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Thermoacoustic Analysis of Combustion Instability Importing RANS Data

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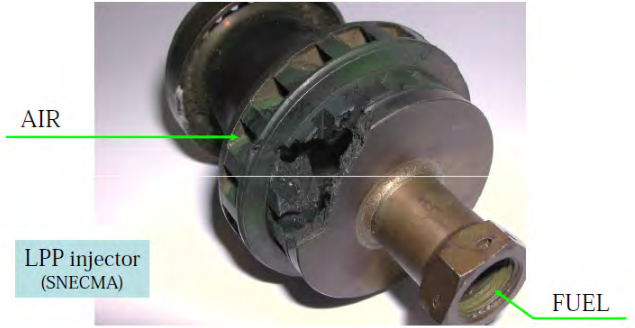
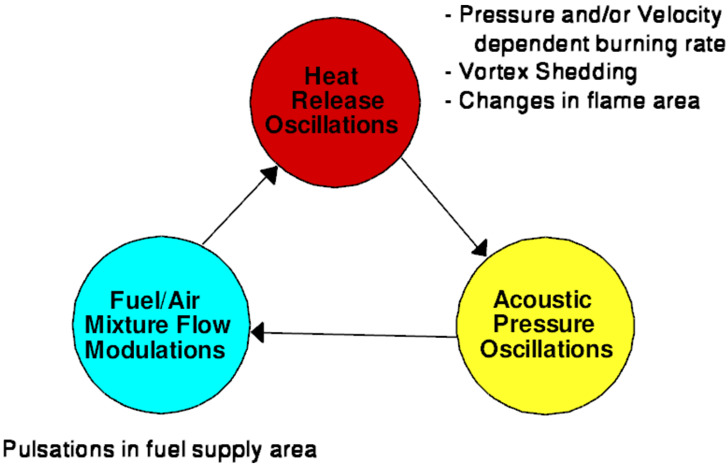
Something to be avoided about Thermoacoustic Instability!



Franck Nicoud, University of Montpellier, VKI Lecture, Nov. 2010

Origin of Thermoacoustic Instability



Thermoacoustic Instabilities

They are due to the coupling between the unsteady heat release rate and the acoustic oscillations inside the combustion chamber.

Gain of Acoustic Energy from Heat Release:

$$\left\langle \frac{1}{C_p T} \int \int \int_v p' q' dv \right\rangle > Losses \Longrightarrow Instability$$

$p' \longrightarrow$ acoustic pressure fluctuations; $q' \longrightarrow$ heat release fluctuations.

Wave Equation

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

where q' is fluctuation of the heat input per unit volume:

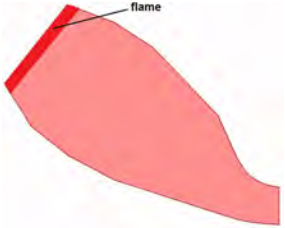
$$\frac{q'(\mathbf{x})}{\overline{q}(\mathbf{x})} = -\mathcal{K} \frac{u_i'(t - \tau(\mathbf{x}))}{\overline{u}_i}$$

How to model heat release fluctuations ?

Heat Release Model

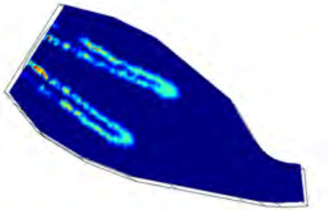
$\Longrightarrow$

Flame Sheet. Simplified approach and useful for the comprehension of the phenomenon and for sensitivity analyses. **Is it realistic ?**



$\Longrightarrow$

Flame Sheet inside a realistic configuration of combustion chamber. **Does it describe the actual flame ?**



$\Longrightarrow$

Spatial Distribution of the Flame inside a realistic configuration of combustion chamber. **It is close to the actual flame, but it is not enough !**

Objectives

- Investigate the thermoacoustic behavior of a practical annular combustion chamber using COMSOL Multiphysics;
- Introduce the actual temperature field and the actual flame shape as from RANS simulation;
- Examine the influence of the flame parameters.

Mathematical Model

Eigenfrequency Analysis

Perturbations are expressed by complex functions of time and position, so that the acoustic pressure waves are governed by:

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

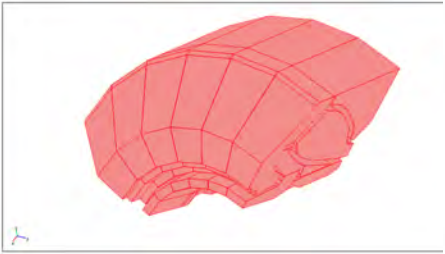
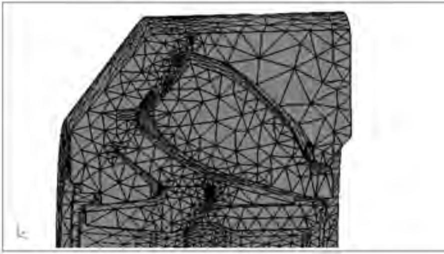
where $\lambda = -i\omega$ is the complex eigenvalue of the system:

- Real part $\Longrightarrow$ Eigenfrequency;
- Imaginary part $\Longrightarrow$ Growth Rate:
  - Growth Rate Positive $\Longrightarrow$ Unstable Mode;
  - Growth Rate Negative $\Longrightarrow$ Stable Mode.

In COMSOL

physics	$\Longrightarrow$	**Acoustics**
application module	$\Longrightarrow$	**Pressure Acoustics**
study	$\Longrightarrow$	**Eigenfrequency**

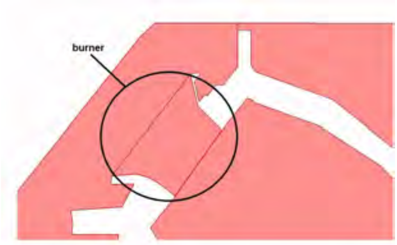
Ansaldo Energia Annular Combustion Chamber
3D FEM Geometry

Boundary Conditions

- Closed End at Inlet and at Outlet;
- Symmetric Boundary Conditions in order to study a quarter of the chamber instead of the whole.

Burner Modeling

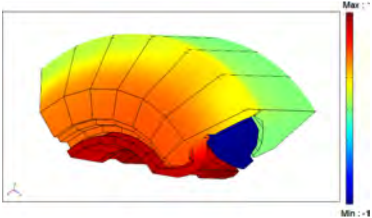


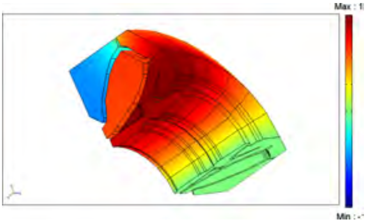
Burner Transfer Matrix (see Campa and Camporeale, COMSOL Conference 2010)

$$\begin{bmatrix} \frac{p'}{\bar{\rho} c} \\ u' \end{bmatrix}_d = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} \frac{p'}{\bar{\rho} c} \\ u' \end{bmatrix}_u$$

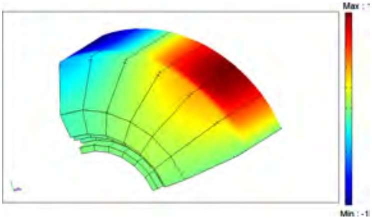
the matrix elements are function of the **Mach number**, the **area ratio** α, the **pressure loss coefficient** ζ, the **effective less** l_{eff}. Data are the ones from the actual Ansaldo Energia machine.

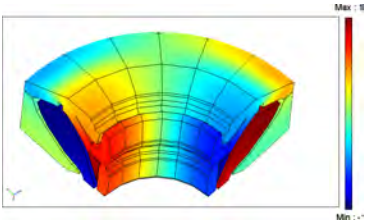
Modal Analysis





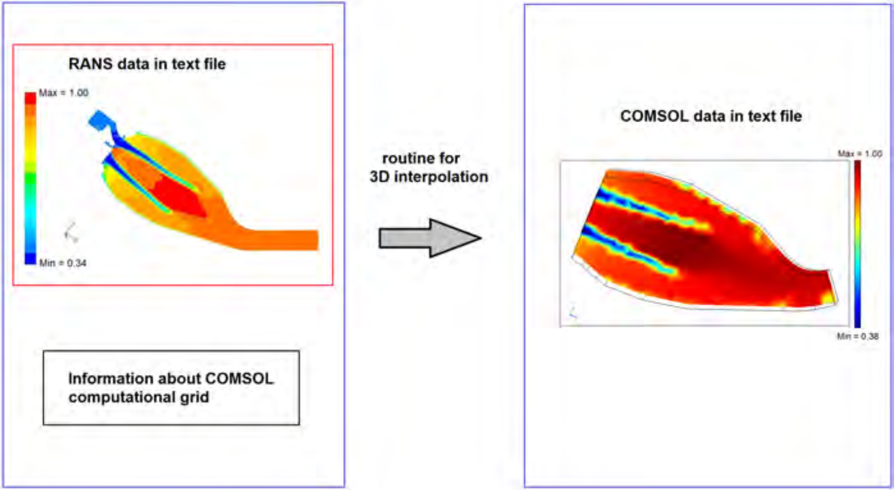
On the left side Mode 3, axial waveform, and on the right side Mode 4, azimuthal waveform $n = 1$.



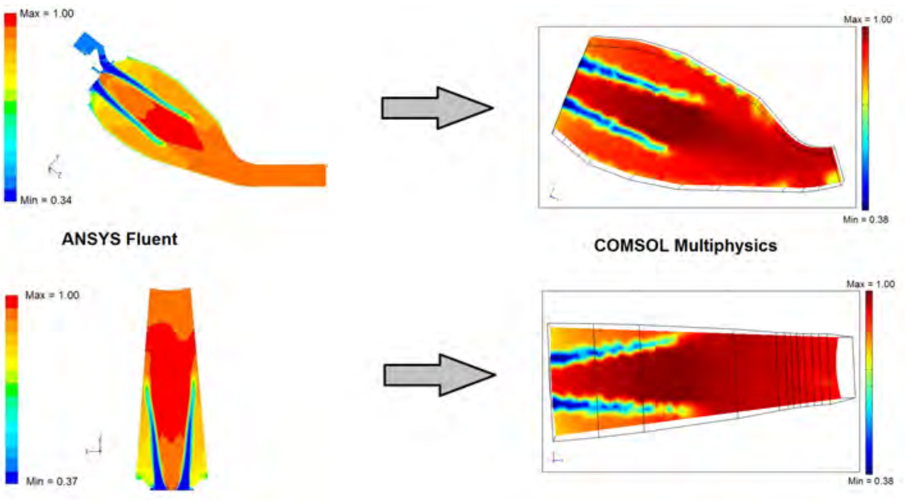


On the left side Mode 8, azimuthal waveform $n = 3$ in the plenum, and on the right side Mode 13, azimuthal waveform $n = 2$.

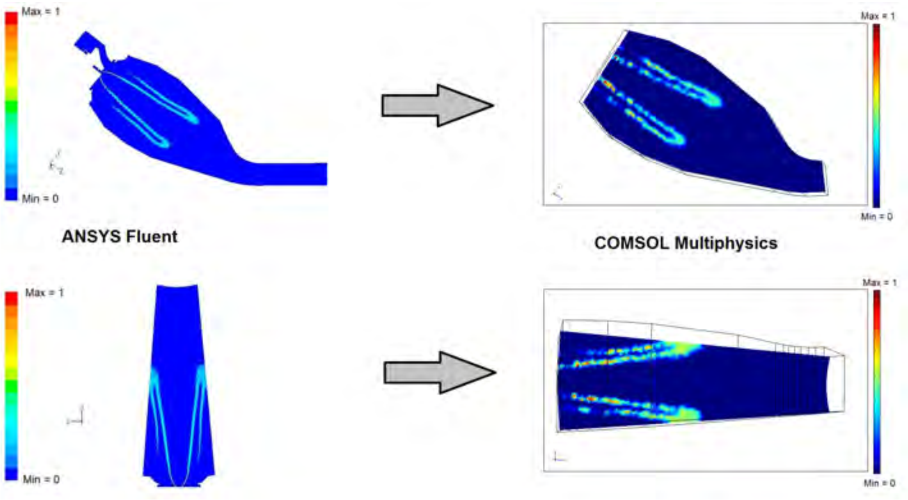
Import RANS data in COMSOL



Import Temperature field in COMSOL



Import Reaction Rate field in COMSOL



Rate of Reaction

Actual Flame Sheet

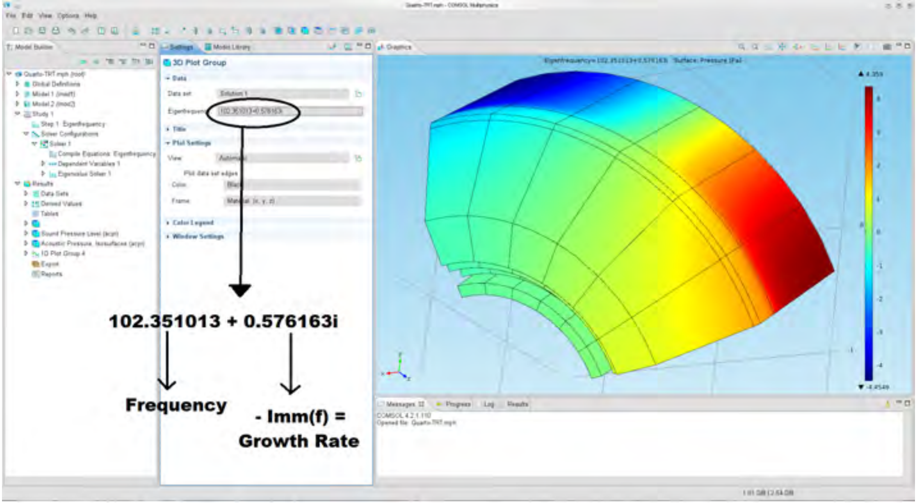
$$\frac{q'(\mathbf{x})}{\overline{q}(\mathbf{x})} = -\kappa \frac{u_i'(t-\tau(\mathbf{x}))}{\overline{u}_i}$$

where $\overline{q} = RR(\mathbf{x}) \cdot LHV$

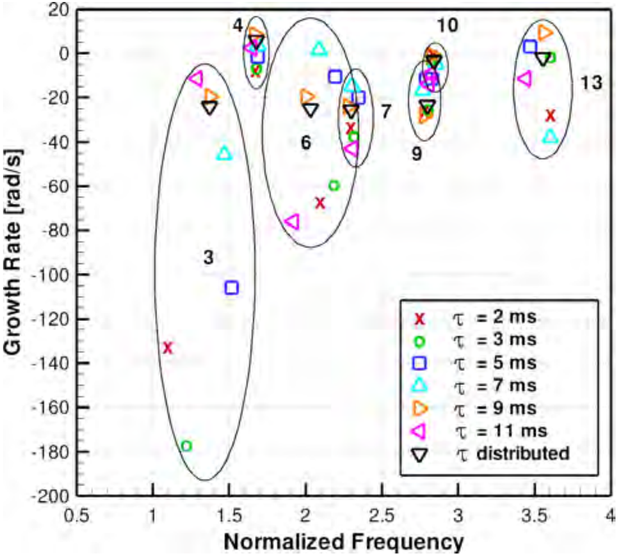
being *RR* the *Rate of Reaction* as it comes from the RANS simulations and *LHV* is the Lower Heating Value of the fuel.

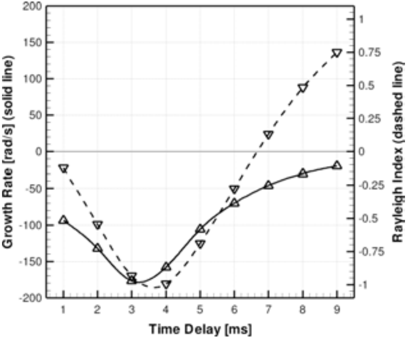
1. $\overline{q} = 0$ and $\widehat{q} = 0$ when *Rate of Reaction* is lower than an inferior limit, which is properly defined;
2. in the other points $\overline{q}$ (volumetric heat release W/m^3) is calculated considering the Lower Heating Value and the Rate of Reaction.

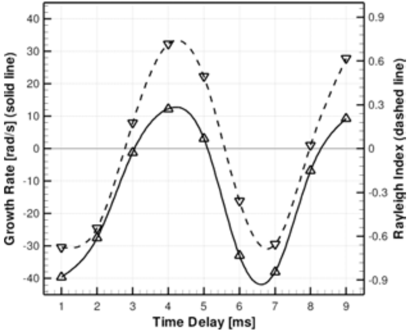
Snapshot of the Eigenvalue Problem Solution in COMSOL.



Combustion chamber modes for different values of τ.







Rayleigh Index

It is an important indicator of thermo-acoustic coupling:

$$R_i = \frac{\int_V \widehat{p}\widehat{q} dV}{\overline{\widehat{p}\widehat{q}}}$$

Conclusion

- An actual annular combustion chamber has been examined;
- The actual operative conditions have been exported from RANS simulations into COMSOL Multiphysics;
- More detailed analysis when spatial distributions of temperature and heat release are considered;
- The effects of the 3D distribution of the flame inside the combustor can be investigated;
- The effects of the non linearity of the heat release can be investigated in the future.

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