Many thanks to Ed law for inviting me to give this course in this stimulating setting. It is a pleasure to be here and share ideas and some of our research with you.

The focus is on combustion dynamics with special attention to swirling flames and annular systems dynamics which are important for gas turbines. We’ll try to cover fundamentals and practical applications.

Thanks to Nicolas Noiray, Paul Palies, Frédéric Boudy, Jean-François Bourgouin, Jonas Moeck, Kevin Prieur, Guillaume Vignat, Antoine Renaud and Davide Laera for their many contributions.
The Eiffel tower was built by Gustave Eiffel in 1889.

On February 24th 1954, at the controls of a Mystere IV, Constantin Rozanoff is the first French pilot to break the sound barrier with a French built airplane.

The beginnings of aeronautics

December 17, 1903 First motored flight of the Wright brothers Orville and Wilbur Wright at Kitty Hawk (North Carolina)
General introduction and background

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New technologies promote acoustic coupling problems

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Domestic boiler

Powerplant

~ 1 GW\(_{th}\)

Process heater

~ 1 MW\(_{th}\)

Gas turbine

~ 100 MW\(_{th}\)

Case 1

During unstable operation, lateral walls of this boiler are “breathing” highlighting large pressure oscillations within the system

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Combustion dynamics issues in gas turbines

Combustion dynamics degrades operation of many practical systems and in extreme cases leads to failure.

Challenges

1. Gain an understanding of the processes driving and coupling combustion instabilities
2. Develop models for the nonlinear dynamics observed in practice: limit cycles, triggering, mode switching, hysteresis...
3. Derive predictive analytical and numerical tools for combustion dynamics
4. Design novel instability control systems (passive, dynamical, active)

Case 2: Combustion dynamics in modern gas turbines

Difficulties are related to the reduced stability of lean premixed combustors widely used in gas turbines.

Analysis must take into account physical and geometrical complexities including:

1. A turbulent swirling flame,
2. Resonant acoustic characteristics of the system,
3. Reduced damping rates
4. Complicated boundary conditions

Premixed gas turbine combustor
Numerical simulation of instabilities has to deal with complex swirling injection configurations, turbulent flows, acoustic flame coupling, dynamics of upstream and downstream components.

Lean premixed combustion generates low levels of NOx but is susceptible to pressure coupling and instability. Predictive tools are needed to design stable combustors. Such tools are not available but their development is an objective for the future.

Thermoacoustic interactions in gas turbine combustors

Adapted from Paschereit et al (1998)
Case 3

Multipoint injection swirled burner
Barbosa, Scouflaire, Ducruix

The flow is from left to right in the video

**Stable regime:** the combustion zone (luminous region) features small stochastic fluctuations around its mean location due to turbulence. Radiated noise remains weak and broadband: “combustion roar”.

**Unstable regime:** Large synchronized motions with a strong harmonic content. Intensification of luminosity near the wall: enhanced heat fluxes to the boundaries. Oscillations induce flame flashback.

**Combustion instability mechanism**

- Production of a flow perturbation
- This induces a combustion perturbation
- Acoustic feedback links the unsteady combustion process to flow perturbation
- The system is unstable if gain exceeds damping
Basic interactions leading to combustion instabilities

**Organ pipe instabilities**

**Stable regime**
- Turbulent fluctuations
- Small amplitudes
- Broadband noise
- Combustion noise

**Unstable regime**
- High amplitude self-sustained cyclic oscillation. The frequency depends on:
  - the flame position within the tube
  - the tube length
  - the boundary conditions
Vortex driven instabilities in a premixed combustor ($f=530$ Hz)


Schlieren images of the unsteady flow (flow from right to left)

Heat release images ($C_2$ radical emission)

Numerical simulation of vortex driven instability. Flow from left to right (flame is thickened, flow is forced at the oscillation frequency $f=530$ Hz)

Angelberger et al (1999, 2001)

Experiment schlieren image of the flow (Poinsot et al. 1987)

Simulation: temperature distribution

Vortex driven combustion instability

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Turbulent flame response to acoustic waves

Plane acoustic waves
Flame stabilizer
Driver units
Combustor

Turbulent premixed propane/air flame

Schlieren images of premixed turbulent ducted flame

Air/propane

No acoustic modulation

Air/propane

With acoustic modulation $f=1210$ Hz


Fuel mass fraction (external acoustic modulation)

Computation (C. Nottin, 1999)
Why is combustion so susceptible to instabilities? Some standard reasons:

1. The power density associated with combustion is sizable. A small fraction of this power is sufficient to drive the oscillations.

Power level: 2.5 GW
Power Density: \( E_c \approx 50 \text{ GW m}^{-3} \)

A fluctuation of 20% in pressure (about 2 MPa) corresponds to a power density

\[ E_a \approx 0.4 \text{ MW m}^{-3} \]

The acoustic power is a small fraction of the thermal power

\[ \frac{E_a}{E_c} \approx 10^{-5} \]
(2) Combustion involves time lags. Reactants introduced in the chamber at one instant are converted into burnt gases at a later time.

Consider the following model including a restoring force with delay:

\[
\frac{d^2 x}{dt^2} + 2\zeta \omega_0 \frac{dx}{dt} + \omega_0^2 x(t - \tau) = 0
\]

Assume that the time lag is small and expand the last term in a Taylor series up to first order:

\[
\frac{d^2 x}{dt^2} + (2\zeta - \omega_0 \tau)\omega_0 \frac{dx}{dt} + \omega_0^2 x = 0
\]

The model features a negative damping coefficient if

\[2\zeta < \omega_0 \tau\]

The system is unstable when the time lag is sufficiently large.

Sensitive time lag theory

Luigi Crocco (1909-1986) one of the founders of combustion instability theory, professor at Princeton for many years. He spent the later part of his life in Paris and was a professor at Ecole Centrale Paris for a few years.

H.S. Tsien (Tsien Hsue-Shen or Qian Xuesen) (1911-2009), went to study at Caltech under the supervision of von Karman, one of the founders of the Jet Propulsion Laboratory, and later « Father of China’s Space Program »

Frank Marble (1918-2014), professor at Caltech, jet propulsion pioneer.
Resonant interactions may readily occur in the weakly damped geometries used in modern combustors.

Among the possible coupling modes acoustics is dominant.

If the frequency is low
\[ \lambda > d \]
wave propagation is longitudinal and this gives rise to system instabilities.

If the frequency is high
\[ \lambda < d \]
the coupling may involve transverse modes giving rise to chamber instabilities.

Classification

(Barrère and Williams, PCI 1969)

**System Instabilities**
- Involve the entire system
- Longitudinal wave propagation
- Low frequency range

**Chamber Instabilities**
- Resonant modes of the chamber
- \( \lambda \approx \) typical transverse dimension
- High frequency range

**Intrinsic Instabilities**
- Depend on the combustion process itself
- High frequency range

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Theoretical and experimental investigations for basic understanding of combustion instability in high performance devices (rocket engines, jet engines...)

Synthesis, theoretical modeling, further experiments

Detailed experiments, active control demonstrations

CD for gas turbines, numerical modeling, active control scale-up, LES, azimuthal coupling

Objectives

1. Identify the main mechanisms governing combustion instabilities

2. Illustrate these mechanisms by experiments, that can also serve to validate predictions

3. Derive theoretical and modelling tools to analyze combustion dynamics.

4. Provide fundamental elements for the prediction of linear and nonlinear stability of combustors