Combustion instabilities

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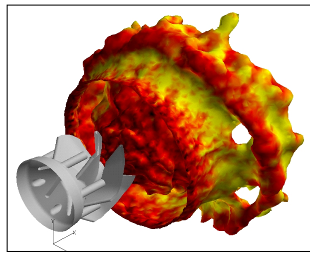

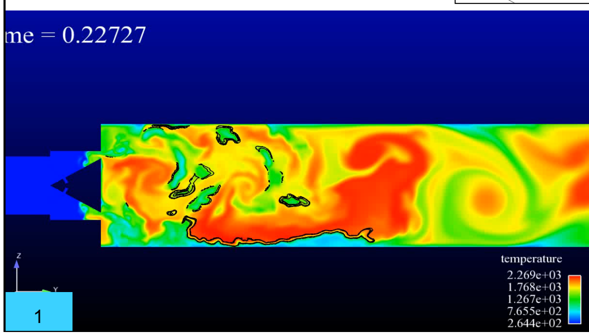

INSTABILITIES ARE EVERYWHERE IN MECHANICS

IN FLUID MECHANICS TOO… AND IN REACTING FLOWS

Reacting flows are dominated by mechanisms which exhibit instabilities:

- **hydrodynamics --> Kelvin Helmholtz in shear layers.** (C. M. Ho and P. Huerre *JFM* 1984, 16.)

- **instabilities at interfaces between liquid fuel and air**

- **kinetics: the existence of chemical reactions leads to additional instabilities of flame fronts --> thermodiffusive instability, formation of cells**

- **structures: vibration of the combustor walls can couple with the flames**

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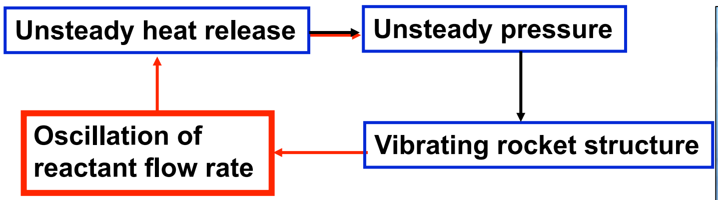
A classification of instabilities in combustion (Barrere, Wiliams, Putnam) introduced in the 60s is based on the size of the components involved in the instability:

- **Intrinsic: modes which are due only to local, short distance interactions between kinetics and flow. Ex: formation of cells (small size, high frequencies)**

- **Chamber: modes due to the whole flame where vortices, created by the instabilities of the shear layer, couple with the flame front (mid size, mid frequencies)**

- **System: modes where the whole combustor is involved: long wavelengths, low frequency**

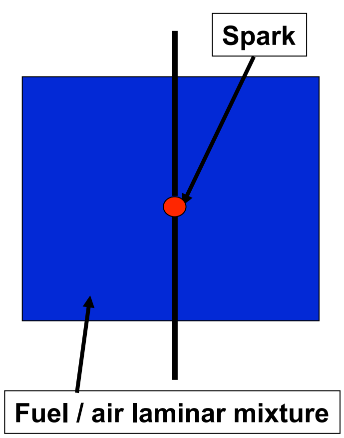
EXAMPLE OF SYSTEM INSTABILITY: THE POGO EFFECT

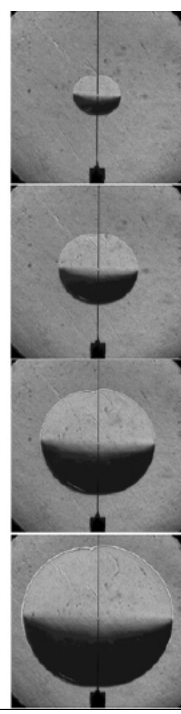


Saturn V fist stage
Soviet Union's N1-L3 rocket

INTRINSIC INSTABILITY

Growth of a spherical laminar flame ignited by a spark.



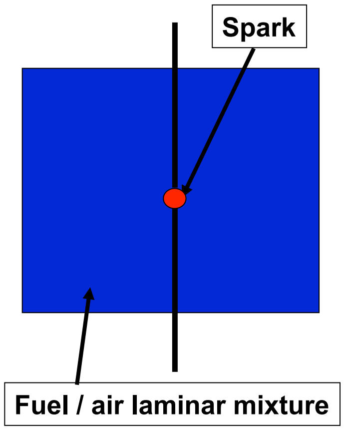


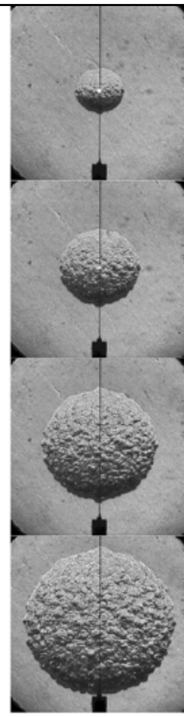
PROPANE / AIR:
Perfectly smooth laminar spherical front

Time

Law et al 30th Symp. (Int.) on Comb.

HYDROGEN / AIR: Formation of cells on the flame front

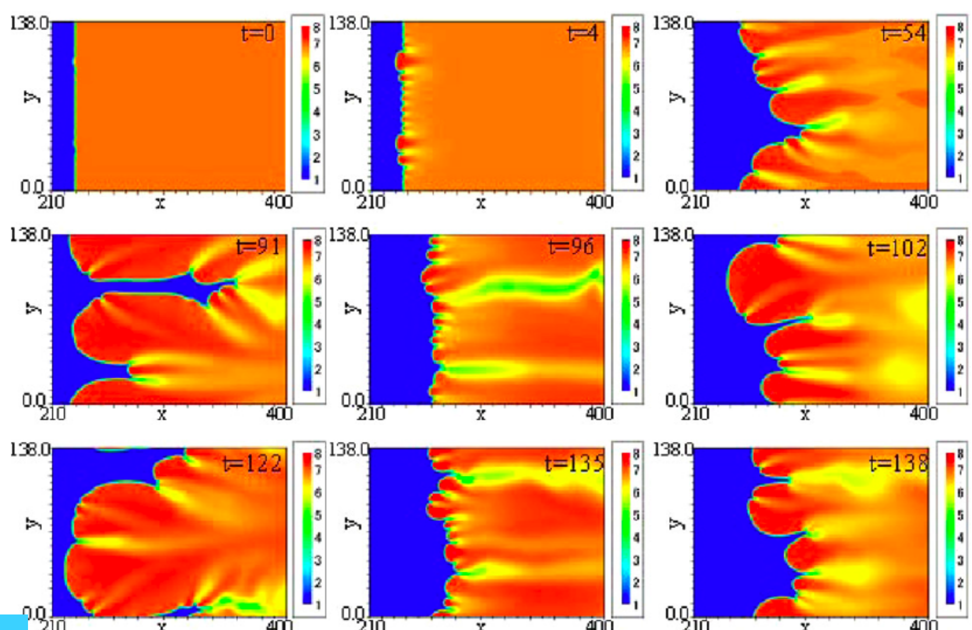




Time

Law et al 30th Symp. (Int.) on Comb.

S. Kadowaki et al. / Proceedings of the Combustion Institute 30 (2005) 169–176



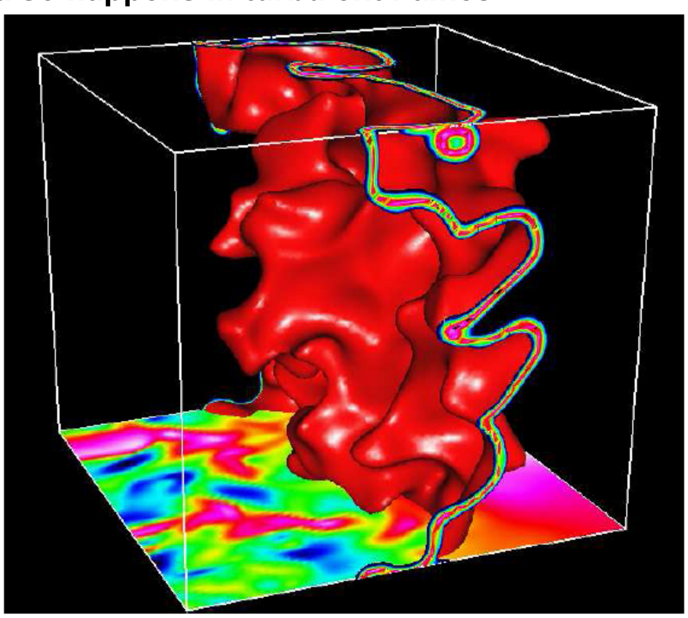
WHEN DO WE OBSERVE THERMODIFFUSIVE INSTABILITIES ?

- **Controlled by the Lewis number of the deficient reactant. For example for a lean H2/air flame, Lewis of the deficient fuel= Lewis (H2)=0.3**

- **If this Lewis number is less than a critical value given by asymptotic analysis (typically 0.5), cellular instabilities can appear**

- **Whether the growth rate of these instabilities is sufficiently large to play a role in real (turbulent) flames depends on the flame itself. Most turbulent combustion models do not incorporate effects of Lewis numbers but they should.**

This also happens in turbulent flames

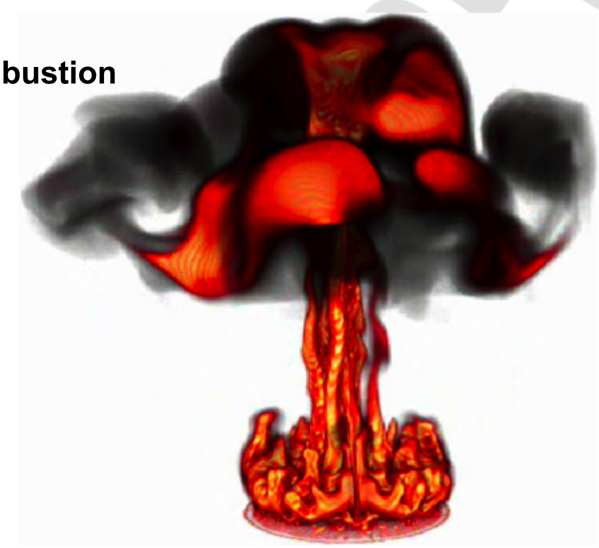


Boughanem and Trouvé

CHAMBER INSTABILITY: acoustics + cells

CHAMBER INSTABILITY: 'puffing'

Gravity + combustion



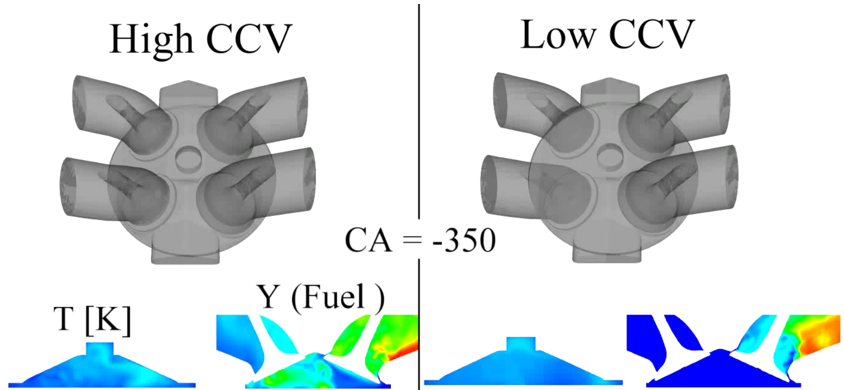
A. Violi, S. Yan, E.G. Eddings, A. Sarofim, S. ...a, T. Faravelli, E. Ranzi, *Combust. Sci. ...l.* 174 (2002) 3990417.

Computational combustion

Charles K. Westbrook[a,*], Yasuhiro Mizobuchi[b], Thierry J. Poinsot[c], Phillip J. Smith[d], Jürgen Warnatz[e]

CYCLE TO CYCLE INSTABILITIES

- In piston engines, one cycle every 100 or 1000 cycles can fail or burn too slowly or too fast (knock, rumble)



SGEmac project

Consecutive cycles by LES of a spark ignition engine

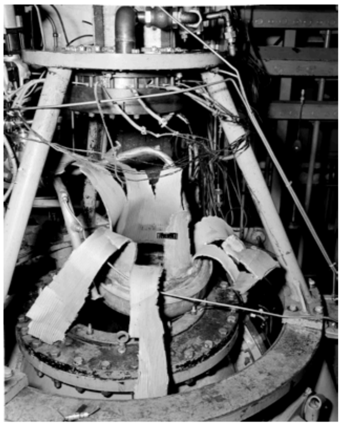
Unstable by dilution operating point

Compression ratio : 9.9
Engine speed : 1200 rpm
Fuel : C_3H_8
Equivalence ratio : 1
Dilution by N_2 : 32 % vol.
Mean IMEP : 3.2 bars
cov(IMEP) : 7.2 %

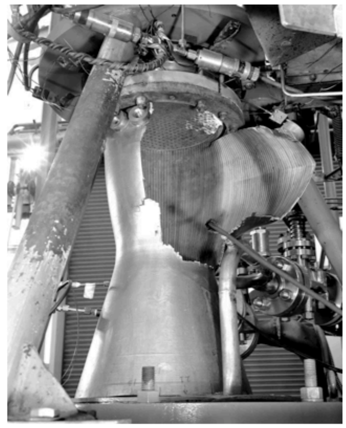
Granet et al., Combustion and Flame, in press, doi:10.1016/j.combustflame.2011.11.018
Enaux et al., Flow Turbulence and Combustion 86 (2), pp 153-177, 2011
Enaux et al., Proceedings of the Combustion Institute, 33 (2), pp 3115-3122, 2011

A specific class of combustion instabilities: « thermoacoustics »

In combustion chambers, acoustics and combustion can couple, leading to unpleasant consequences....

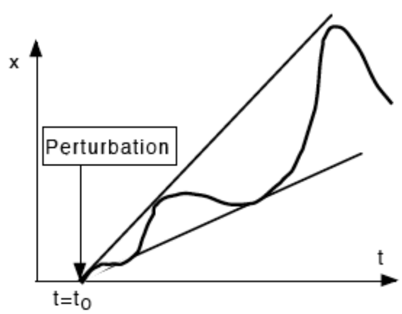


Liquid rocket engine (NASA 1957)

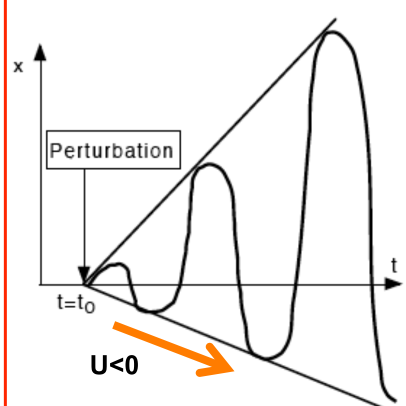


Liquid rocket engine (NASA 1963)

There are two main classes of instabilities in flows (Monkewitz, Huerre):



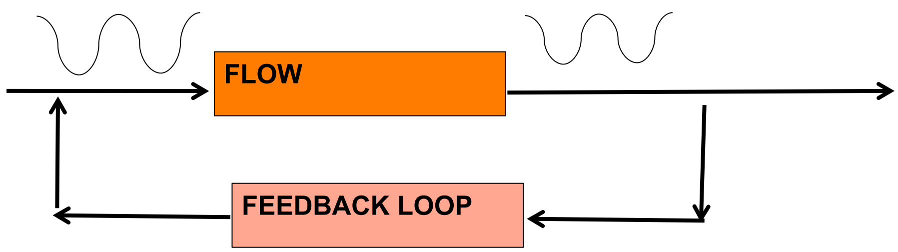
CONVECTIVE (*AMPLIFIER*)



ABSOLUTE (*RESONATORS*)

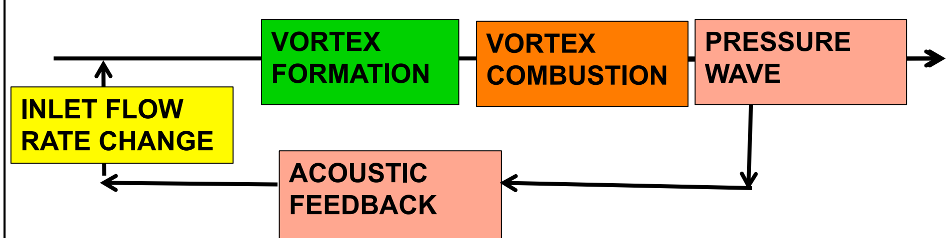
Absolute instabilities usually are linked to 'information' propagating upstream

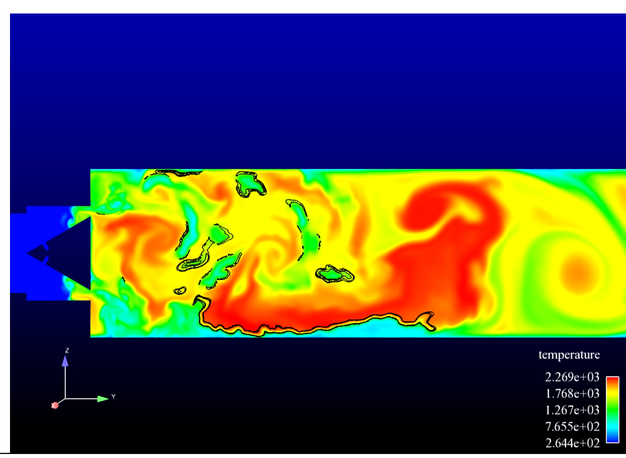
Convective instability (amplifier)



Absolute instability (resonator)

Ch. 8 Sec. 8.5.2

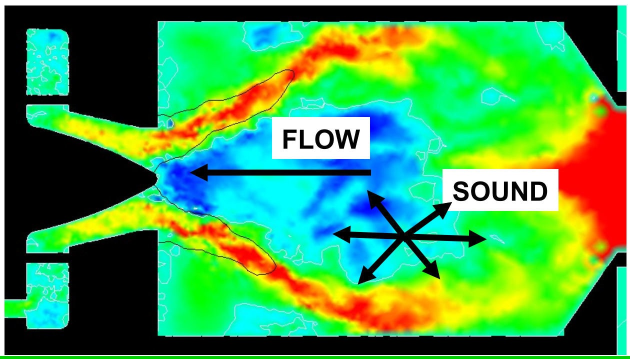




In combustion chambers, we find:

- **Acoustics because the flames are confined**
- **Recirculation zones**

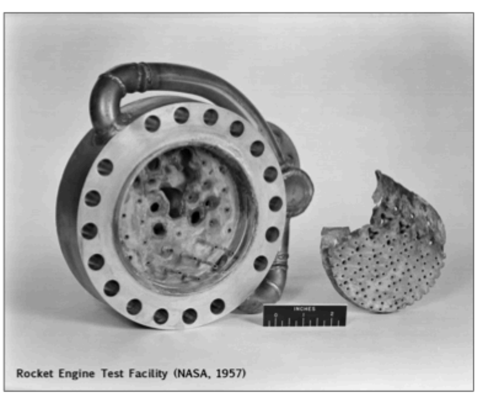
==> information can propagate upstream by convection or by acoustic waves

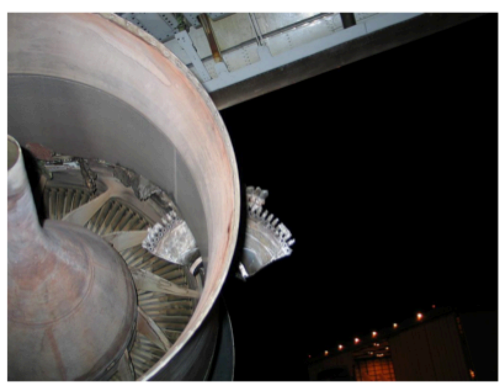


ABSOLUTE INSTABILITIES ARE EXPECTED !

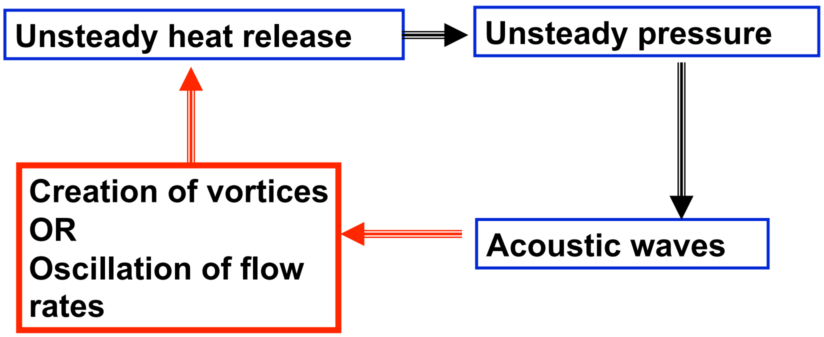
Concentrate on confined flames in combustion chambers surrounded by walls:

'Thermoacoustics' (coupled instabilities between acoustics and combustion) become possible -> these absolute instabilities are the worst instabilities in combustors



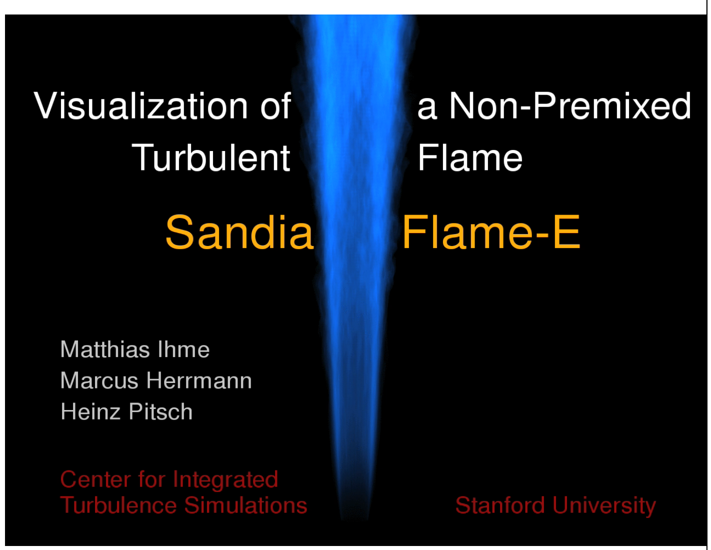


Not a new problem: Thermoacoustics is known since Lord Rayleigh *Nature* 1878.



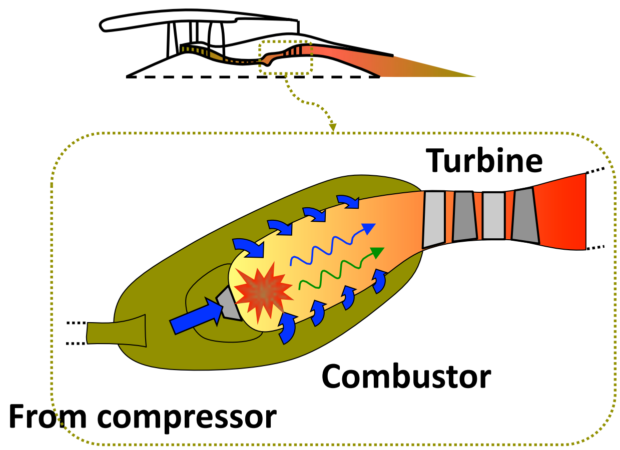
Why acoustics and flame can couple: 1/ Flames make noise...

Free flames:
- Make noise
- Are not influenced by noise

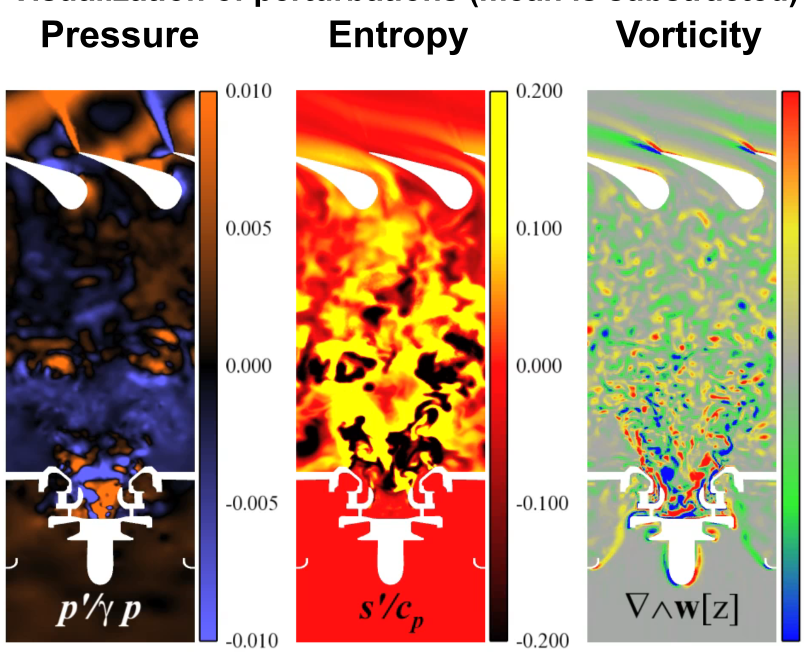


2/ In a confined domain (as in most combustors), noise travels and comes back

The acoustic waves produced by combustion can reflect on walls, inlets, outlets… and come back to the flame zone.



Visualization of perturbations (mean is substracted)



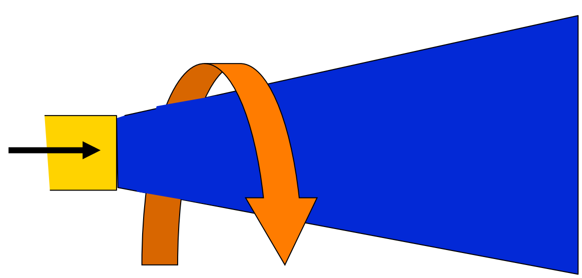
3/ Flames are **sensitive** to noise

When acoustic waves come back to the flame, they can create new perturbations, closing the instability loop

Unsteady heat release → Unsteady pressure → Acoustic waves → Creation of vortices OR Oscillation of flow rates → Unsteady heat release

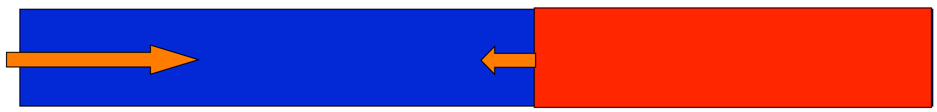
A specific feature of combustion chambers: SWIRL.

Swirl is a rotation of the flow along its axis



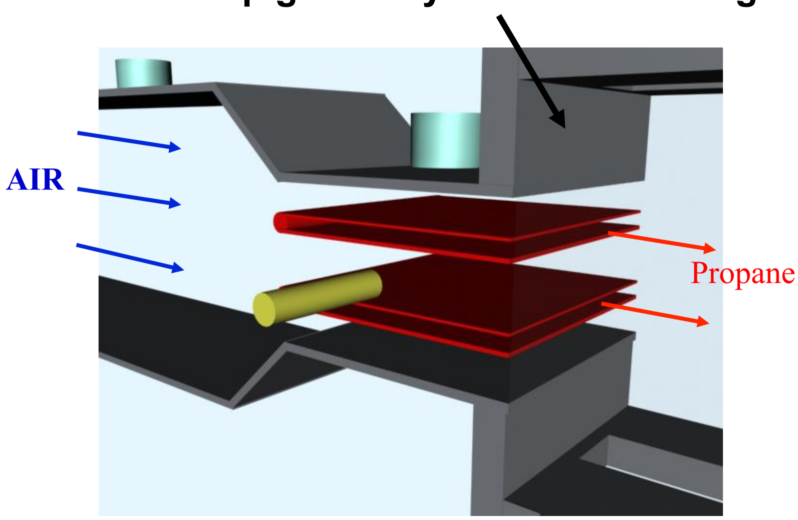
Swirl: why ?

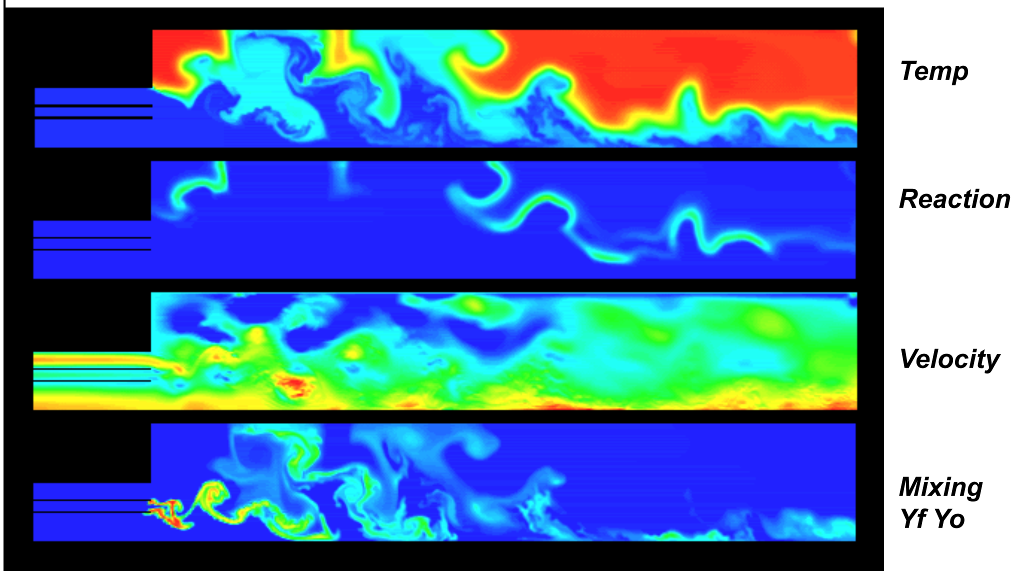
Flame stabilization !: flames do not propagate at high speeds. Typically CxHy+Air flames move at sL=50 cm/s. CxHy/O2 flames at a few m/s.



As soon as the flow speed is larger than a few m/s, flames can be stabilized only by a recirculation zone containing burnt bases to ignite the incoming gases.

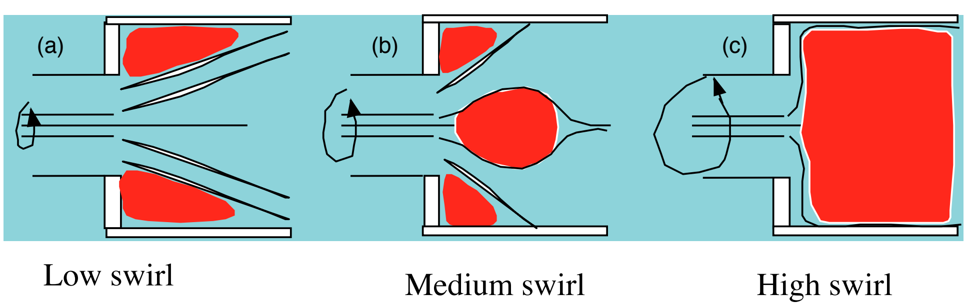
How do you create a recirculation zone ?
Solution 1: dump geometry. Backward facing step





Another solution to create recirculation is SWIRL:

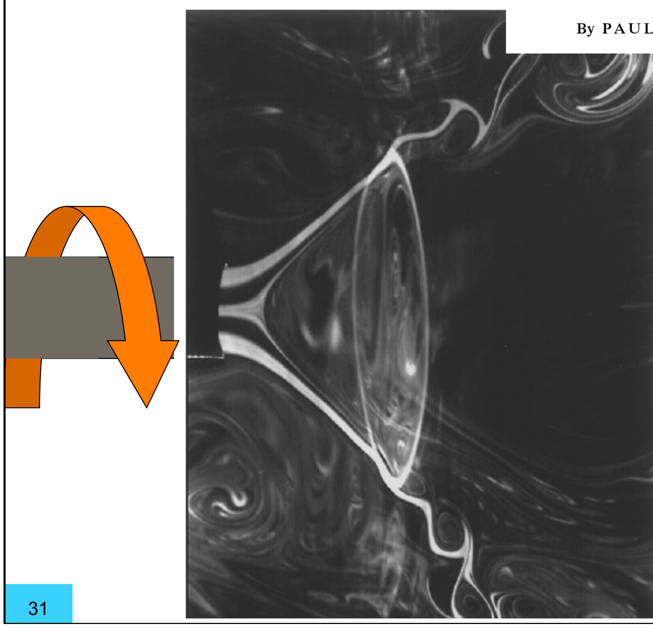
- **Swirl creates a low velocity region in the jet axis.**
- **Strong swirl allows to create recirculation zones**
- **These zones do not touch walls.**



J. Fluid Mech. (1998), vol. 376, pp. 183–219. Printed in the United Kingdom 183

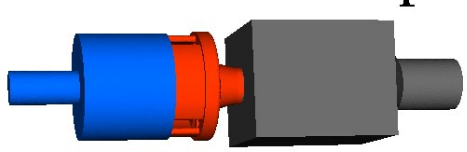
Experimental study of vortex breakdown in swirling jets

By PAUL BILLANT[1,2], JEAN-MARC CHOMAZ[1] AND PATRICK HUERRE[1]



How is swirl introduced ?

PRECCINSTA EU project

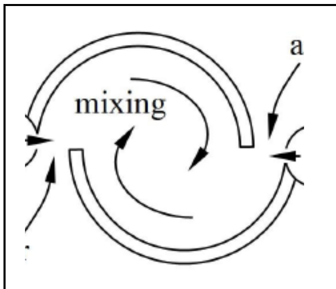


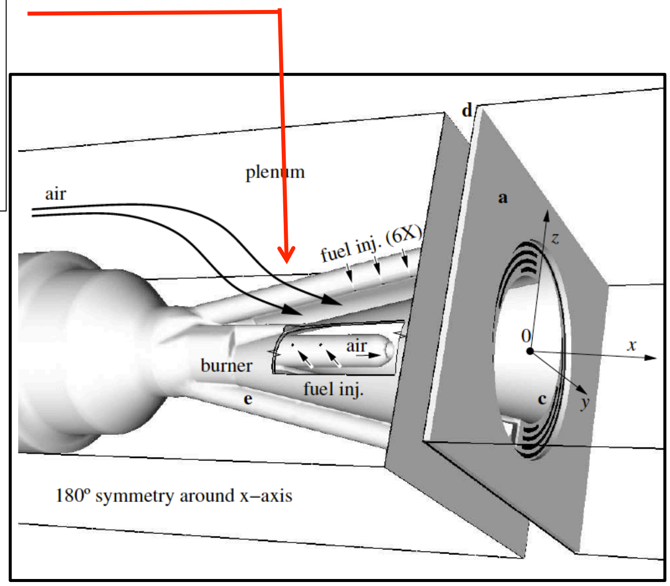
Mesh | device fully meshed
3 million cells
3D unstructured

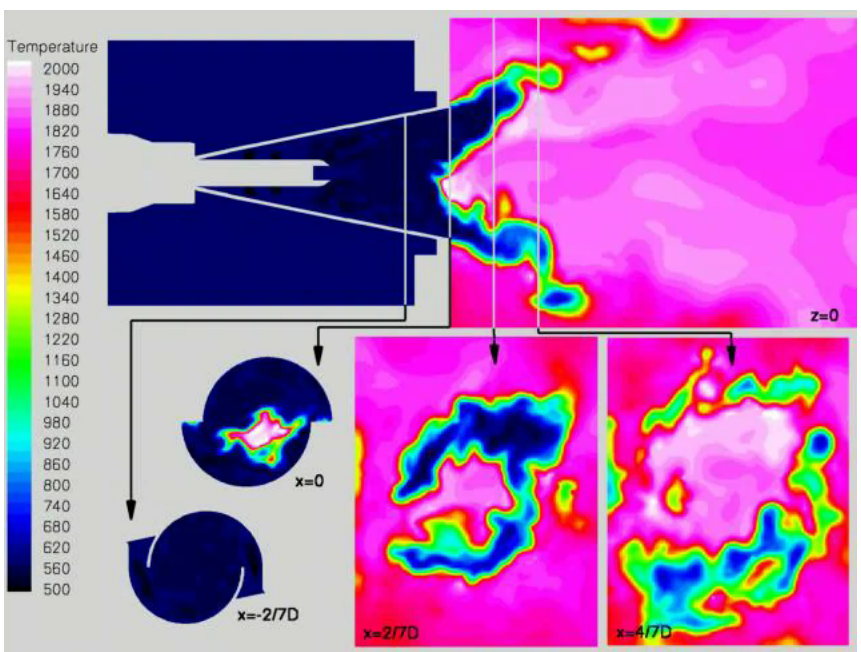
Measurement performed by DLR

CERFACS

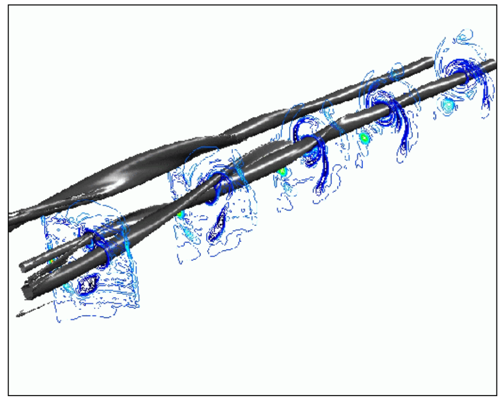
Turbomeca groupe snecma


mixing
a


d
plenum
air
a
fuel inj. (6X)
z
0
air
x
burner
fuel inj.
e
c
y
180º symmetry around x−axis


Temperature
2000
1940
1880
1820
1760
1700
1640
1580
1520
1460
1400
1340
1280
1220
1160
1100
1040
980
920
860
800
740
680
620
560
500
z=0
x=0
x=-2/7D
x=2/7D
x=4/7D

Have you seen swirled jets before ? Yes, in the sky !

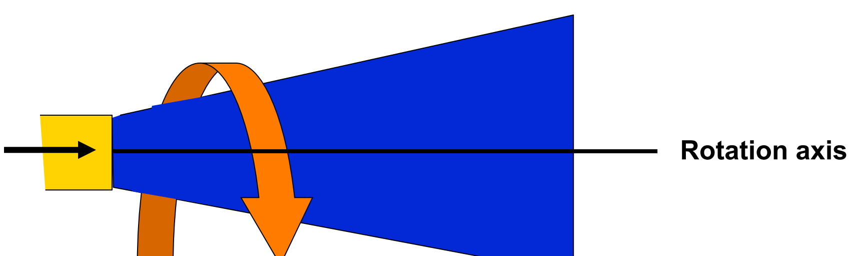


So SWIRL is good for combustion chambers !
But a swirled flow exhibits instabilities:

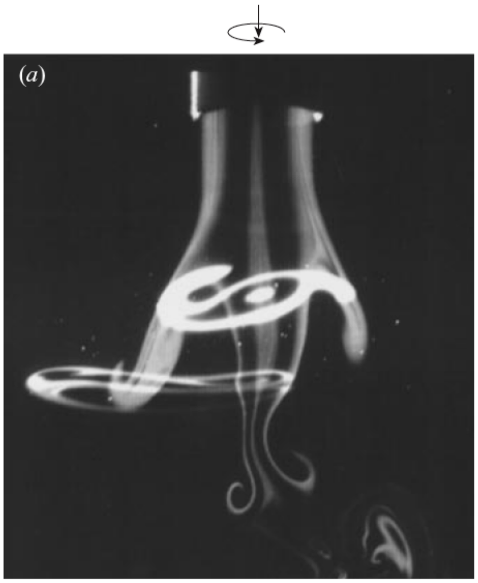
- the same as in jets: Kelvin Helmholtz

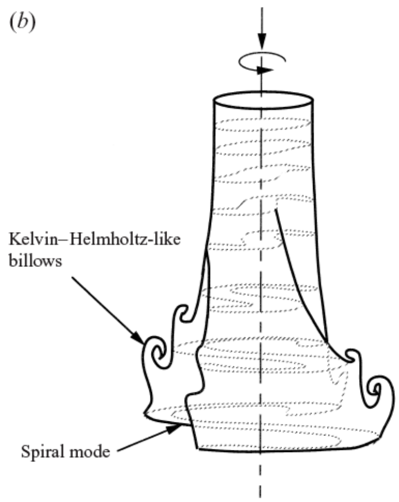
+

- new modes due to rotation (and since we have introduced negative velocities, absolute modes !)



206 *P. Billant, J.-M. Chomaz and P. Huerre*





Something that turns can lead to ‘precession’:

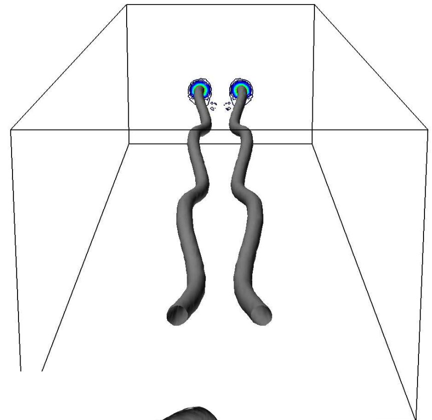
Louis Poinsot

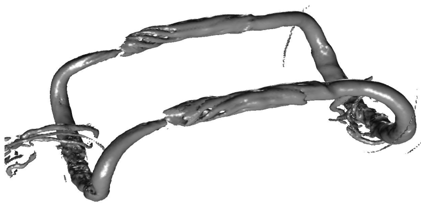
Naissance : 3 janvier 1777
Clermont-en-Beauvaisis
(France)

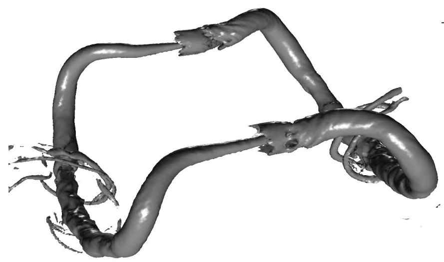
Décès : 5 décembre 1859
Paris (France)

For a swirled flow: the rotation axis itself turns. Not necessarily in the same direction as the mean flow

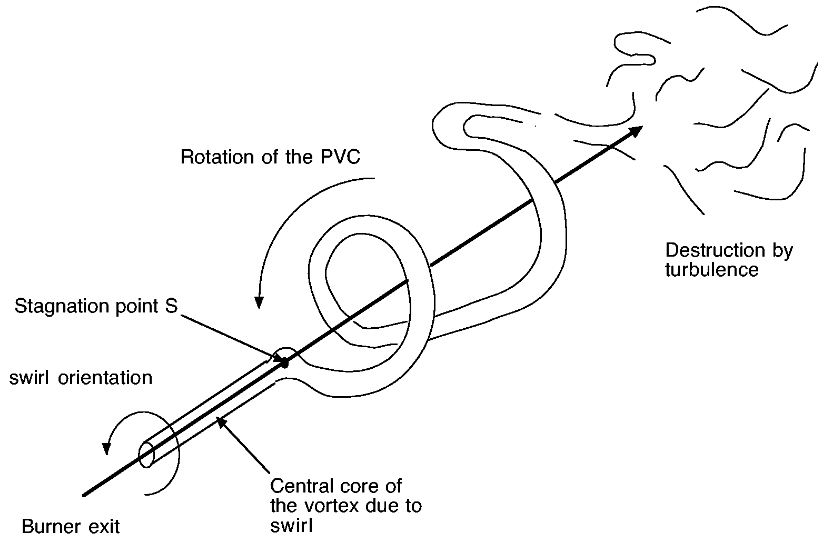
One example of swirled flow instabilities: the Crow mode.



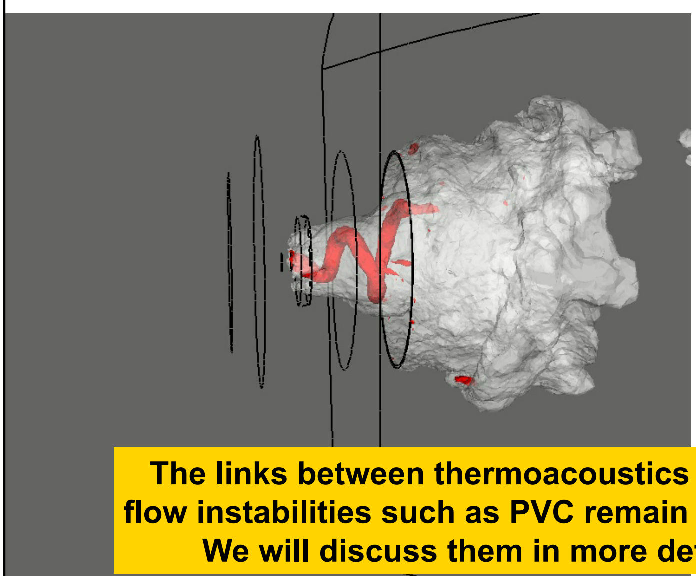




Swirled flows have another specific instability: precessing vortex cores



PVC visualized in LES of a swirled reacting flow:



White surface: flame surface

Red surface: low pressure surface

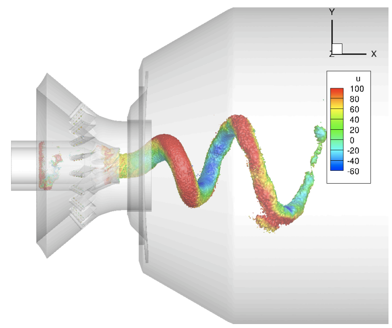
The links between thermoacoustics and swirling flow instabilities such as PVC remain unclear today. We will discuss them in more details later.

HOW CAN WE STUDY THERMOACOUSTICS ?

Why acoustics and combustion interact

Effects of combustion instabilities in gas turbines

Examples of studies of combustion Instabilities in gas turbine configurations



Ch. 8

Interaction acoustics / combustion

Not a classical topic: USUALLY, pressure waves are not important in subsonic flames. They are a by-product of combustion and produce noise (combustion noise can be important !). But there is no need to account for them in computing the flames themselves.

In thermoacoustics, when acoustics DO modify flames, we need to develop a theory able to compute reacting flows and acoustics.

Textbooks:

Crighton, Dowling, Ffowcs Williams,Heckl and Leppington « *Modern methods in analytical acoustics* » 1992, Springer -> acoustics

Poinsot and Veynante « *Theoretical and numerical combustion* » 3rd ed, 2012 download at www.cerfacs.fr/Elearning -> combustion theory and simulations

Williams « *Combustion theory* » 1985. -> theory

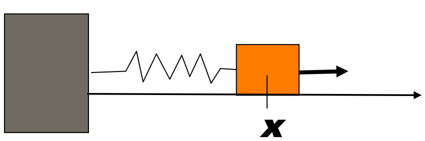
CLASSICAL METHODS TO STUDY RESONATORS:

Two approaches:

- Approach 1: take the conservation equations, linearize them, look for eigenmodes. Objective: find frequency and growth rate as well as mode structure (p'(x))
- Approach 2: define a proper energy of the system: assume it changes harmonically, find the frequency and growth rate. Objective (less ambitious): find instability criteria

Before looking at flames: let us do a small exercice on the pendulum…

The linear oscillator with no forcing:



v=dx/dt

$$m\ddot{x} + kx = 0$$

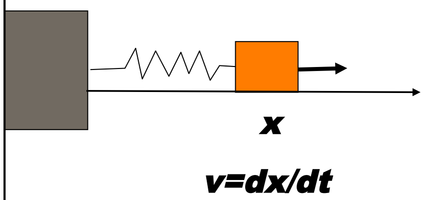
Spring force: *F* = -k*x*
Mass *m*

Approach 1: just solve it !

$$x = \hat{x}e^{i\omega t}$$

With: $\omega = (k/m)^{1/2}$

The linear oscillator with no forcing: energy definition



$$m\ddot{x} + kx = 0$$

Multiply by the velocity *v=dx/dt* and integrate*:*

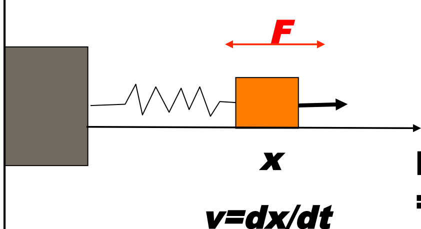
$$\frac{1}{2}m\dot{x}^2 + \frac{1}{2}kx^2 = E$$

E **is the total energy of the system**

Here *E* is constant.

The linear oscillator with forcing:

$$m\ddot{x} + kx = F$$



$$\omega = (k/m)^{1/2}$$

If we do not know F, cant say much ==> Approach 1 is limited

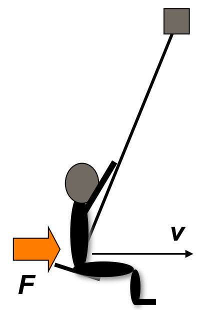
BUT Approach 2 can be used:
Multiply by *v* and integrate*:*

$$\frac{1}{2}m\dot{x}^2 + \frac{1}{2}kx^2 = \boxed{E + \int_0^t Fv\,dt}$$

This is the total energy of the system

$$\frac{1}{2}m\dot{x}^2 + \frac{1}{2}kx^2 = E + \int_0^t F v dt$$

The total energy of the system will grow if:



$$\boxed{\int_0^t F v dt > 0}$$

This is an 'instability' criterion: if the force *F* and the velocity *v* are such that the integral of their product is positive (ie if *F* and *v* are 'in phase'), instability will grow because the total system energy grows.

If you have a swing at home, you knew this already ?

The linear oscillator with forcing: comparing the two methods in a case where *F* = a *v*

Approach 1:

$$x = \hat{x}e^{i\omega t}$$

$$\omega = -ai/(2m) + \sqrt{k/m - a^2/(4m^2)}$$

Instability if Re(ω) < 0 if if a > 0

Approach 2: instability if criterion is positive:

$$\int_0^t F v dt = a \int_0^t v^2 dt > 0 \quad \text{if} \quad a > 0$$

Linear vs non linear. Exp. growth vs limit cycles

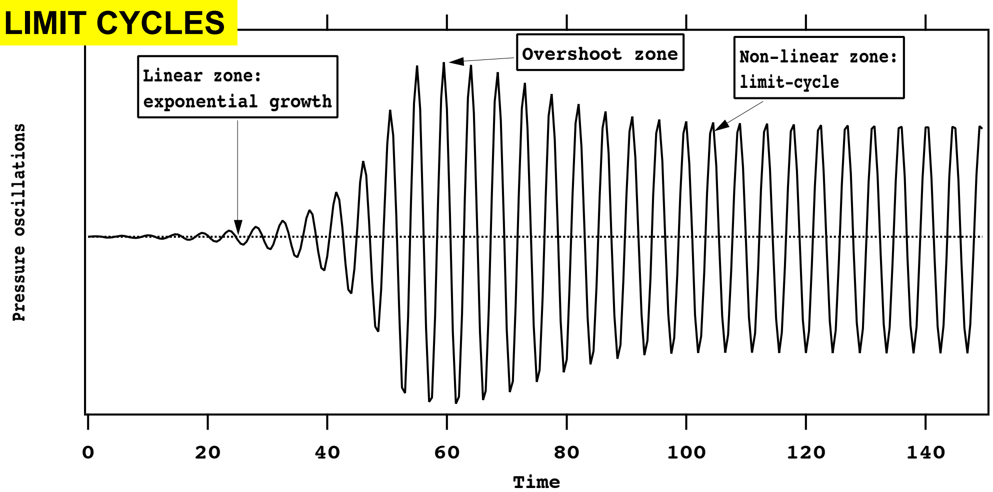
The previous equations are linear.

They can tell us whether:
- The system is stable: Re(ω) >0
- The system is neutral: Re(ω) =0
- The system is unstable: Re(ω) <0.

$$x = \hat{x} e^{i\omega t}$$

If the system is unstable, the instability will grow. Where it will stop cannot be predicted with this linear approach. After the instability starts, different outcomes can be obtained at longer times:
- The system can reach a limit cycle
- The combustor can explode
- The operator may stop combustion because of vibrations
- The system may quench on its own

LIMIT CYCLES



Linear phase
Exponential growth
of the amplitude

Non linear phase
Limit cycle

Acoustic solvers

?

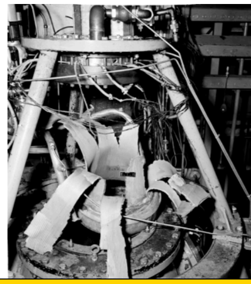
LES and expts

DESTRUCTION

Limit cycles are only ONE form of final results in thermoacoustics:

If the loss term is not sufficient, the amplitude of oscillations might grow until something really unpleasant occurs:

- the combustor can explode because the structure does not resist

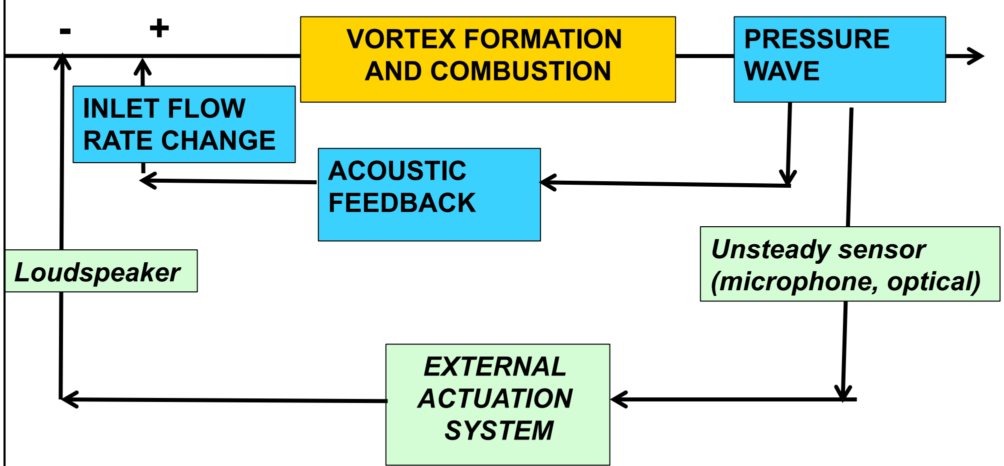


In industrial gas turbines, the system switches off when pressure oscillation or structure vibration levels are too high

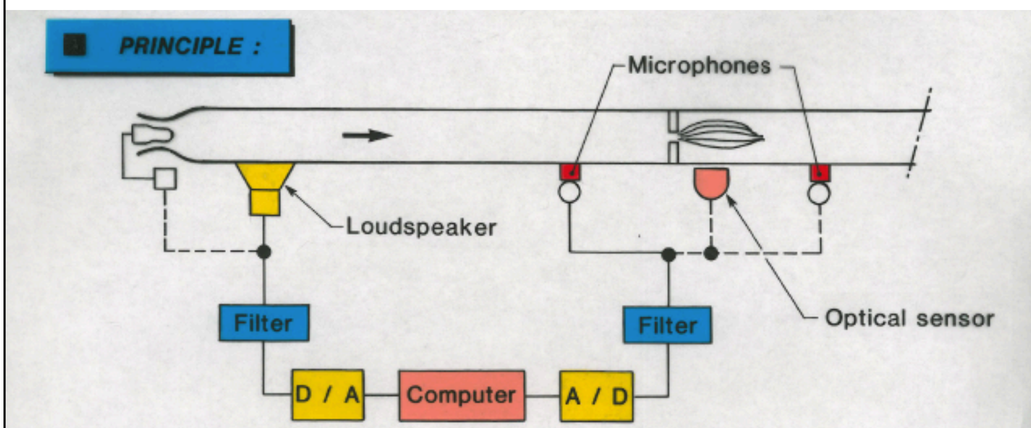
- the flame can also quench, unable to resist to oscillations. This can happen without making any noise.

How do we know ? Thanks to active control (see review on active control of combustion: McManus, Poinsot and Candel, PECS, 1993, 19).

ACTIVE CONTROL OF COMBUSTION INSTABILITIES:

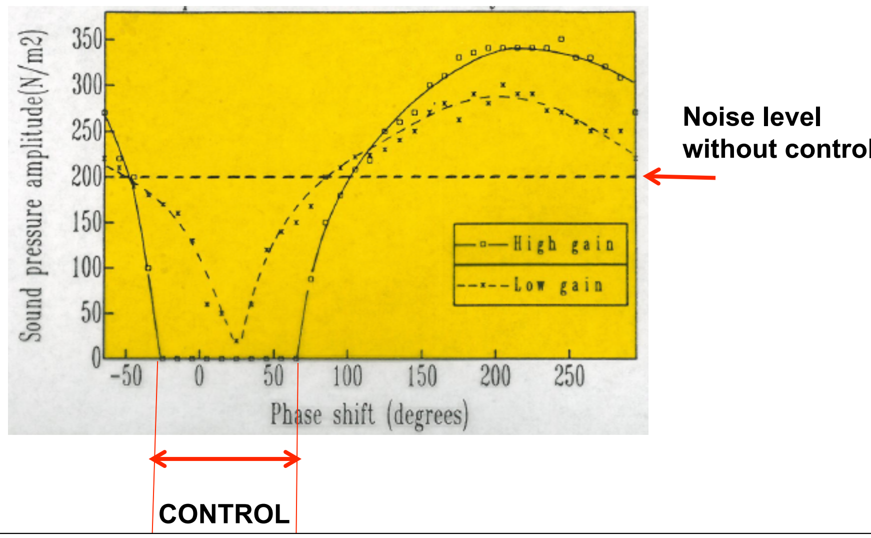


What is active control of combustion instabilities ? Example for a laminar Bunsen flame



CROCCO and CHENG (1956) , MARBLE and COX (1955)
DINES (1984) , HECKL (1985) , LANG et al (1987), POINSOT et al (1987), Chu et al(87)
DOWLING , BLOXSIDGE , HOOPER and LANGHORNE (1987-AIAA-87-0433)

When the gain is small, the instability is reduced
When the gain is larger, the instability is killed



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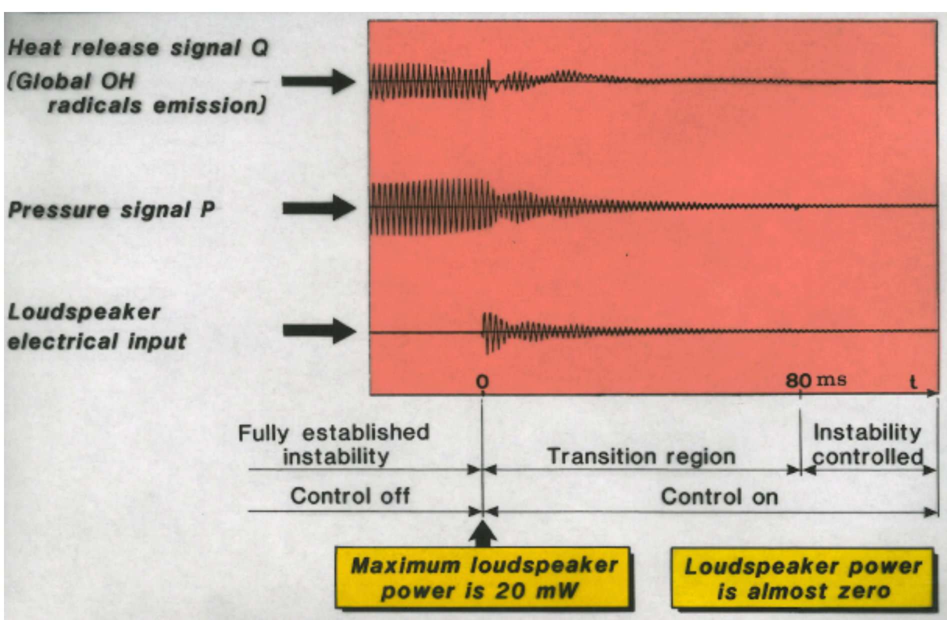

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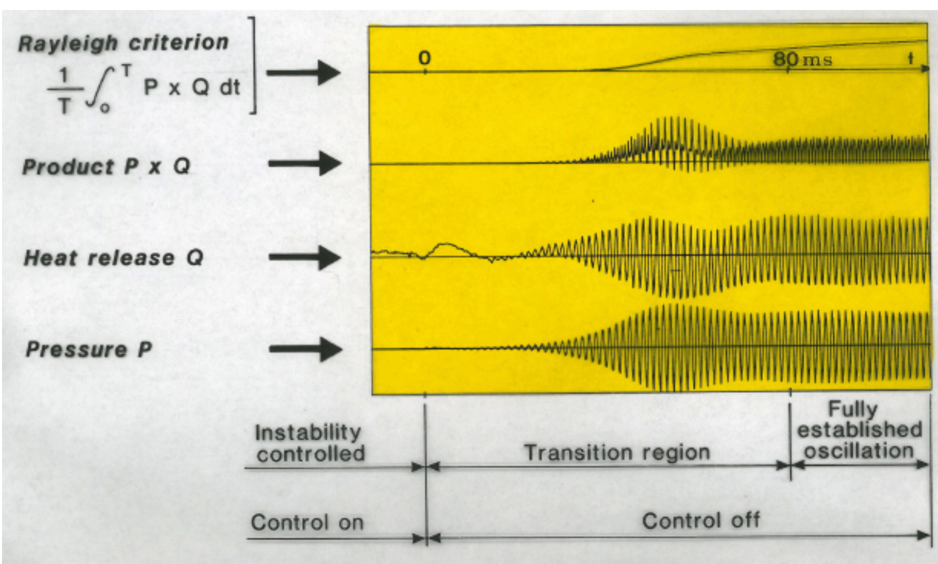
Active control research for thermoacoustics has been very strong in the 90s. Patents were taken in many labs (EM2C) and companies (GE). Industrial demonstrations on real engines worked:

- **Industrial gas turbines: active control was used in Siemens gas turbines** (Seume, J., Vortmeyer, N., Krause, W., Hermann, J., Hantschk, C., Zangl, P., Gleis, S., and Vortmeyer, D. Application of active combustion instability control to a heavy duty gas turbine. ASME Journal of Engineering for Gas Turbines and Power 120 (1998), 721–726.)

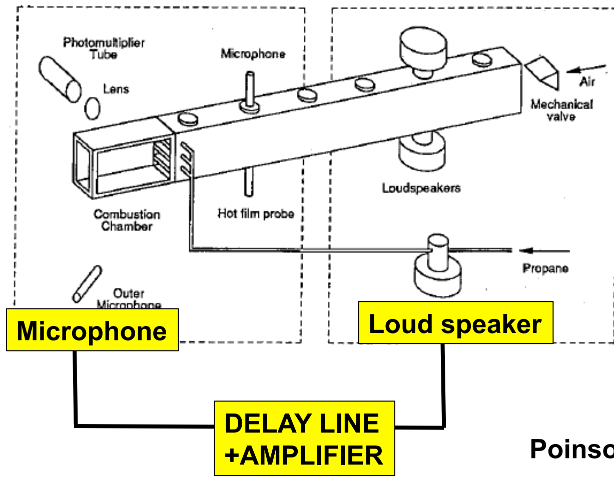
- **For aeroengines, certification issues killed the idea**

But for scientific investigations, active control remains a great tool because it allows to let the instability start 'on request'

Initiating an instability on demand with active control:

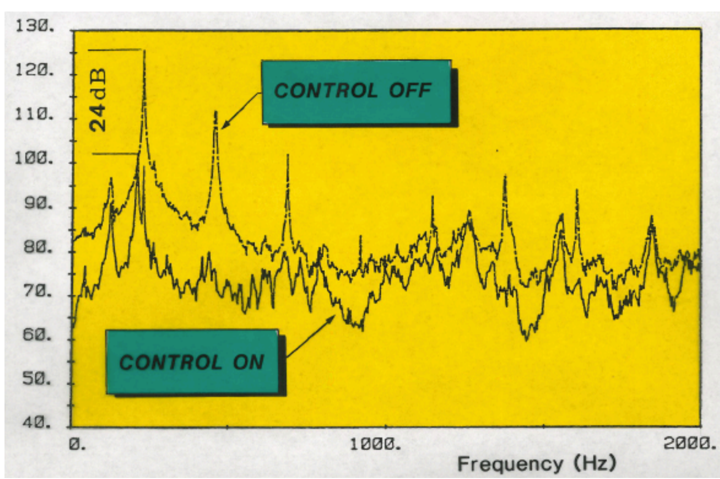


Other example: a turbulent burner. This combustor is unstable but it can be stabilized using active control:



Poinsot et al J. Phys. 1992

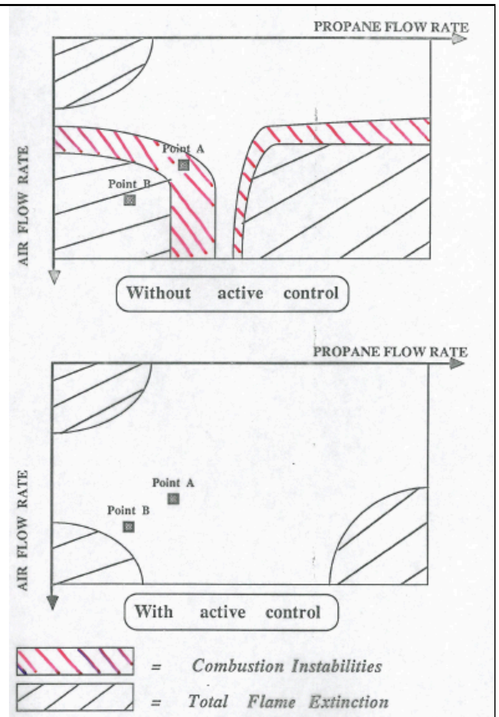
Point A: with and without control



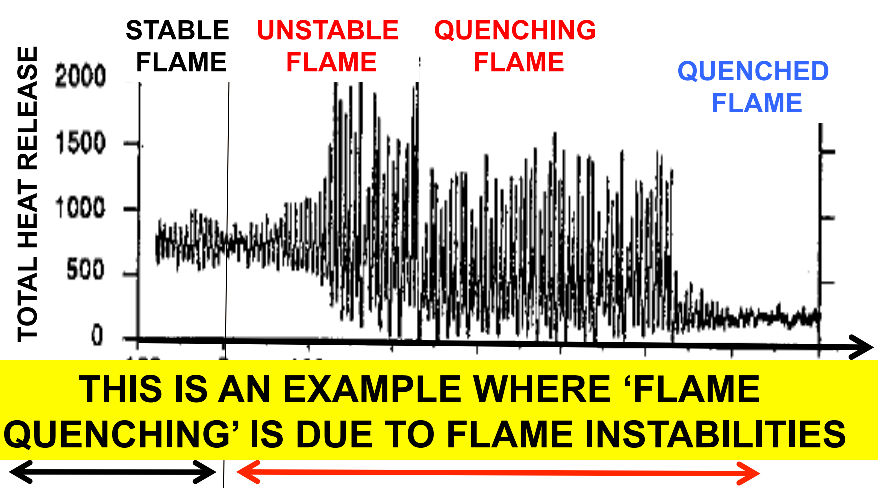
Active control allows not only to control unstable modes but also to extend the domain of operation of the burner (in a fuel/ air flow rate diagram):

- with control, point A is unstable (limit cycle) without control and becomes stable with control

- with control, point B does not burn without active control. With control it burns and is stable

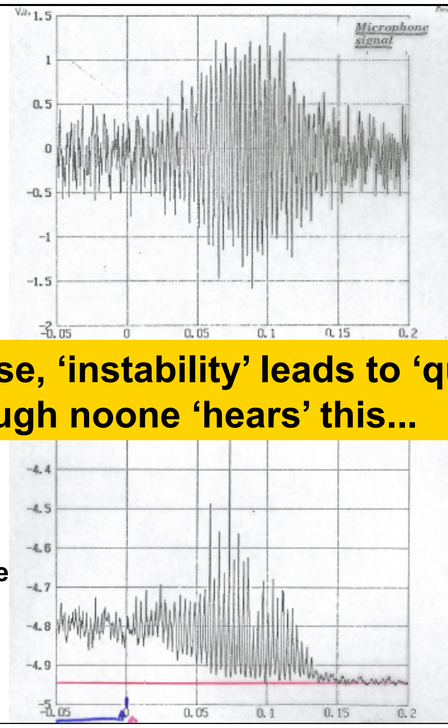


For point B: the flame starts oscillating and ... Quenches !



THIS IS AN EXAMPLE WHERE 'FLAME QUENCHING' IS DUE TO FLAME INSTABILITIES

Noise



Heat release

In this case, ‘instability’ leads to ‘quenching’
Even though noone ‘hears’ this...