, comparison between conical and cylindrical flame region shapes.

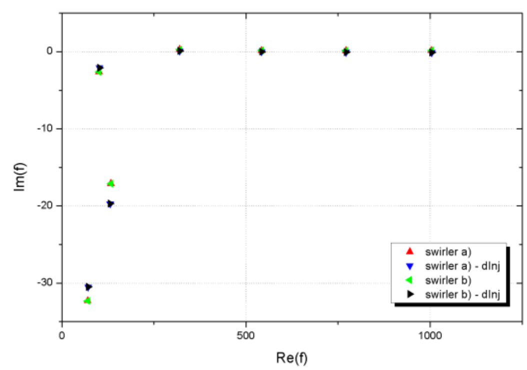

Figure 9: Complex eigenfrequencies, comparison between different injection system geometries and different FTFs.

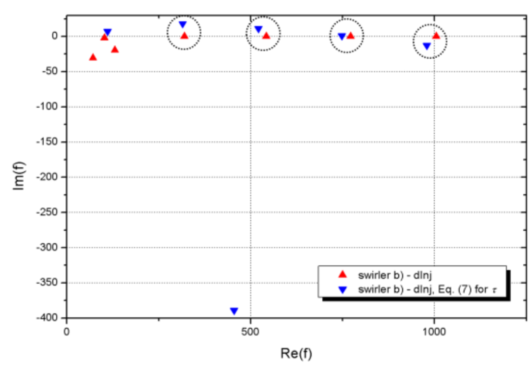

Figure 10: Complex eigenfrequencies, comparison between constant and variable τ.

3.5 Comparison with 1D network based solver

In order to assess the reliability of the procedure, FEM results were compared with results obtained with an in-house developed acoustic network based solver. This solver, called TA-1D allows us to compute planar modes in cylindrical geometries. The injection system, as well as the flame region, was modeled using equivalent cylinders. In particular, the injection system was reproduced using two cylinders in series configuration. The first one was characterized by a section equal to the swirler inlet area and a length equal to the mean swirler radial path; for the second one, a section equal to the swirler exit area and a length equal to the mean axial flow path were assumed. Resonant frequencies obtained with TA-1D are very close to FEM results especially in the passive simulation. In Figure 11, as an example, modal shapes of the third mode obtained in the passive simulation with COMSOL and TA-1D are compared with each other: the good agreement between the different solvers is shown.

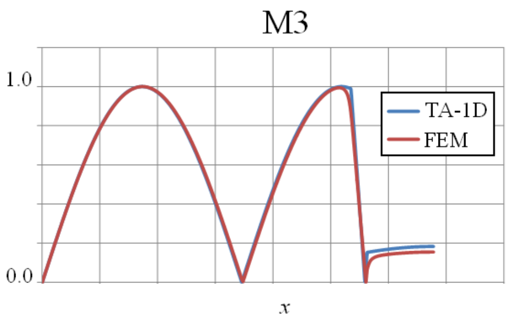

Figure 11: Normalized acoustic pressure for the third mode (passive simulation), comparison between FEM and TA-1D.

3.6 Comparison with experiments

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, air-fuel ratio and fuel mass flow rate distribution between pilot and main injections. In order to perform a better comparison with experiments, another test point was considered. A thermo-acoustic simulation was performed using the injection system b) and the FTF of Eq. (5). Table 1 summarizes the main features of the two cases analyzed in this work: case 1 is the test point analyzed in previous sections; case 2 is the new test point.

Figure 12 shows a comparison between complex eigenfrequencies of the two test points analyzed in this work. Excepting the first mode, resonant frequencies increase with pressure without changing the stability properties. Comparisons with experiments (not reported here) showed that numerical simulations under-predict frequency values in both cases. Much more agreement was found considering the expression of Eq. (7) for τ. The main reason of this behavior could be ascribed to the simple form used for the FTF which not consider the real combustion physical process of liquid fueled gas turbines. In particular the fuel evaporation time is neglected. A better agreement with experiments could be reached by properly calibrating K and τ (dependence on operating conditions has also to be evaluated) or by developing a new FTF. These important modeling aspects are addressed to future works.

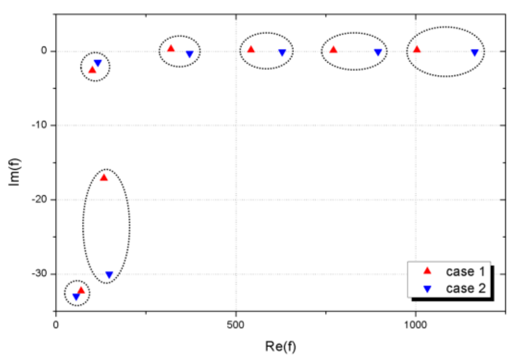

Figure 12: Complex eigenfrequencies, comparison between case 1 and case 2.

Table 1: Main features of the two test points

	case 1	case 2
mean pressure [bar]	5.38	22.0
inlet air temperature [K]	623	838
FAR	47	45
P/T [%]	20	10

3.7 Modal shapes

For the sake of completeness, in Figure 13 modal shapes (in terms of acoustic pressure) of the first eight eigenmodes are reported.

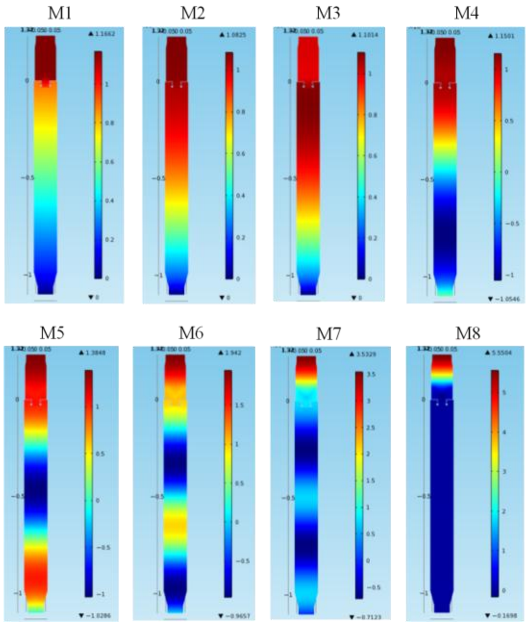

Figure 13: modal shape of the first eight modes (case with mean pressure equal to 22 bar).

4. Conclusions

The acoustic FEM eigenvalue solver has been successfully applied to predict the thermoacoustic behavior of a tubular combustor in terms of resonant frequencies and acoustic modes. A criterion to simplify the geometry of the double swirler injector was defined allowing the reduction of the number of elements necessary to model this component. The influence of flame region shape on the eigenfrequencies computation was investigated together with the effect of two different expressions for the flame transfer function. Comparisons with available experimental data showed the necessity of an improved FTF, more suitable for liquid fueled gas turbine where the evaporation process could play an important role in the flame heat release fluctuations.

5. References

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