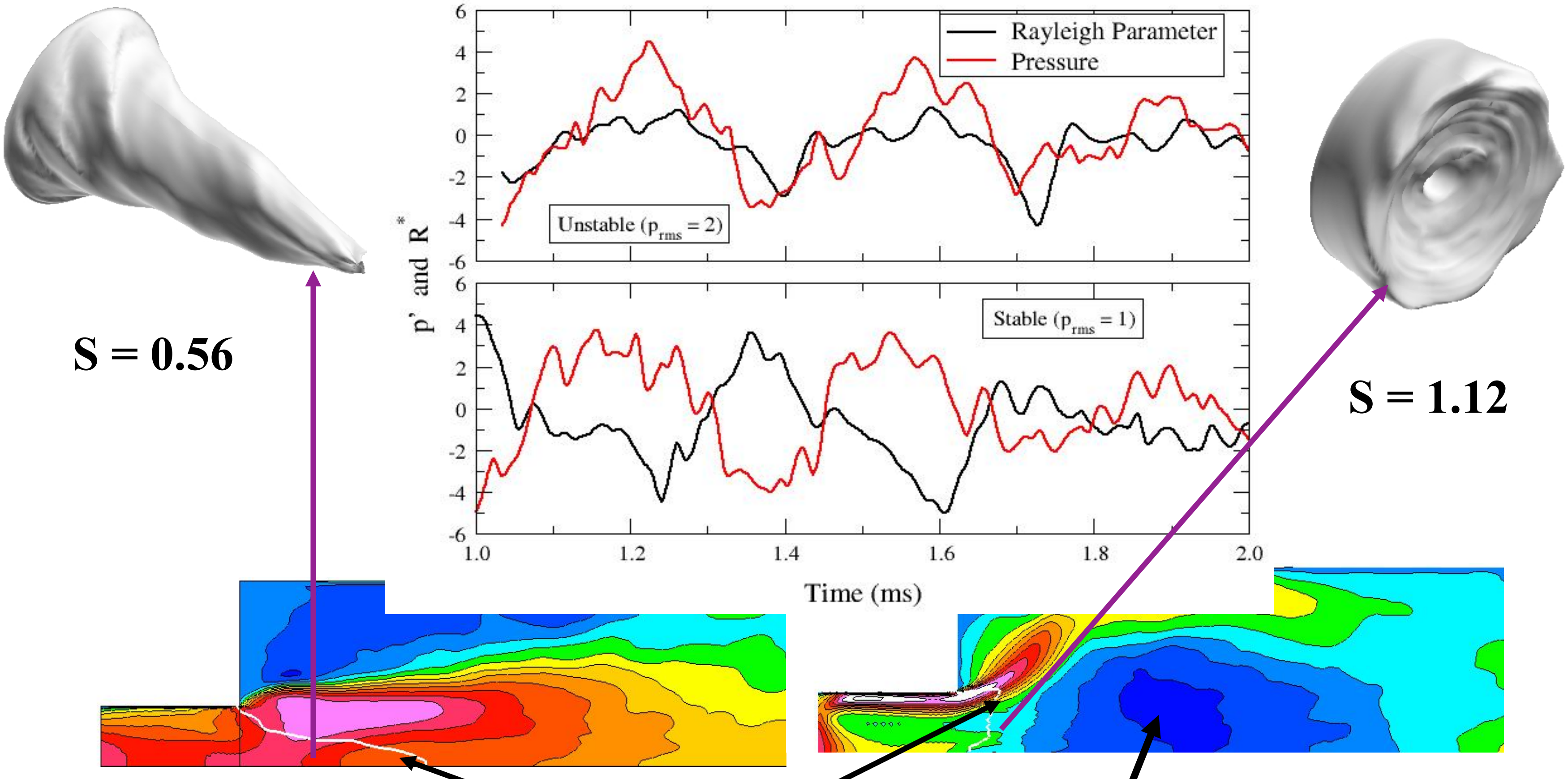
Lecture 6
Combustion Instability and Lean Blow Out

- **CI: Coupling between acoustics, vortex motion and heat release leads to enhancement of pressure oscillation**
  - **Many sources: fuel feed oscillations, acoustic boundary conditions, unsteady flame and/or vortex motion**
- **LBO: flame blowout in the lean flammability limit**
- **CI and LBO may be linked or not depends on the burner design and combustion conditions**
  - **In general they are two different physics and can be considered separately**
- **CI may require full compressible treatment!**
  - **Naturally couple acoustics-vortex-flame interactions**

Day 2, Lecture 6, Suresh Menon, Georgia Tech

Flame-Vortex Interaction in Swirling Flow



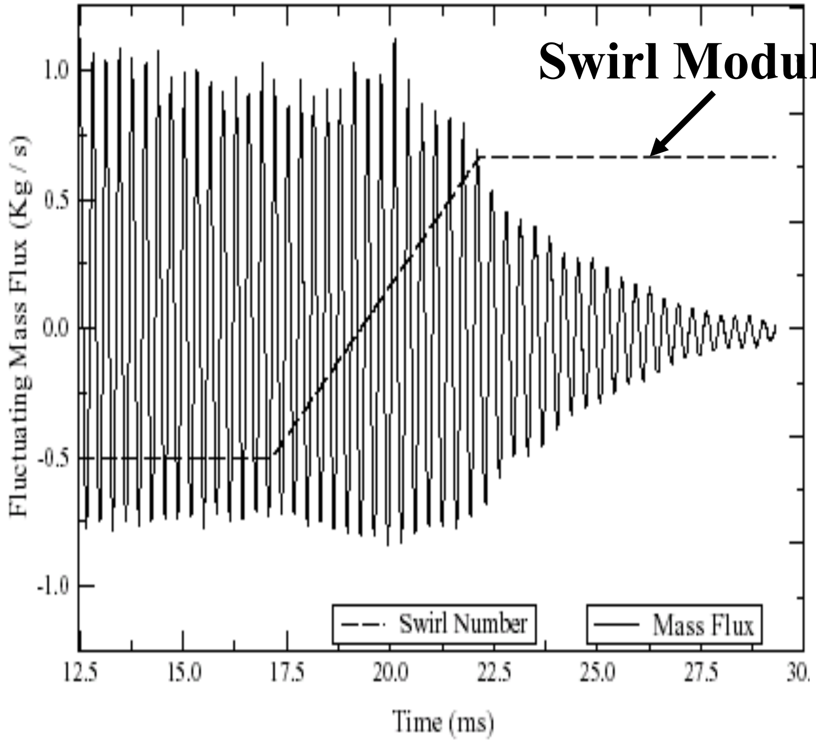
S = 0.56

S = 1.12

FLAME

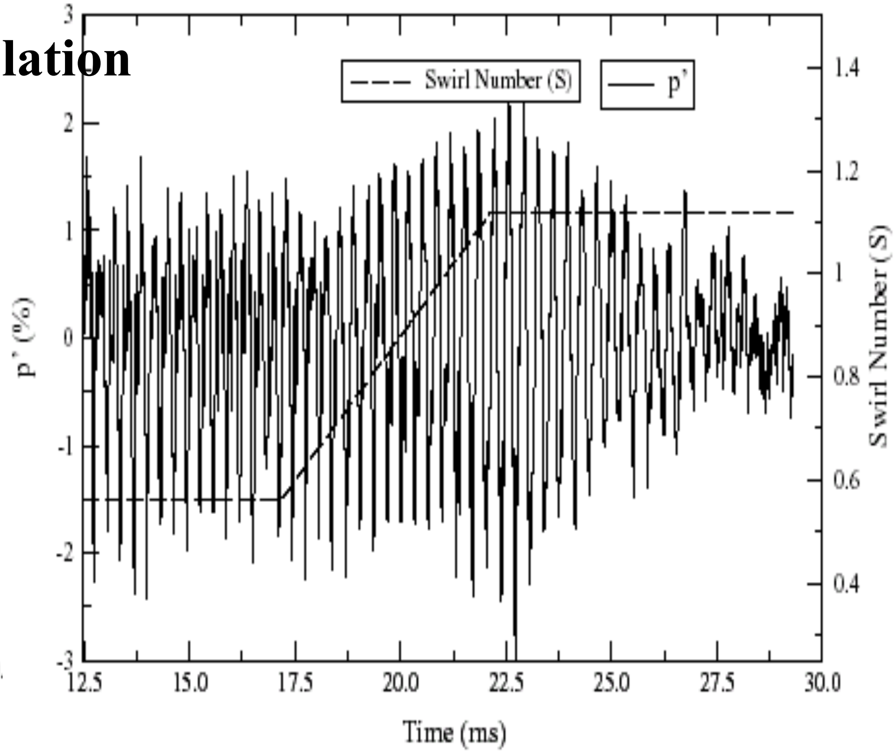
VORTEX BREAKDOWN BUBBLE

Open Loop Control: Swirl Modulation



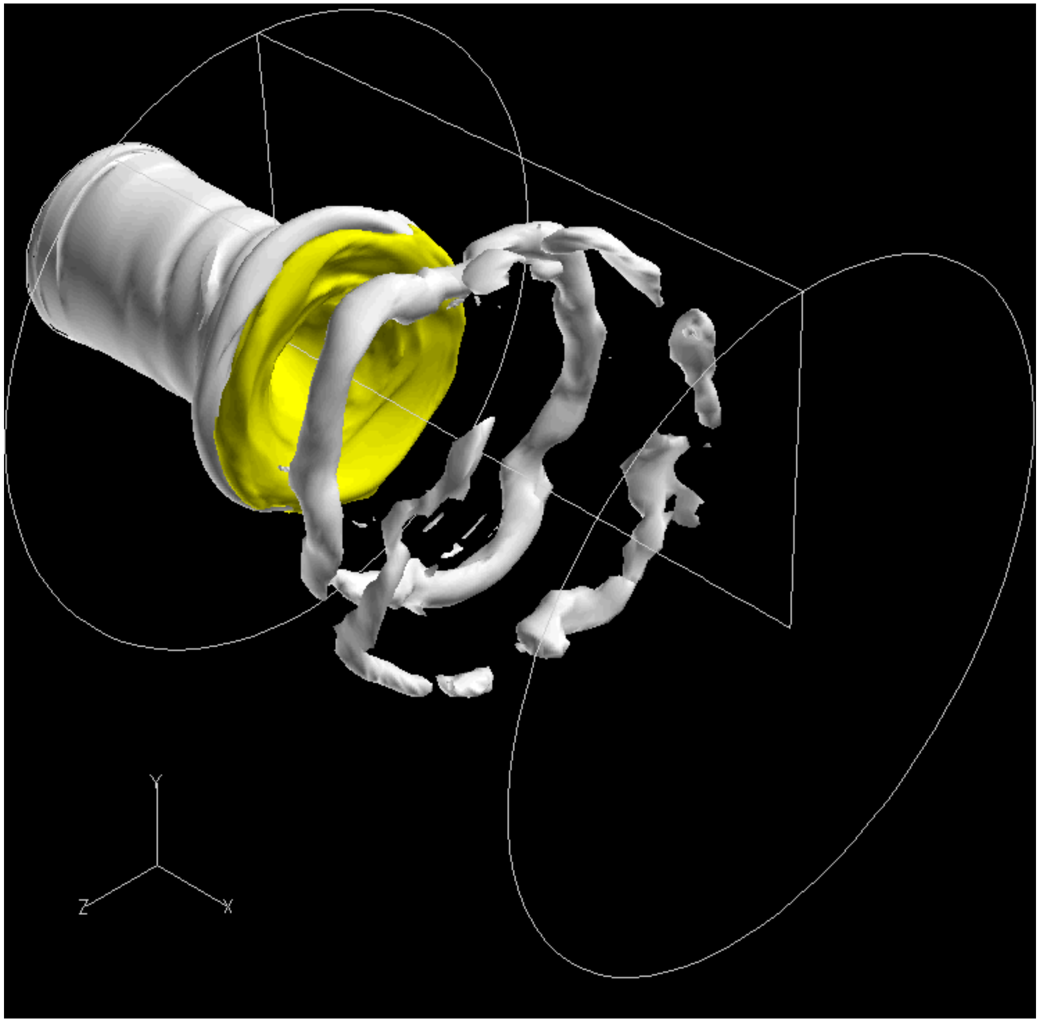
Swirl Modulation

Inflow Mass Flux

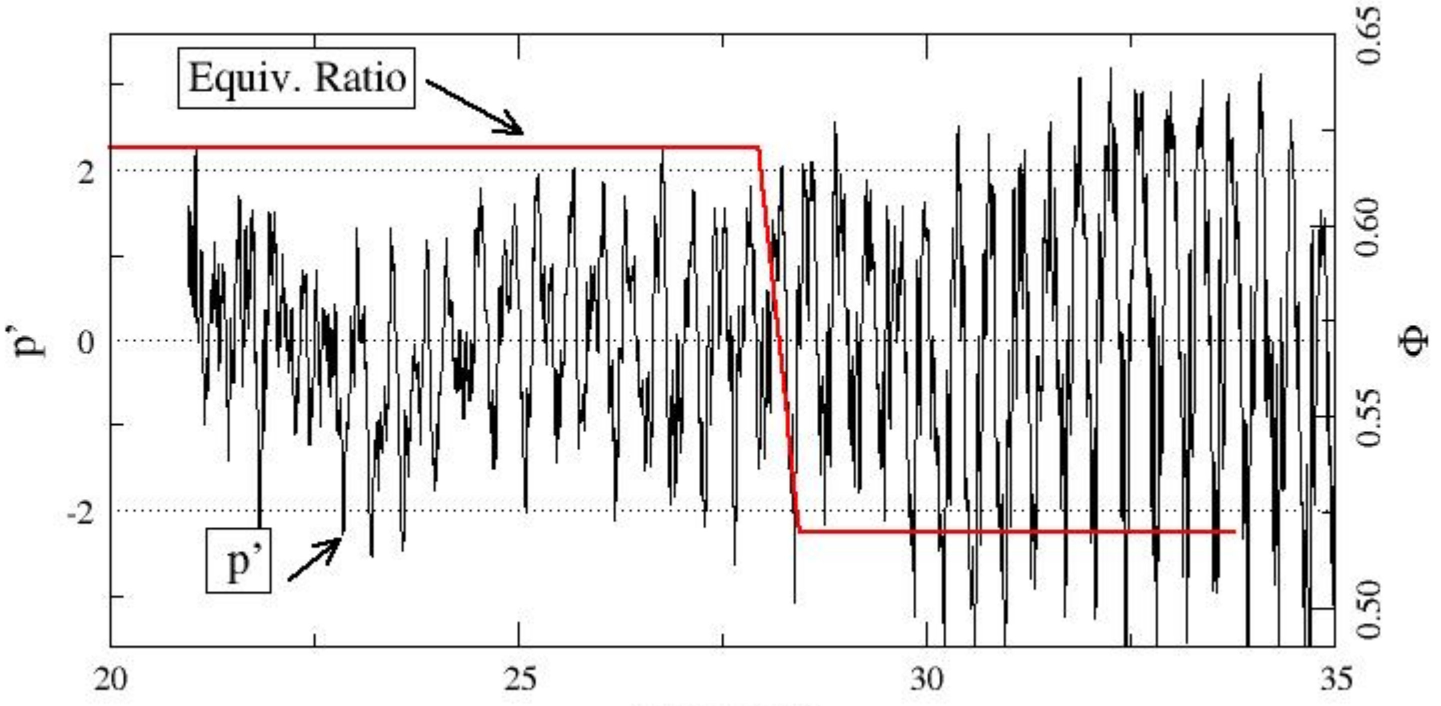


Pressure Fluctuation

Swirl Modulation

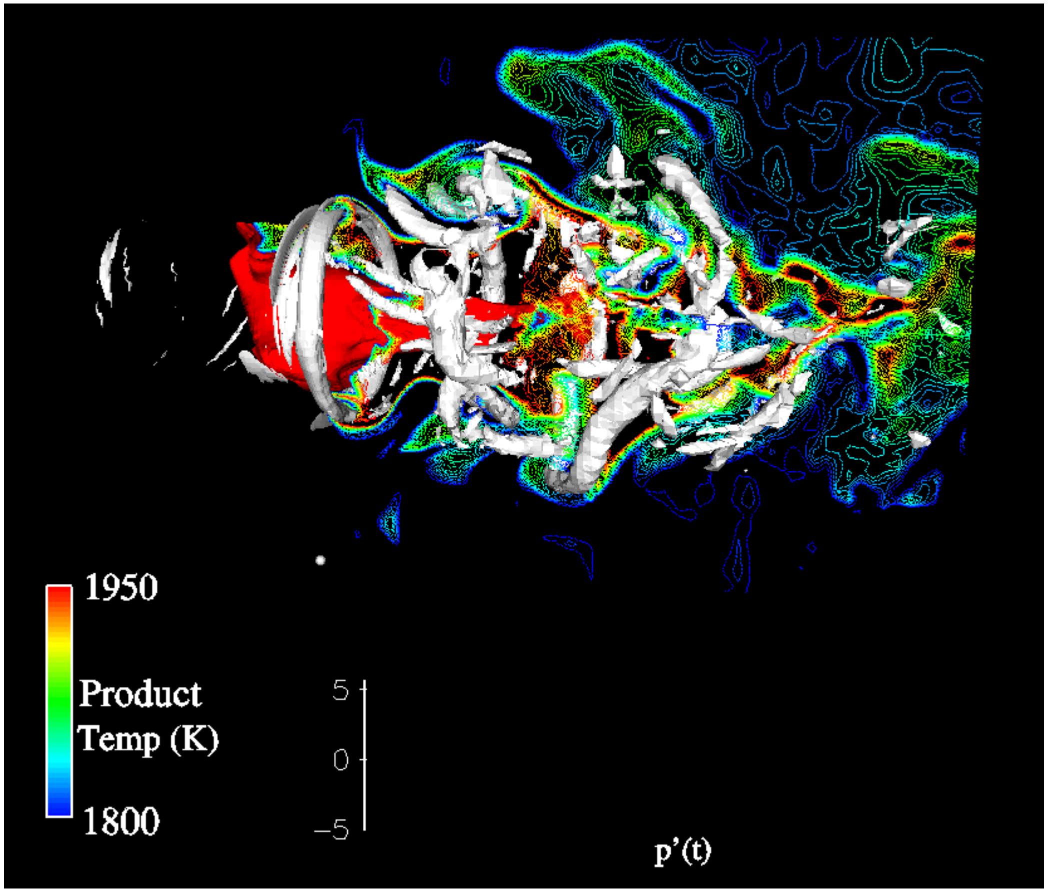


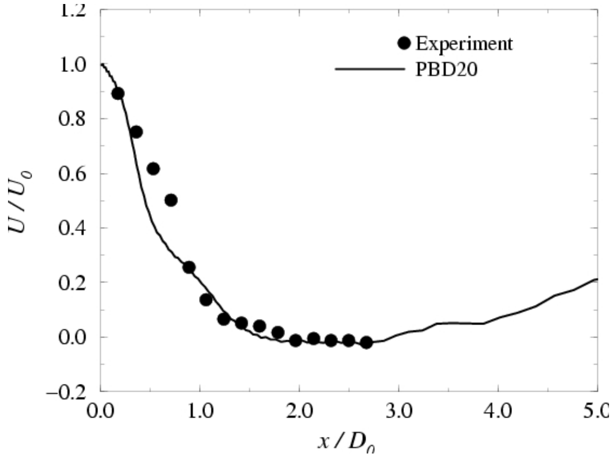
Inlet Equivalence Ratio Modulation

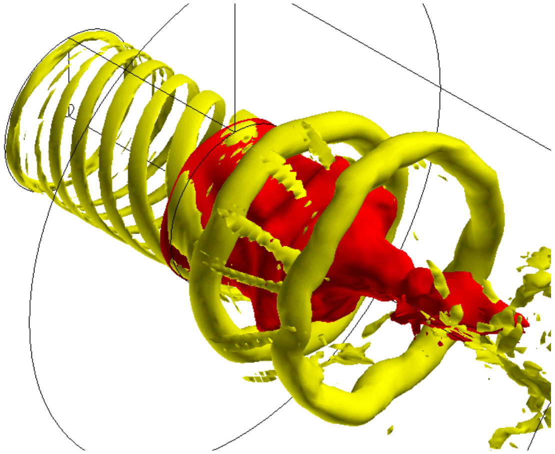


- **For Φ = 0.62: p' *rms* = 1.0 Φ = 0.52: p' rms = 1.75**
- **Much Faster Response: 3.5 vs. 15 cycles for swirl modulation**
  - **fuel modulation control is a practical solution**

Fuel Modulation of Combustion Instability







GE LM6000

LES of combustion instabilities in gas turbines

- **Gas turbine chamber designs are prone to combustion instabilities and especially to azimuthal modes [7, 8, 9, 10]**
- **Experimentally and numerically difficult and expensive to study => single burner rigs ==> impossible to study azimuthal modes**

[7] S. Evesque, W. Polifke and C. Pankiewitz. Spinning and Azimuthally Standing Acoustic Modes in Annular Combustors. AIAA paper 2003-3182
[8] T. Lieuwen, V. Yang, Combustion Instabilities in Gas Turbines Engines, Operational Experience, Fundamental Mechanisms and Modeling, AIAA, 2005
[9] C. O. Paschereit,B. Schuermans and P. Monkewitz. Non-linear combustion instabilities in annular gas-turbine combustors. 44th AIAA Aerosp. Sci. Meeeting and Exhibit 2006
[10] W. Krebs, P. Flohr, B. Prade and S. Hoffmann. Thermoacoustic stability chart for high intense gas turbine combustion systems, CST, 174, 2002

Courtesy T. Poinsot

Numerical simulation of combustion instabilities

- **Two computational techniques have the potential to predict azimuthal modes: acoustic tools and LES [11, 12, 13, 14]:**

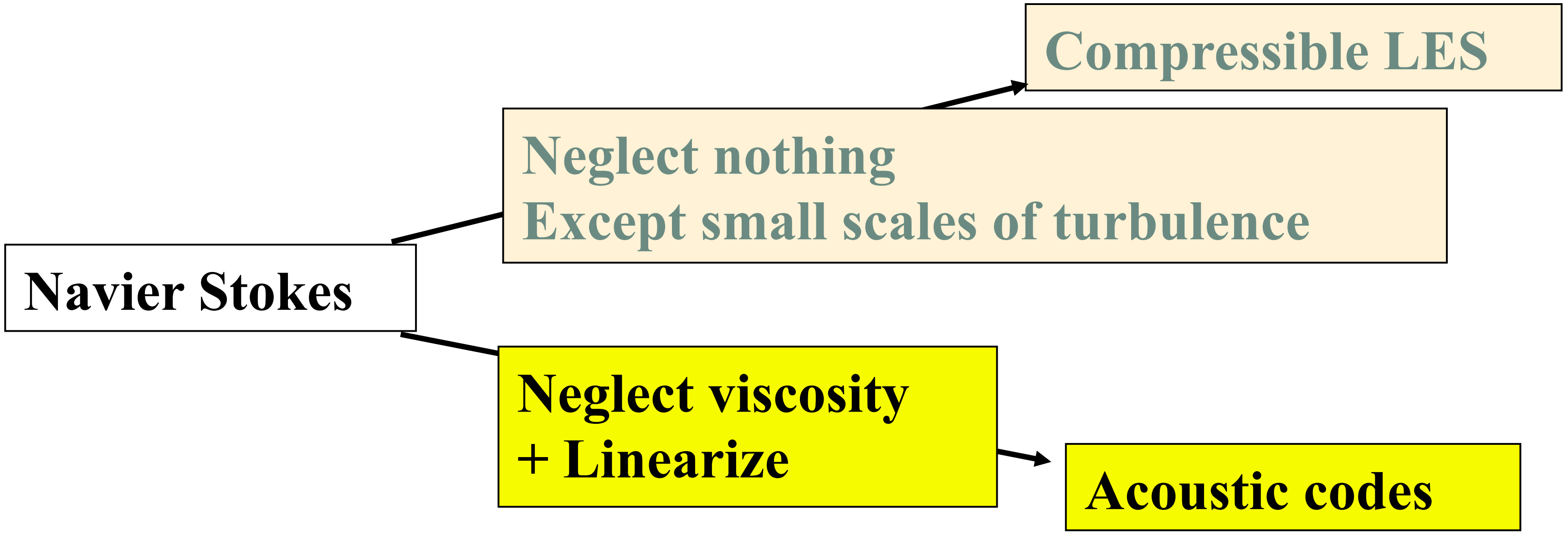
Compressible LES

Neglect nothing
Except small scales of turbulence

Navier Stokes

Courtesy T. Poinsot

Numerical simulation of combustion instabilities



Navier Stokes

Neglect nothing
Except small scales of turbulence

Compressible LES

Neglect viscosity
+ Linearize

Acoustic codes

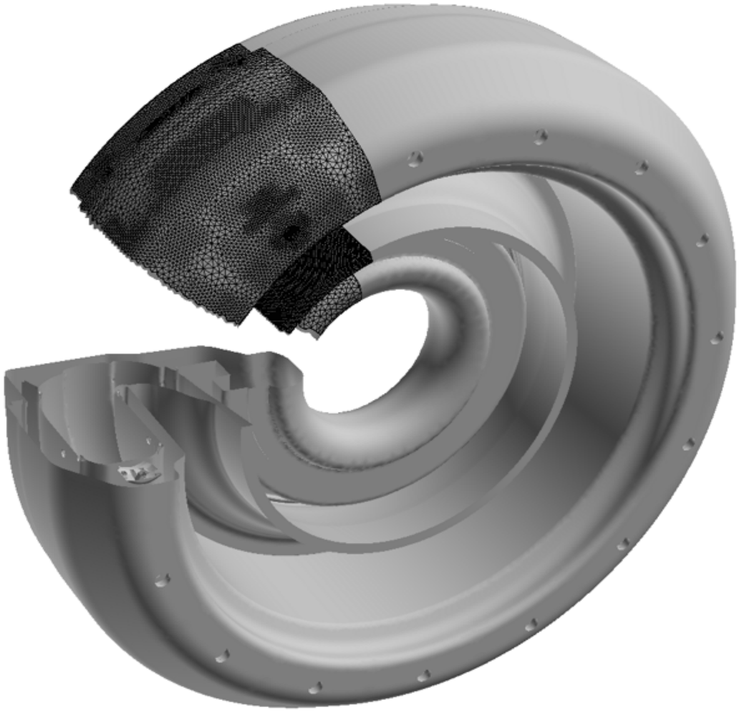
Here we will try to use LES

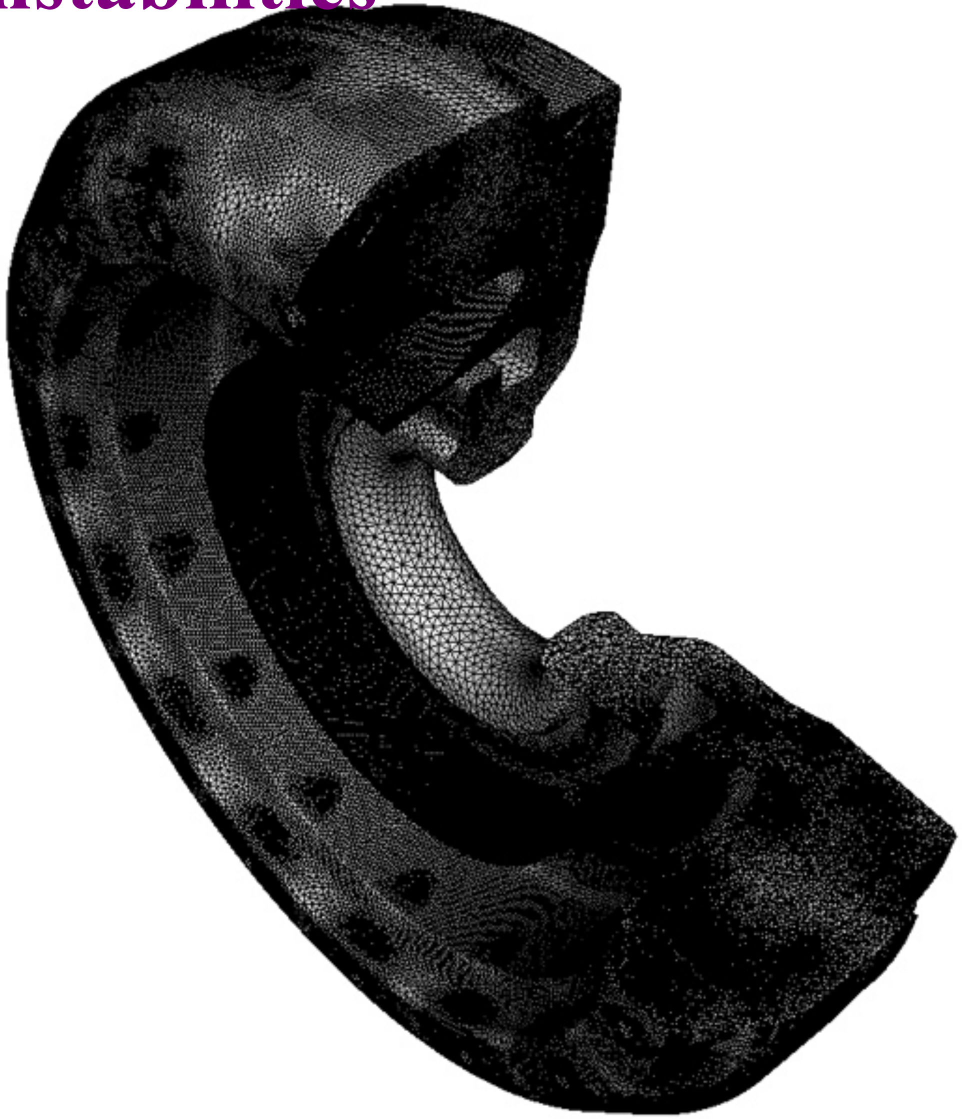
[11] L. Selle, G. Lartigue, T. Poinsot, R. Koch, K.-U.Schildmacher, W. Krebs, B. Prade, P. Kaufmann, D. Veynante, Combust. Flame, 2004
[12] L. Benoit, F. Nicoud, Int. J. Numer. Meth. Fluids, 2005
[13] S. R. Stow and A. P. Dowling. Modelling of circumferential modal coupling due to Helmholtz resonators. ASME Paper 2003-GT-38168
[14] N. Patel and S. Menon Simulation of spray–turbulence–flame interactions in a lean direct injection combustor. Combustion and Flame, 153, I-2, 228-257

Courtesy T. Poinsot

LES of combustion instabilities

- **42 million tetrahedra**

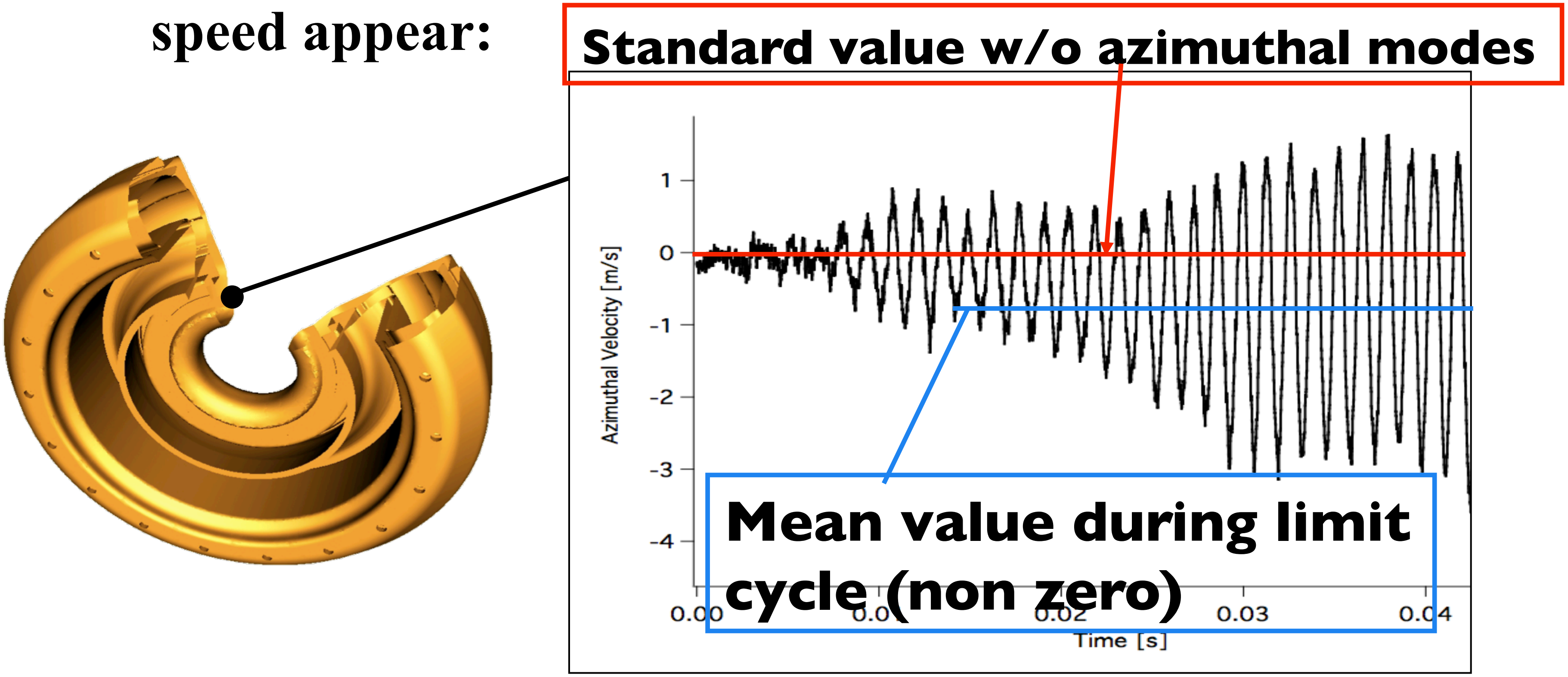




Courtesy T. Poinsot

LES of combustion instabilities

- **After t=0, self-established oscillations of the azimuthal speed appear:**



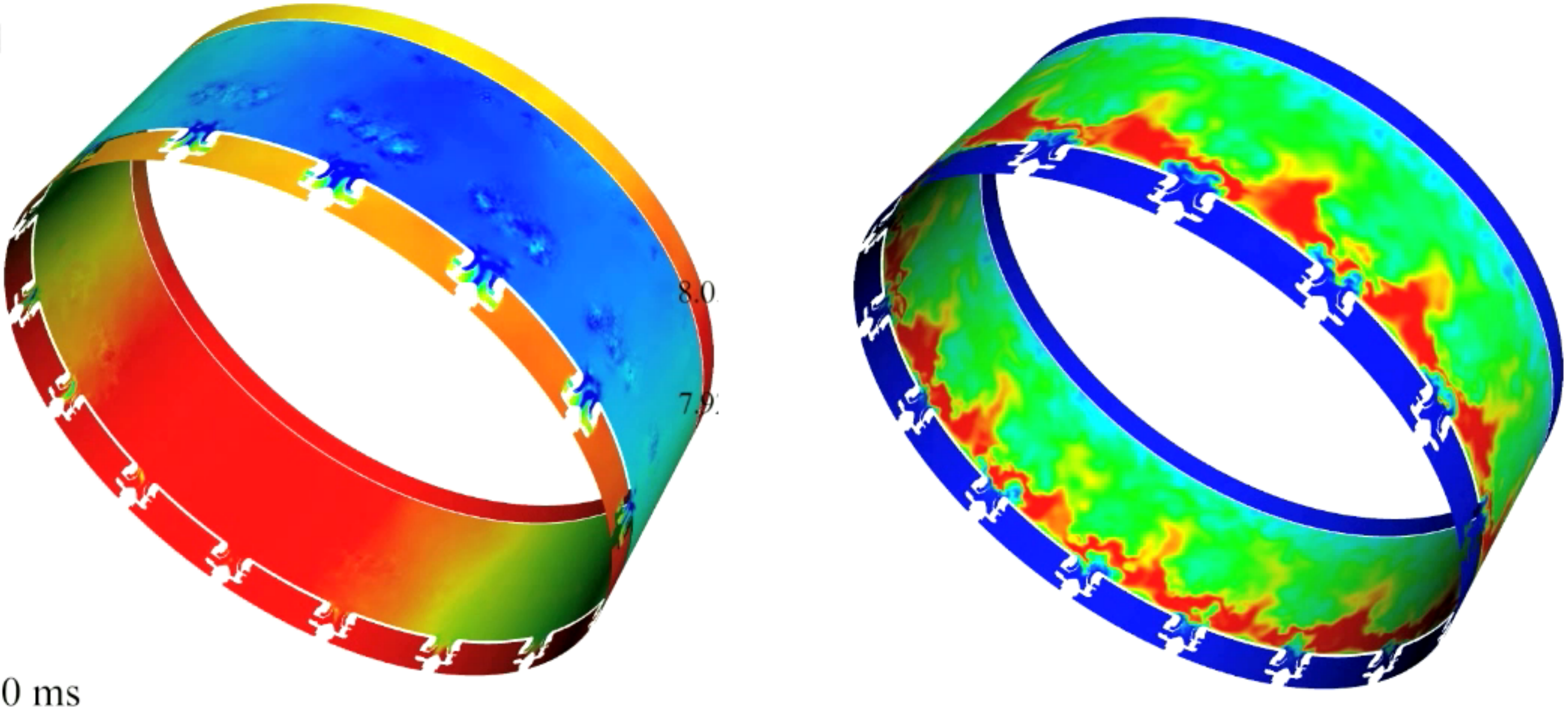
Standard value w/o azimuthal modes

Mean value during limit cycle (non zero)

- **This frequency matches the value of the first azimuthal mode found by the experiment**

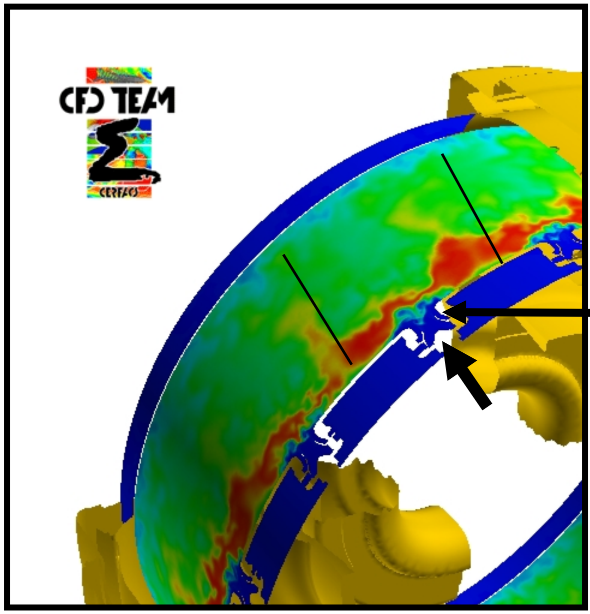
Courtesy T. Poinsot

LES of combustion instabilities



38.36000 ms

Azimuthal instability scenario



Flow rate in burner N

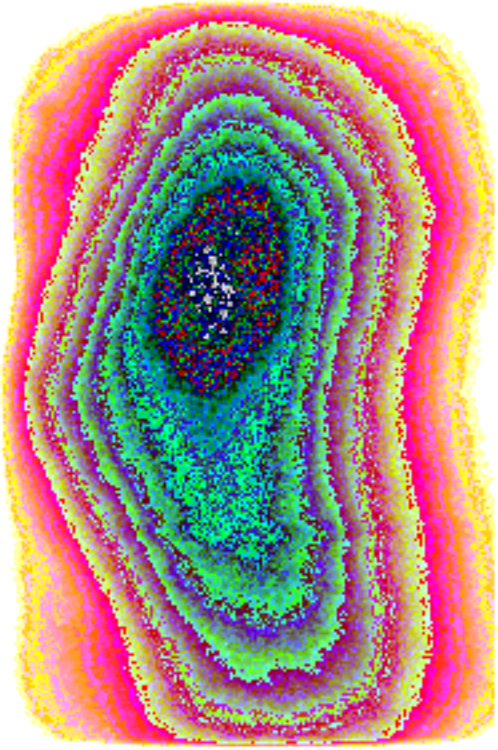
1. Azimuthal wave passes on sector N
2. Flow rate in swirler N changes
3. Reaction rate in sector N changes after 0.6 ms
4. Reaction rate changes when the pressure is positive satisfying the Rayleigh criterion

Thermo-acoustic System Analysis

Why is it important?

ALSTOM

- Probably more than 90% of the development effort in GT combustors is linked to flame dynamics (pulsations, life-time, heat loading, operation concepts, emissions, …)

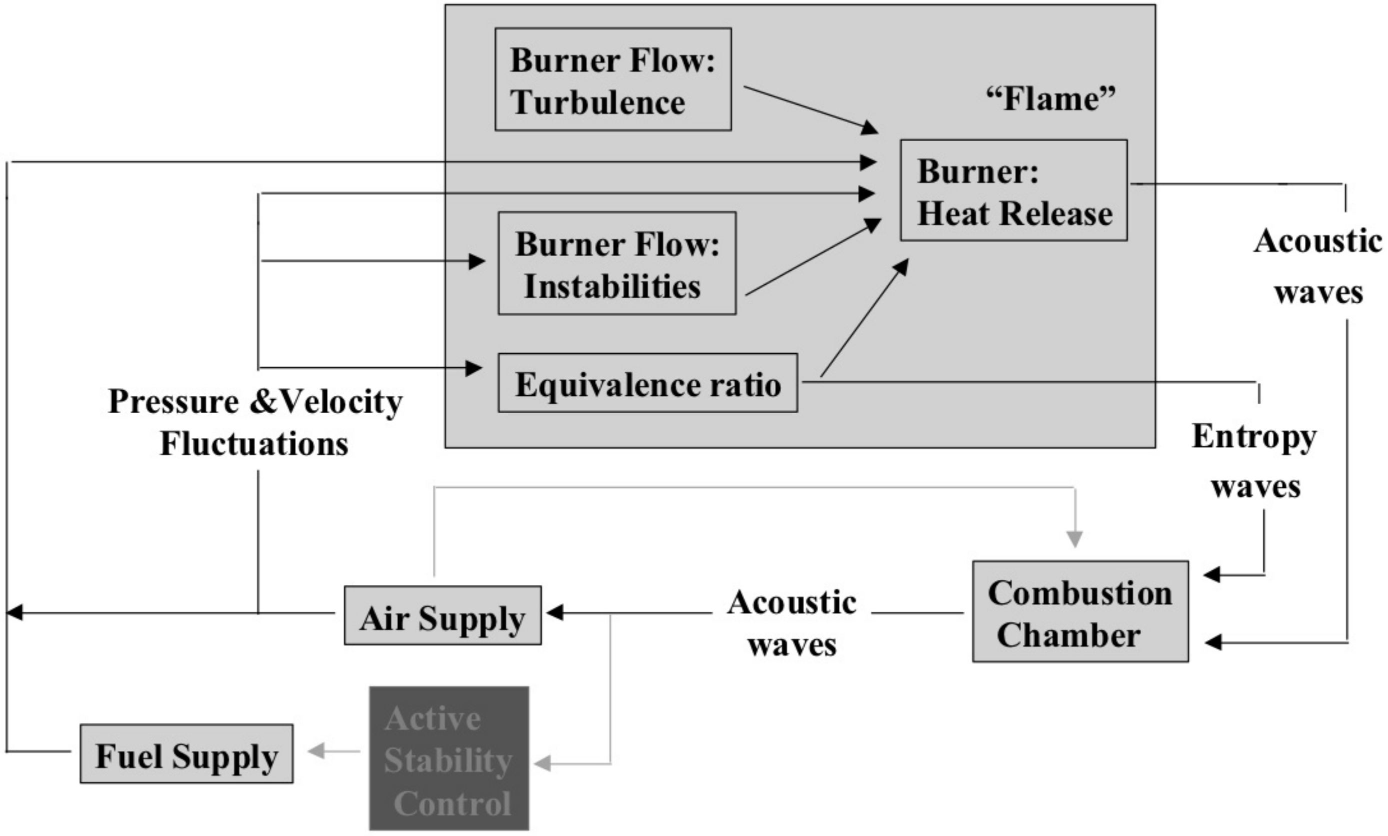


Courtesy: Flohr

Thermo-acoustic System Analysis

Why is it a challenge?

ALSTOM



Highly coupled problem: fluid flow - combustion - acoustics

Courtesy: Flohr

Thermo-acoustic System Analysis

How to Use CFD for transfer functions

ALSTOM

- Brute-force approach
  - Full system simulated with unsteady CFD
    - forced or self-excited instabilities
    - difficult to control numerical boundaries and numerical noise
    - full (thermo-)acoustic feedback often not simulated
    - excessive numerical cost
- Hybrid approach
  - Use combination of acoustic networks and CFD analysis
    - Steady CFD to derive TF model parameters
    - Unsteady CFD for burner flame region + acoustic boundaries

Key challengse for hybrid approach: transfer function extraction method & impedances at boundaries

Courtesy: Flohr

CFD Transfer Function Extraction

Use Tricks from Real Experiments

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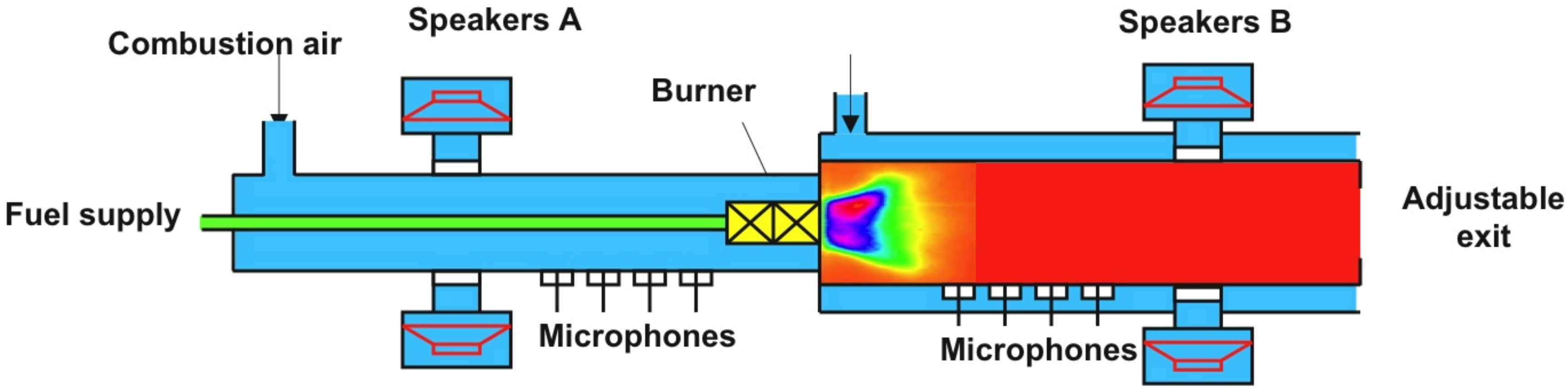
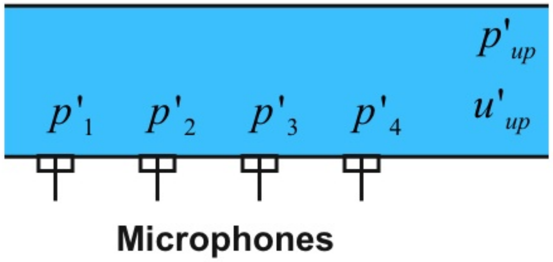
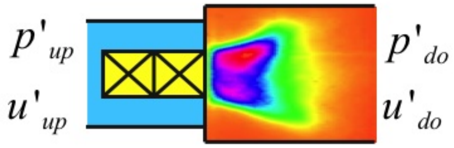




$$\begin{bmatrix}\hat{p}_1\\ \vdots\\ \hat{p}_N\end{bmatrix} = \begin{bmatrix} e^{-i\omega\frac{x_1}{c+\bar{u}}} & e^{i\omega\frac{x_1}{c-\bar{u}}}\\ \vdots & \vdots\\ e^{-i\omega\frac{x_N}{c+\bar{u}}} & e^{i\omega\frac{x_N}{c-\bar{u}}}\end{bmatrix}\begin{bmatrix}\hat{f}\\ \hat{g}\end{bmatrix}$$

$$\begin{bmatrix}\hat{p}_{up}\\ \hat{u}_{up}\end{bmatrix} = \begin{bmatrix}1 & 1\\ 1 & -1\end{bmatrix}\begin{bmatrix}\hat{f}\\ \hat{g}\end{bmatrix}$$



$$\begin{bmatrix}\hat{p}^A_{do} & \hat{p}^B_{do}\\ \hat{u}^A_{do} & \hat{u}^B_{do}\end{bmatrix} = \begin{bmatrix}T_{11} & T_{12}\\ T_{21} & T_{22}\end{bmatrix}\begin{bmatrix}\hat{p}^A_{up} & \hat{p}^B_{up}\\ \hat{u}^A_{up} & \hat{u}^B_{up}\end{bmatrix}$$

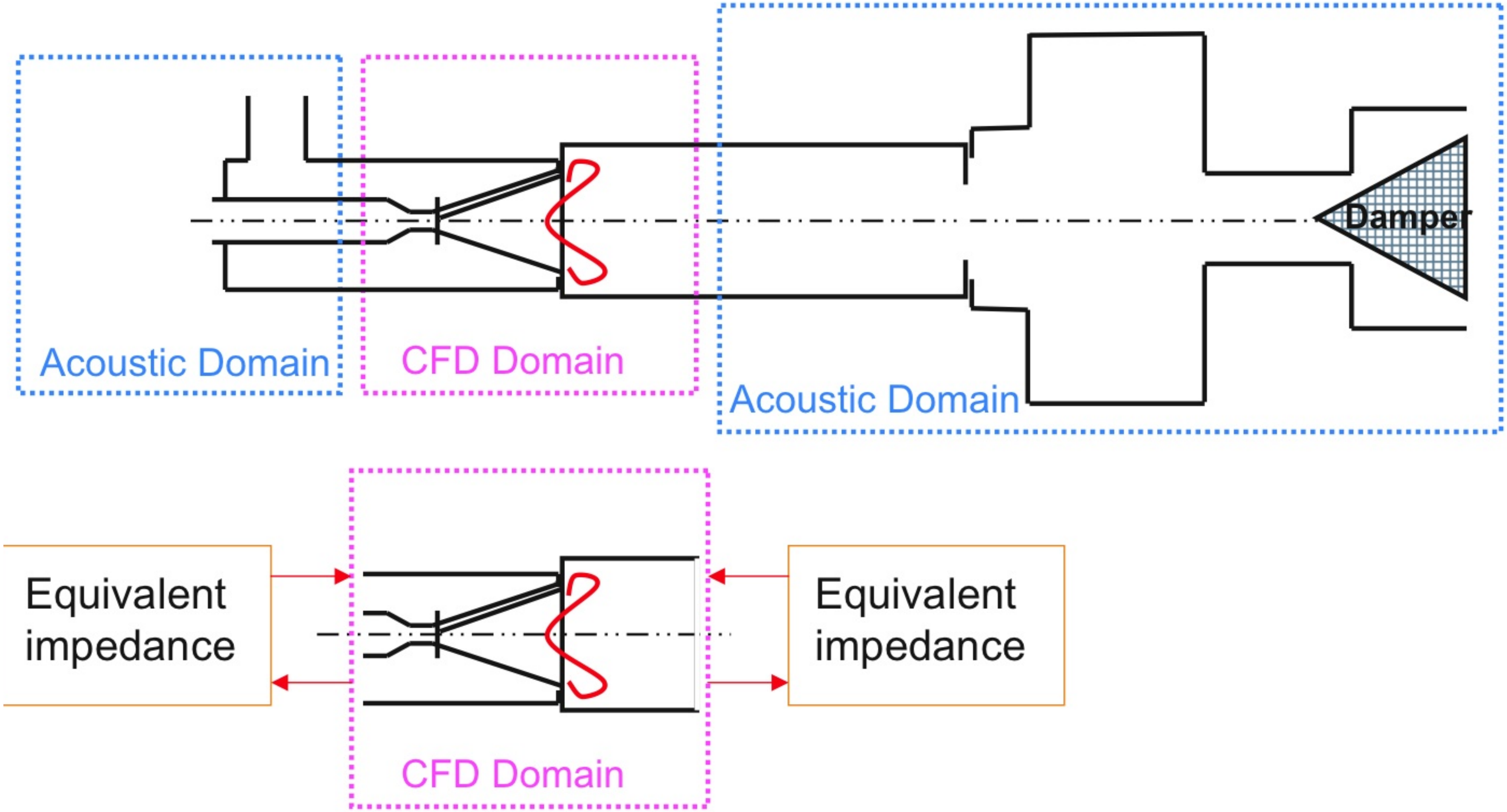
Four equations, four unknown: solve for T

Numerical noise is similar to experimental noise

Courtesy: Flohr

CFD Impedance Boundary Condition

Time domain boundary condition



Courtesy: Flohr