Using High Performance Computing to predict Combustion Instabilities in aeroengines

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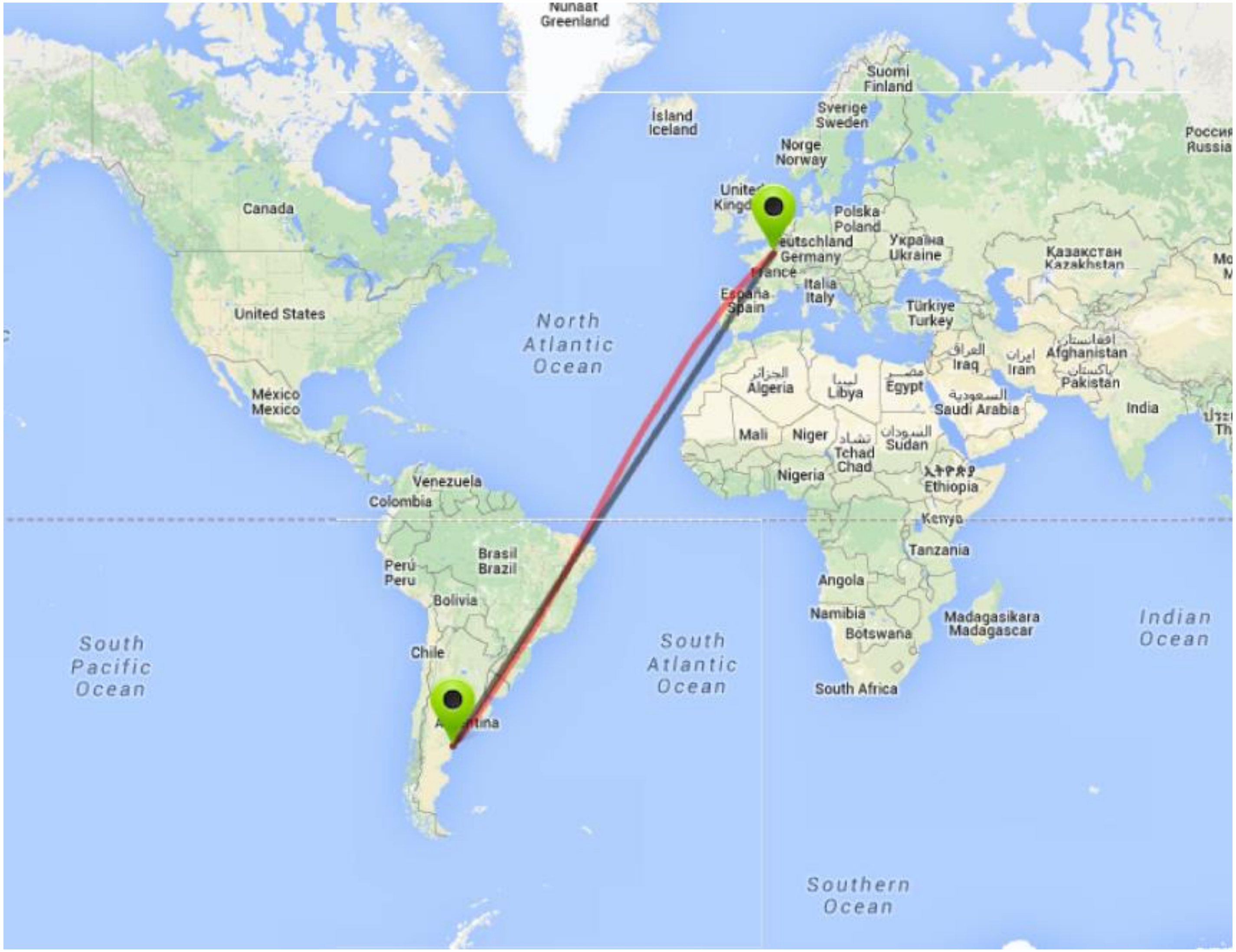
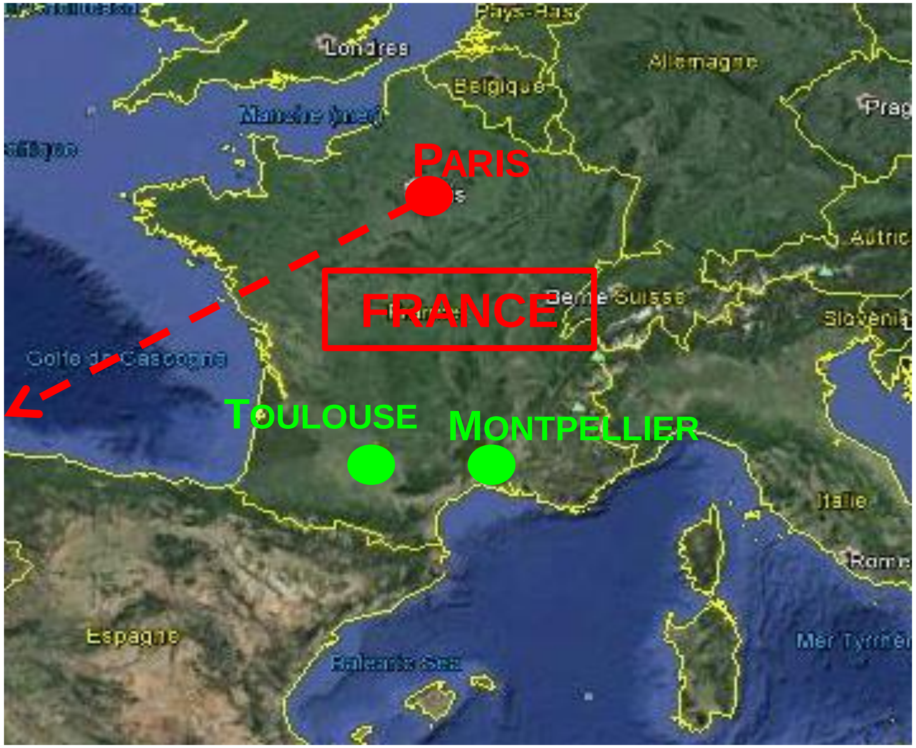
and

CERFACS

Where I come from



MY TWO SCIENTIFIC LIFES



IN MONTPELLIER

Laboratory of Mathematics and Modelling of Montpellier University

CARDIO-VASCULAR BIOMECHANICS - 1ST TALK

IN TOULOUSE

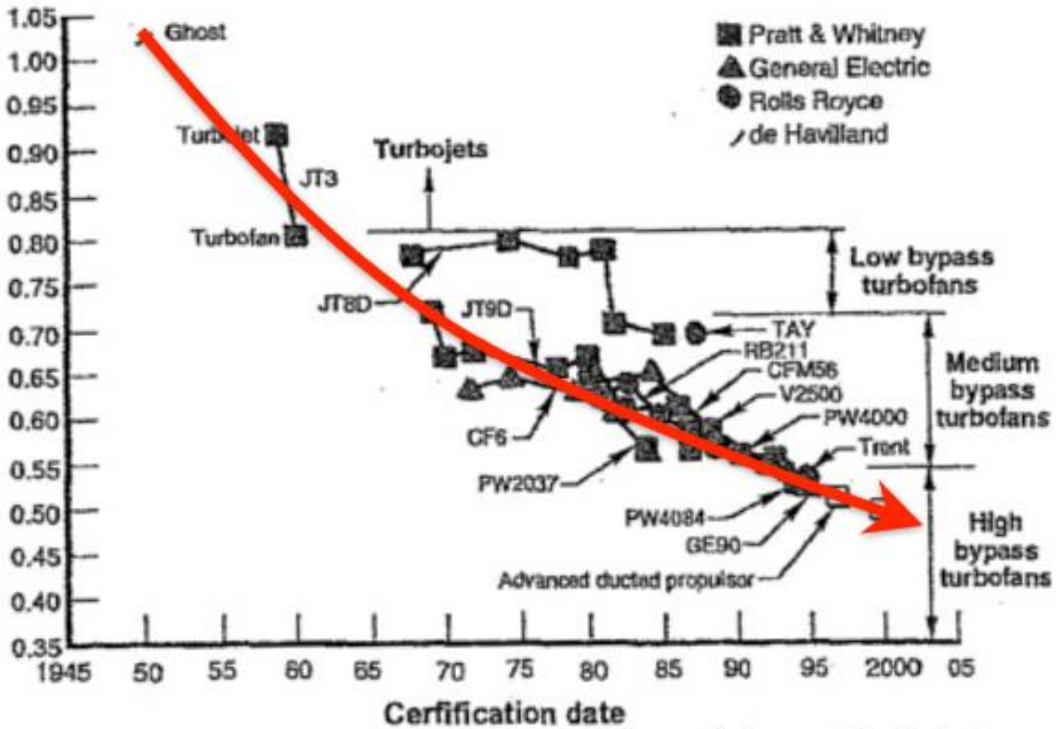
European Center for Research and Advanced Training in Scientific Computing

COMBUSTION INSTABILITIES - 2ND TALK

CONTEXT

- Aeronautical industries want to reduce the fuel consumption, pollution, noise, etc…
- Strong improvements since the last decades

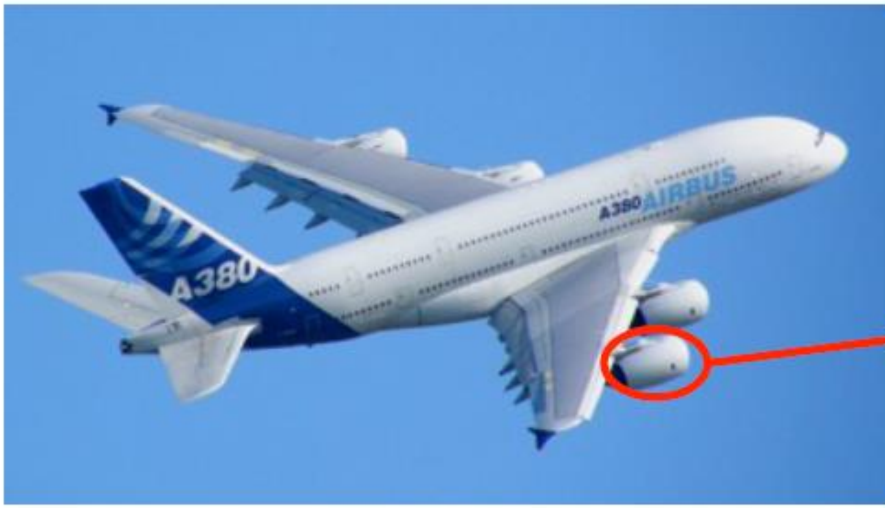
Thrust-specific
Fuel consumption

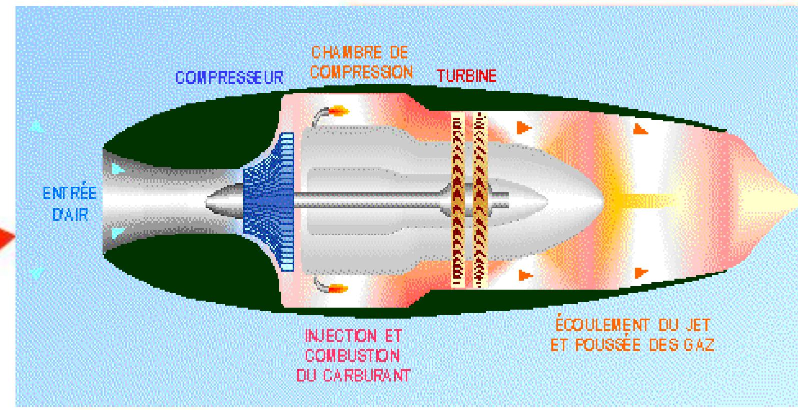


Reproduced from Koff, J. Propul. Power 2004

CONTEXT

- A key element is the combustion chamber



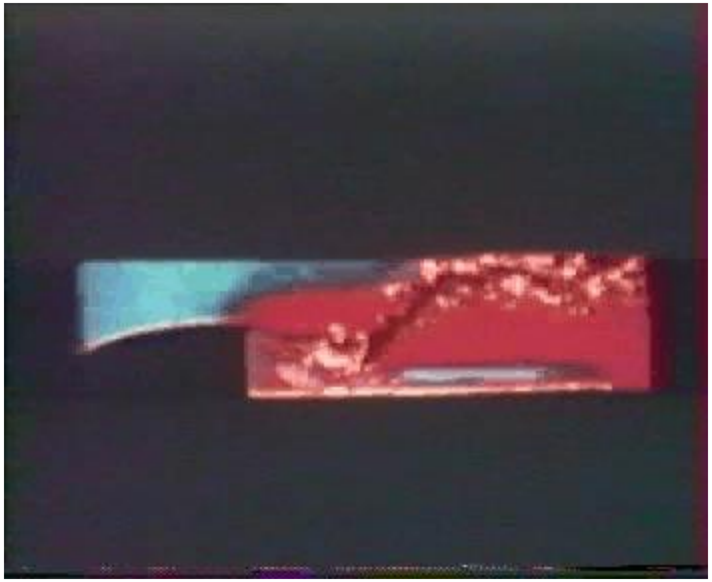


- It is possible to act on the fuel/air injection, the mixture ratio, flame temperature, etc..
- New technological choices are promising …

but tend to make combustion chamber **more prone to instabilities**

THERMO-ACOUSTIC INSTABILITIES

Premixed gas →



The Berkeley backward facing step experiment.

FLOW VISUALIZATION : RED AREAS DENOTE BURNT GAS.

THERMO-ACOUSTIC INSTABILITIES

- Self-sustained oscillations arising from the coupling between a source of heat and the acoustic waves of the system

- Known since a very long time (Rijke, 1859; Rayleigh, 1878)

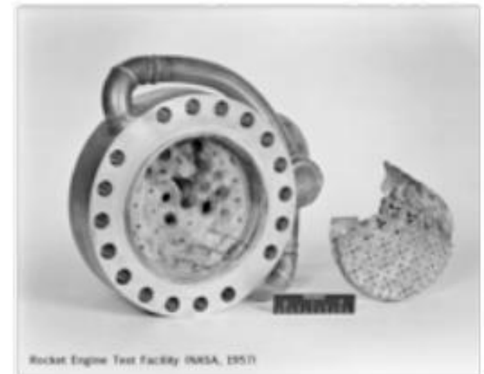
"If heat be given to the air at the moment of greatest condensation or be taken from it at the moment of greatest rarefaction, the vibration is encouraged."

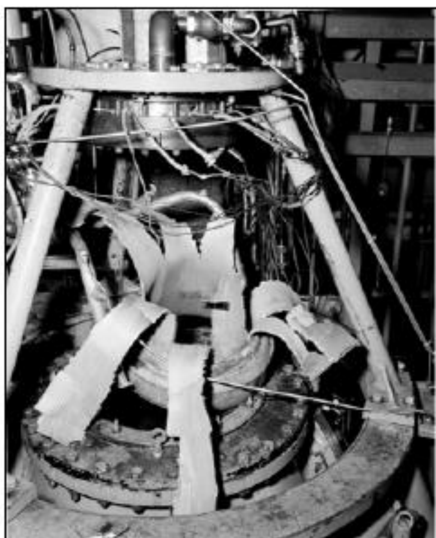
- Not fully understood yet …

- but surely not desirable …

BETTER AVOID THEM …

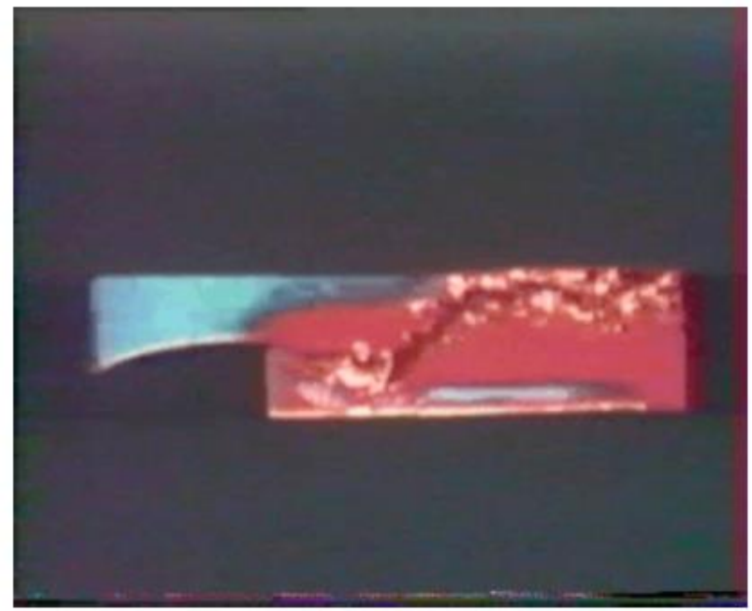
- Consequences:
  - Loss of performance
  - Extinction
  - Premature fatigue
  - Engine damage



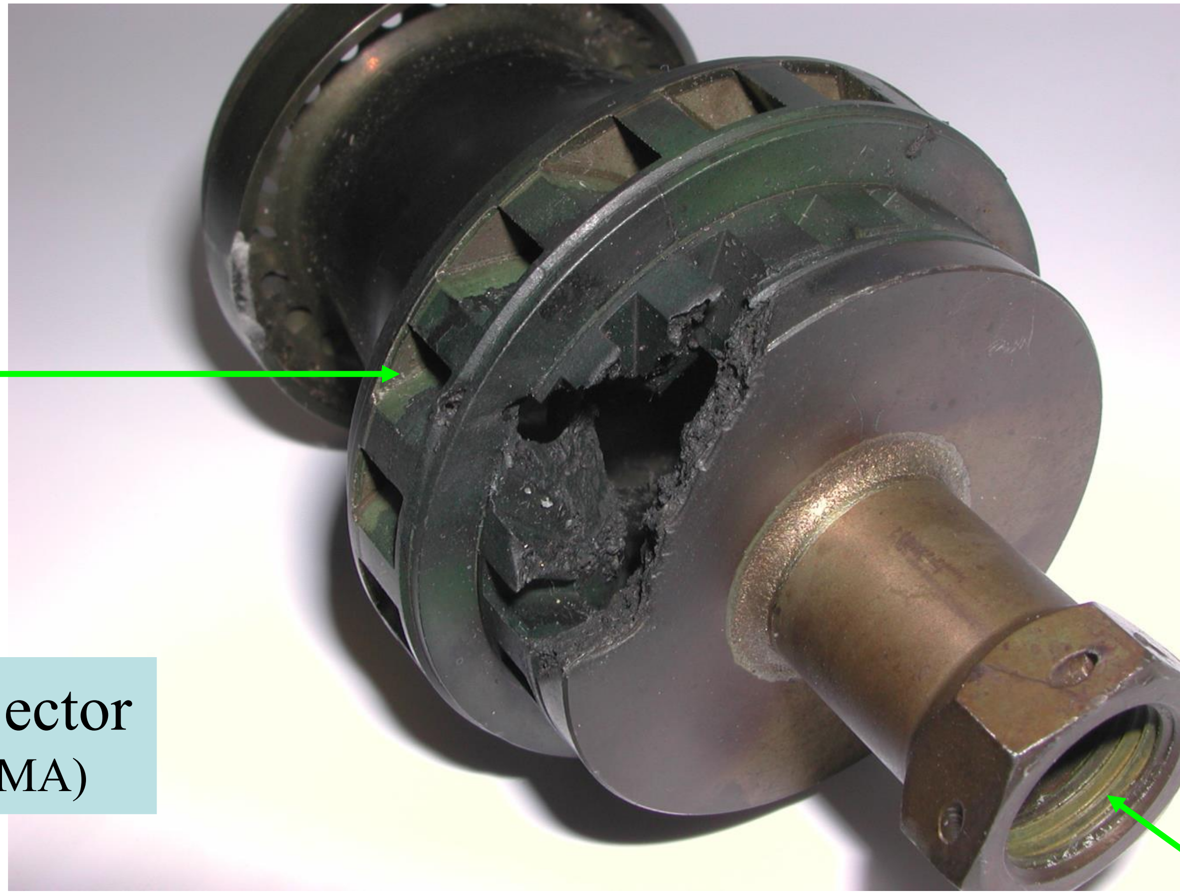


Liquid rocket engine (NASA 1957)

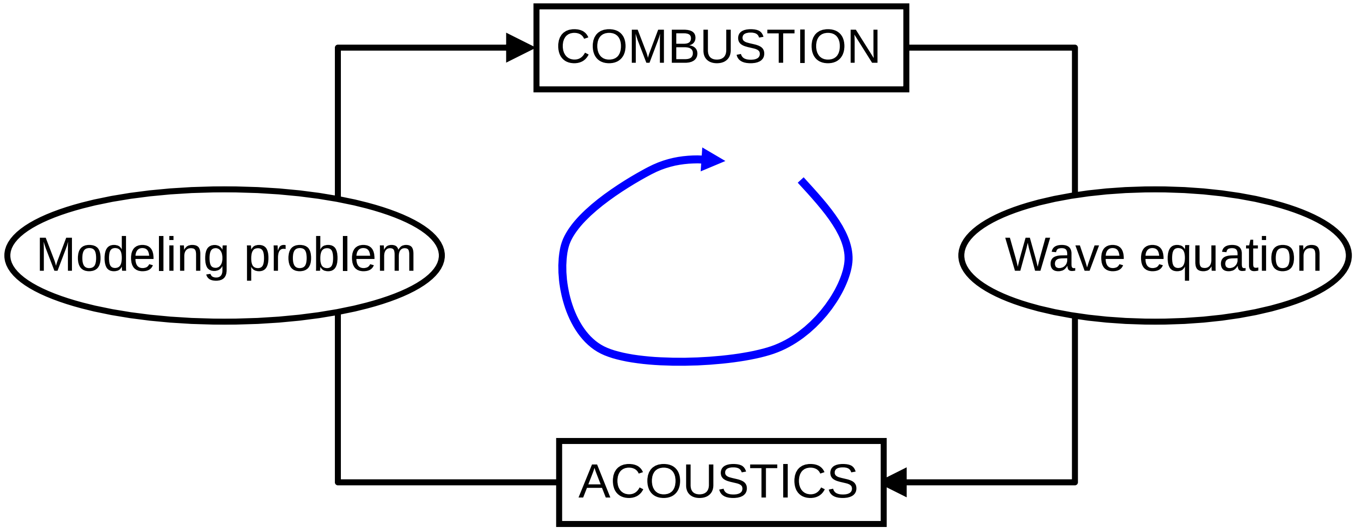
Liquid rocket engine (NASA 1963)



BETTER AVOID THEM …



FLAME/ACOUSTICS COUPLING



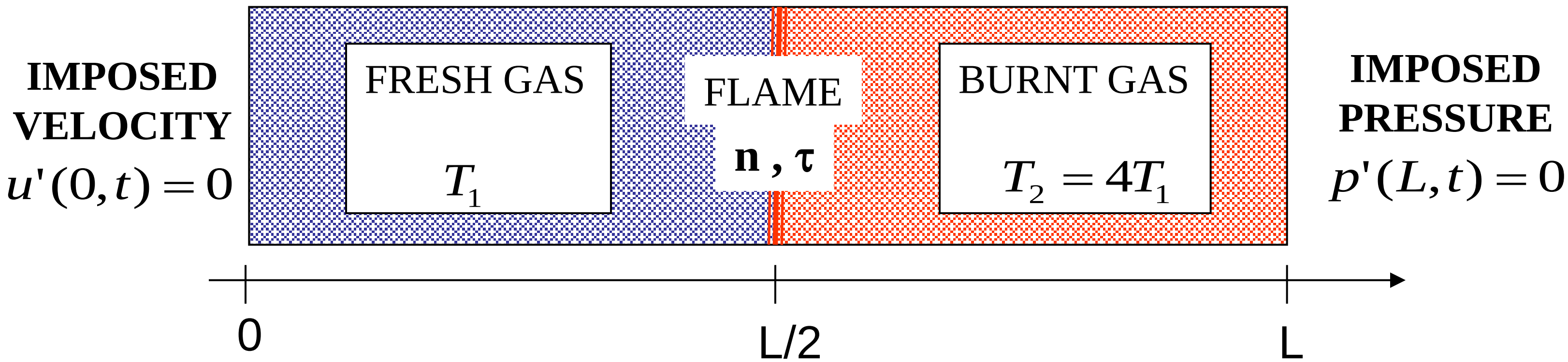
Rayleigh criterion:
Flame/acoustics coupling promotes instability if pressure and heat release fluctuations are in phase

OUTLINE

1. **A simple case**
2. Computing the whole flow
3. Computing the fluctuations only
4. An actual study case

A TRACTABLE 1D PROBLEM

- Consider a 1D straight duct hosting an infinitely thin 1D flame which separates unburnt (cold) and burnt (hot) gas



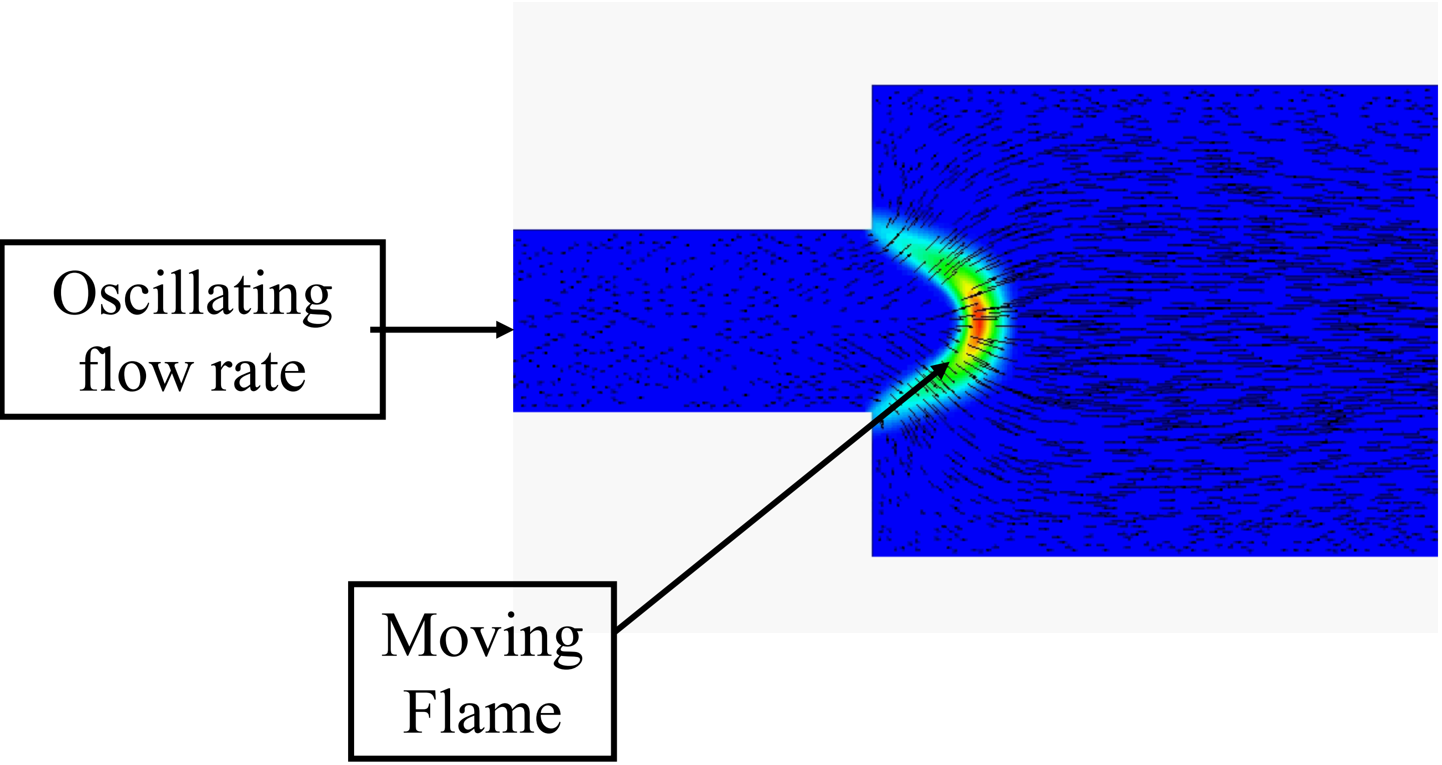
Kaufmann, Nicoud & Poinsot, *Comb. Flame*, 2002

- Assume that the gas are at rest, except for small amplitude acoustic perturbations

- A model describing the response of the flame to acoustic perturbations is needed …

MODELING THE FLAME

- An actual flame is not steady
- Its shape and size may change if the upstream velocity changes
- Example: Numerical simulation of a 2D flame in a dump combustor (A. Giauque, CTR SP Stanford, 2006)



Modeling the flame

- Here the flame is considered 1D but its heat release may vary to reflect an actual deforming flame
- the n-τ model is used to relate the unsteady heat release to the acoustic velocity (Crocco, 1952)

$$\boxed{q'(t) \sim n \times u'(t-\tau)}$$

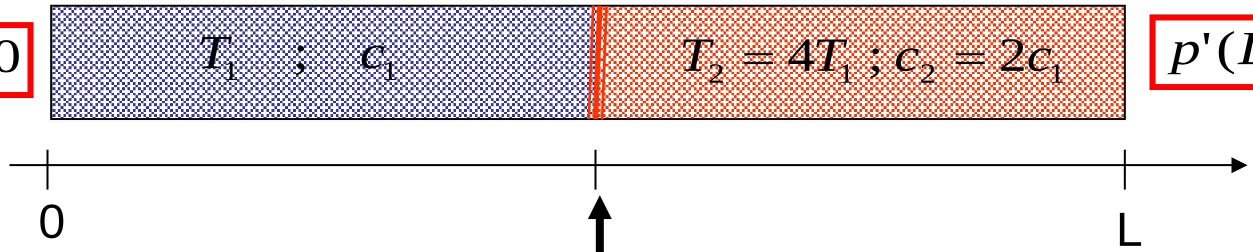
n: amplitude of the flame response

τ: time delay of the flame response

- In this view, the flame is just and only an acoustic element (which is obviously a VERY strong assumption)

EQUATIONS

$\boxed{u'(0,t)=0}$



$\boxed{p'(L,t)=0}$

$$\boxed{\begin{array}{l} 0 < x < \dfrac{L}{2}: \\ \dfrac{\partial^2 p'}{\partial t^2} - c_1^2 \dfrac{\partial^2 p'}{\partial x^2} = 0 \end{array}}$$

CLASSICAL ACOUSTICS
2 wave amplitudes

$$\boxed{\begin{array}{l} \dfrac{L}{2} < x < L: \\ \dfrac{\partial^2 p'}{\partial t^2} - c_2^2 \dfrac{\partial^2 p'}{\partial x^2} = 0 \end{array}}$$

CLASSICAL ACOUSTICS
2 wave amplitudes

$$\boxed{\overbrace{\left[p'\right]_{L/2^-}^{L/2^+} = 0 \quad \text{and} \quad \left[u'\right]_{L/2^-}^{L/2^+} = n \times u'\left(L^-/2, t-\tau\right)}^{\text{TWO JUMP RELATIONS}}}$$

DISPERSION RELATION

- Solve the 4x4 homogeneous linear system to find out the 4 wave amplitudes

- Consider Fourier modes

$$p'(x,t) = \Re\left(\hat{p}(x) e^{-j\omega t}\right) \qquad \begin{cases} \Im(\omega) < 0: \text{ damped mode} \\ \Im(\omega) > 0: \text{ amplified mode} \end{cases}$$

- Condition for non-trivial (zero) solutions to exist

$$\underbrace{\cos\left(\frac{\omega L}{4c_1}\right)}_{\textbf{Uncoupled modes}} \times \underbrace{\left[\cos^2\left(\frac{\omega L}{4c_1}\right) - \frac{3}{4} - \frac{1}{4}\frac{ne^{j\omega\tau} - 1}{ne^{j\omega\tau} + 3}\right]}_{\textbf{Coupled modes}} = 0$$

Stability of the coupled modes

- Eigen frequencies

$$\cos^2\left(\frac{\omega L}{4c_1}\right)-\frac{3}{4}-\frac{1}{4}\frac{ne^{j\omega\tau}-1}{ne^{j\omega\tau}+3}=0$$

- Steady flame *n=0*:

$$\omega_{m,0}=\frac{4c_1}{L}\left[\pm\arccos\left(\pm\sqrt{\frac{2}{3}}\right)+2m\pi\right],\quad m=0,1,2,\ldots$$

- Asymptotic development for *n<<1*:

$$\omega_m=\omega_{m,0}\underbrace{-n\frac{4c_1}{9L\sin\left(\omega_{m,0}L/2c_1\right)}\left[\cos\left(\omega_{m,0}\tau\right)+j\sin\left(\omega_{m,0}\tau\right)\right]}_{\text{Complex pulsation shift}}+o(n)$$

Kaufmann, Nicoud & Poinsot, *Comb. Flame*, 2002

TIME LAG EFFECT

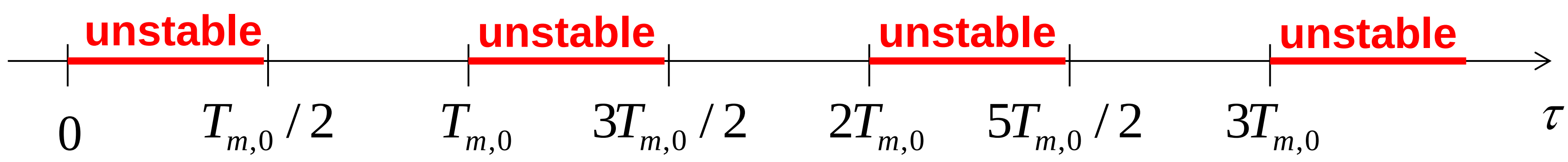
- The imaginary part of the frequency is

$$-n\frac{4c_1\sin(\omega_{m,0}\tau)}{9L\sin(\omega_{m,0}L/2c_1)}$$

- Steady flame modes such that $\boxed{\sin(\omega_{m,0}L/2c_1)<0}$

- The unsteady HR destabilizes the flame if

$$\sin(\omega_{m,0}\tau)>0 \quad\Rightarrow\quad 0<\omega_{m,0}\tau<\pi[2\pi] \quad\Rightarrow\quad 0<\tau<\frac{T_{m,0}}{2}\left[T_{m,0}\right]$$



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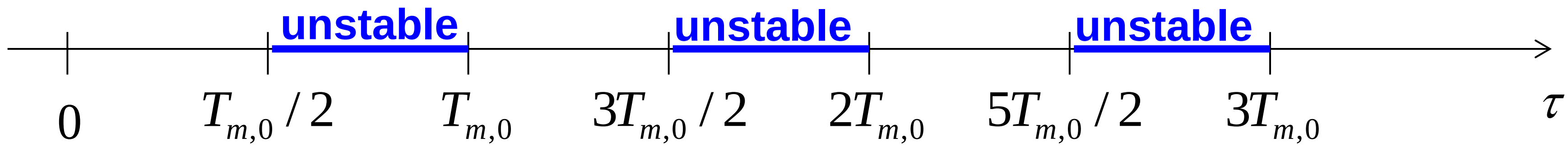
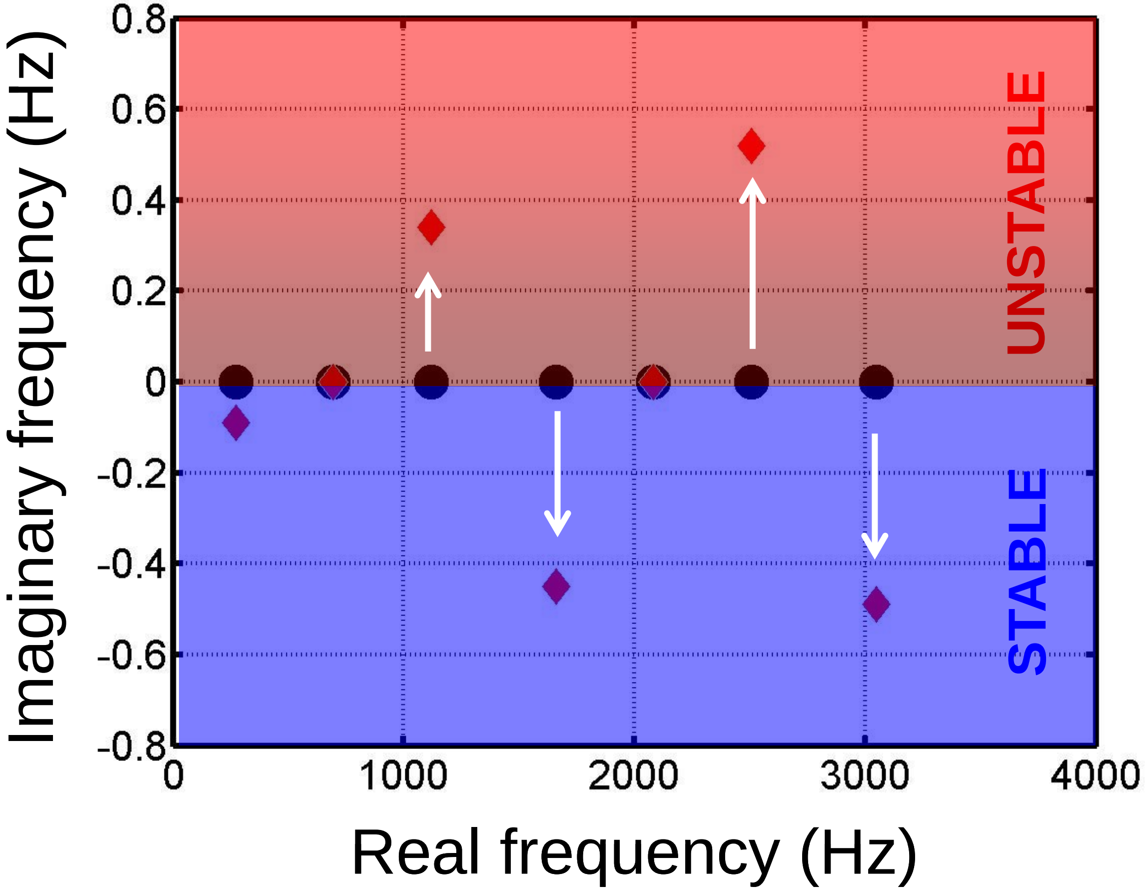


EFFECT OF FLAME-ACOUSTICS COUPLING

$$T_1 = 300\ \mathrm{K}$$
$$L = 0.5\ \mathrm{m}$$

● **Steady flame**

◆ **Unteady flame**
n=0.01
τ=0.1 ms



THE REAL WORLD IS MORE COMPLEX

- Flow physics
  - turbulence, partial mixing, chemistry, two-phase flow , combustion modeling, heat loss, wall treatment, radiative transfer, …
- Acoustics
  - complex impedance, mean flow effects, acoustics/flame coupling, non-linearity, limit cycle, non-normality, mode interactions, …
- Numerics
  - Low dispersive – low dissipative schemes, non linear stability, scalability, non-linear eigen value problems, …

OUTLINE

1. A simple case
2. **Computing the whole flow**
3. Computing the fluctuations only
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NAVIER-STOKES EQUATIONS

- The 3D PDE's governing the flow of a constant density (ρ) fluid are:
  - Mass conservation (continuity):

$$\frac{\partial u_i}{\partial x_i} = 0$$

  - Momentum:

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\nu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right], \qquad \text{with} \quad i = 1,2,3$$

- Remarks:
  - p is pressure and ν is the kinematic viscosity (constant if Newtonian fluid)
  - The non-linear term $u_j \frac{\partial u_i}{\partial x_j}$ arises from the inertia effects ; if large enough, it is responsible for **turbulence** generation

THE EQUATIONS TO BE SOLVED …

- 3D, reacting, multi-species, gazeous mixture …

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_i)}{\partial x_i} = 0$$

$$\frac{\partial(\rho Y_k)}{\partial t} + \frac{\partial}{\partial x_i}\left(\rho\left(u_i + V_{k,i}\right) Y_k\right) = \dot{\omega}_k$$

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial(\rho u_i u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j}$$

$$\rho \frac{DE}{Dt} = -\frac{\partial q_i^*}{\partial x_i} + \frac{\partial}{\partial x_j}(\tau_{ij} u_i) - \frac{\partial}{\partial x_i}(p u_i) + \dot{\omega}_T$$

$$\frac{p}{\rho} = r\, T$$

$$r = R/W$$

$$W = \sum_k X_k W_k$$

$$Y_k = X_k W_k / W$$

$$\dot{\omega}_T = -\sum_k \Delta h^0_{f,k} \dot{\omega}_k$$

$$C_p = \sum_k C_{p,k} Y_k$$

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THE EQUATIONS TO BE SOLVED …

- 3D, reacting, multi-species, gazeous mixture …

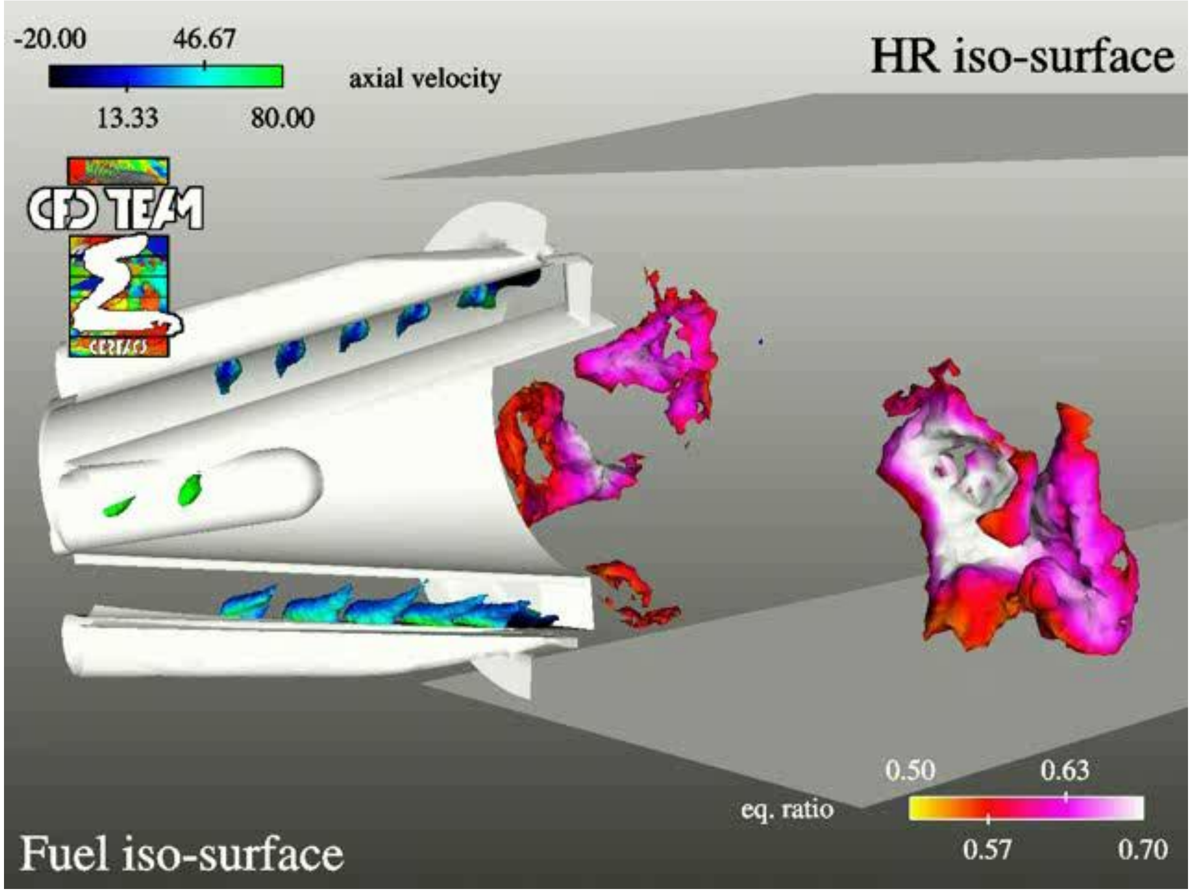
$h_{s,k} = \int_{T_0}^{T} C_{p,k}\, dT$	Sensible enthalpy of species k
$h_k = \int_{T_0}^{T} C_{p,k}\, dT + \Delta h_{f,k}^0$	Specific enthalpy of species k
$h_s = \sum_k h_{s,k} Y_k$	Sensible enthalpy of the mixture
$h = h_s + \sum_k \Delta h_{f,k}^0 Y_k$	Specific enthalpy of the mixture
$h_t = h + u_i u_i / 2$	Total enthalpy of the mixture
$H = h_s + u_i u_i / 2$	Total non chemical enthalpy of the mixture
$E = H - p/\rho$	Total non chemical energy of the mixture

THE EQUATIONS TO BE SOLVED …

- 3D, reacting, multi-species, gazeous mixture … as a first step !!
- Do not forget:
  - 2-phase flow effects, Turbulence modelling, Complex diffusion, …
  - High Performance Computing issues, Huge data management, …

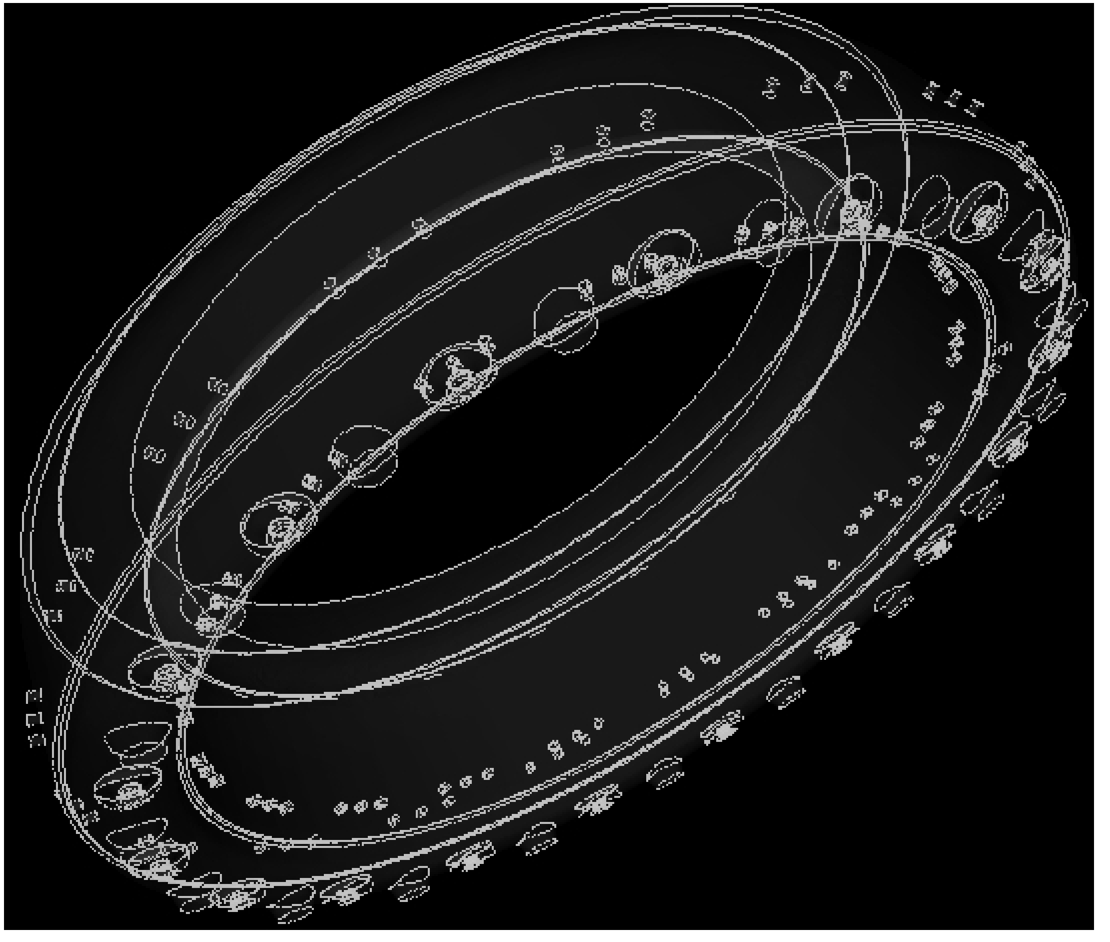
- Large Eddy Simulation is feasible today …

EXAMPLE #1



Alstom injector – P. Schmitt - CERFACS

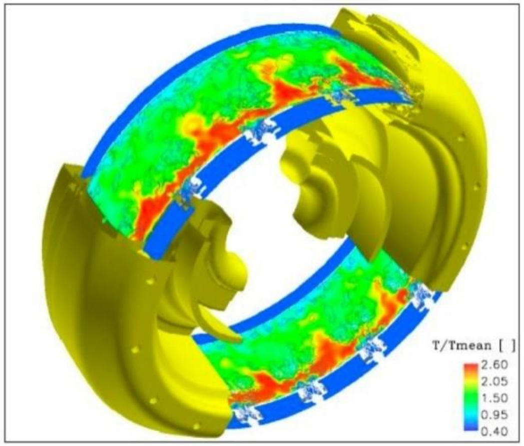
EXAMPLE #2

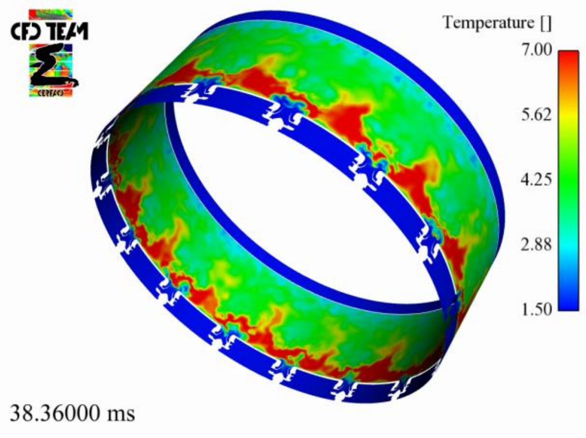


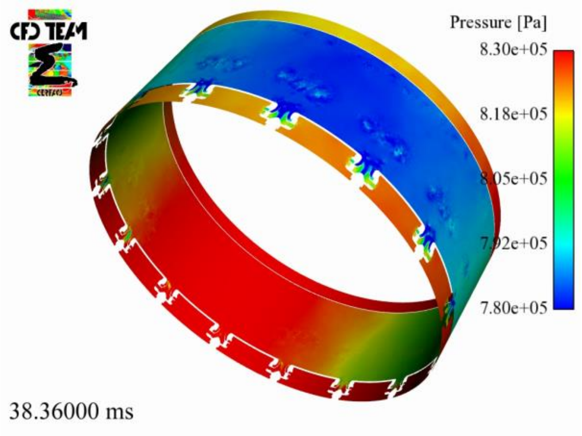
Ignition of a Turbomeca combustion chamber
Y. Sommerer & M. Boileau - CERFACS

EXAMPLE #3

Large Eddy Simulation of a full annular combustion chamber Staffelbach et al., *2008*



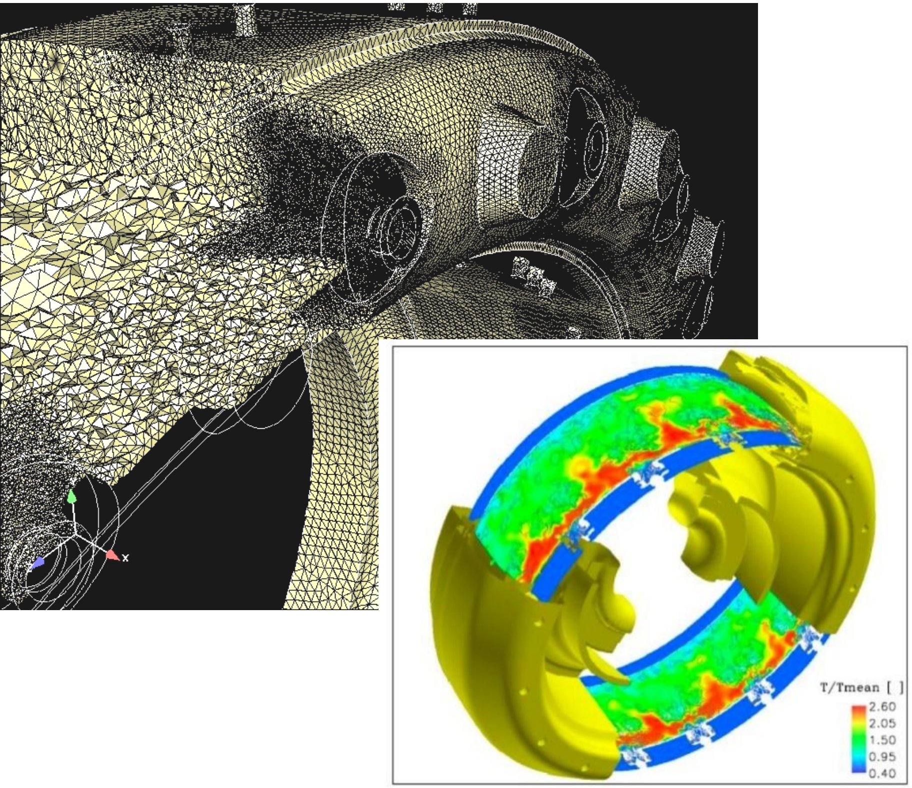


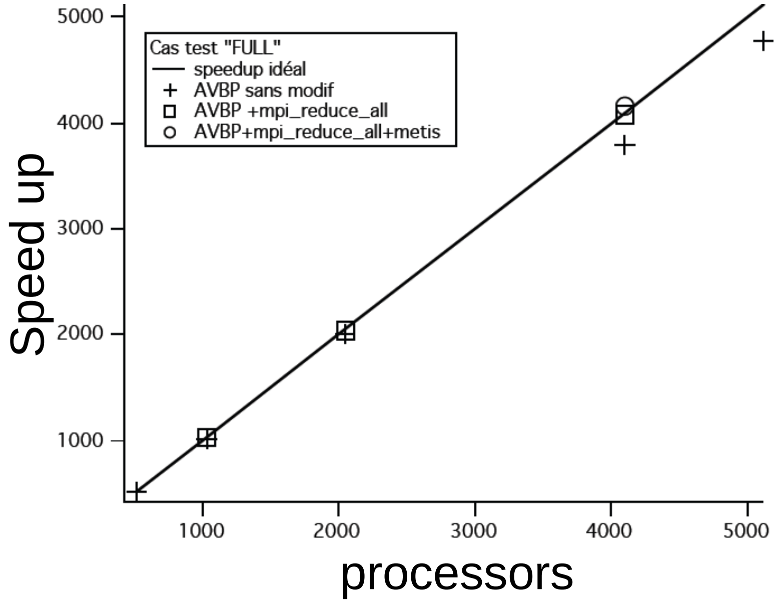


- The first azimuthal mode is found unstable from LES, at 740 Hz
- Same mode found unstable experimentally

PARALLEL COMPUTING

- Large scale unsteady computations require huge computing resources, an efficient codes …





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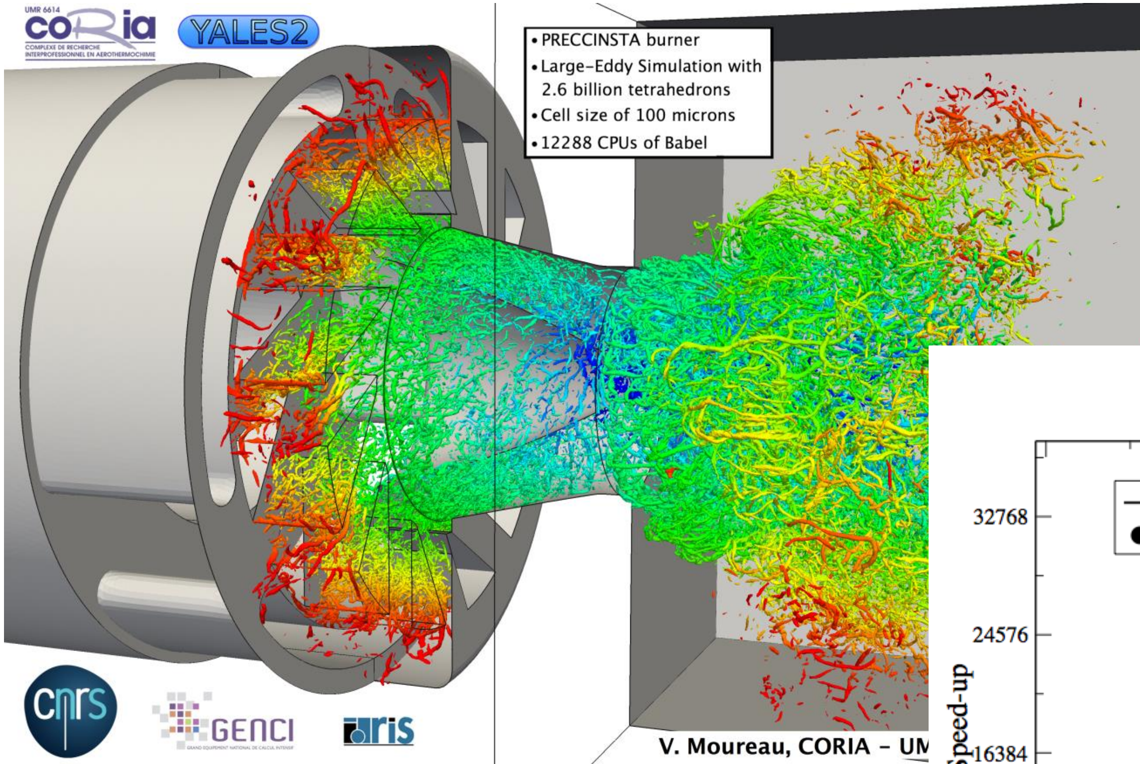

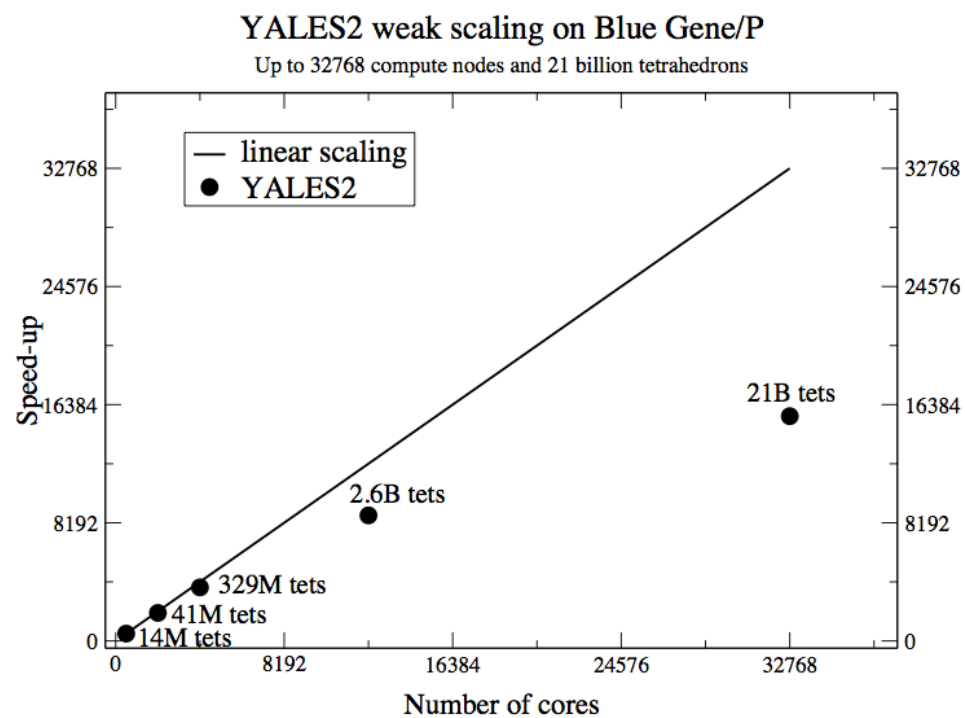

WHY DO WE NEED MORE ?

- LES/brute force bring a partial answer by giving a picture of what happens when a combustor oscillates
- But it does not really say why, how, under which conditions the instabilities appear. And it is really CPU/memory consuming
- Appropriate low order tools are needed to
  - interpret the data and understand the reason why a combustor becomes unstable
  - Perform parametric studies to address questions as:
  - What is the best strategy to stabilize a combustor which proved unstable
  - uncertainty quantification, robust design, margin to stability,…

OUTLINE

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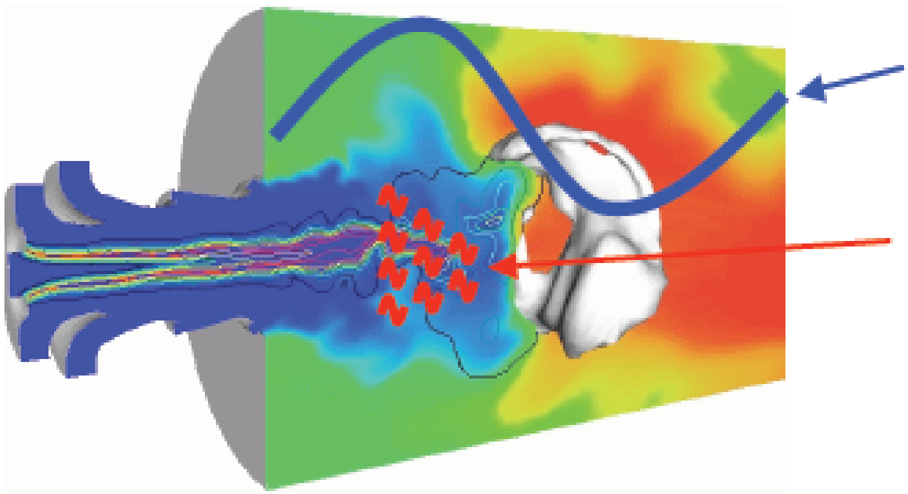
CONSIDERING ONLY PERTURBATIONS

Approach: solve acoustic field using finite volume method



resolve only large scales (acoustic modes)

model small scales (combustion)

⇒ **Compared to LES:**

- simplified system of equations, coarser grid

- requires less computational time

LINEARIZED EULER EQUATIONS

$$\frac{D\rho}{Dt} = -\rho \nabla \cdot \mathbf{u}$$

$$\rho \frac{D\mathbf{u}}{Dt} = -\nabla p$$

$$\frac{Ds}{Dt} = \frac{rq}{p}$$

- **assume homogeneous mixture**
- **neglect viscosity**

- **decompose each variable into its mean and fluctuation**

$$f(\mathbf{x},t) = f_0(\mathbf{x}) + f_1(\mathbf{x},t)$$

- **assume small amplitude fluctuations**

$$\frac{f_1}{f_0} \equiv \varepsilon << 1; \quad f = \rho, p, T, s = C_v \ln\left(\frac{p}{\rho^\gamma}\right)$$

$$\frac{\|\mathbf{u}_1\|}{c_0} \equiv \varepsilon << 1; \quad c_0 = \sqrt{\frac{\gamma p_0}{\rho_0}}$$

Linearized Euler Equations

$$\frac{\partial \rho_1}{\partial t} + \mathbf{u}_0 \nabla \rho_1 + \mathbf{u}_1 \nabla \rho_0 + \rho_0 \nabla \cdot \mathbf{u}_1 + \rho_1 \nabla \cdot \mathbf{u}_0 = 0$$

$$\rho_0 \frac{\partial \mathbf{u}_1}{\partial t} + \rho_0 \mathbf{u}_0 \cdot \nabla \mathbf{u}_1 + \rho_0 \mathbf{u}_1 \cdot \nabla \mathbf{u}_0 + \rho_1 \mathbf{u}_0 \cdot \nabla \mathbf{u}_0 + \nabla p_1 = 0$$

$$\frac{\partial s_1}{\partial t} + \mathbf{u}_0 \nabla s_1 + \mathbf{u}_1 \nabla s_0 = \frac{r q_1}{p_0} - \frac{r q_0 p_1}{p_0^2}$$

- the unknown are the small amplitude fluctuations,
- the mean flow quantities must be provided
- requires a model for the heat release fluctuation q_1
- contain all what is needed, and more …: acoustics + vorticity + entropy

Zero Mach number assumption

- No mean flow or "Zero-Mach number" assumption

$$f(\mathbf{x},t) = f_0(\mathbf{x}) + f_1(\mathbf{x},t); \quad \frac{f_1}{f_0} \equiv \varepsilon << 1; \quad f = \rho, p, T, s = C_v \ln\left(\frac{p}{\rho^\gamma}\right)$$

$$\mathbf{u}(\mathbf{x},t) = \cancel{\mathbf{u}_0(\mathbf{x})} + \mathbf{u}_1(\mathbf{x},t); \quad \frac{\|\mathbf{u}_1\|}{c_0} \equiv \varepsilon << 1; \quad c_0 = \sqrt{\frac{\gamma p_0}{\rho_0}}$$

Equation	Constraint
mass	$M \ll 1$ and $\boxed{M \ll L_f/L_a}$
momentum	$\boxed{M \ll L_f/L_a,}$ $M \ll 1$ and $M \ll \sqrt{L_f/L_a}$
entropy	$M \ll 1$

L_a : acoustic wavelength $\quad L_f$: flame thickness

- Probably well justified below 0.01

LINEAR EQUATIONS

Mass: $$\frac{\partial \rho_1}{\partial t} + \rho_0 div(\mathbf{u}_1) + \mathbf{u}_1 \cdot \nabla \rho_0 = 0$$

Momentum: $$\rho_0 \frac{\partial \mathbf{u}_1}{\partial t} = -\nabla p_1$$

Energy : $$\rho_0 C_v \left[\frac{\partial T_1}{\partial t} + \mathbf{u}_1 \cdot \nabla T_0 \right] = -p_0 \nabla \cdot \mathbf{u}_1 + q_1$$

State: $$\frac{p_1}{p_0} = \frac{\rho_1}{\rho_0} + \frac{T_1}{T_0}$$

- The unknowns are the fluctuating quantities $\boldsymbol{\rho_1}, \mathbf{u}_1, \boldsymbol{T_1}, \boldsymbol{p_1}$

- The mean density, temperature, … fields must be provided

- A model for the unsteady HR q_1 is required to close the system

THE HELMHOLTZ EQUATION

- Since ‘periodic’ fluctuations are expected, let’s work in the frequency space

$$p_1(\mathbf{x},t) = \mathrm{Re}\left(\hat{p}(\mathbf{x})e^{-j\omega t}\right) \qquad \mathbf{u}_1(\mathbf{x},t) = \mathrm{Re}\left(\hat{\mathbf{u}}(\mathbf{x})e^{-j\omega t}\right)$$

$$q_1(\mathbf{x},t) = \mathrm{Re}\left(\hat{q}(\mathbf{x})e^{-j\omega t}\right)$$

- With this notation:
  - $\mathrm{Re}(\omega) = \omega_r$ is the angular frequency of oscillation
  - $\mathrm{Im}(\omega) = \omega_i$ is the growth/decay rate of the fluctuation (unstable if $\omega_i > 0$)

- From the set of linear equations for ρ_1, $\mathbf{u}_1$, p_1, T_1 , the following wave equation can be derived

$$\boxed{\gamma p_0 \nabla \cdot \left(\frac{1}{\rho_0} \nabla \hat{p} \right) + \omega^2 \hat{p} = j\omega(\gamma - 1)\hat{q}}$$

3D ACOUSTIC CODES

- Let us first consider the simple steady flame case (no forcing term):

$$\boxed{\gamma p_0 \nabla \cdot \left(\frac{1}{\rho_0} \nabla \hat{p} \right) + \omega^2 \hat{p} = 0}$$

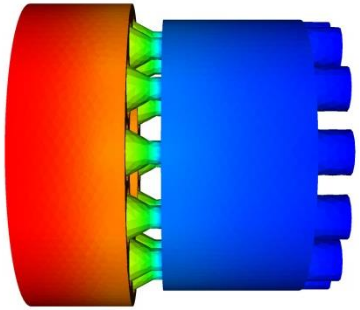
- Boundary conditions may be simple

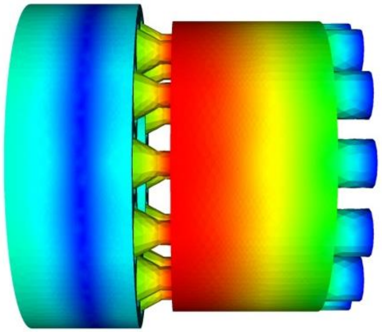
$$\hat{p} = 0 : \text{suitable for outlet to the atmosphere}$$

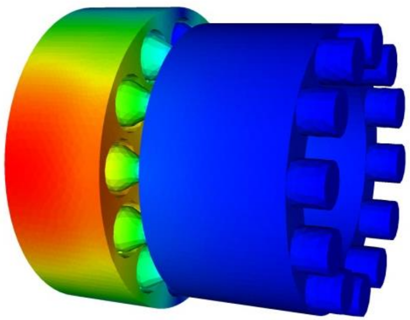
$$\rho_0 \omega \, \hat{\mathbf{u}} \cdot \mathbf{n} = \nabla \hat{p} \cdot \mathbf{n} = 0 : \text{suitable for solid walls, inlet}$$

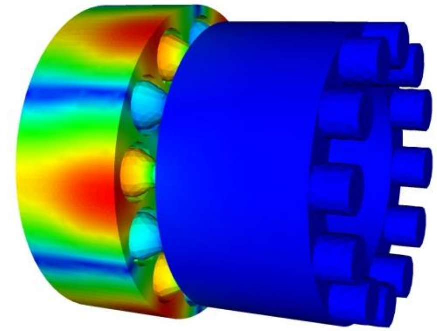
- Or based on a complex valued boundary impedance, suitable for nozzles, upstream/downstream acoustic element

TUM combustor: first seven modes

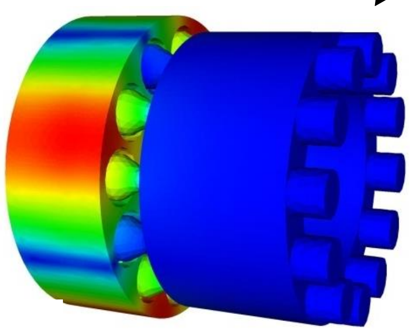


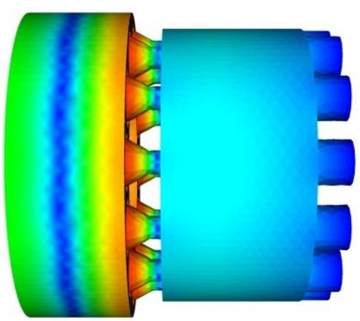


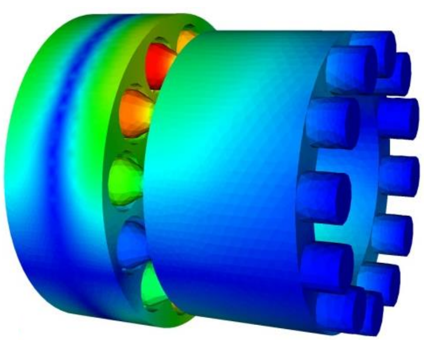




f (Hz)	type
143	1L
286	1C plenum
503	2C plenum
594	2L
713	3C plenum
754	1C combustor
769	3L







QUESTION

- There are many modes in the low-frequency regime
- They can be predicted in complex geometries
- Boundary conditions and multiperforated liners have first order effect and they can be accounted for properly
- All these modes are potentially dangerous

Which of these modes are made unstable by the flame ?

ACCOUNTING FOR THE UNSTEADY FLAME

- Need to solve the thermo-acoustic problem

$$\boxed{\gamma p_0 \nabla \cdot \left(\frac{1}{\rho_0} \vec{\nabla} \hat{p} \right) + \omega^2 \hat{p} = j\omega(\gamma - 1)\hat{q}}$$

- The unsteady heat release must be modelled to close the problem

- This is certainly the most difficult part of the modeling effort required to represent thermo-acoustic instabilities

- As already discussed for the simple 1D configuration, q may be related to the acoustic velocity upstream of the flame

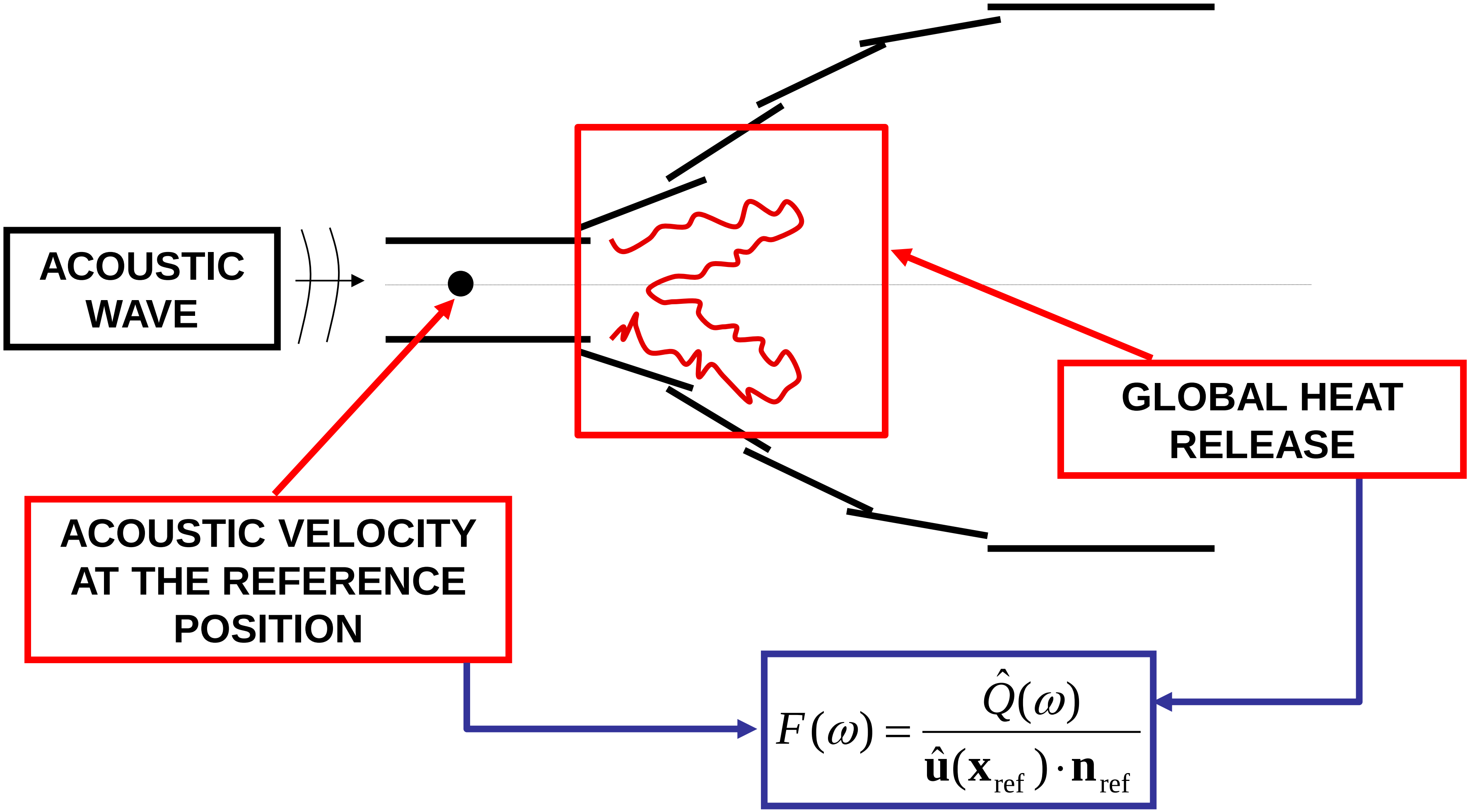
Flame Transfer Function

- The flame response can be deduced from either
  - Theoretical model for simple flames (e.g.: Schuller et al., Comb. Flame, 2003)
  - Experimental data (e.g.: Palies et al. Comb. Flame, 2010)
  - Large Eddy Simulation (e.g.: Giauque et al., J Turb., 2005)

- In many cases, only information about the volume integrated heat release is available through a global flame response:

$$\hat{Q}(\omega) = F(\omega) \times \hat{\mathbf{u}}(\mathbf{x}_{ref}) \cdot \mathbf{n}_{ref} \qquad \hat{Q} = \int_{\Omega} \hat{q} \, d\Omega$$

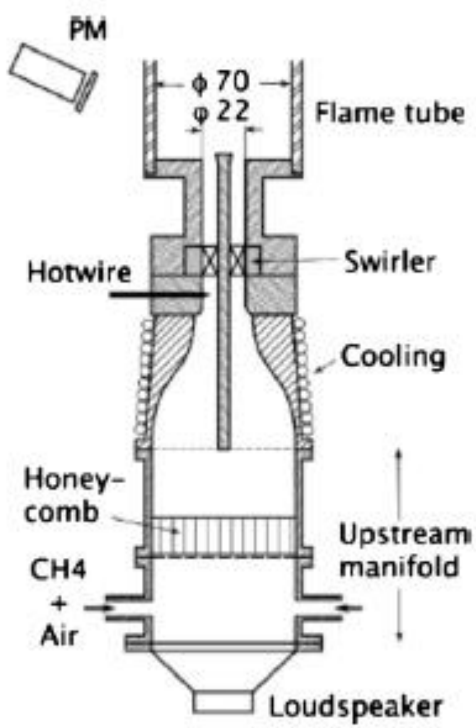
GLOBAL FLAME TRANSFER FUNCTION



$$F(\omega) = \frac{\hat{Q}(\omega)}{\hat{\mathbf{u}}(\mathbf{x}_{\mathrm{ref}}) \cdot \mathbf{n}_{\mathrm{ref}}}$$

VALIDATION

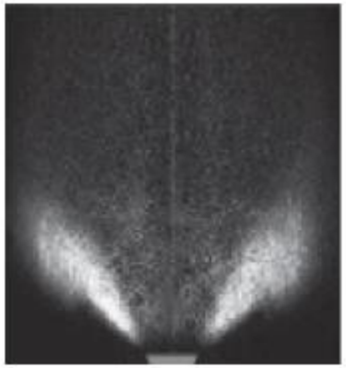
- This strategy was used for example by Silva et al. Comb. Flame, 2013
- Swirled stabilized combustor studied at EM2C (Palies et al., Comb. Flame, 2011) with 24 different configurations



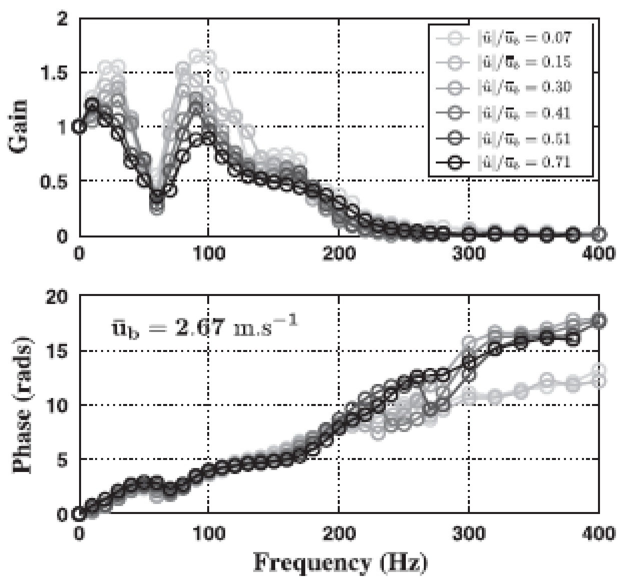
CASE	Flame A				Flame B			
	C01	C02	C03	C04	C01	C02	C03	C04
Experiment	S	S	S	U	S	S	S–U	U
Simulation	??							
	C05	C06	C07	C08	C05	C06	C07	C08
Experiment	S	S	S–U	U	S	S	S	U
Simulation	??							
	C09	C10	C11	C12	C09	C10	C11	C12
Experiment	S	S	S–U	U	S	S	S–U	U
Simulation	??							

S: stable regime **U: Unstable regime**

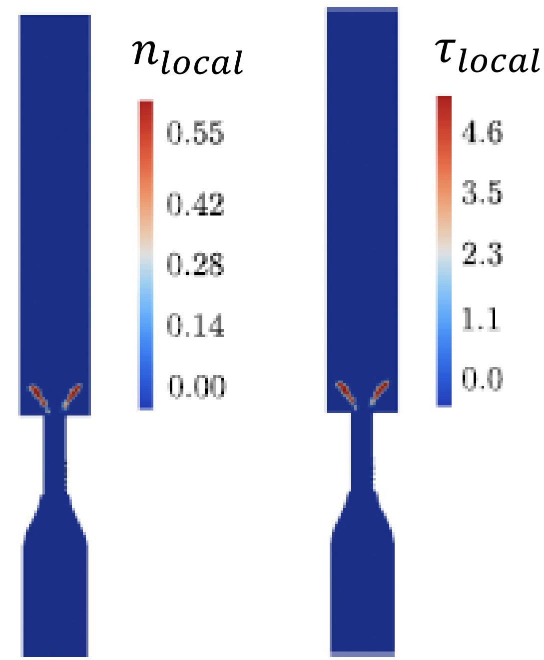
VALIDATION



Flame shape by
chemiluminiscence



Global Flame transfer Function
from experiment (Palies et al. Comb. Flame, 2010)



Field of Flame Transfer Function
useable in a Helmholtz solver

VALIDATION

- This strategy was used with some success (Silva et al. Comb. Flame, 2013) …

CASE	Flame A				Flame B			
	C01	C02	C03	C04	C01	C02	C03	C04
Experiment	S	S	S	U	S	S	S–U	U
Simulation	S	S	S	U	S	S	S–U	U
	C05	C06	C07	C08	C05	C06	C07	C08
Experiment	S	S	S–U	U	S	S	S	U
Simulation	S	S	S–U	U	S	S	S–U	U
	C09	C10	C11	C12	C09	C10	C11	C12
Experiment	S	S	S–U	U	S	S	S–U	U
Simulation	S	S	U	U	S	S	S	U

	S: STABLE	U: UNSTABLE	S-U: MARGINAL
EXPERIMENT	No activity	Strong amplitude	Small amplitude
SIMULATION	$\omega_i < damping$	$\omega_i > damping$	$\omega_i \approx damping$

Only 3 cases (out of 24) with **partial** disagreement

OUTLINE

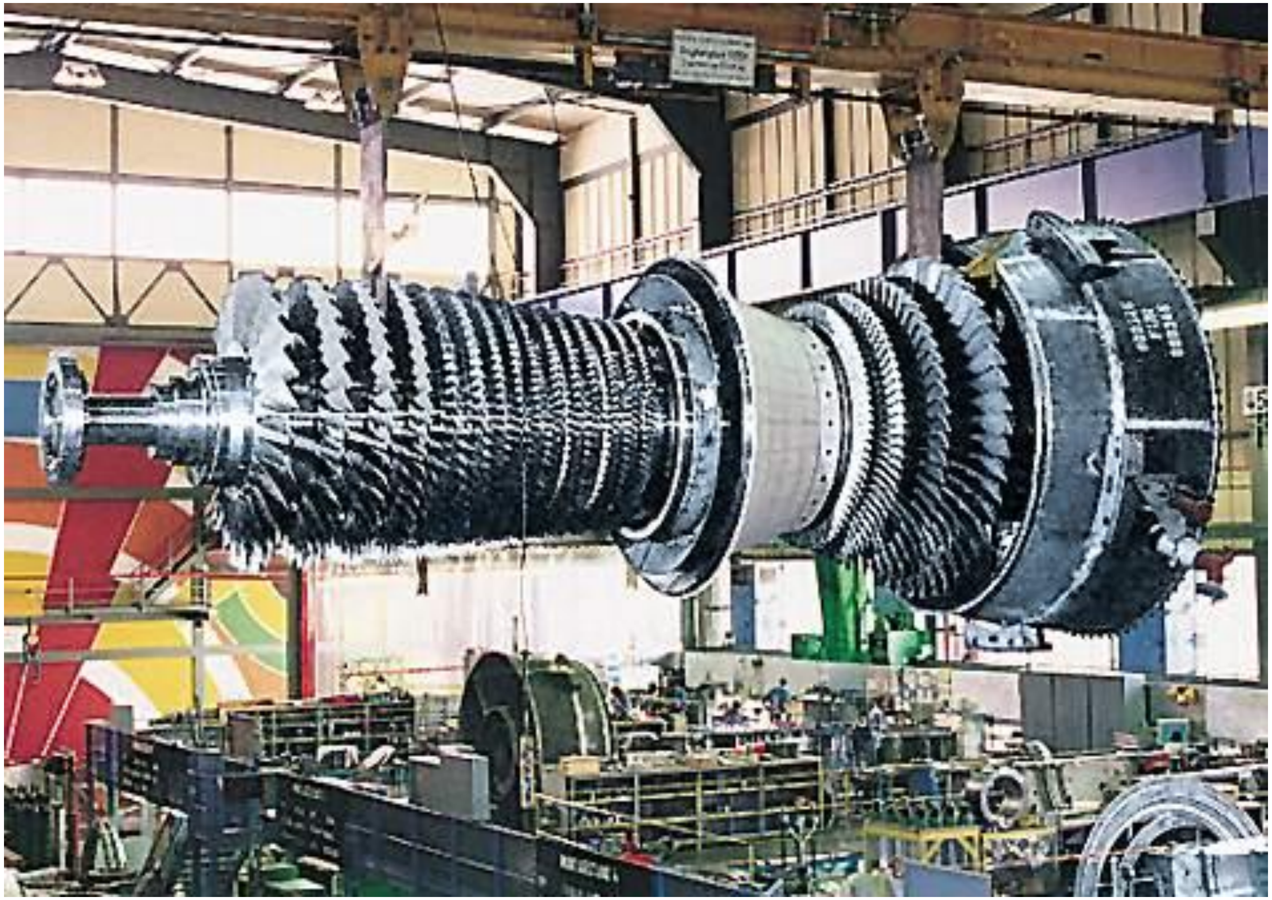
1. A simple case
2. Computing the whole flow
3. Computing the fluctuations only
4. **An actual study case**

THE AVSP THERMOACOUSTIC SOLVER

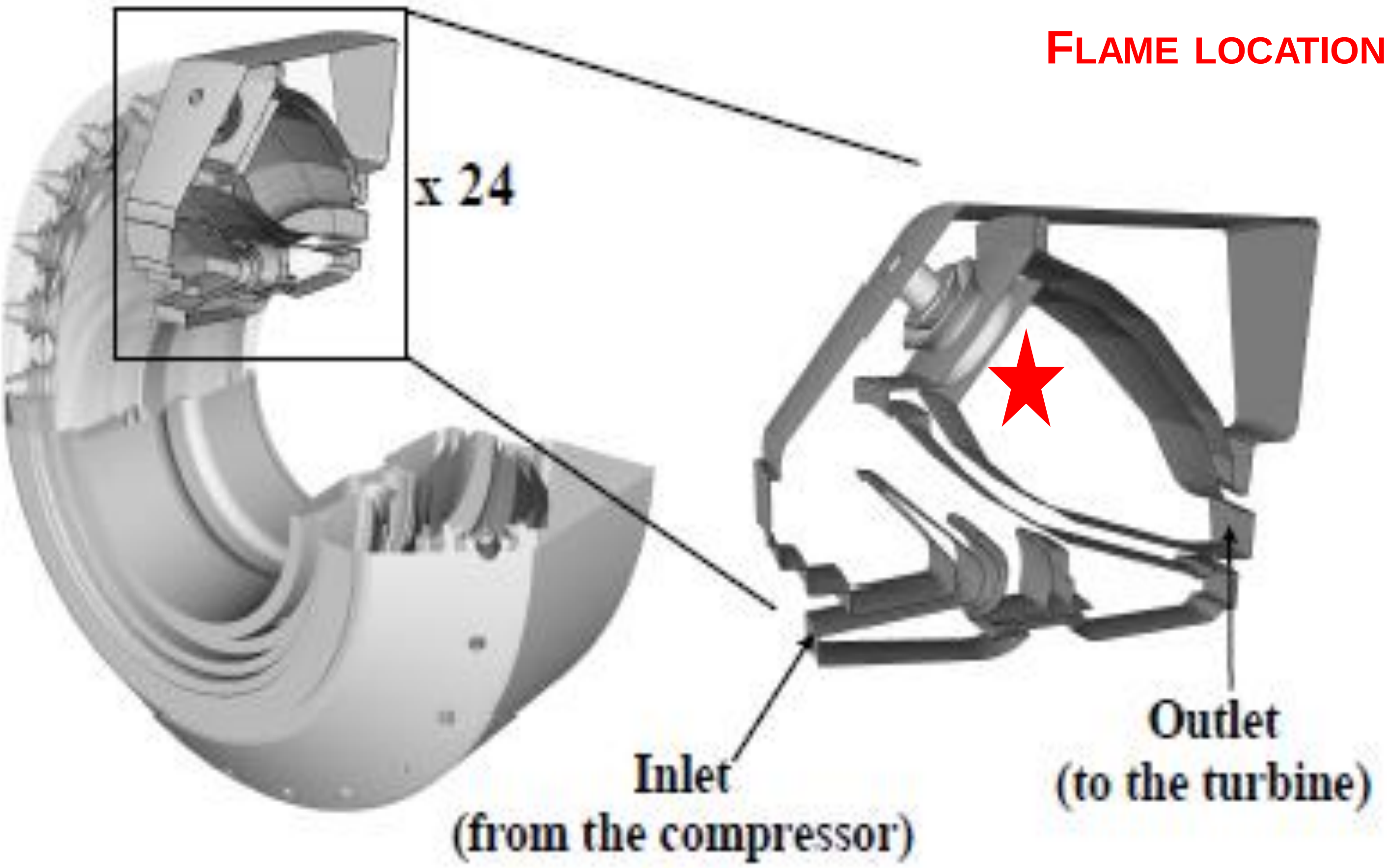
- Main contributors:
  - L. Benoit, C. Sensiau, E. Gullaud, E. Motheau, P. Salas, C. Silva, K. Wieczorek, A. Ndiaye, F. Ni
  - A. Dauptain, L. Giraud, G. Staffelbach, F. Nicoud, Th. Poinsot

- Support from SAFRAN/SNECMA (since 2000) as well as ANR and EU
- Integrated in the C3SM framework for generating Human-Machine Interface
- Now in use in design departments in the SAFRAN Group

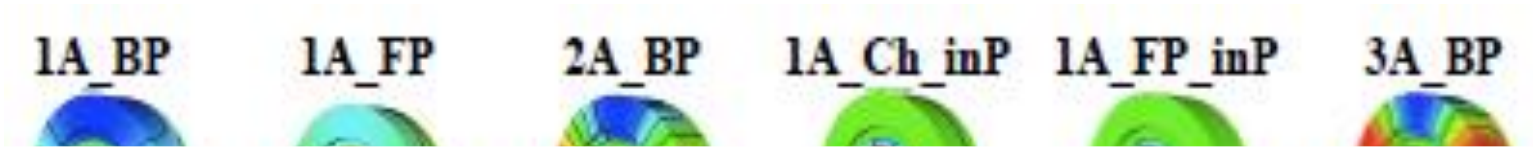
AN ACTUAL INDUSTRIAL CASE



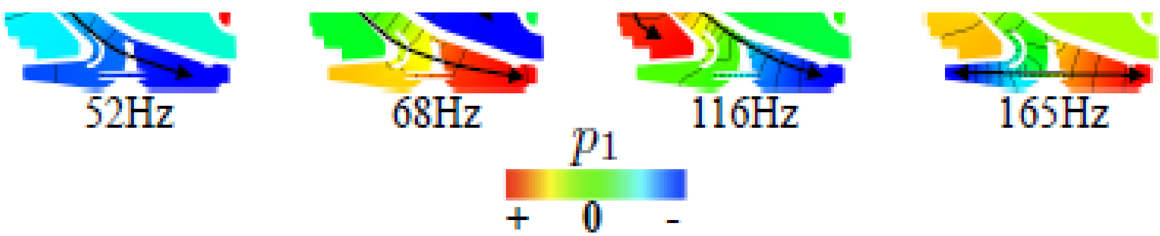
AN ACTUAL INDUSTRIAL CASE



CLASSICAL ACOUSTIC ANALYSIS



Which of these modes are made unstable by the flame ?



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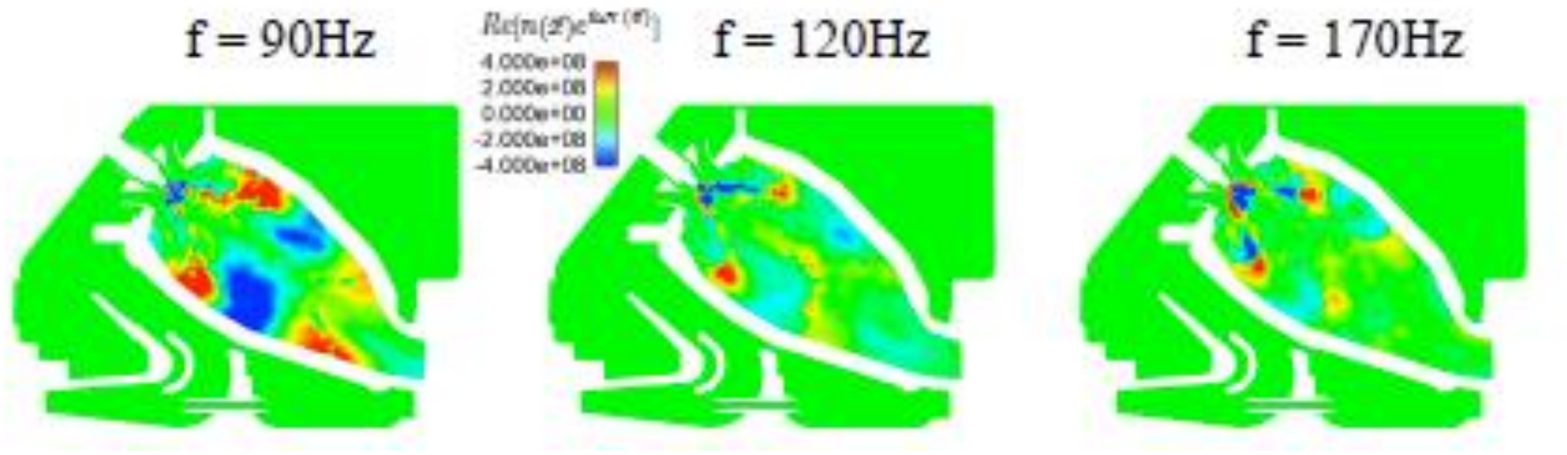
FLAME RESPONSE FROM LES

- A large Eddy Simulation (solving the whole set of flow equations) has been performed to numerically measured the flame transfer function
- Several pulsed LES were performed since the results depend on the frequency od excitation



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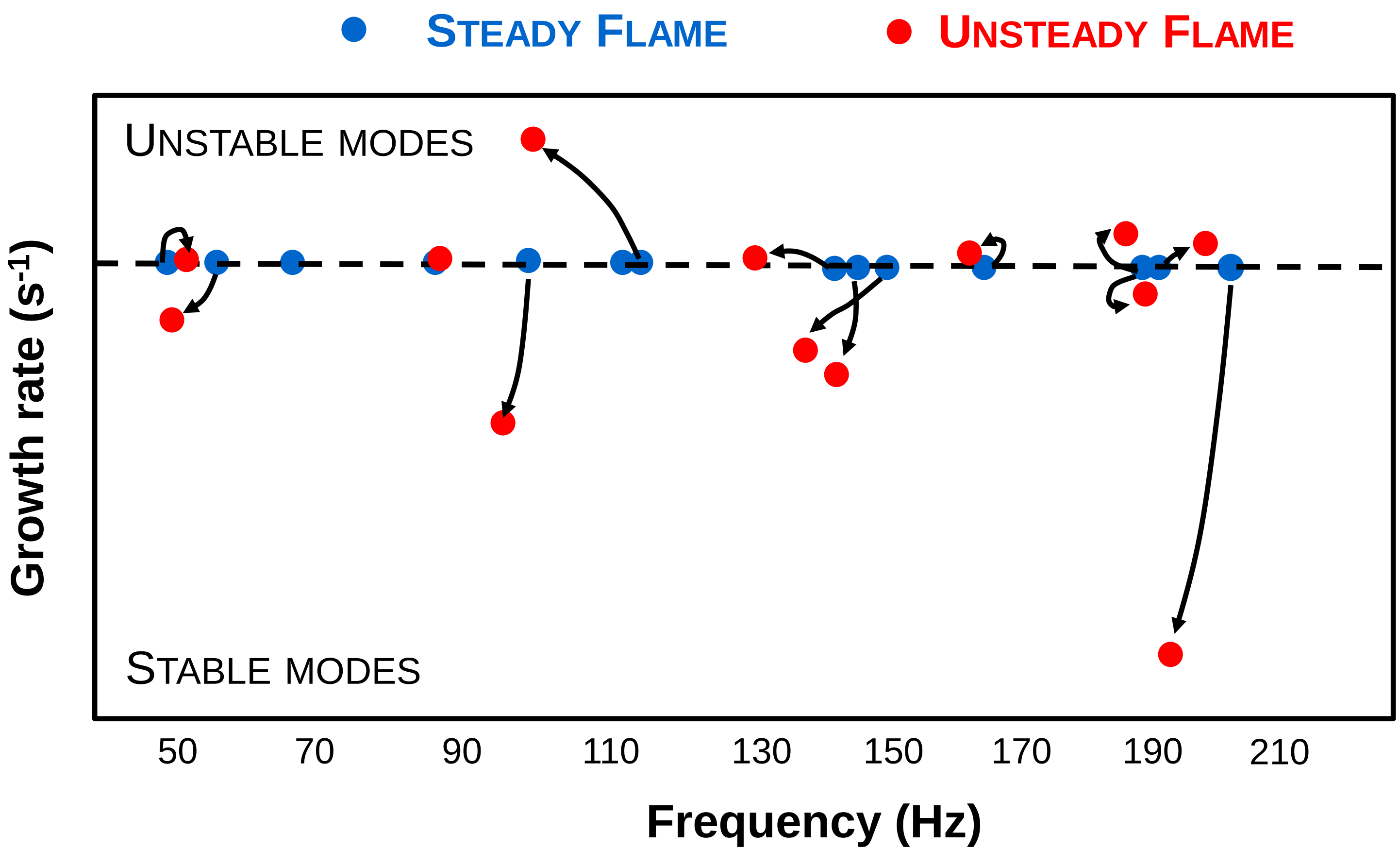
EFFECT OF THE FLAME ON ACOUSTICS



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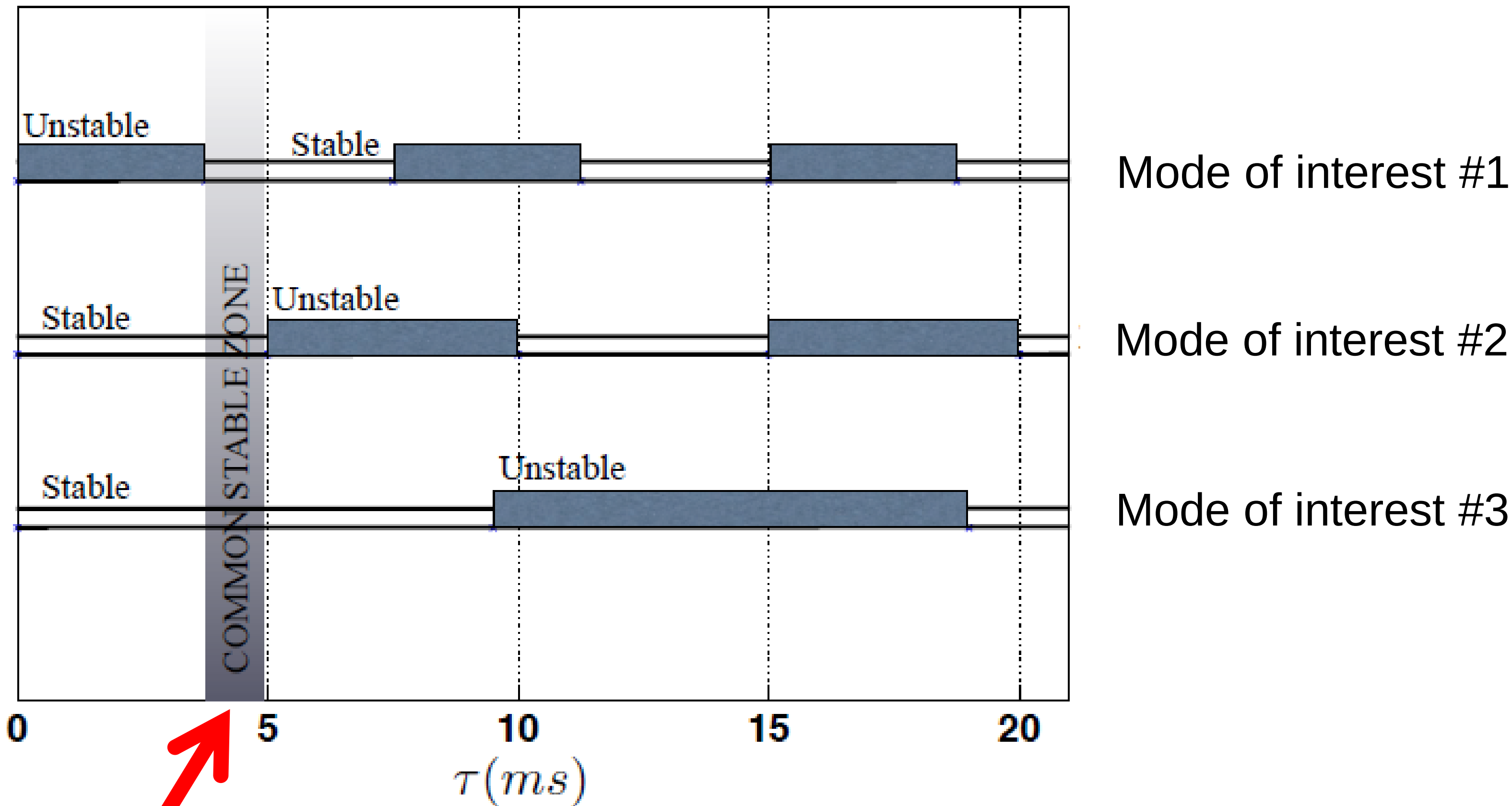
PARAMETRIC STUDY: TIME DELAY



THE SWIRLER SHOULD BE DESIGNED IN SUCH A WAY TO PRODUCE A TIME DELAY OF THE FLAME RESPONSE IN THIS RANGE

THANK YOU !!

More details, slides, papers, …

http://www.math.univ-montp2.fr/~nicoud/

http://www.cerfacs.fr