Gas turbine combustor thermoacoustics

An introduction

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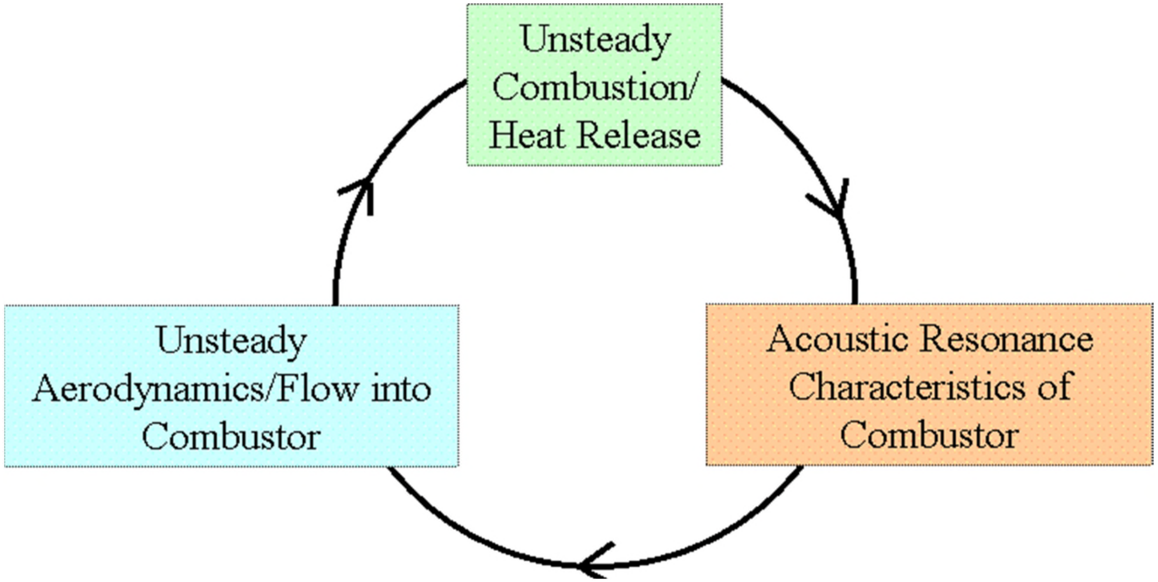
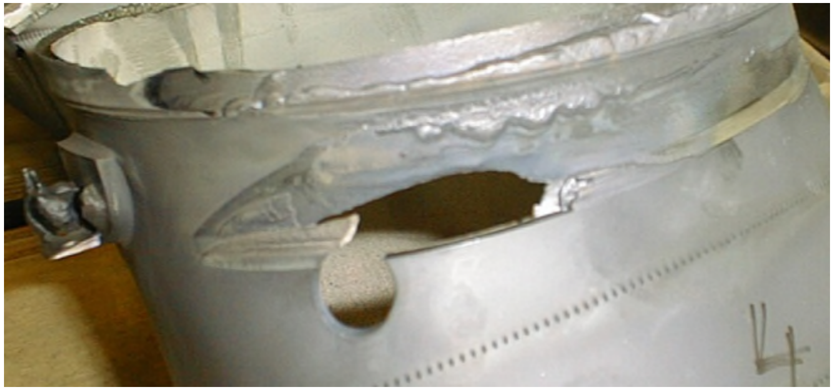
Problem statement



- Drive towards low emissions => lean burn combustion
- Lean AFRs => combustor is more likely to be prone to heat release fluctuations and thermoacoustic problems

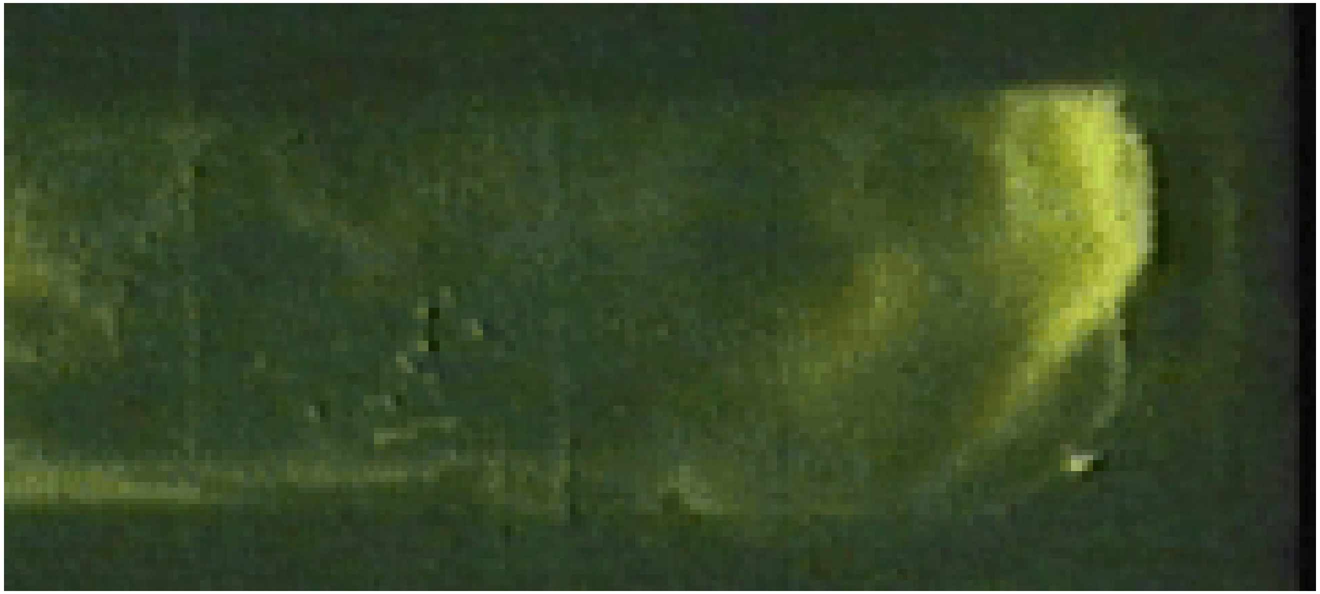
Types of combustion noise

- Different types of combustion noise:
  - High Frequency Rumble (HFR): ~500Hz, mainly circumferential mode, can affect integrity
  - Low Frequency Rumble (LFR): ~200Hz, axial mode due to entropy waves (non-uniformity of temperature field)
  - Buzz: ~100Hz, axial mode affecting afterburners, can couple with LP shaft vibration
  - Screech: ~2kHz, radial mode, affecting afterburners integrity through enhanced heat transfer to liner
  - Indirect noise: entropy waves hit choked nozzle introducing noise sources in turbines, can be a problem because noise sources coming from other components are reducing
- Combustion noise can be more than just annoying



Rumble Damaged RB211 DLE discharge nozzle

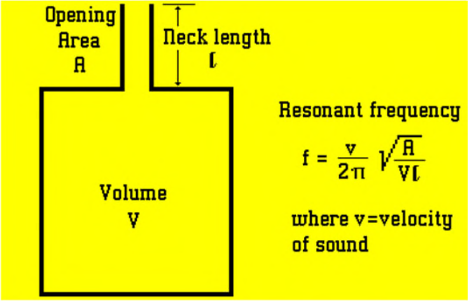
TA at work



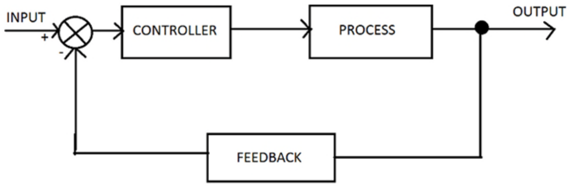
Approaches to TA instabilities

- Design it out:
  - Identify TA-desirable design features – hard to do
  - Carry forward only designs showing acceptable level of pressure fluctuations – problem: TA instabilities may manifest themselves only at relatively late stages of the design
- Damp it:
  - Introduce dampers:
    - frequency targeted dampers (e.g. Helmholtz resonators) work well only on a narrow frequency band
    - broadband dampers (e.g. viscous dampers) may not reduce the pressure fluctuation enough
  - Volume can be at a premium – solution is inherently more suitable for industrial gas turbine combustors
  - Cooling is a challenge: both types rely on introducing flow fluctuations at the wall
- Control it out:
  - Apply active control: impose frequency and amplitude dependent fluctuations of the fuel – reliability and durability of the actuators are issues

Fuel injector



Helmholtz resonator



Control system

TA modelling

- The problem has to be simplified to make it tractable
- Starting point: Navier-Stokes equations
- Assumptions:
  - Thin annular combustors or long cannular combustors with no significant radial fluctuations => modes are azimuthal, axial or a combination thereof
  - Linear regime: looking for susceptibility of fluctuations to become unstable
  - Viscous effects can be neglected
- Because of linearity:

$$p = \bar{p} + p'(x, \theta, t),$$

$$p' = \mathrm{Re}\left(\hat{p}(x,\theta)\mathrm{e}^{\mathrm{i}\omega t}\right), \qquad \hat{p} = \sum_{n=-N}^{N} p^n \mathrm{e}^{\mathrm{i}n\theta}.$$

- NS equations can be reduced to the inhomogeneous wave equation:

$$\frac{1}{\bar{c}^2}\frac{\bar{\mathrm{D}}^2 p'}{\mathrm{D}t^2} - \nabla^2 p' = \frac{\gamma - 1}{\bar{c}^2}\frac{\bar{\mathrm{D}}q'}{\mathrm{D}t}$$

- Equations are usually resolved in the frequency domain
- Frequency is complex: imaginary part linked to the growth rate, real part is instability frequency

Flame transfer function

- The inhomogeneous wave equation can be solved if a model of the heat release fluctuations is available
- The Flame Transfer Function (FTF) is defined as the ratio of heat-release perturbations to flow perturbations as a function of frequency:

$$\frac{\hat{Q}}{\bar{Q}} = T(\omega)\frac{\hat{m}}{\bar{m}}.$$

- The flame transfer function can come from analytical models, experiments or CFD.
- A simple analytical model is

$$T(\omega) = -k\mathrm{e}^{-\mathrm{i}\omega\tau},$$

where τ can be interpreted as the fuel convection time.

- If instead of a single time delay, a uniform distribution is assumed ($\tau - \Delta\tau$ to $\tau + \Delta\tau$):

$$T(\omega) = -k\mathrm{e}^{-\mathrm{i}\omega\tau}\frac{\sin(\omega\Delta\tau)}{\Delta\tau}.$$

- Such models can be fitted to the measured or simulated flame response at a range of frequencies

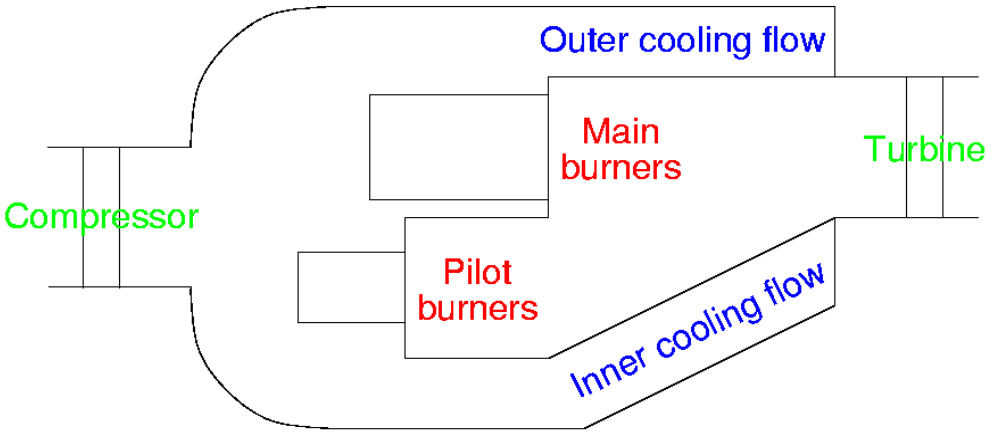
Flame transfer function vs flame describing function

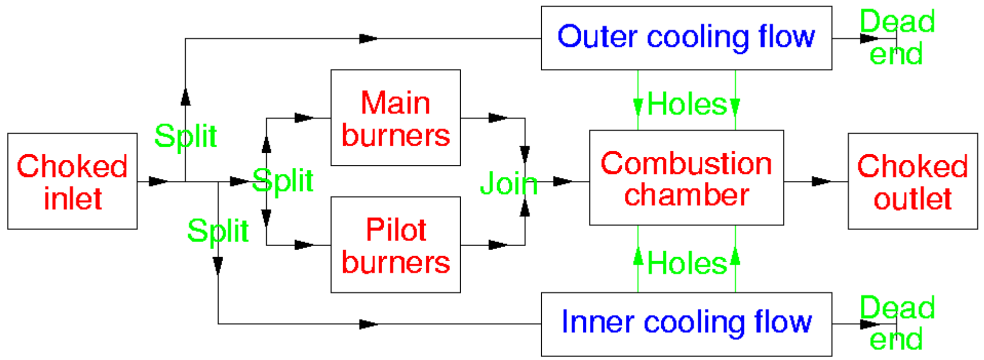
- The flame transfer function approach applies in the linear domain (i.e. stable vs unstable)
- As such, it does not allow calculating the amplitude of the fluctuations
- In order to capture non-linear effects, a flame describing function has to be available:

$$T = T(A, \omega)$$

- Unstable modes will not grow indefinitely: the amplitude of fluctuations will stop when offset by damping effects
- The resulting TA instability is called <u>limit cycle</u>
- In conventional rigs, measurements of TA instabilities (e.g. pressures, velocities, heat release, etc) are usually associated to limit cycles, hence the flame transfer function cannot be directly derived. The resulting amplitudes are referred to as saturation amplitudes
- Using a FDF allows calculating the amplitude of oscillations
- However, to be of use in modelling, FDFs should be defined for a range of amplitudes going from zero to the saturation value

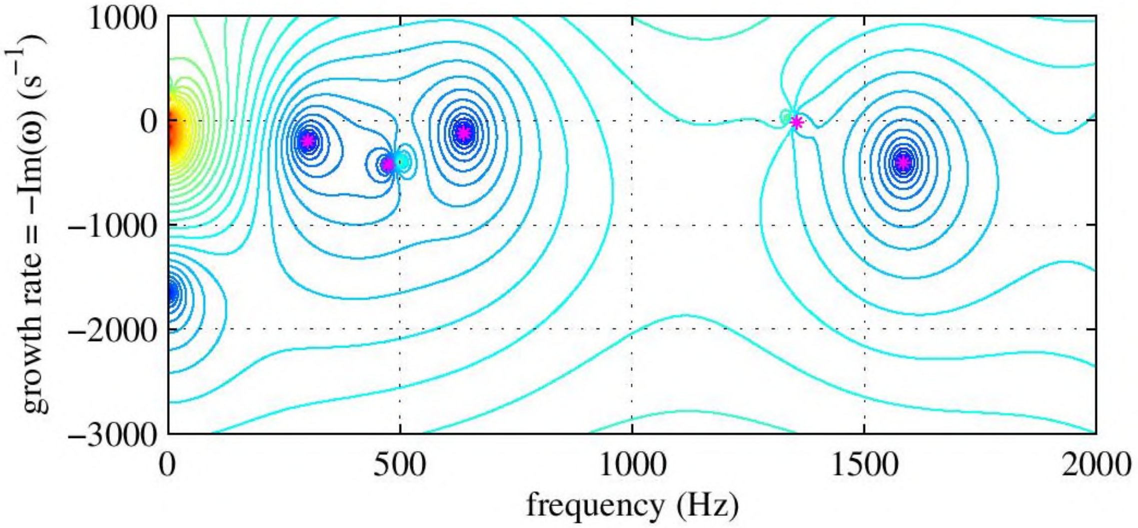
How to model a combustor



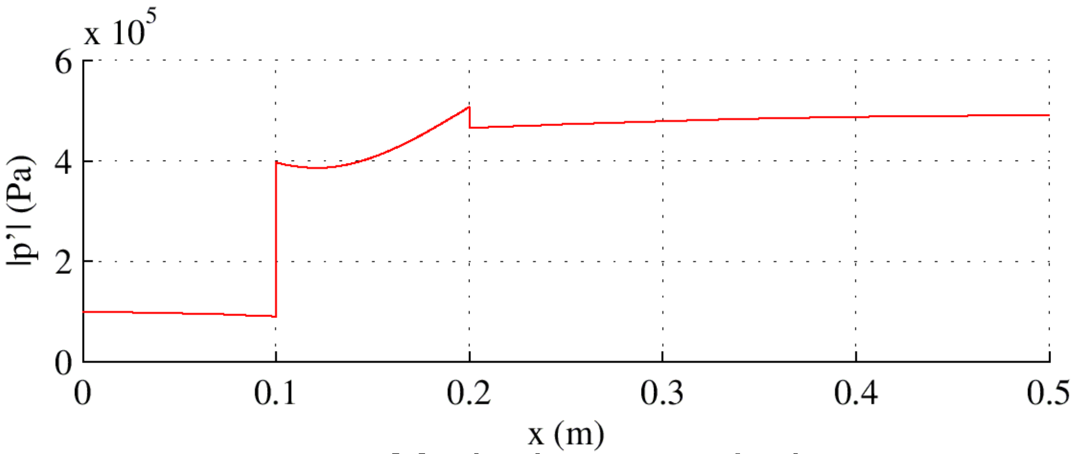


- The system's acoustics is approximated by using acoustic paths
- Large volumes have to be modelled directly
- Acoustic boundary conditions have to be realistic (e.g. choked, open ended, impedance based, etc)

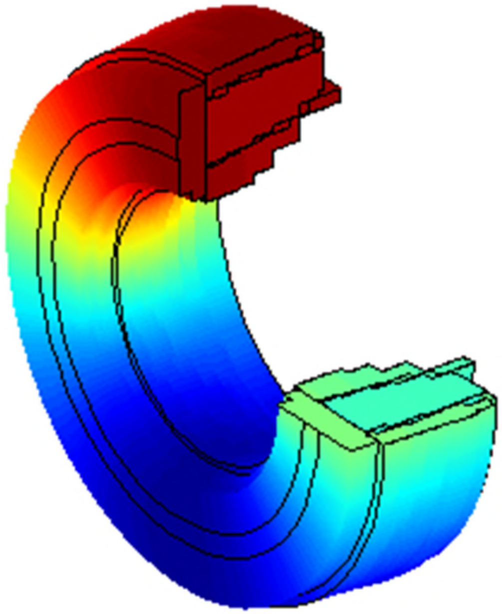
Typical results



Mode instability analysis



Modeshape analysis



Visualisation of azimuthal mode

How to obtain a FTF

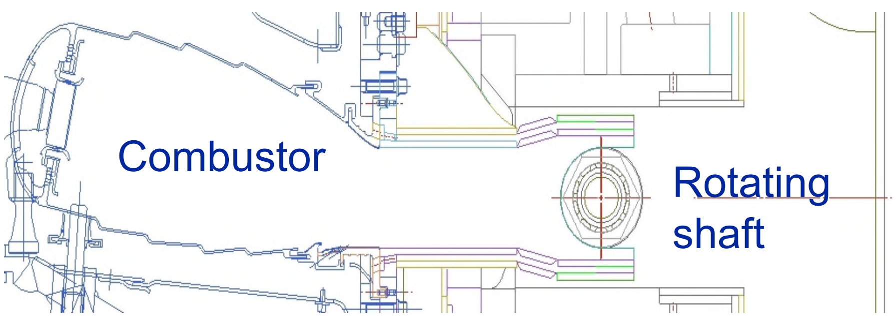
- There is no “one size fit all” FTF
- FTFs are strongly dependent of geometry and operating conditions: thermoacoustics can be very sensitive to even small changes in geometry/operating conditions (“cliff edge” behaviour)
- Changes to the fuel injector are a classical cause for appearance of TA problems
- Analytical models can be useful to fit to experimental or numerical data, but are unlikely to provide accurate guidance on the susceptibility to TA instabilities
- FTFs can be derived:
  - Experimentally: by forcing a flame in the linear regime for a range of frequencies at which the heat release and velocity fluctuations are measured
  - Numerically: CFD can be used to simulate the flame forcing and derive the flame response in a similar manner to experiments

How experiments can help

- Cold flow single sector: in-depth characterisation of steady/unsteady fuel injector aerodynamics – no reaction, no acoustics
- Forced cold flow single sector: in-depth characterisation of unsteady aerodynamic response to acoustic forcing – no reaction
- Single sector reactive (low to high P): characterisation of flame response to single sector rig's acoustics (possibly with advanced laser diagnostics for measuring heat release and fuel placement) – limited representation of acoustics
- Single sector siren rig: characterisation of flame response to axial harmonic forcing up to cruise pressure (possibly with advanced laser diagnostics) – siren rig
- Full annular: characterisation of flame response to actual combustor geometry up to max pressure achievable by the rig for the combustor size – high Technology Readiness Level (TRL) test required for verification of other combustion parameters, but limited diagnostics can be applied. Need for restricted build

COST and REPRESENTATIVENESS

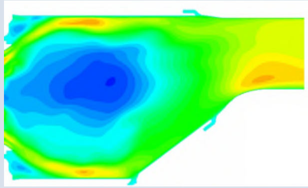
Siren rig layout



Combustor Technology Development

TRL

Low order modelling & CFD



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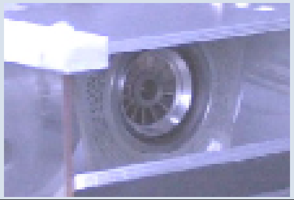
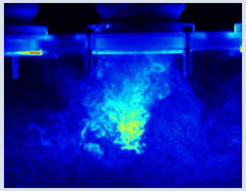
LP combustion, spray diagnostics, aerodynamics and fuel stability.





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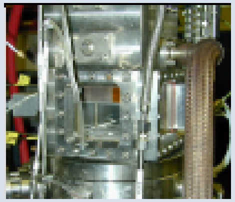
2 sector sub-atmospheric & HP Single Sector



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HP and sub-atmospheric annular & HP multisector

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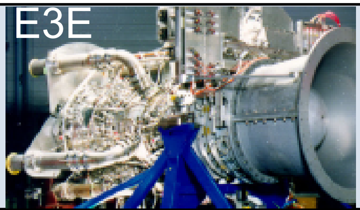
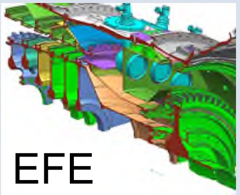
Engine Demonstrators





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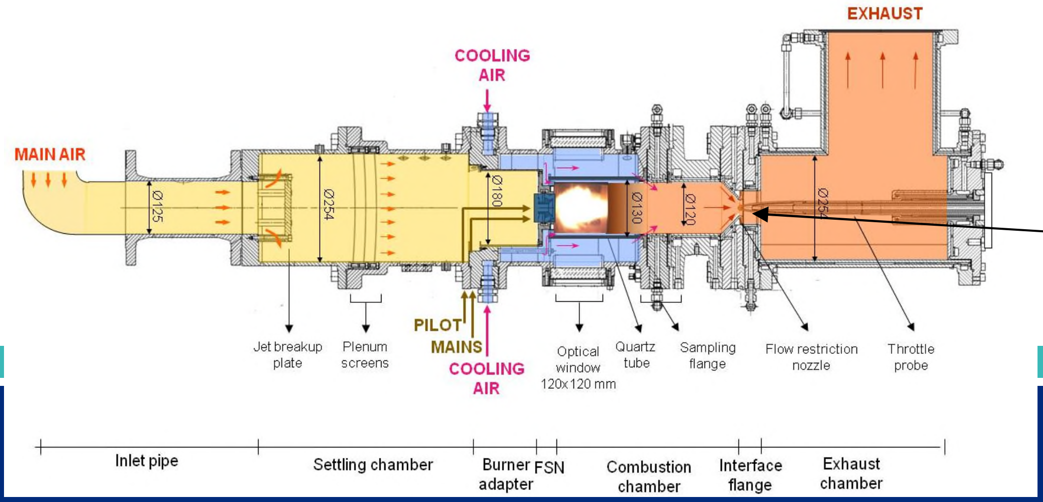
The challenge of siren rig testing

- Often TA problems surface at a late stage of the combustor verification process
- A low TRL filter is required
- Issues to be addressed for siren rig testing:
  - Unsteady heat release difficult to measure for partially premixed and diffusion flames
  - Response of flame to axial forcing may be unrepresentative of circumferential modes
  - Pressure effects: engine MTO pressure are getting higher and higher
  - Amplitude effects: siren has to be designed to be able to modulate the amplitude of the forcing to remain in linear regime
  - Contribution of potential coupling between entropy waves and HFR not accounted for before full annular testing
  - Even full annular testing may not be sufficiently representative of the forcing the combustor will be subject to in an engine (e.g. forcing by the rotors)
  - System effects: geometry upstream and downstream of the fuel injector may not be representative of engine
  - Rig effects: rig will have its own acoustic resonance, which may mask the injector response

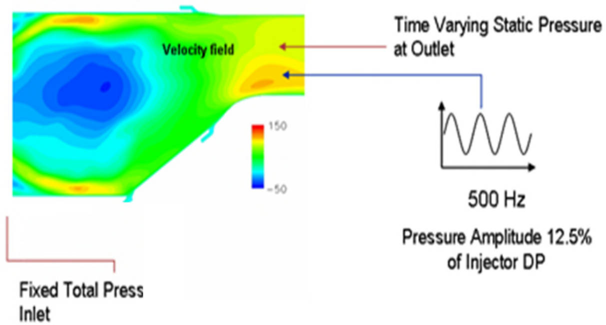


Siren position

Rolls-Royce

How CFD can help

- CFD can be used to derive the FTF
- Approach is based on forcing the CFD for a range of frequencies to calculate heat release and velocity fluctuations



- Different numerical approaches are being pursued for derivation of FTF, all based on unsteady CFD:
  - Turbulence modelling:
    - Large Eddy Simulation (LES)
    - Unsteady RANS (uRANS)
  - Compressibility effects:
    - Incompressible to assess “hydrodynamic” behaviour of flame
    - Compressible to account for density changes with pressure
  - Effect of fuel break up on time delay:
    - Simplified modelling of prefilmer through Volume of Fluids (VoF)
    - Estimate of time delay due to break up based on first principles

The challenge of the numerical siren

- Issues:
  - Impact of compressibility on flame response:
    - Compressibility effects on density combine with combustion effects on density
    - Flow inertia requires explicit modelling of fuel injector in reactive compressible simulation
  - Boundary conditions/extent of computational domain:
    - Explicit modelling of fuel injector may be required to simulate impact of pressure waves on wakes from swirlers
    - Anechoic or impedance-based boundary conditions to be used for compressible solution
  - Time delay contribution of spray break up:
    - For airblast injectors with long prefilmers, time to break up is comparable to convective time from end of film to flame front
  - Role of fuel passage dynamics:
    - Instability can be affected by fuel passages not running full
    - Fuel passages can respond to air pressure oscillations
  - Flame response to different types of forcing (axial vs circumferential):
    - HFR's mode is azimuthal in annular combustors, whereas forcing is axial in experimental and numerical sirens => flame response could be different
    - Injector-to-injector interaction may be important

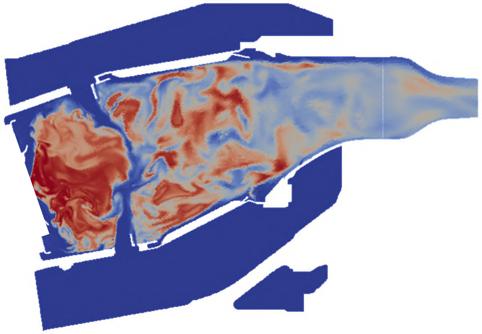
The challenge of the numerical siren

- Contribution of entropy waves:
  - At the moment, 1D modelling assumes either perfect or no mixing of entropy non-uniformities in acoustic calculations. Some reasonable level of mixing would be required
- Turbulence modelling:
  - Injector flows are better predicted by LES, however turn around time can be very long => uRANS may be a more pragmatic solution, but predicted spectra will be much less rich of peaks
- Multi-modal behaviours:
  - injectors can show propensity to relax on different flow configurations depending on operating conditions and geometry changes
- Acoustic modelling approach:
  - FTF is a fundamentally 1D quantity linking unsteady heat release rate to unsteady velocity, whilst acoustics is modelled in 2D (radial component is neglected in thin annular combustors). However, flame response may be 2 - 3D
- Forcing:
  - Broadband is most appropriate, but time consuming
  - Harmonic can be misleading for wide range of frequencies
  - Impulse perturbs the system but potentially in a non representative way
- Rumble and structures:
  - Clear definition of acceptable levels of rumble

Deriving LFR TFs from forced CFD

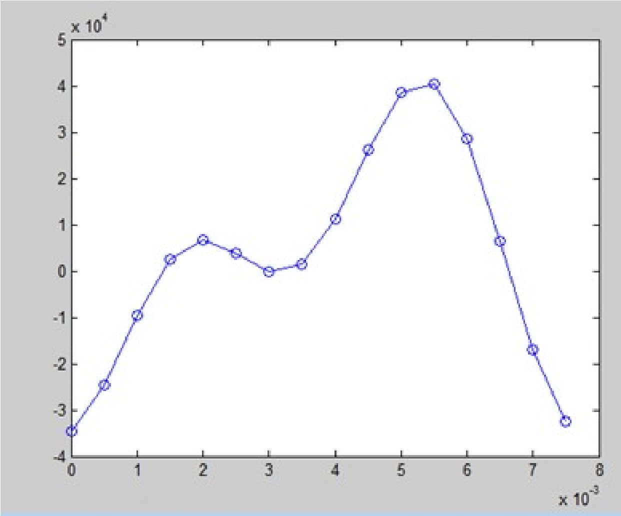
Inlet forcing (Input) → LES transfer function → Flame response (Output)

- Fuel is forced by step change
- Gain and phase of the FTF and TTF is computed and supplied to LOTAN



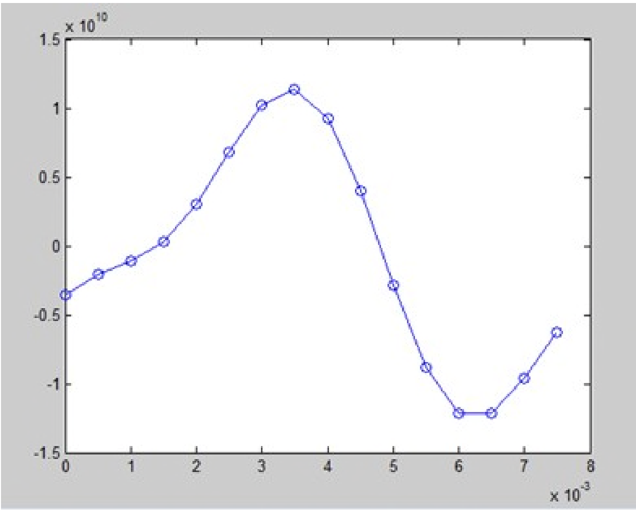
$$FTF(\omega) = \frac{\widehat{HR}_{volume}(\omega)}{\widehat{\dot{m}}_{fuel}(\omega)} \qquad TTF(\omega) = \frac{\hat{T}_{outlet}(\omega)}{\widehat{\dot{m}}_{fuel}(\omega)}$$

Outlet T



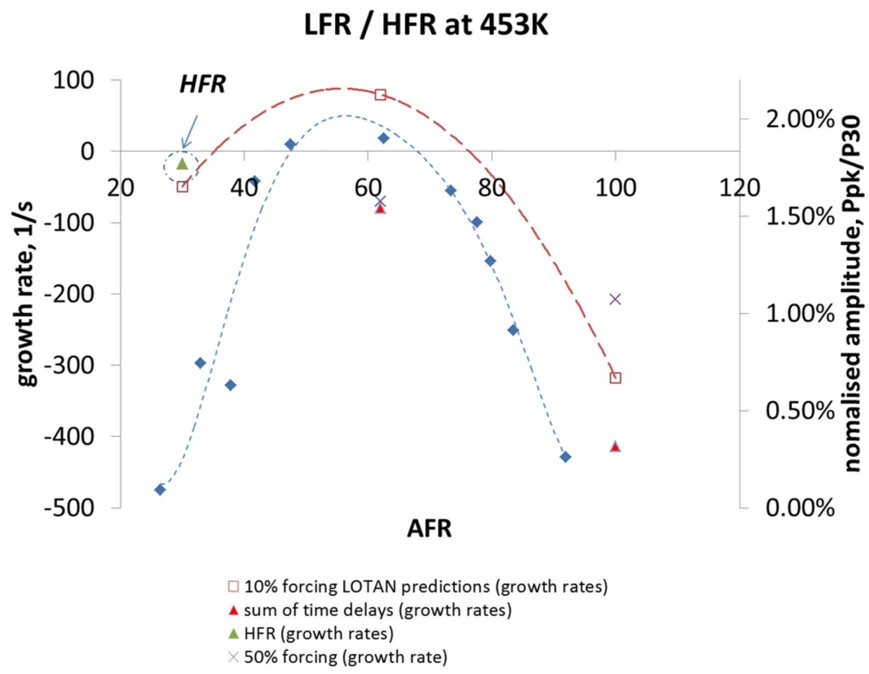
time

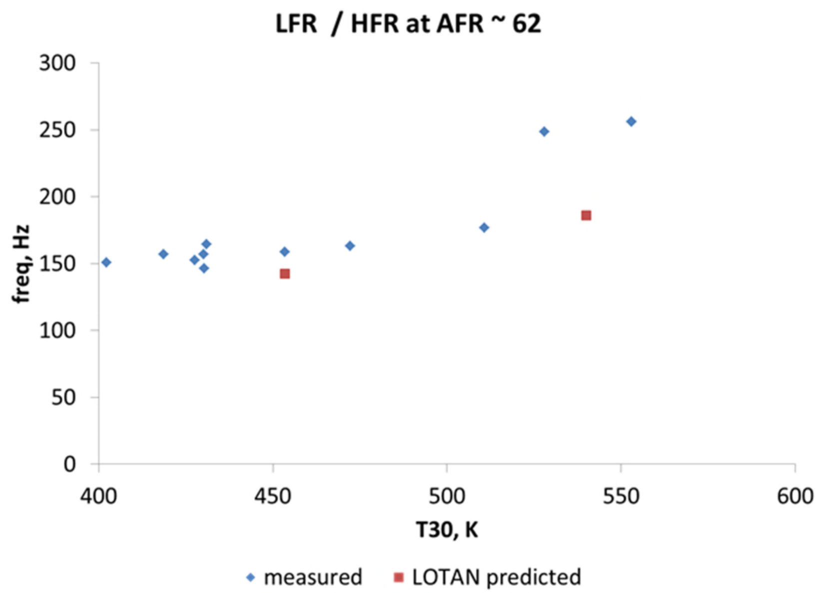
Heat release



time

LOTAN predictions – growth rate and frequencies



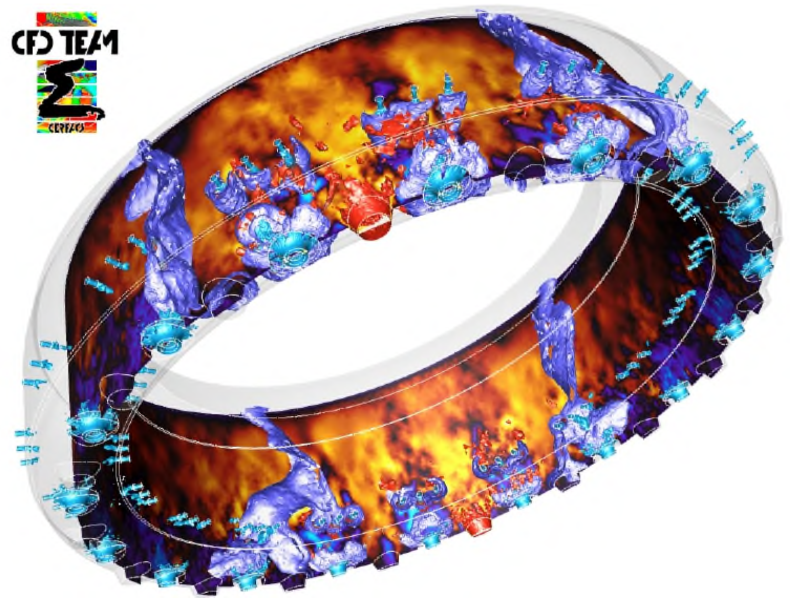


Conclusion on flame forcing

- TA tests and simulations are highly challenging
- Experimental and numerical approaches based on derivation of FTF have been demonstrated to be successful for prediction of TA instabilities of some gaseous flames
- The matter is very much a research topic

Alternative numerical approaches

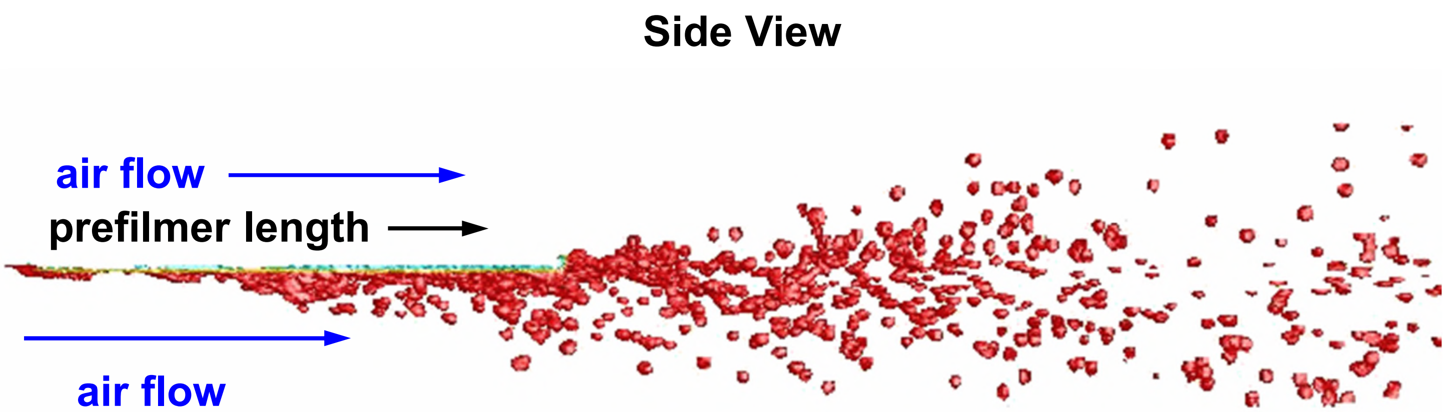
- Industrial combustors can be affected by high frequency transverse modes to which low order modelling is not applicable
- Alternative approaches have been developed, e.g.:
  - Full blown compressible simulations with acoustic boundary conditions:
    - Computationally expensive (large grids, small timesteps)
    - Limited to the time domain => no information about the range of modes present
  - Linear Euler approaches: 3D
    - Can be run in the frequency domain
    - Flame model has to come from forced CFD or analytical approach



Compressible LES of a full annular combustor (courtesy of CERFACS)

Effect of spray on TA

- TA instabilities are linked to the interaction between pressure and heat release fluctuations. Heat release is a function of the local air to fuel ratio.
- So, the response of the spray to pressure fluctuations can have a significant role by increasing the time delay of the FTF, especially for airblast atomisers
- Different sensitivities to spray effects on TA depending on the fuel injector design



Engine vs rig effects on TA

- Single sector test rig with forcing can be useful if:
  - Damping effects of the wall are not dominating
  - Injector P/D (pitch-to-diameter ratio) in full annular configuration is high => no sector to sector interaction
  - Wavelength of TA instability is larger than injector pitch
- Full annular test rig is high TRL but:
  - Inlet acoustics has to be set up to be representative of HPC outlet
  - Pressure levels reached may not be engine representative
  - No effects due to rotor forcing
- Engine is the real thing, but:
  - Too late to fix design problems
  - Too expensive for design iterations

Single sector rig
Single sector rig

Full annular rig

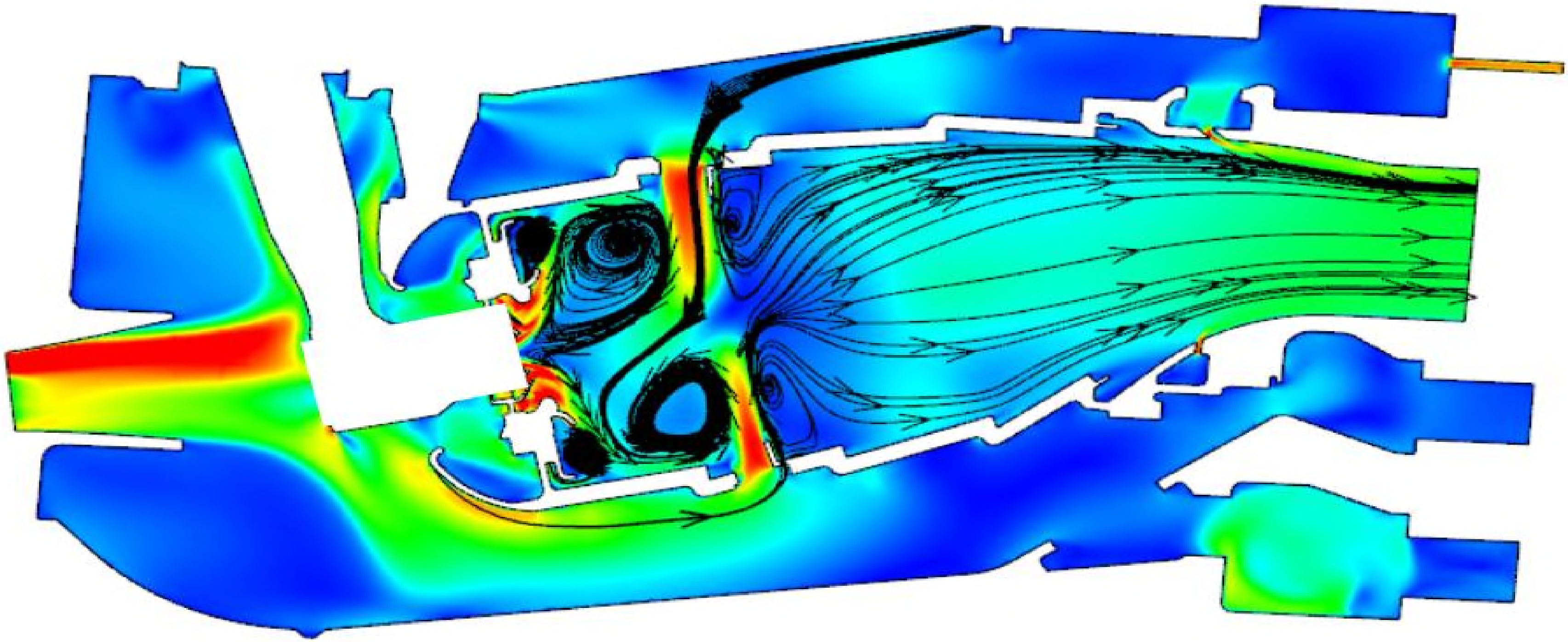
Engine

Effects of hydrodynamic instabilities on TA

- Incompressible aerodynamic phenomena can be a cause of TA instabilities:
  - Vortex shedding from fuel injectors
  - Flow separations
- These problems can be spotted by aerodynamic testing or LES
- Periodic phenomena can lock in with acoustics only if the frequencies are consistent (i.e. the same or harmonics)

Effect of external aerodynamics on TA

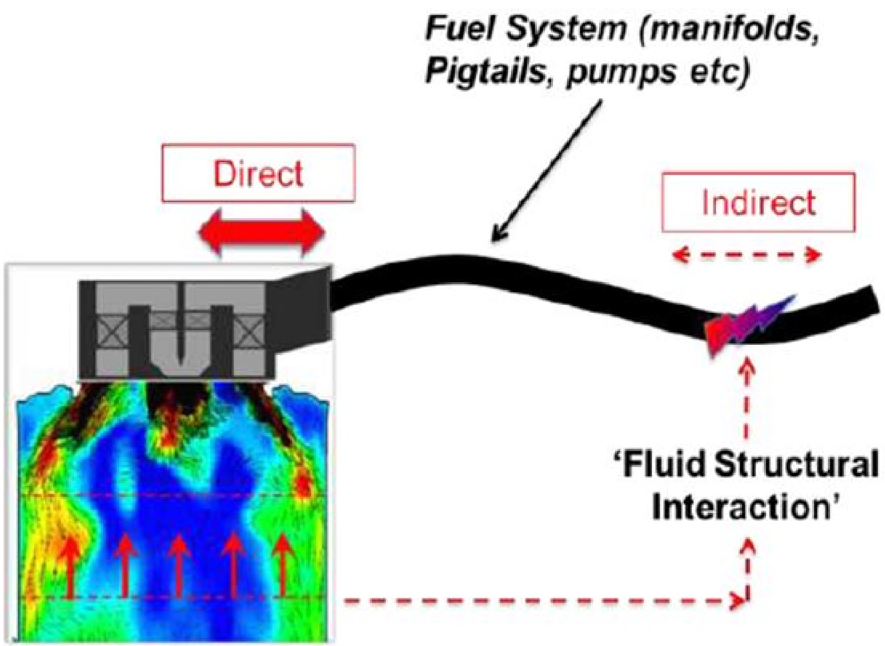
- Cavities external to the flametube can have a resonant effect
- Unsteady aerodynamic phenomena can lock in with characteristic frequencies



Full system aerodynamics

Fuel flow effects on TA

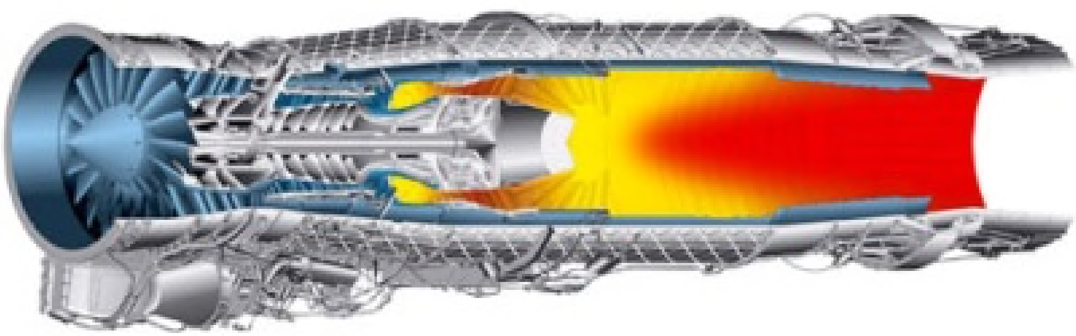
- Fuel pumps can induce fuel flow fluctuations leading to TA instabilities
- Mechanical vibration can introduce forcing to the fuel delivery (fluid-structure interaction)



Fluid-structure interaction

Afterburner TA instabilities

- Afterburners can suffer from buzz and screech
- Buzz: low frequency, axial model linked to propagation of entropy waves. It can be modelled in 1D/2D
- Screech: high frequency transverse mode, requires introduction of dampers, can only be modelled in 3D
- Afterburner TA instabilities can be a show stopper



EJ200 engine cutaway

Summary

- TA instabilities pose a serious risk to engine development
- Low order modelling can be used to understand problems, but FTF/FDF is required
- Deriving FTF from experiments is possible, but challenging
- Deriving FTF from CFD requires very careful modelling
- Some success has been shown using CFD for gaseous flames, FTF for liquid fuelled combustors is more difficult to derive
- There are many different possible causes for TA instabilities
- Rich and lean burn combustors can be affected, but lean ones are more susceptible to TA instabilities
- Afterburners suffer from TA instabilities as well
- The topic is focus of intense research