



*Università degli Studi di Firenze*

Dipartimento di Energetica Sergio Stecco



COMSOL Conference  
Europe 2012

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

A. Andreini<sup>1</sup>, B. Facchini<sup>1</sup>, **A. Giusti**<sup>1</sup>, F. Turrini<sup>2</sup>, I. Vitale<sup>2</sup>

<sup>1</sup> Energy Engineering Department, University of Florence

<sup>2</sup> AVIO S.p.A.



# Outline

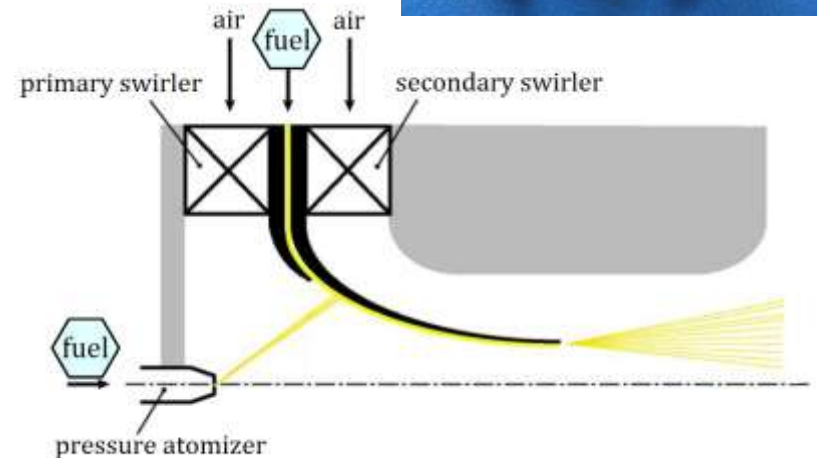
- Introduction and motivations
- Mathematical model
- Use of COMSOL Multiphysics
- Results
- Conclusions

# Introduction and motivations

## Prediction of thermoacoustic instabilities in a aero-engine combustor

- Reduction of pollutant emissions
  - Lean low emission combustion systems
  - Engine operated near blow-out limits
  - Combustion instabilities
    - Coupling between pressure oscillations and flame heat release fluctuation
    - Directly related to passenger security
    - The use of liquid fuel (partially premixed flames) makes the physical modeling much more difficult

PERM (Partially Evaporating and Rapid Mixing)



# Mathematical model

- Solution of thermoacoustic problem: determining the resonant frequencies of the combustor and their stability properties
- Frequency domain analysis
  - Physical problem described by an inhomogeneous wave equation

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

$$\varphi(t) = \text{Re}(\hat{\varphi} e^{i\omega t})$$

- RHS term represents heat release fluctuations
  - To be modeled by means of a Flame Transfer Function (FTF)

$$\hat{q} = K f(\hat{u}_i, \hat{p}_i) \exp(\lambda \tau_{tot})$$

- Quadratic eigenvalue problem solved using the **acoustic module** of COMSOL Multiphysics

# Mathematical model

- Main assumptions of the model
  - Linearity
  - Negligible mean flow
    - Mean flow Mach number equal to zero
- Main output of the thermoacoustic analysis:
  - Complex eigenvalues
    - Real part  $\rightarrow$  frequency of oscillations
    - Imaginary part  $\rightarrow$  growth rate (stability of the mode)
  - Eigenmodes
    - The shape of the acoustic mode related to a particular resonant frequency

# Mathematical model

- Two different FTF considered:

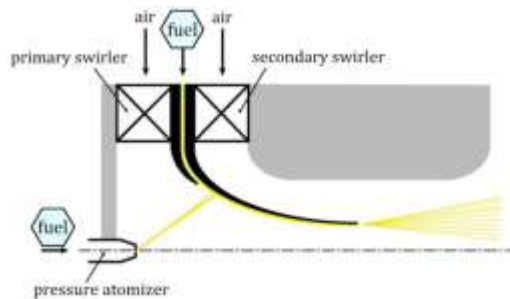
- 1) Single injection

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

The delay time  $\tau$  considered in this work only accounts for the convection time from injection to flame position

- 2) Double injection

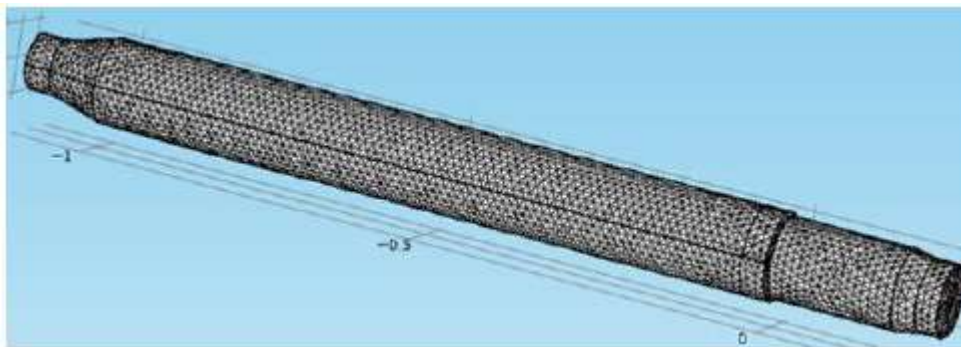
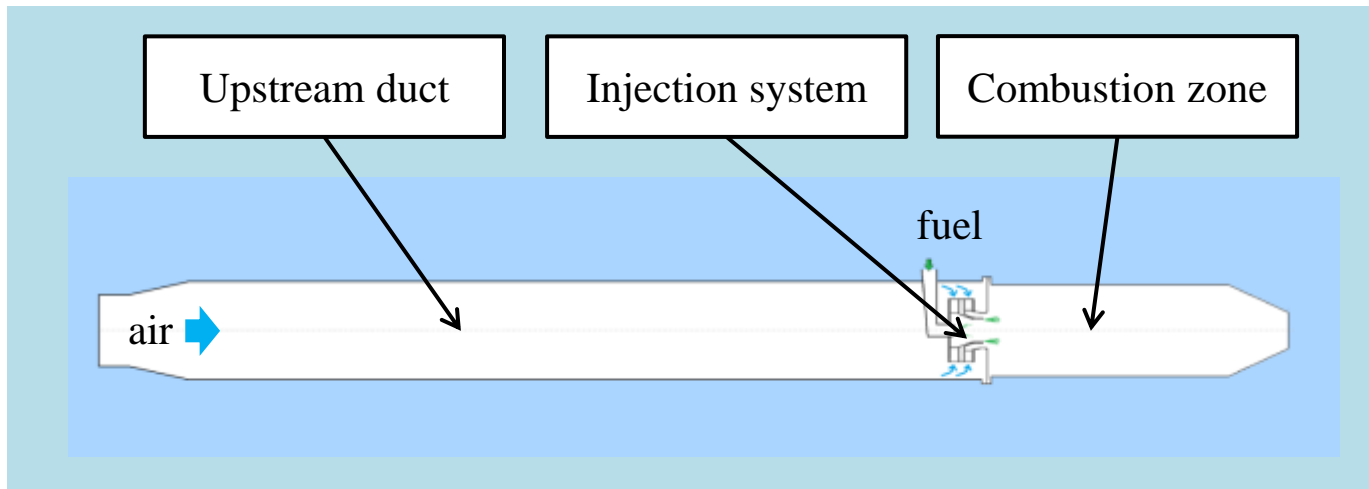
$$\hat{q}_{dInj} = -K_1 \frac{\bar{Q}_1}{\bar{u}_1} \hat{u}_1 \exp(\lambda \tau_1) - K_2 \frac{\bar{Q}_2}{\bar{u}_2} \hat{u}_2 \exp(\lambda \tau_2)$$



The contribution of the pilot injector and film breakup have been considered separately. Constants  $K$  were proportional to the injected fuel mass flow rate.

# Use of COMSOL

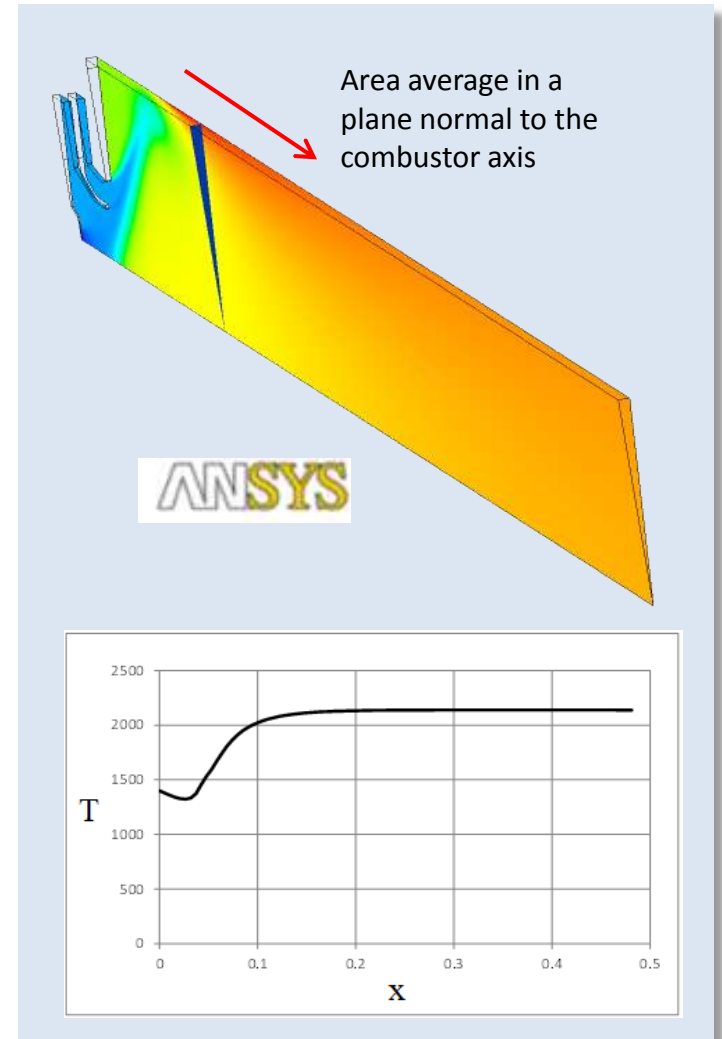
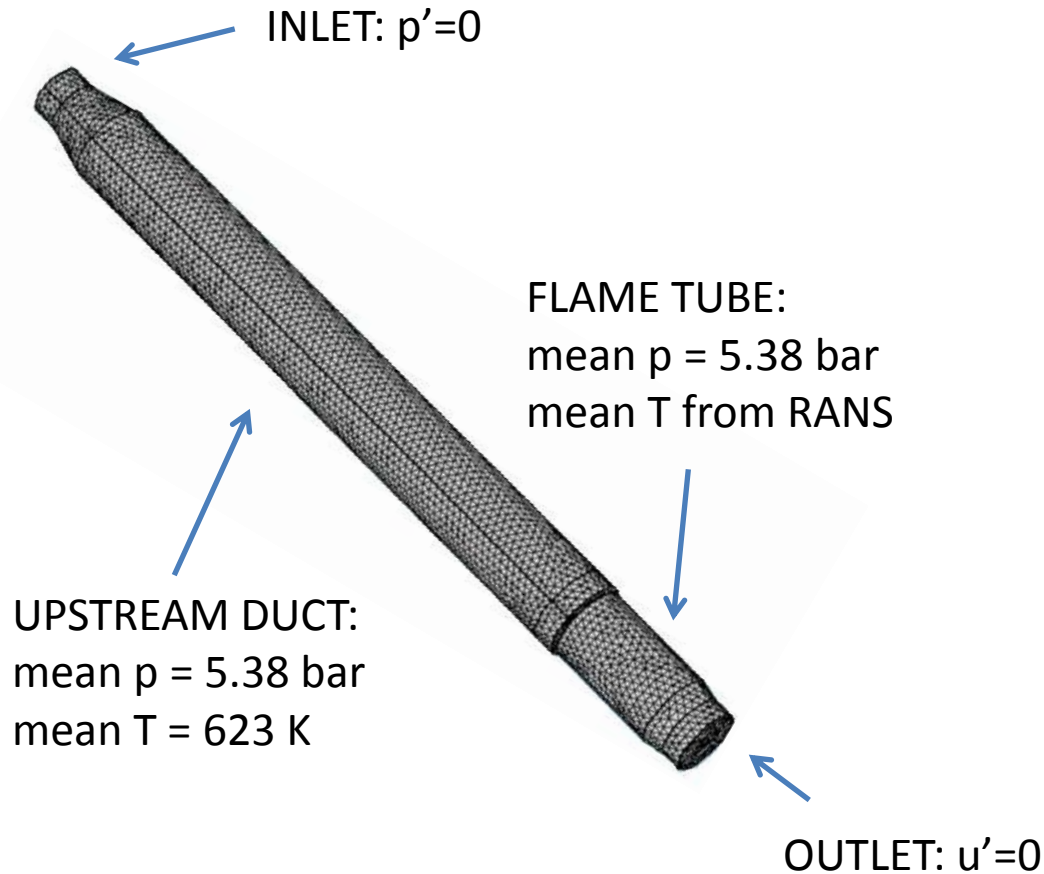
- Geometry: tubular combustor with PERM injection system



Complicated injection system geometry: a lot of elements are required to correctly represent all features.

# Use of COMSOL

- Boundary conditions





# Use of COMSOL

- Injection system preliminary analysis
  - Objective: reducing the geometrical complexity of the injection system without significantly affecting the acoustic response of the combustor
  - Three different geometries considered



a) Real geometry



b) Annular inlets

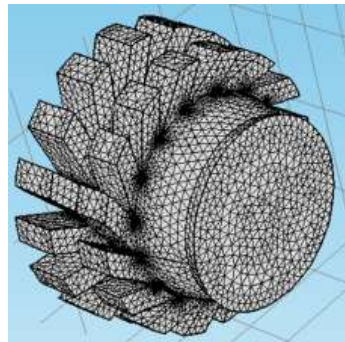


c) Annular inlets without internal separation

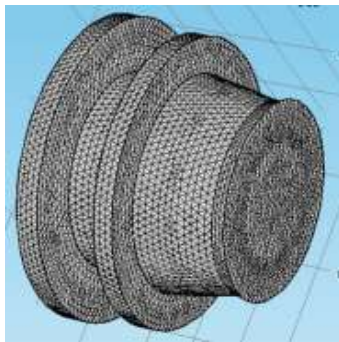
# Use of COMSOL

- Injection system preliminary analysis: stand alone analysis
    - Eigenfrequency analysis with plenum ( $p'=0$ ) conditions at both inlet and outlet.
- Results:

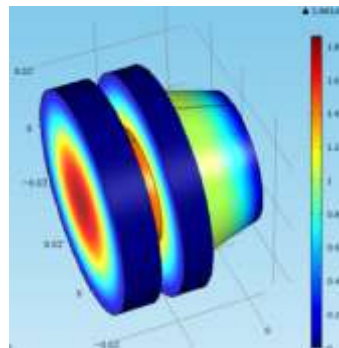
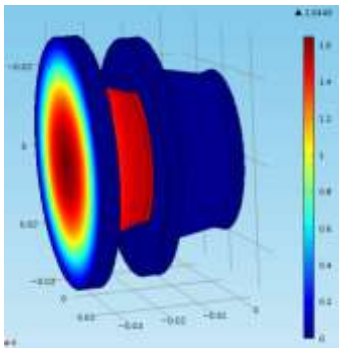
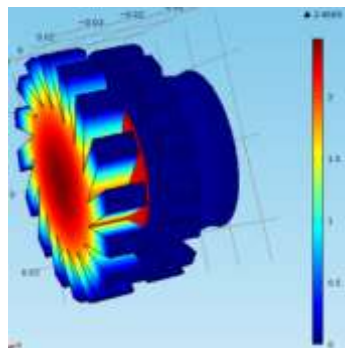
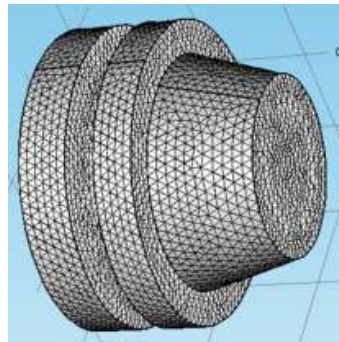
a)



b)



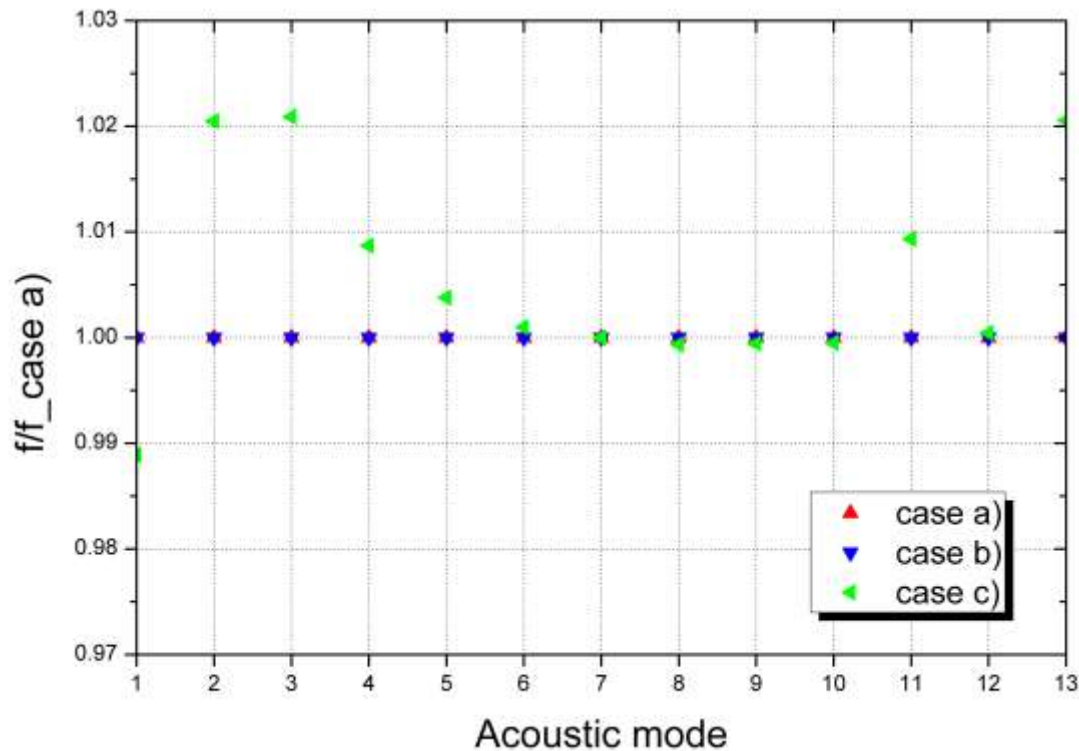
c)



- Case a) requires twice the elements of cases b) and c) with the same maximum element size
- The first resonant frequency has a value  $> 4\text{kHz}$
- Internal separation significantly affects modal shapes
- Case b) the best compromise

# Use of COMSOL

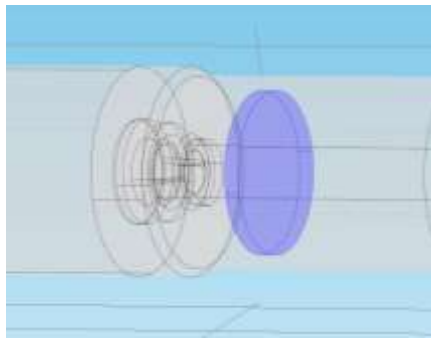
- Injection system preliminary analysis
  - Passive simulation of the combustor with the three different types of injection system



- In the injection system the mean flow velocity could not be negligible
- The performed analysis does not account for the effects of mean flow on the acoustic field
- **Substituting the injection system with a transfer matrix?**

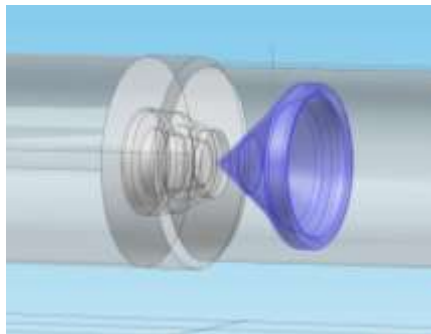
# Use of COMSOL

- FTF has to be activated in the flame region.
- Two different flame region shapes analysed:



## 1) Conical shape

- Obtained from CO mixture fraction iso-contour of a preliminary RANS simulation

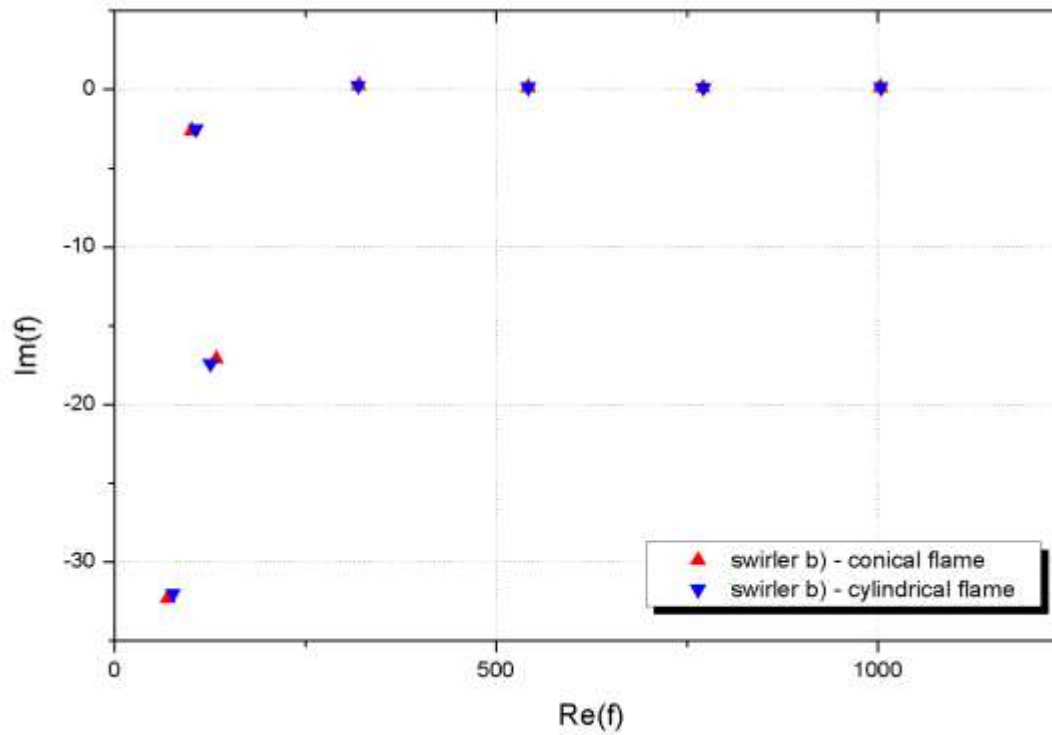


## 2) Cylindrical shape

- Same volume of the conical flame
- Centroid placed in the center of mass of the conical flame

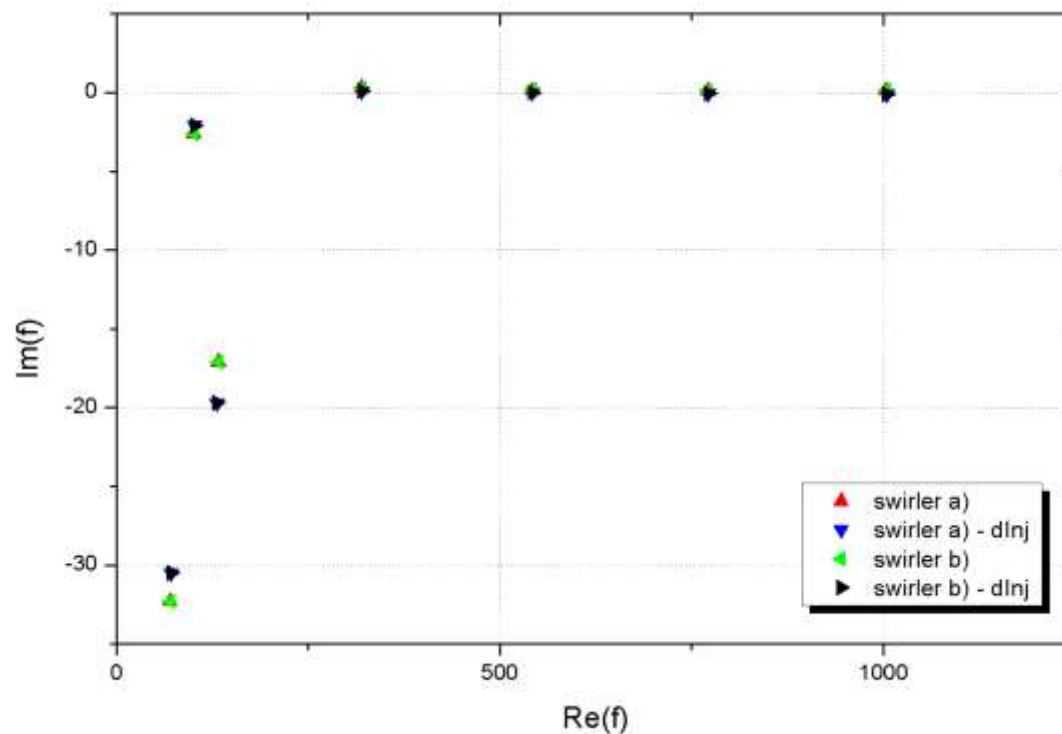
# Results

- Comparison between different flame shapes
  - Results obtained with the two different flame shapes are very similar to each other
  - Small differences at low frequencies



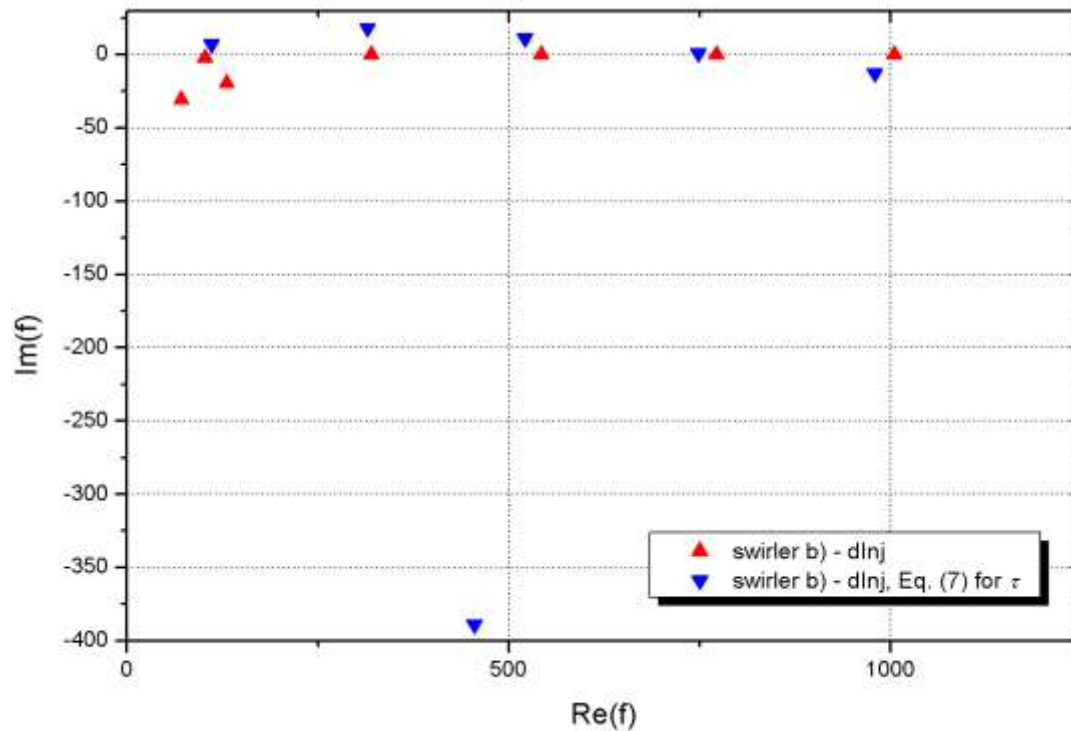
# Results

- Comparison between different injection system geometries and different FTFs
  - Swirler a) and b) give the same results also in the active simulation
  - The model used for the FTF influences the growth rate at low frequencies



# Results

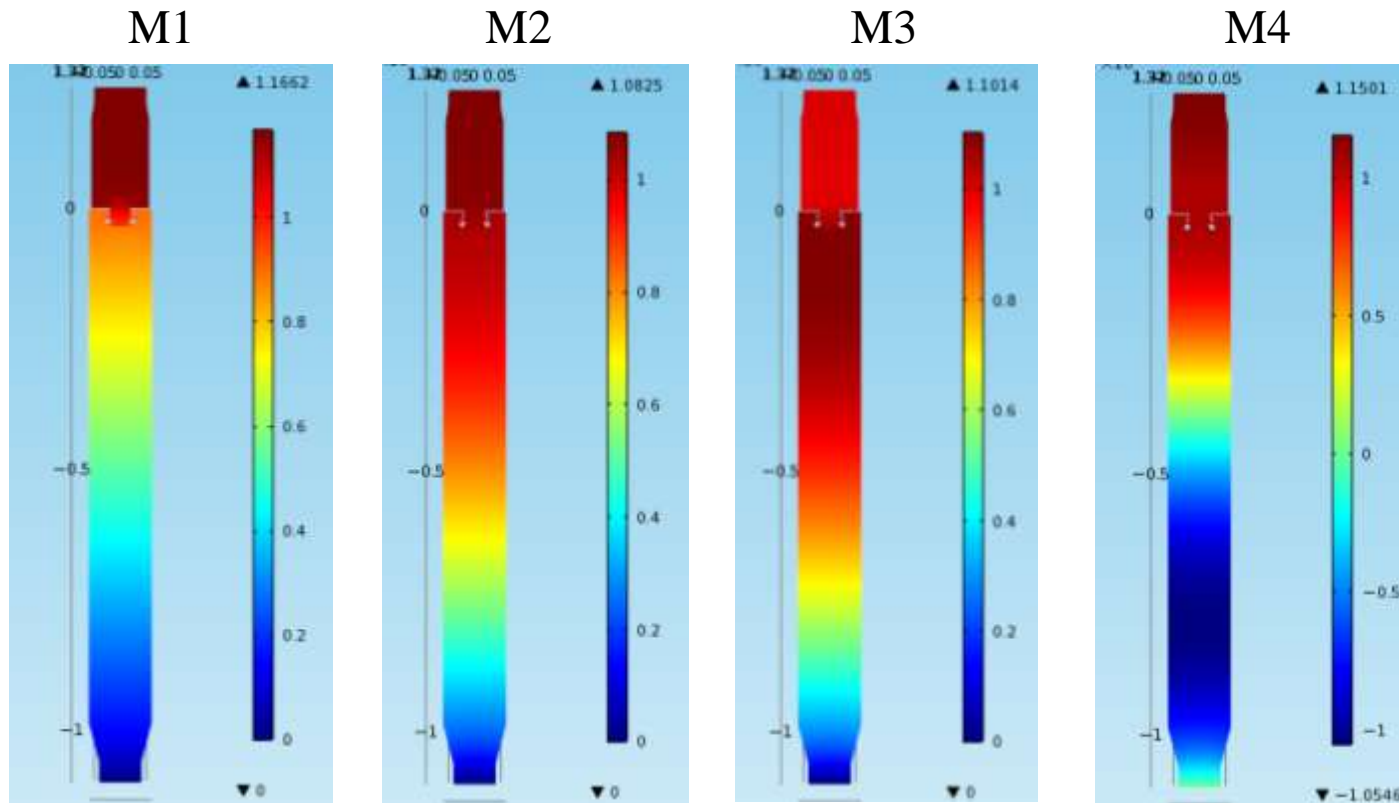
- Delay time as a function of flame position
  - The expression and the value of delay time highly influence the results of the acoustic analysis



$$\tau_{conv} = \frac{x}{\bar{u}}$$

# Results

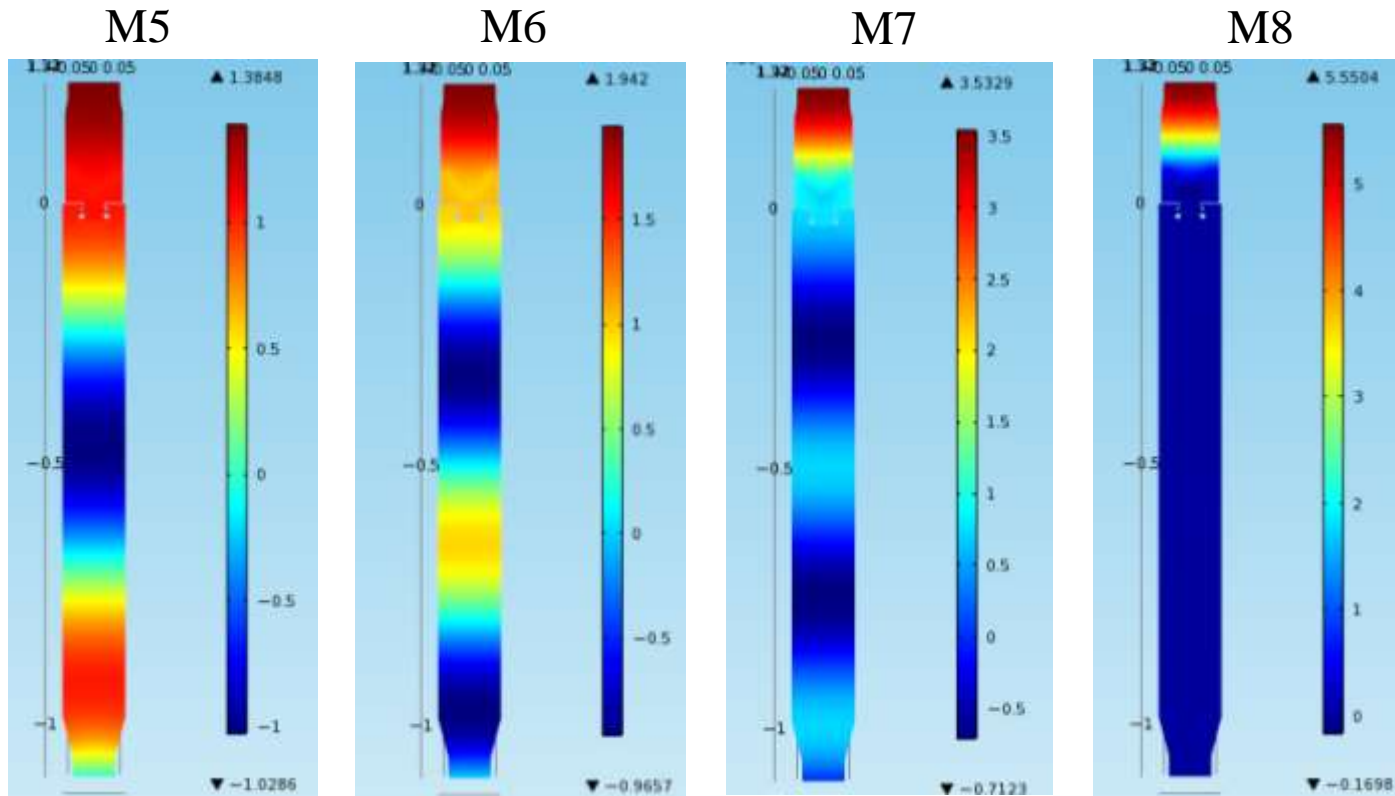
- Example of modal shapes





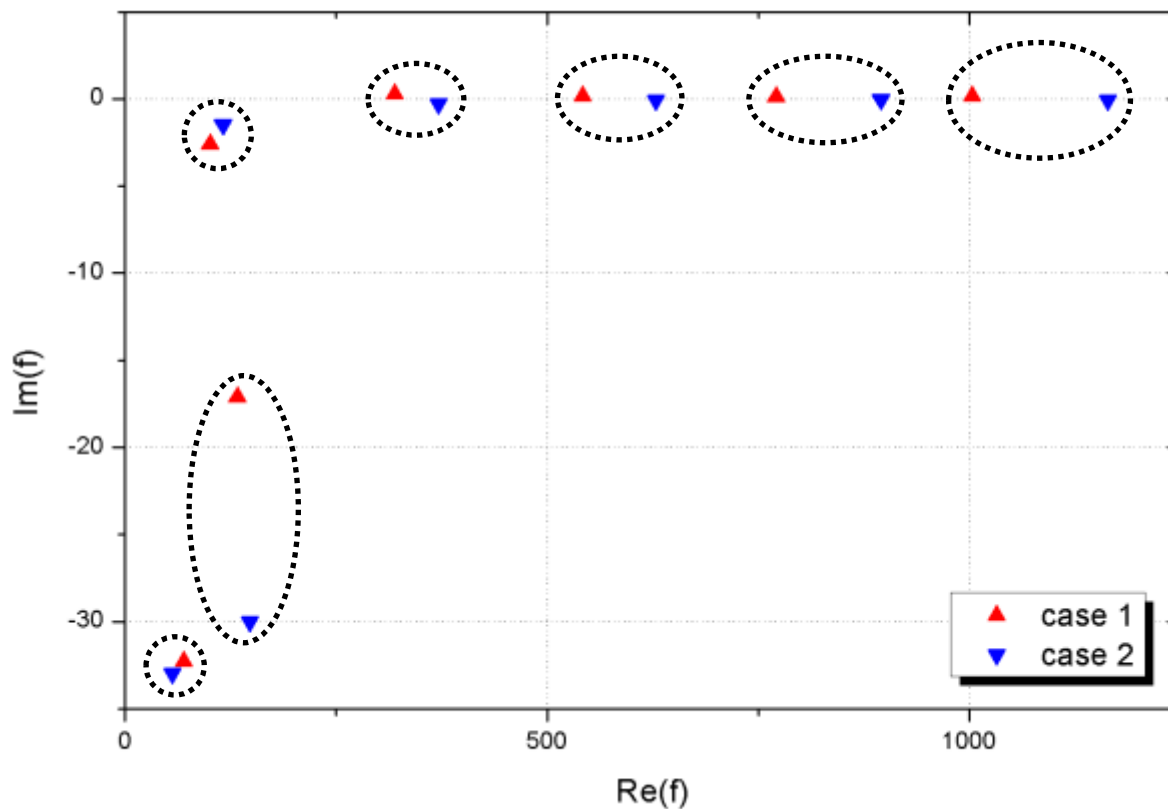
# Results

- Example of modal shapes



# Results

- Comparison with experiments (not shown here)



- Two different cases tested ( $p_2 > p_1, T_2 > T_1$ )
- Numerical simulations underpredict values of resonant frequencies
- A better agreement with experiments could be reached by properly calibrating the parameters  $K$  and  $\tau$  of the FTF or by developing new FTFs

# 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.



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Thank you for your attention!

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