Imperial College
London

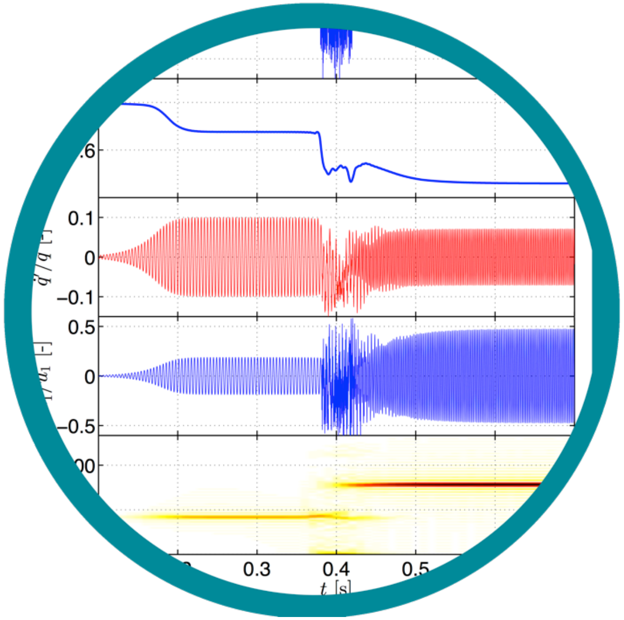
Thermoacoustic instabilities

Prof Aimee S. Morgans

Department of Mechanical Engineering

Combustion SIG Meeting

September 28th 2017



Acoustic excitation of flames

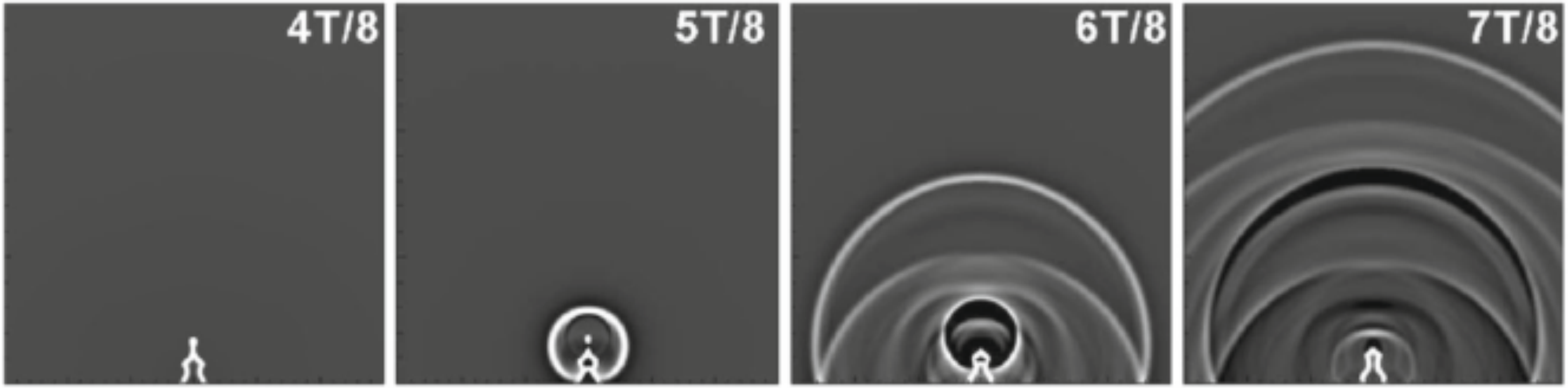
- Acoustic waves cause flame unsteadiness

Movie by Daniel Durox, EM2C Lab, Centrale Supelec, Paris

Flame unsteadiness generates acoustic waves

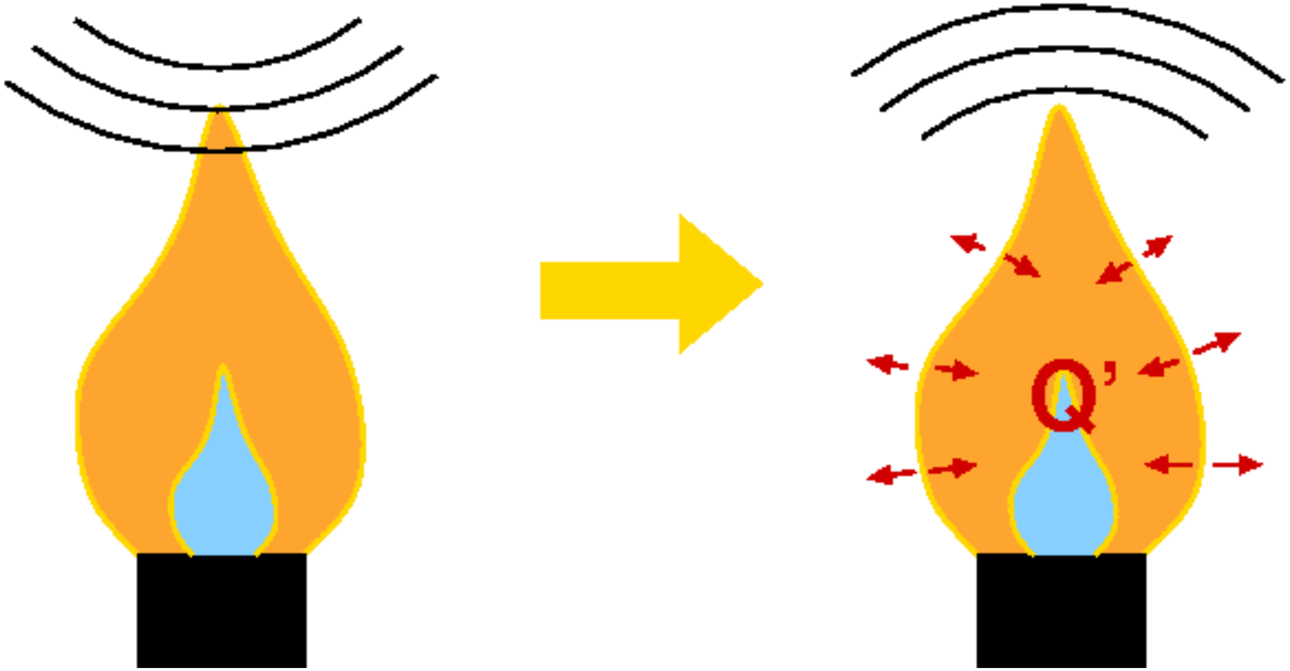
Imperial College London

- Unsteady flames generate new sound waves

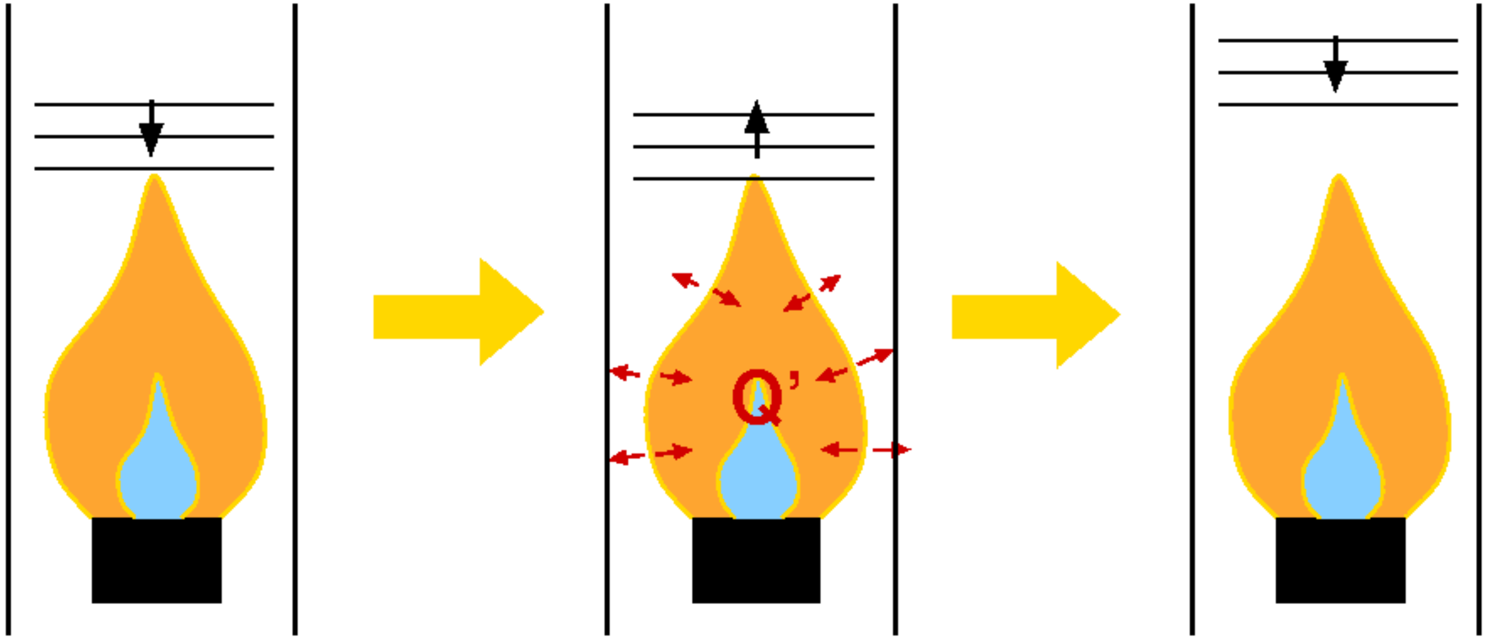


From Talei et al, Theoretical and Computational Fluid Dynamics, 2014

Acoustic excitation of a flame in free space



Acoustic excitation of enclosed flame



Possibility for successively growing oscillation amplitudes

→ Thermoacoustic instability

(AKA combustion instability)

Thermoacoustic instability in a Rijke tube

Quartz tube, open at both ends with a Bunsen flame inside

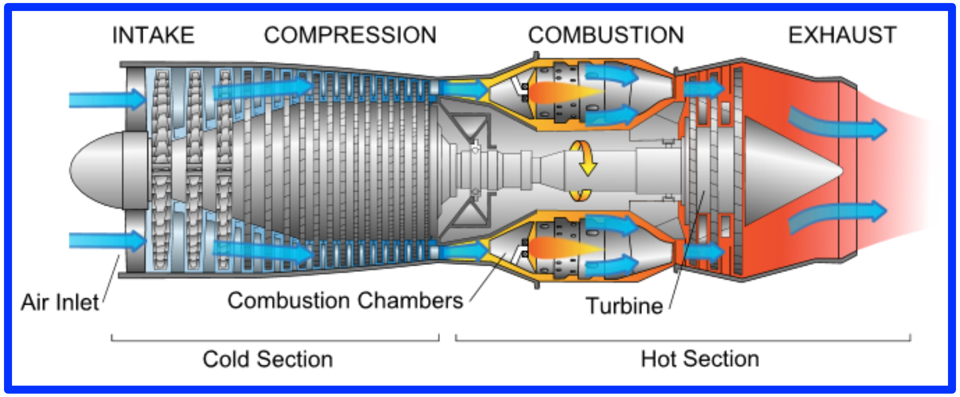
Thermoacoustic instability in gas turbines

Imperial College London

Gas turbine combustors:

NO_x emissions a major air quality issue

Low NO_x ➔ lean premixed combustion ➔ combustion instability

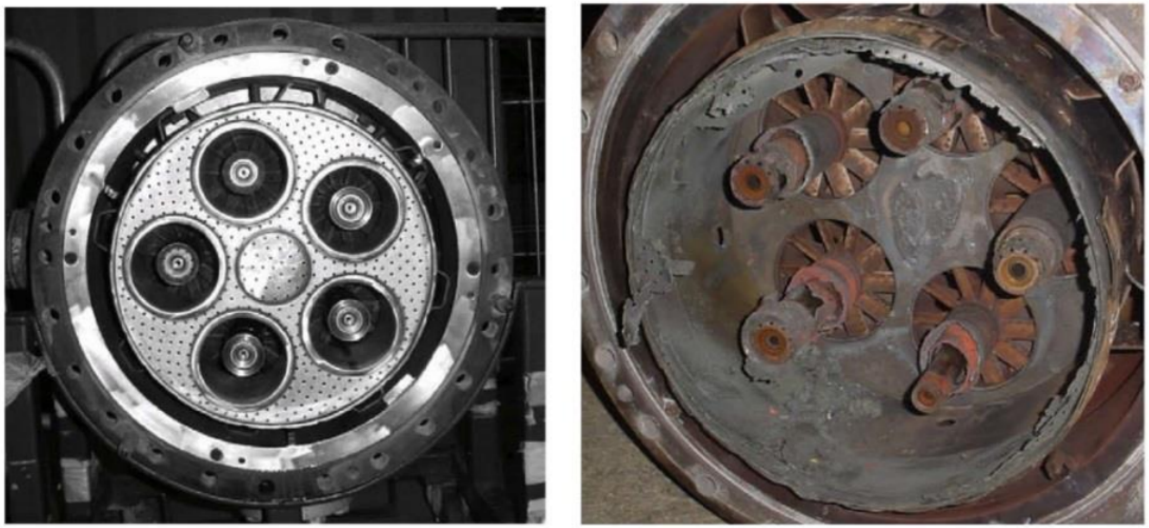


Thermoacoustic instability in gas turbines

Gas turbine combustors:

NO_x emissions a major air quality issue

Low NO_x → lean premixed combustion → combustion instability

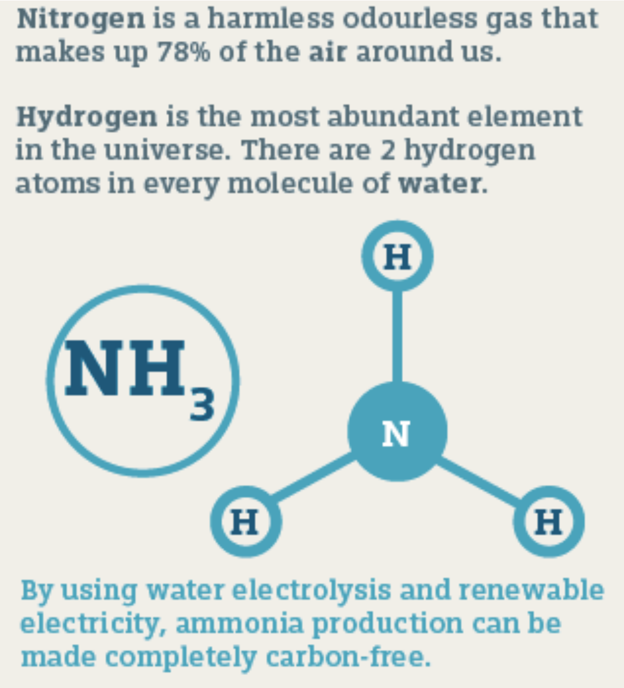


(Top) Burner assembly before and after combustion instability (Goy et al. 2005)
(Left) Turbine blade damage caused by combustion instability

Gas turbines in a low carbon future

- Combustion of hydrogen / ammonia generated as by-products from renewable energy. These also suffer from combustion instability.

From Siemens ‘Green’ ammonia leaflet, https://www.siemens.co.uk/pool/insights/siemens-green-ammonia.pdf



Nitrogen is a harmless odourless gas that makes up 78% of the air around us.

Hydrogen is the most abundant element in the universe. There are 2 hydrogen atoms in every molecule of water.

By using water electrolysis and renewable electricity, ammonia production can be made completely carbon-free.

By switching to renewable electricity to make ammonia we could save over 40 million tons of CO2 each year in Europe alone, or over 360 million tons worldwide.

We can also burn ammonia to make electricity when the wind is not blowing.

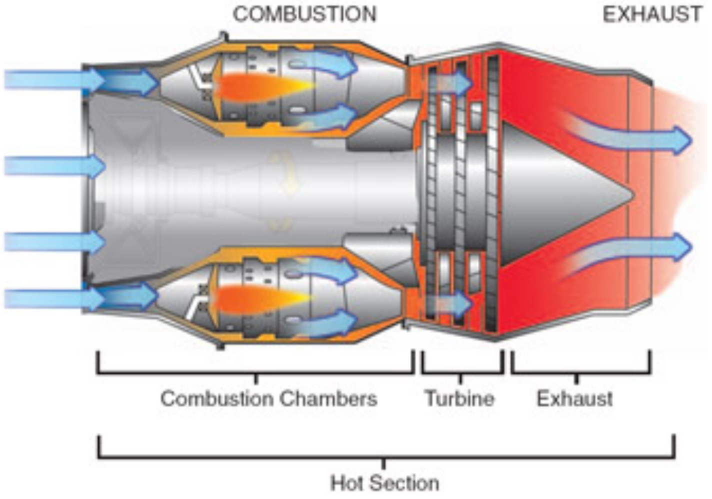
Gas turbine thermoacoustic instability

- Combustion instability still can’t be reliably predicted…

- Why can’t we use computational fluid dynamics?

  Range of length/time scales very large (long acoustic wavelengths versus tiny chemical reaction and turbulent lengths)

- What about experiments?
  - annular geometries, multiple burners
  - high temperatures and pressures
  - TRL5: Millions of £ spent



Thermoacoustic instability analysis and prediction

- Multi-scale treatment

Flame unsteadiness

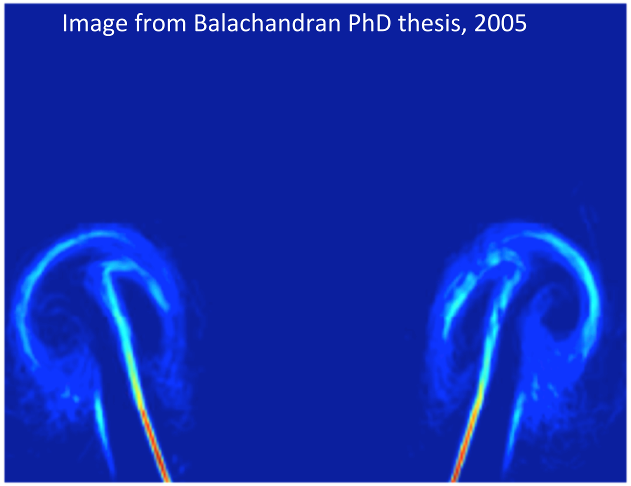


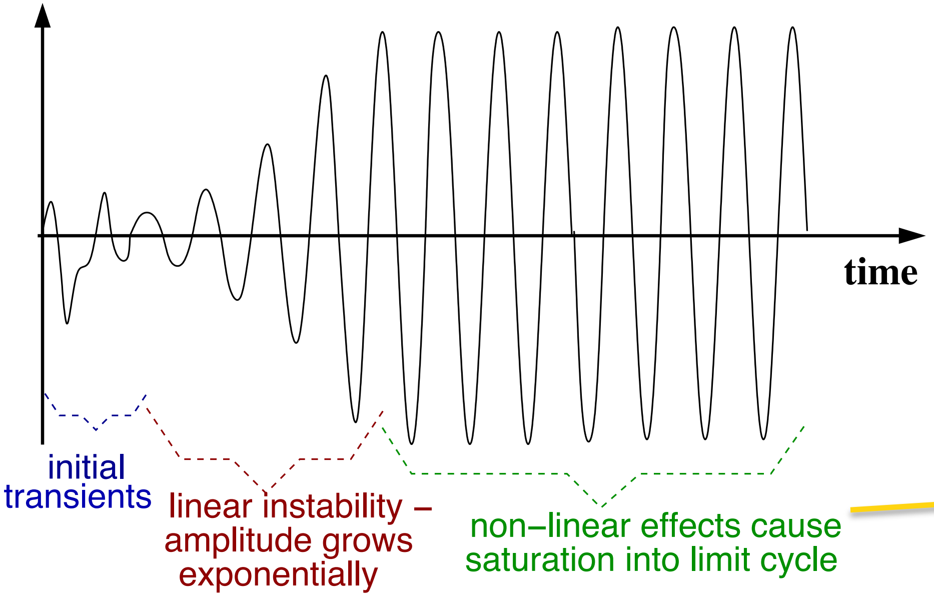
Image from Balachandran PhD thesis, 2005

Linear acoustic wave treatment

Flame model from experiments or Computational Fluid Dynamics

Coupled analysis/ prediction

Linear treatment of acoustic waves



Non-linearity comes from the flame response, not the acoustic waves

Acoustics in limit cycle $\frac{p'}{\bar{p}} \lesssim 0.1$

$$\frac{p'}{\bar{p}} \gg \left(\frac{p'}{\bar{p}}\right)^2 \qquad \frac{\rho'}{\bar{\rho}} \gg \left(\frac{\rho'}{\bar{\rho}}\right)^2$$

Linear treatment of acoustic waves

Two options:

- Assume zero mean flow (but allow complex geometry and mean temperature field) ➔ HELMHOLTZ SOLVER (e.g. COMSOL, AVSP)

$$\frac{1}{\bar{c}^2}\frac{\partial^2 p'}{\partial t^2} = \frac{\partial^2 p'}{\partial x_i^2}$$

solve stationary wave equation in frequency domain

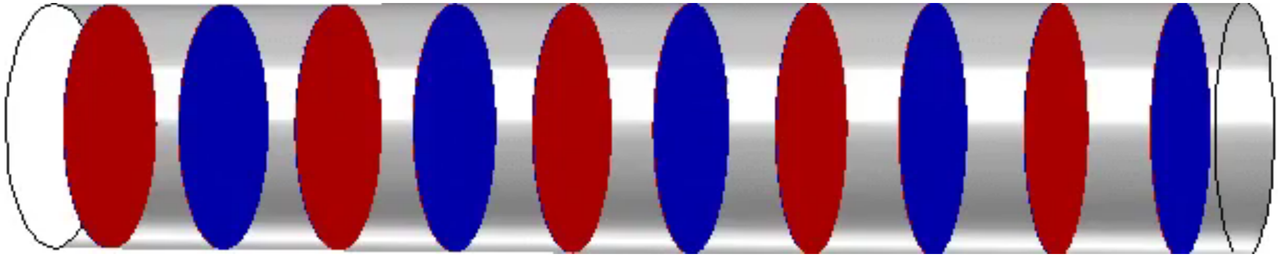
- Account for mean flow (but use network of simple geometry modules) ➔ LOW ORDER NETWORK APPROACH (e.g.OSCILOS, LOTAN)

$$\frac{1}{\bar{c}^2}\frac{\bar{D}^2 p'}{Dt^2} - \nabla^2 p' = 0$$

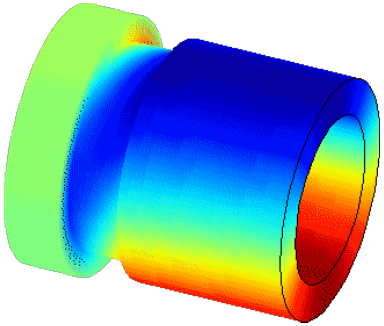
solve convected wave equation assuming low spatial-dimension

Low order network approach

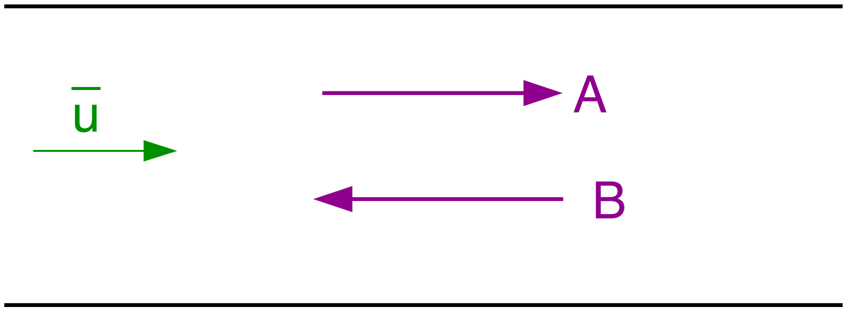
- Linear and with low spatial dimension (due to low frequency):



Movie from Dr Matthew Wright, ISVR, University of Southampton



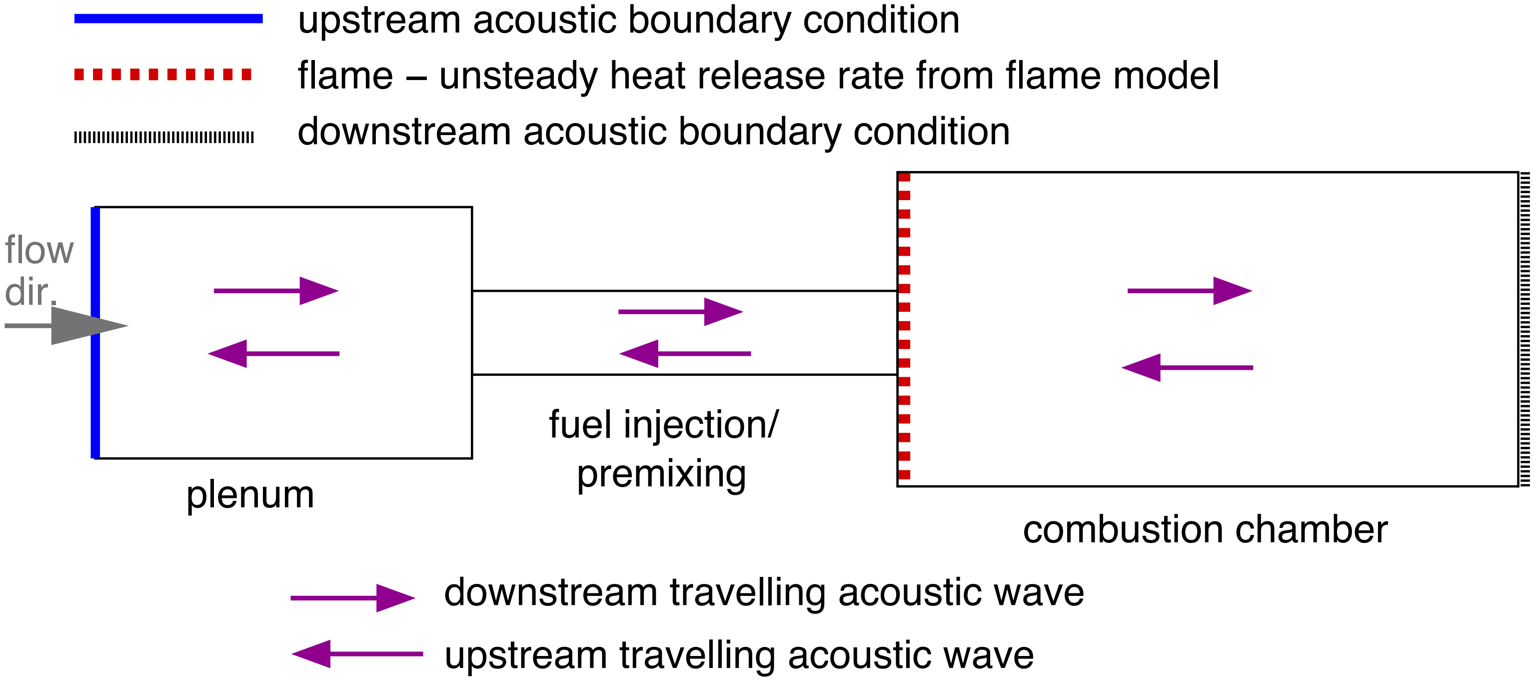
- Acoustic waves satisfy convected wave equation: $\frac{1}{\bar{c}^2}\frac{\bar{D}^2 p'}{Dt^2} - \nabla^2 p' = 0$



$$p(x,t) = \bar{p} + A\left(t - \frac{x}{\bar{c}+\bar{u}}\right) + B\left(t + \frac{x}{\bar{c}-\bar{u}}\right)$$

Low order network approach

- Network of geometry modules with 1-D acoustic waves
- Acoustic boundary conditions at inlet/outlet.
- Linearised flow conservation eqns at junctions and across flame



upstream acoustic boundary condition

flame – unsteady heat release rate from flame model

downstream acoustic boundary condition

flow dir.

plenum

fuel injection/
premixing

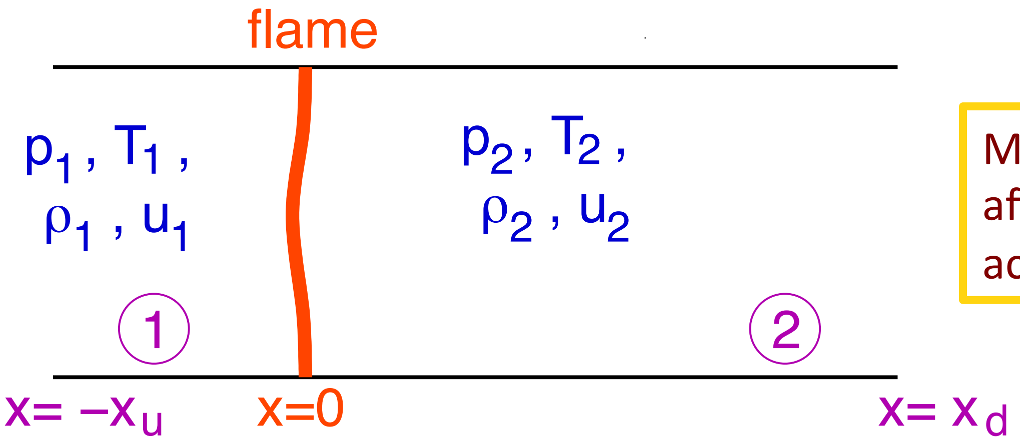
combustion chamber

downstream travelling acoustic wave

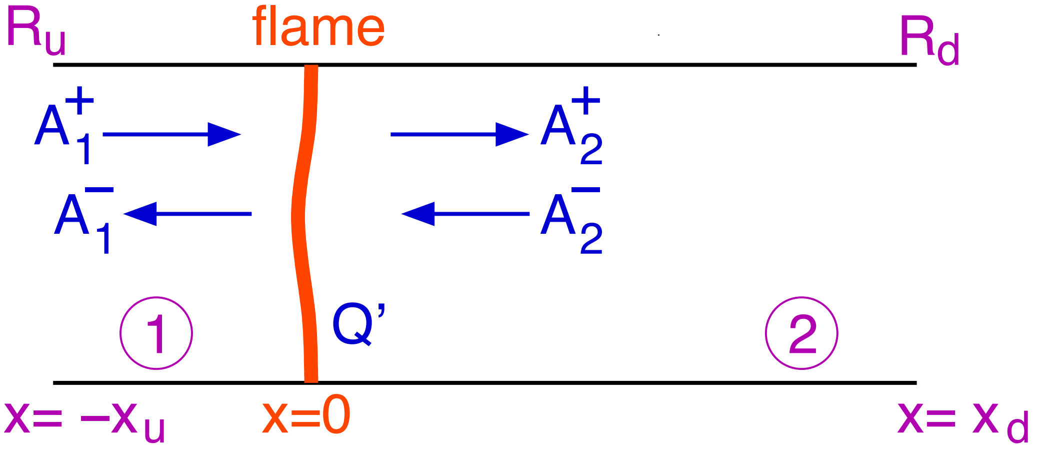
upstream travelling acoustic wave

Acoustic treatment of flame

- Flame short compared to acoustic wavelengths



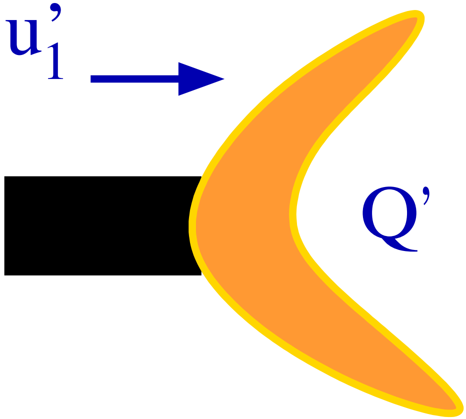
Mean heat release rate affects mean conditions across flame



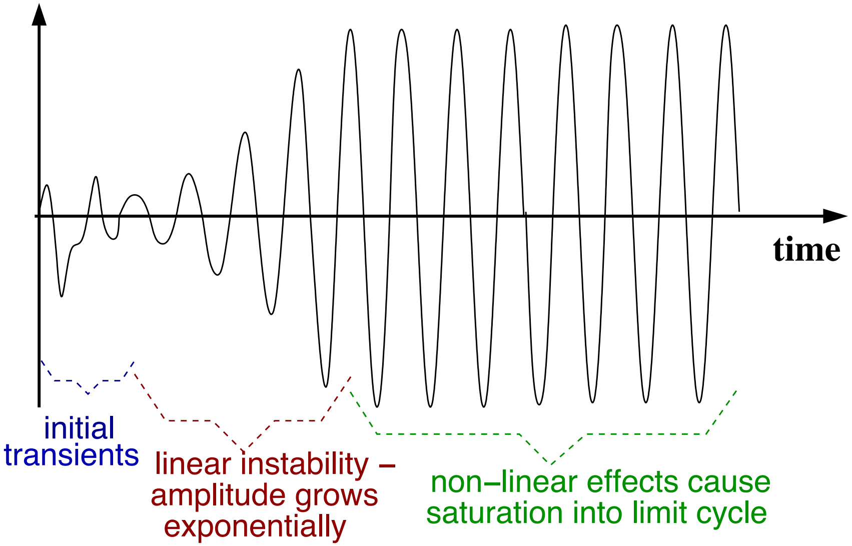
Fluctuating heat release rate affects acoustic wave strengths either side of flame

Flame models

- Flame model describes response of Q’ to acoustic velocity just ahead of flame



- Linear flame models can be used to predict “modes” (frequency and growth rate) of combustor, but not limit cycle behaviour

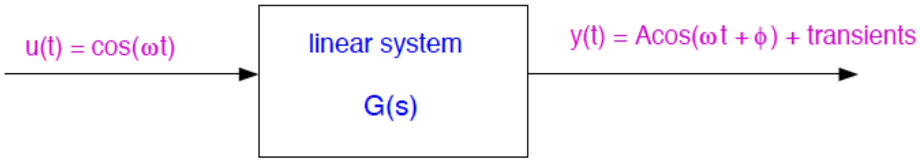


➔ Need modelling framework for nonlinear flame models

The Flame Transfer Function

Flame transfer function (linear)

$G(i\omega)$ a) is a complex number b) varies with frequency



u(t) = cos(ωt)

linear system

G(s)

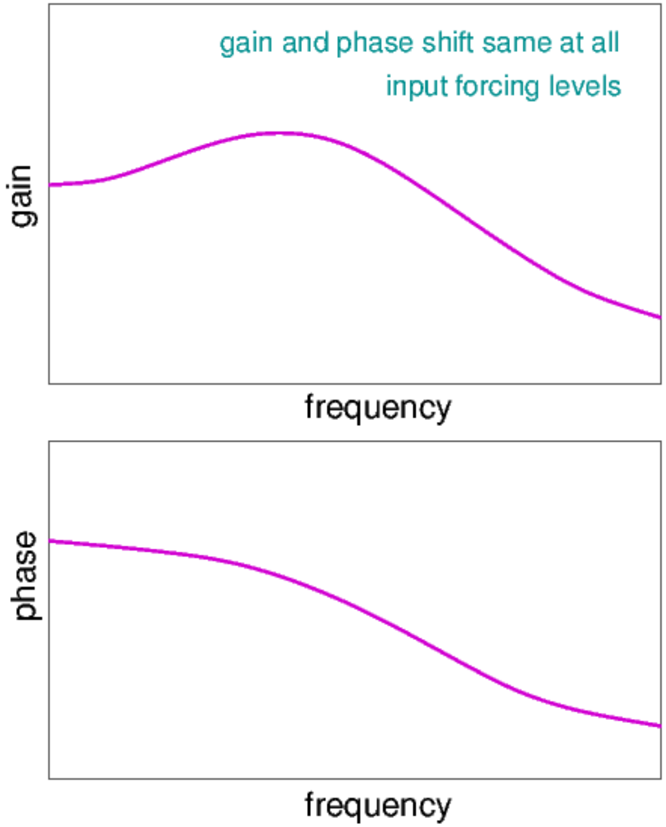
y(t) = Acos(ωt + ϕ) + transients

$A = |G(i\omega)|$ $\phi = \angle(G(i\omega))$

$$\frac{\hat{Q}(s)}{\overline{Q}} = H(s)\frac{\hat{u}_1(s)}{\overline{u}_1}$$

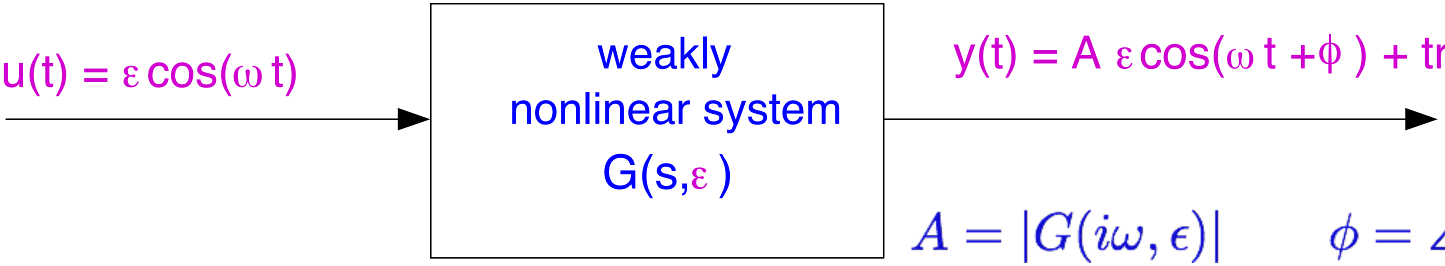
$$s = i\omega$$

Transfer function (linear systems)



gain and phase shift same at all input forcing levels

The Flame Describing Function



u(t) = ε cos(ω t)

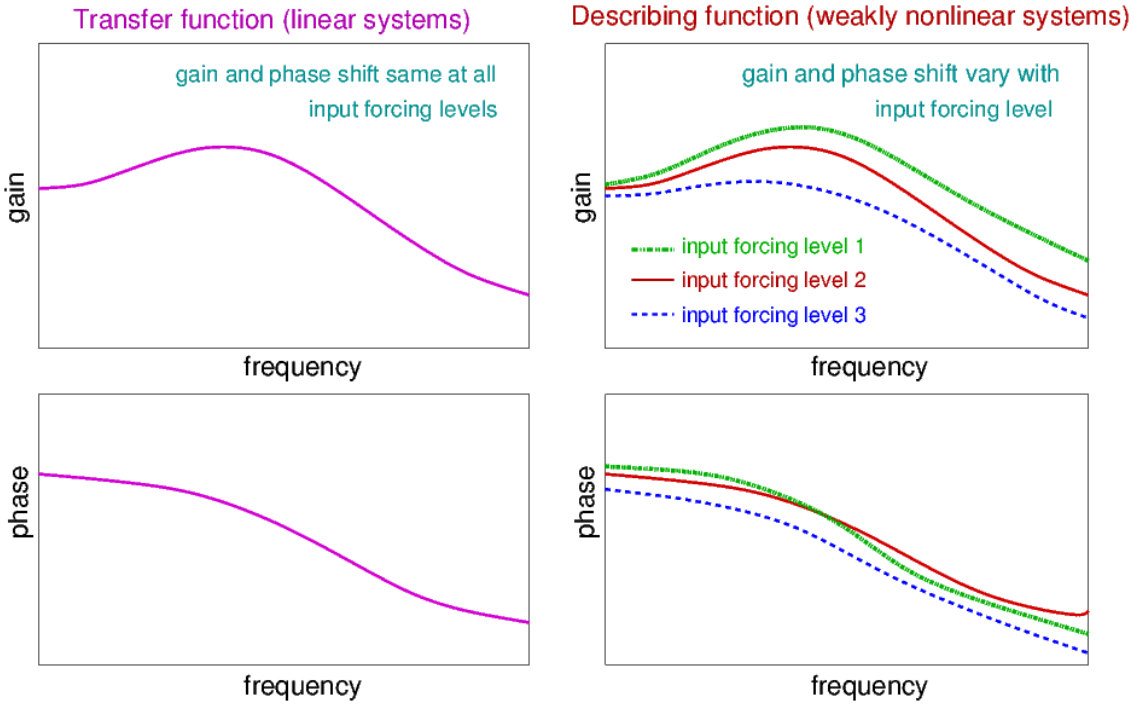
weakly
nonlinear system
G(s,ε)

y(t) = A ε cos(ω t +ϕ) + transients

$A = |G(i\omega, \epsilon)| \qquad \phi = \angle(G(i\omega, \epsilon))$

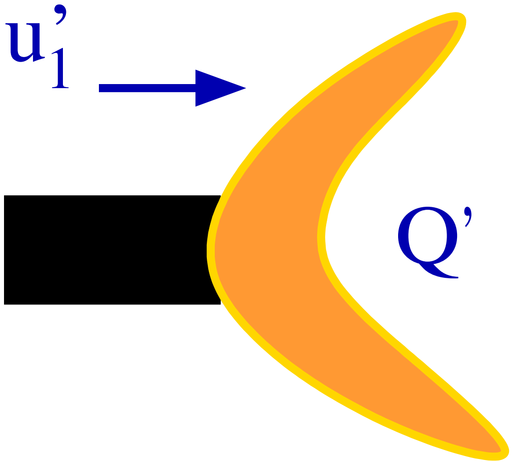
Flame describing function
(weakly linear)
A(ω,ε) and ϕ(ω,ε)
(ε = forcing amplitude)

$$\frac{\hat{Q}(s)}{\overline{Q}} = H\left(s, \frac{\hat{u}_1(s)}{\overline{u}_1}\right)\frac{\hat{u}_1(s)}{\overline{u}_1}$$



The Flame Describing Function

$$\frac{\hat{Q}(s)}{\overline{Q}} = H\left(s, \frac{\hat{u}_1(s)}{\overline{u}_1}\right)\frac{\hat{u}_1(s)}{\overline{u}_1}$$

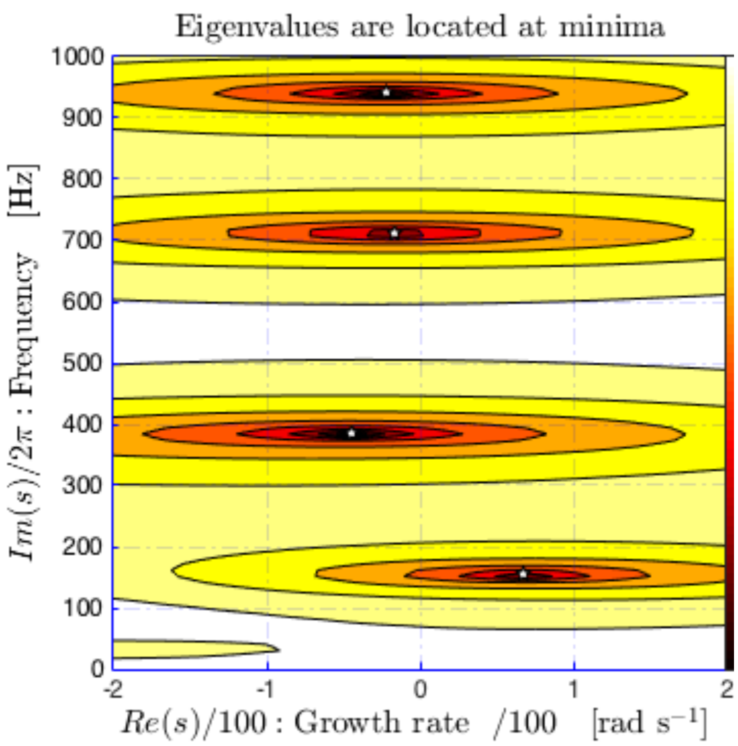


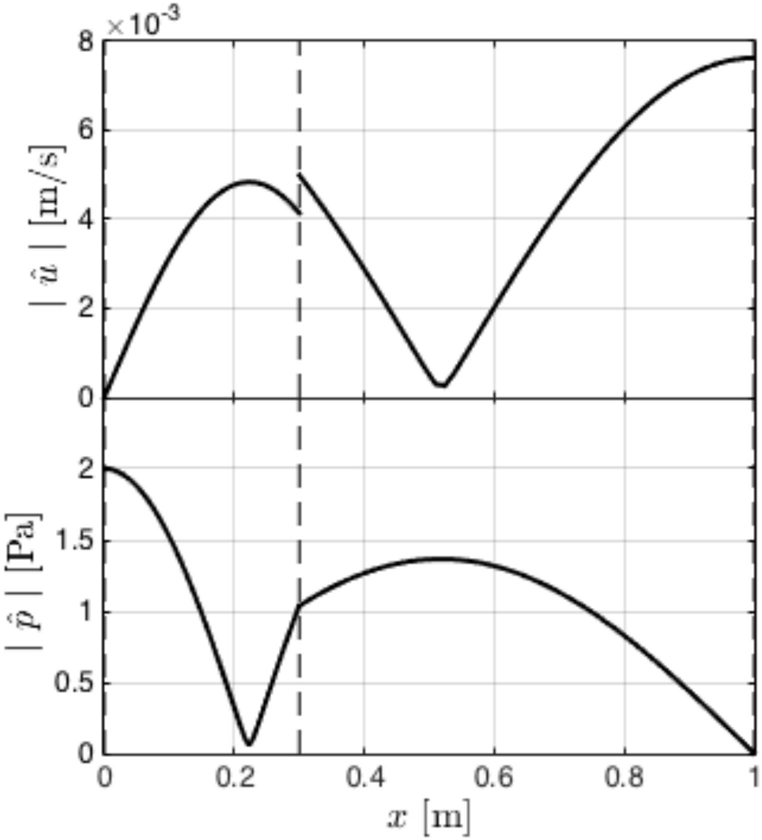
Procedure for FDF (experimental or numerical):

- Apply harmonic velocity forcing upstream of flame across different frequencies and forcing amplitudes
- After transients have died away, measure gain and phase shift for each frequency/amplitude level.

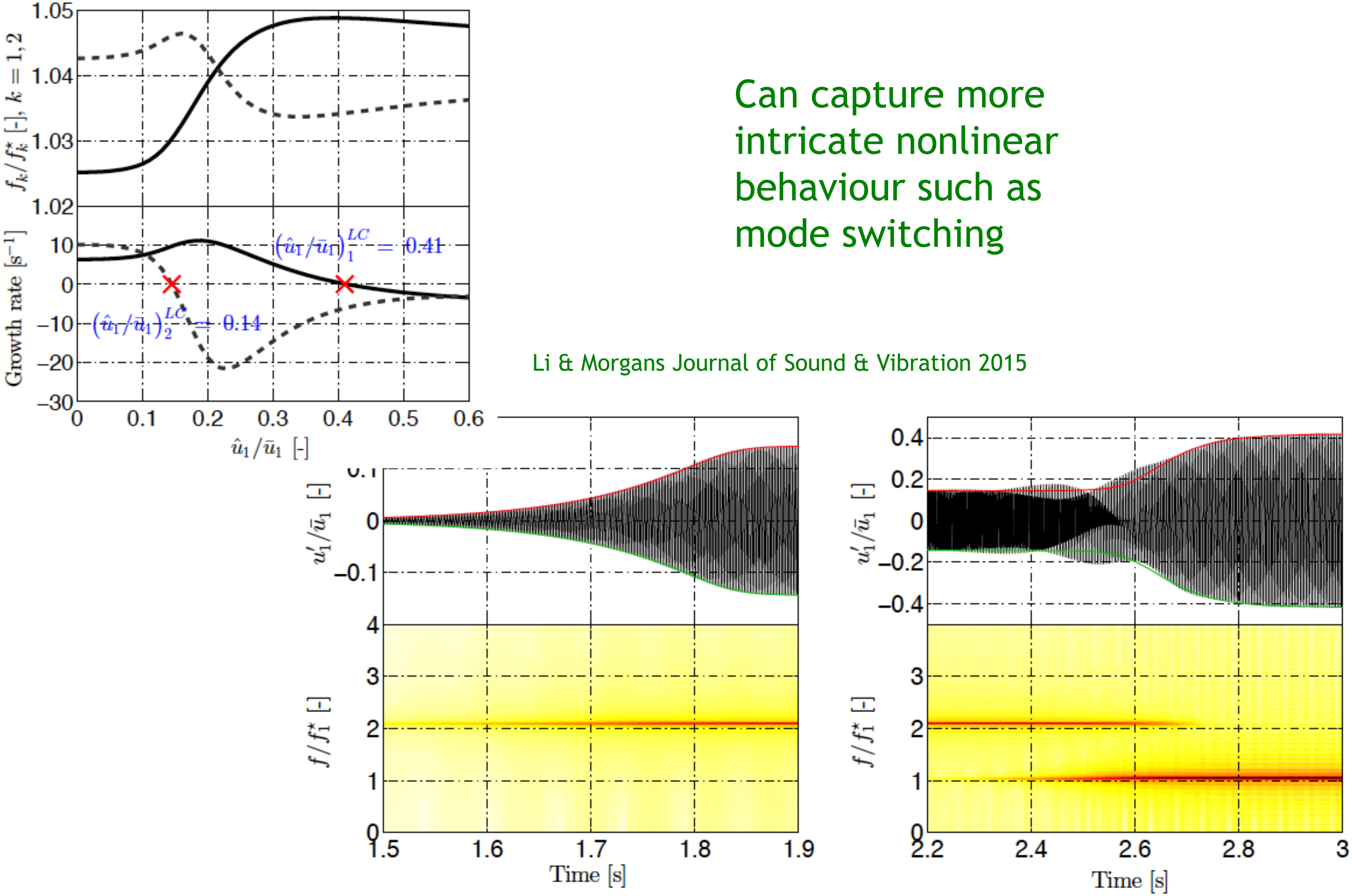
Coupled predictions with linear flame models

Modal frequencies, growth rate and modeshapes





Coupled predictions with nonlinear flame models



Can capture more intricate nonlinear behaviour such as mode switching

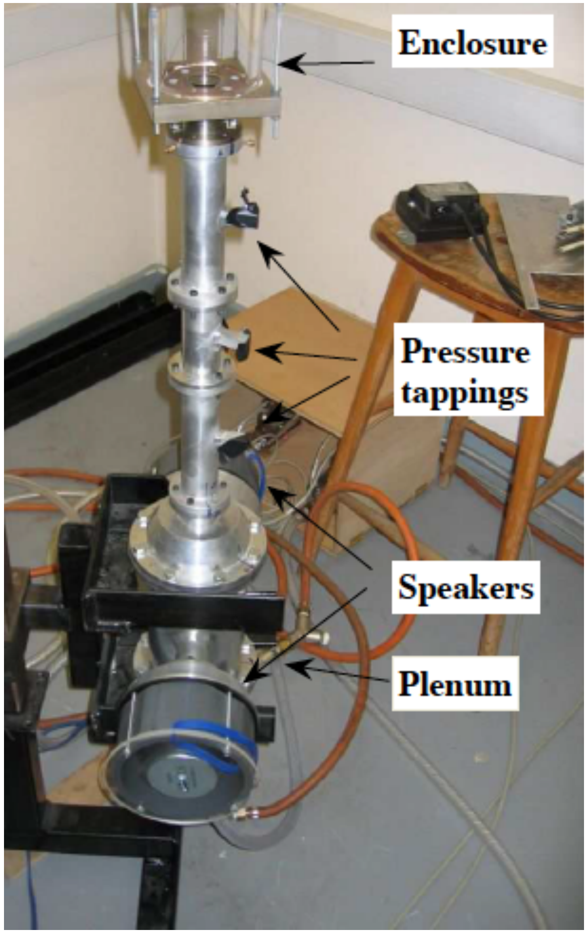
Li & Morgans Journal of Sound & Vibration 2015

Fully computational prediction of thermoacoustic instability?

Imperial College London

Laboratory combustor:

- Partially premixed turbulent flame combustor
- End combustor or flame 'enclosure' can be short or long

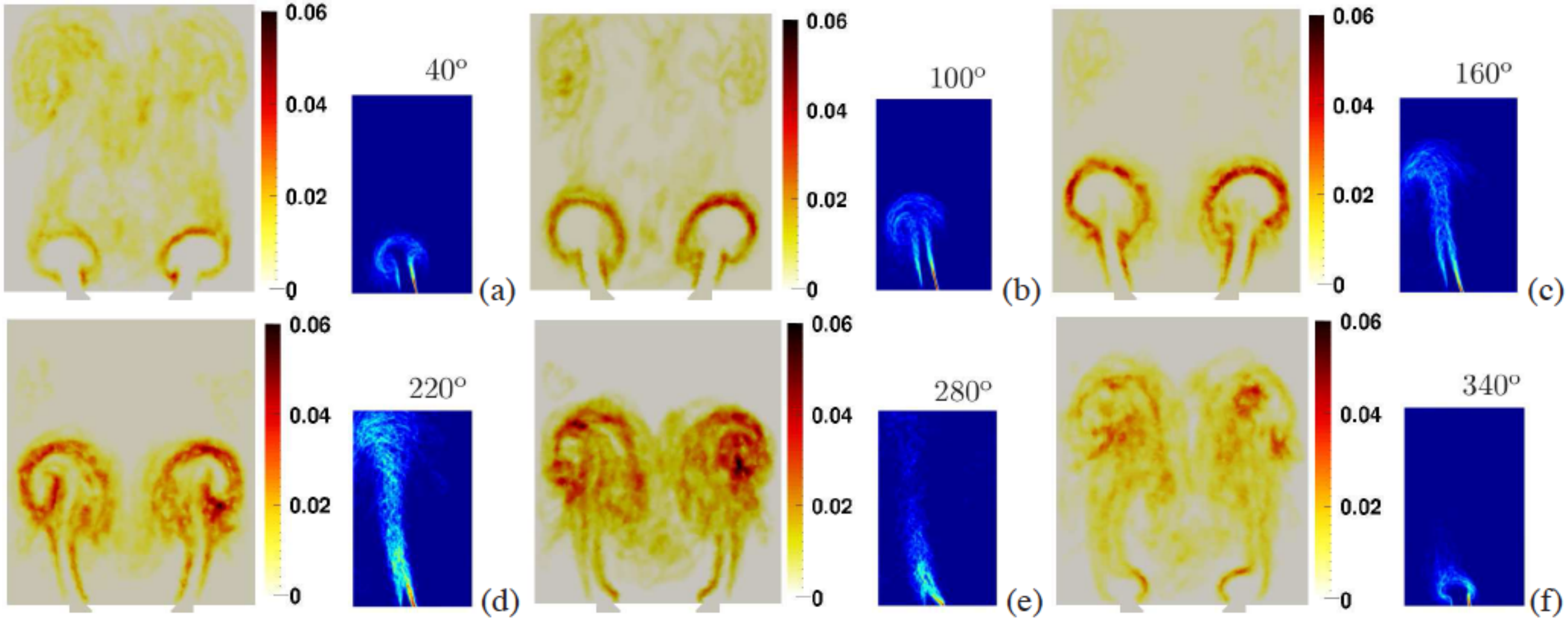


*Balachandran PhD thesis 2005

FDF from reacting flow simulations

Incompressible LES using Open Source CFD code OpenFOAM (ReactingFOAM, one-step chemistry, PaSR for turbulence-combustion interaction, WALE SGS)

Equiv ratio ϕ = 0.55, flame response to velocity forcing at 160Hz (A=0.65)*#



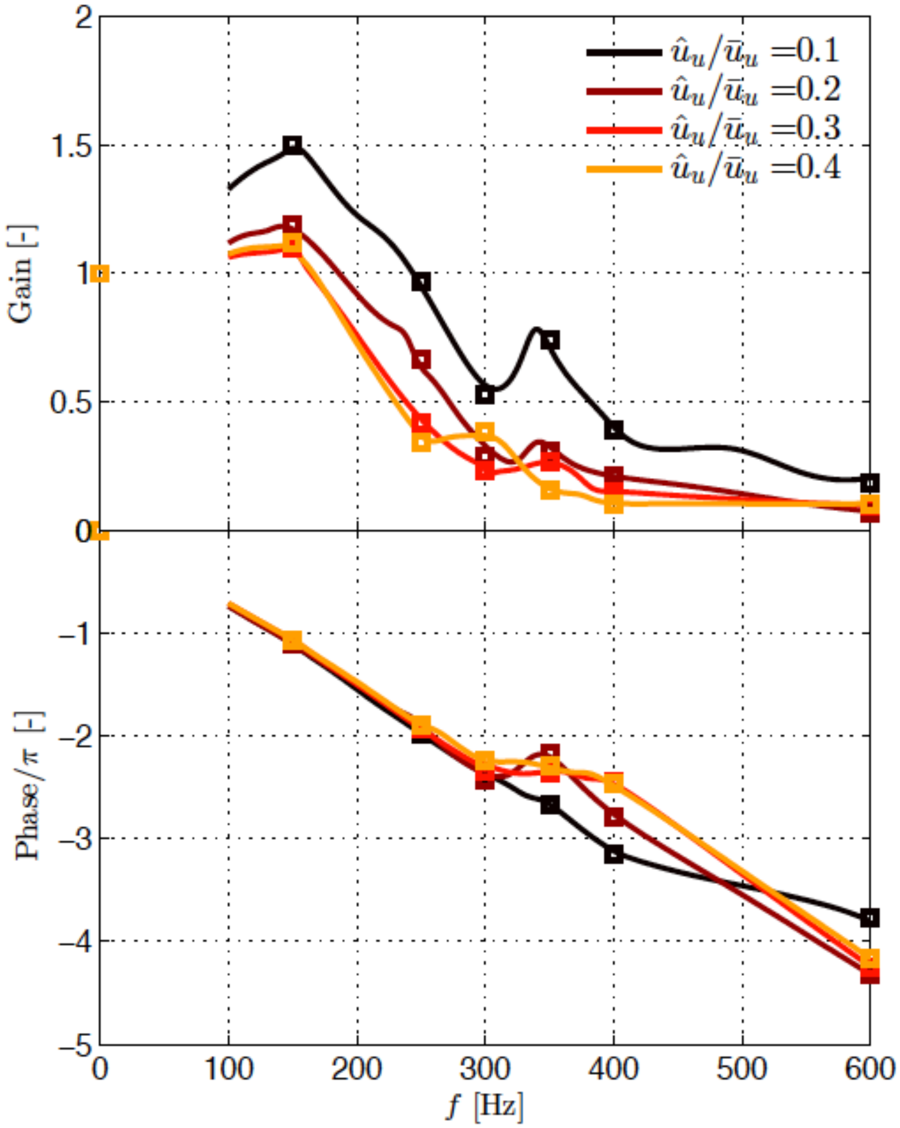
*Han, Li & Morgans, Combustion & Flame 2015

FDF from reacting flow simulations

1-step chemistry, partially-stirred reactor model for turbulence-chemistry interaction

Full LES flame describing function ϕ=0.61

Fitting done within OSCILOS*

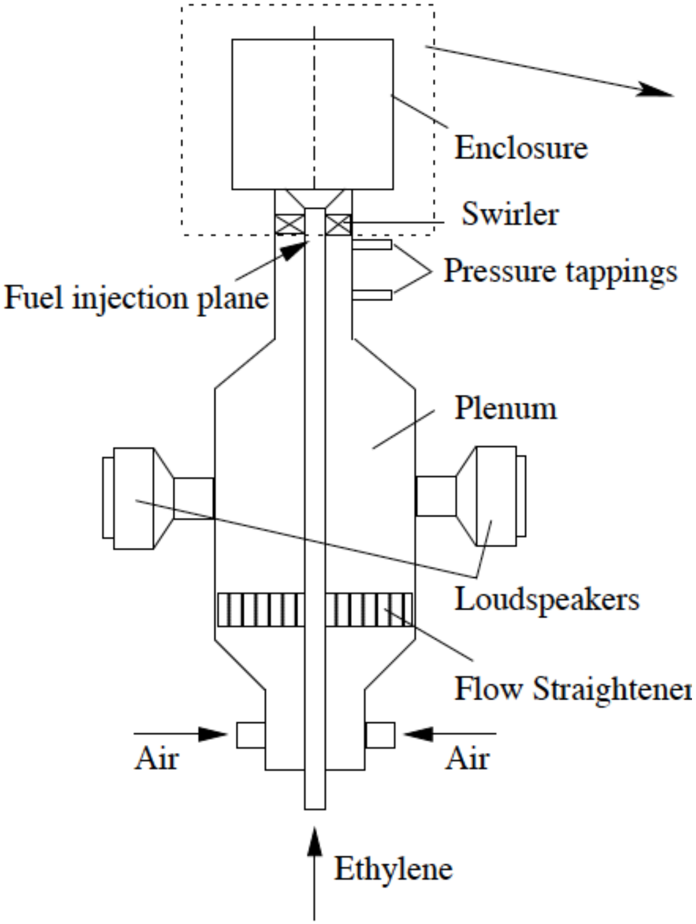


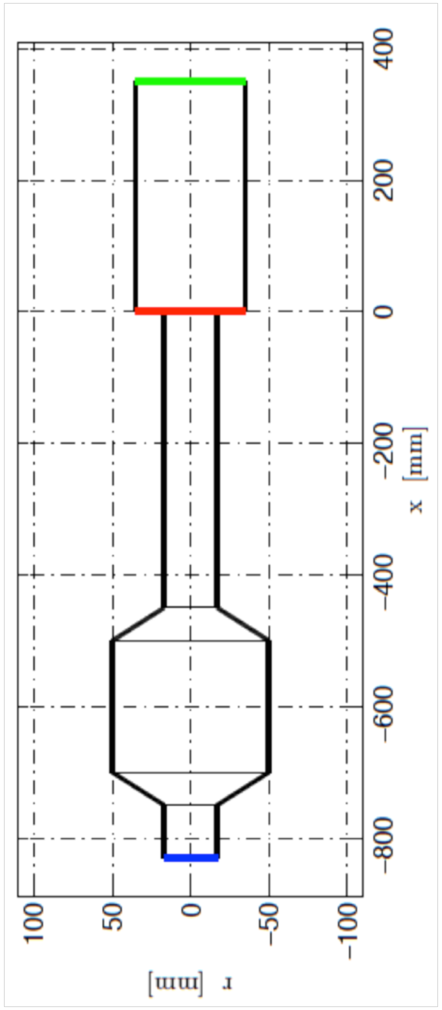
*Han, Li & Morgans, Combustion & Flame 2015

Low order simplified network

OSCILOS module geometry

Closed inlet and open outlet boundary conditions:



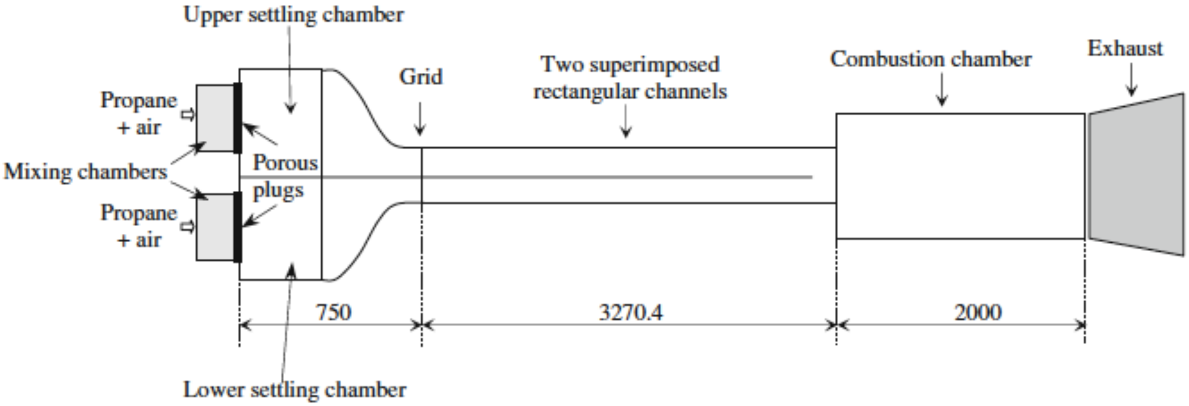


Coupled low order prediction of limit cycle oscillations

	Experiments	**Low order prediction***
Instability frequency (Hz)	348	343
Instability amplitude **(normalised velocity before flame)**	0.21	0.26

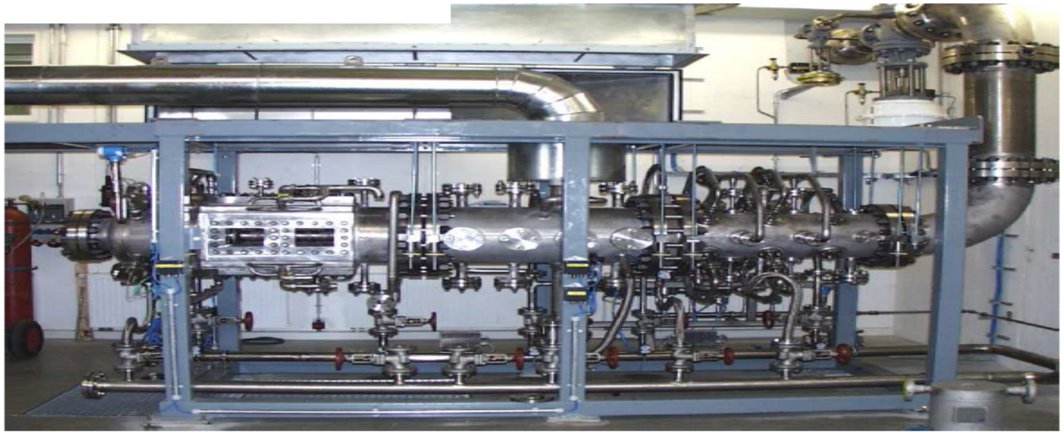
*Han, Li & Morgans, Combustion & Flame 2015

Now more complex combustion rigs…



ORACLES combustor

Adapted Siemens SGT-100 gas turbine combustor

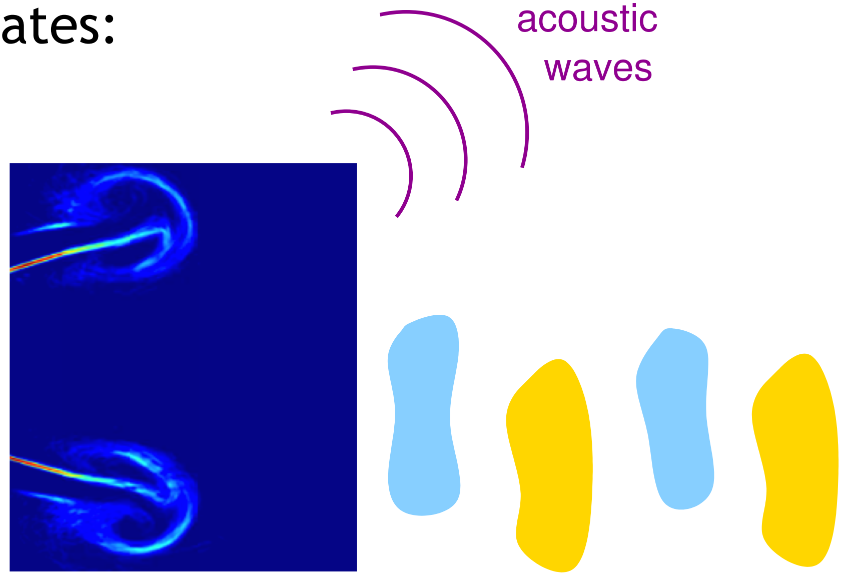


Open questions on reduced chemistry, turbulence-combustion interaction models, spray flames

Indirect combustion noise (entropy noise)

Entropy noise is one (of two) components of combustion noise

Unsteady combustion generates:



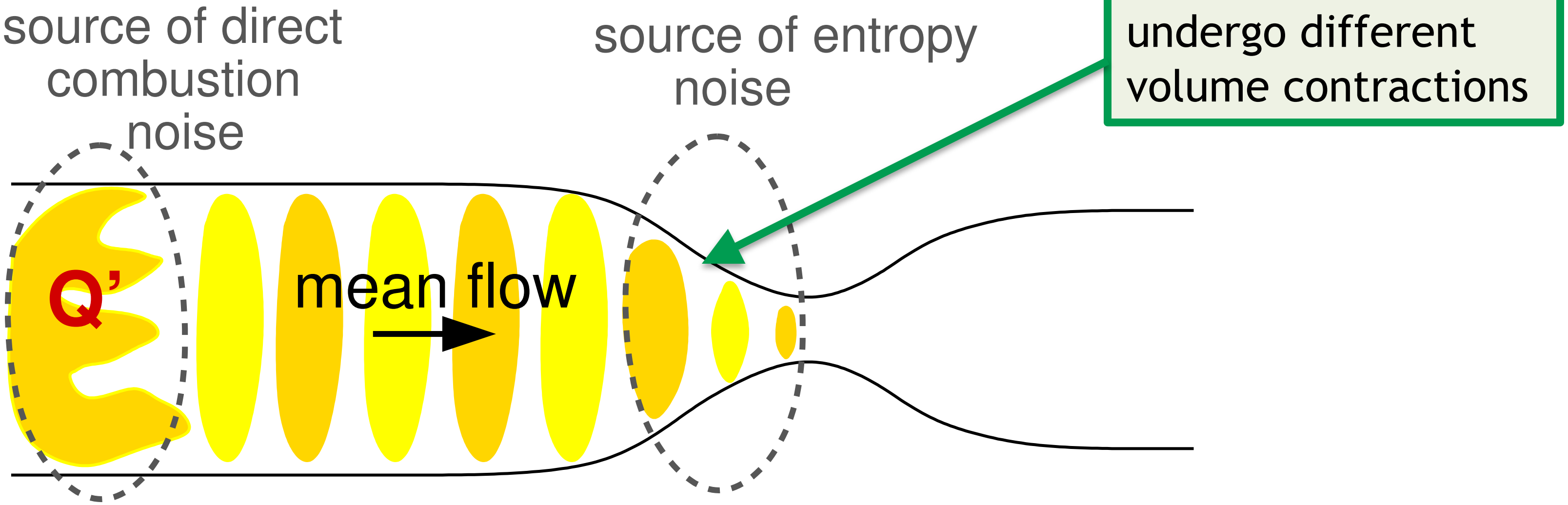
Flame image courtesy of R. Balachandran

- Acoustic waves which propagate within the combustor.
- Entropy waves (hot/cold spots) which are “swept” downstream, advecting with the flow. In a non-accelerating flow they are “silent”.

Indirect combustion noise (entropy noise)

- Q: If entropy waves are silent, what is "entropy noise"?

- A: When the flow is accelerated, acoustic, entropy and vorticity waves all become coupled. Thus by accelerating entropy waves, new acoustic waves are generated*.



Regions of fluid with different densities undergo different volume contractions

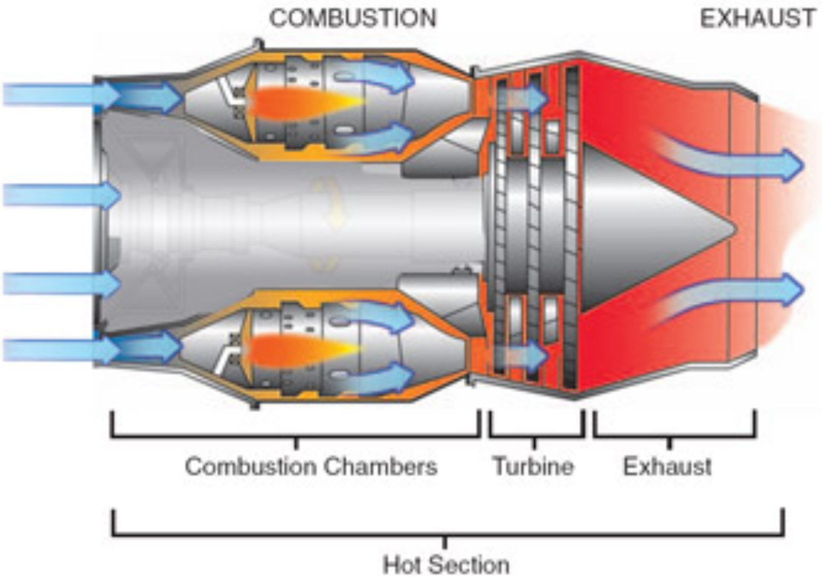
* Marble & Candel 1977

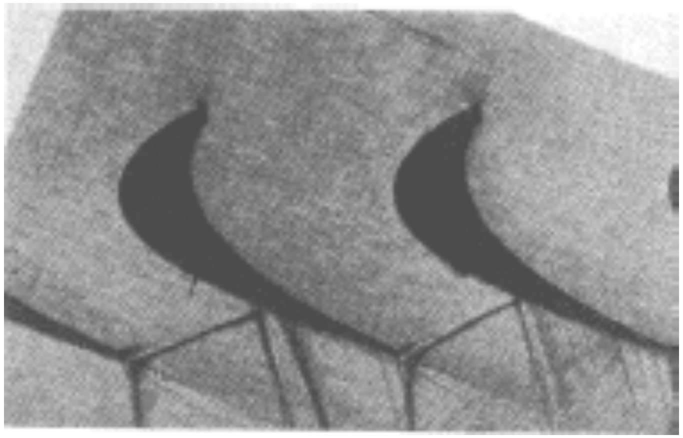
Entropy noise in gas turbines

Imperial College London

- Q: Are entropy waves accelerated in real combustion systems?

- A: Yes! In a gas turbine, the flow undergoes rapid acceleration through the combustor exit and first turbine stage. The entropy waves then generate "entropy noise".



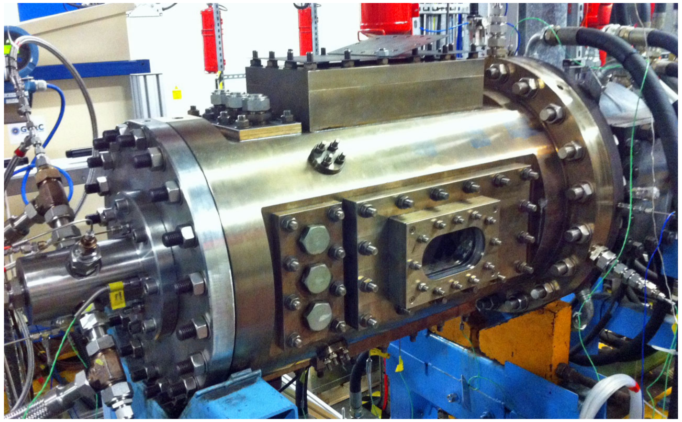


Stator exit shock waves from Mee et al. (1992)

Thermoacoustic instability in the UK

Imperial College London

Cardiff GTRC facility



Cambridge annular rig

- Experimental facilities set-up for thermoacoustic analysis at:

  Loughborough, Cardiff, Cambridge, UCL, Imperial College London

- Simulations supported through UKCTRF (ARCHER)

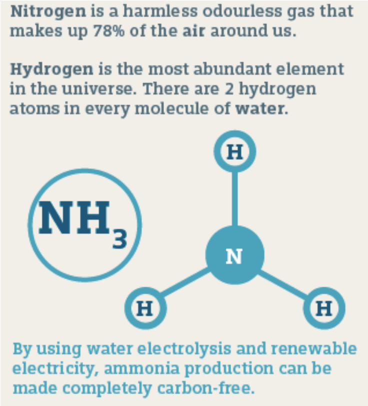
- Current EPSRC support:
  - CHAMBER grant (Imperial/UCL)
  - Flex-E-Plant (Loughborough + many others)
  - ARCHER through the UKCTRF
  - A few PhDs through Imperial CDT, Cambridge/Loughborough CDT
  - Co-funding from industry (Rolls-Royce UTCs, Siemens)

Thermoacoustic instability in the UK

A few ideas for future collaboration:

- Predicting instability in more industrially-relevant experiments
  (need lots of thermoacoustic characterisation: boundary conditions, flame describing function, mean temperature profile)
- Multiple interacting flames or burners
- Transverse modes (challenging for acoustic modelling and flame modelling)

- Hydrogen/ammonia combustion
- Distributed propulsion on aeroplanes (Aerospace Technology Institute)



Nitrogen is a harmless odourless gas that makes up 78% of the air around us.

Hydrogen is the most abundant element in the universe. There are 2 hydrogen atoms in every molecule of water.

By using water electrolysis and renewable electricity, ammonia production can be made completely carbon-free.