Dealing with Power Generation Gas Turbine Combustor Thermoacoustics

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Note:

- The examples and information in this presentation reflect the author's own experience
- All manufacturers have had problems and failures due to thermoacoustics and the examples in this presentation do not imply that the gas turbines featured are more susceptible to problems than others
- All manufacturers have suitable and robust methods for the detection and control (where appropriate) of thermoacoustic events in their gas turbines
- The author thanks Uniper Technologies for permission to use images and examples. The interpretation of these images and examples is that of the author and may not reflect the views of Uniper Technologies.

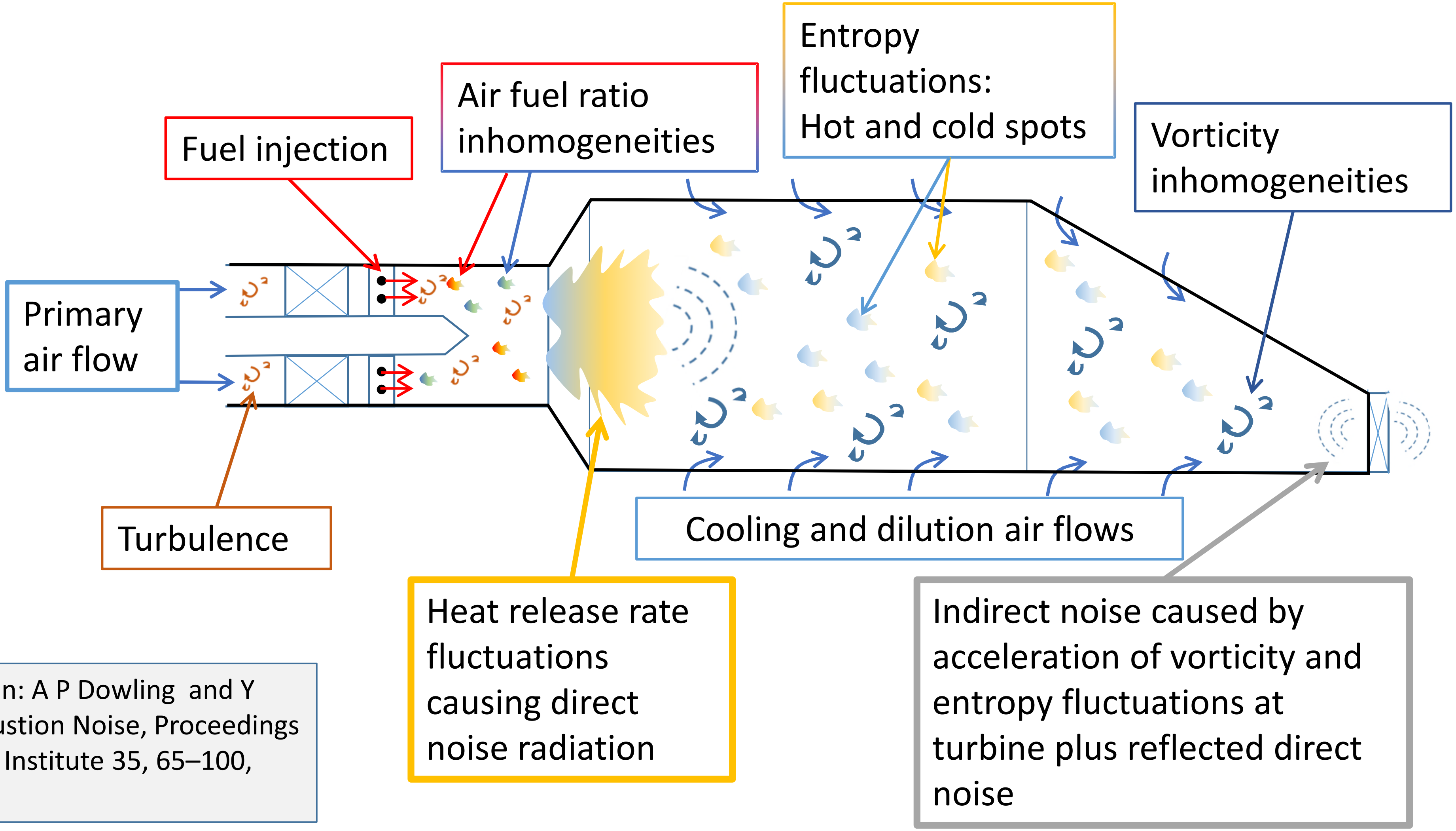
Thermoacoustics Lecture

Intended Outcomes.

Following this lecture you should be able to:

- List typical problems associated with thermoacoustic (TA) pressure oscillations
- Describe the feedback mechanism that leads to high amplitude (TA) pressure oscillations
- Outline methods for dealing with TA problems during gas turbine operation
- Identify combustor design features and operating conditions that affect TA oscillations
- Outline the methods by which the occurrence of TA problems can be predicted during the design process

Combustion Noise Sources in a Gas Turbine



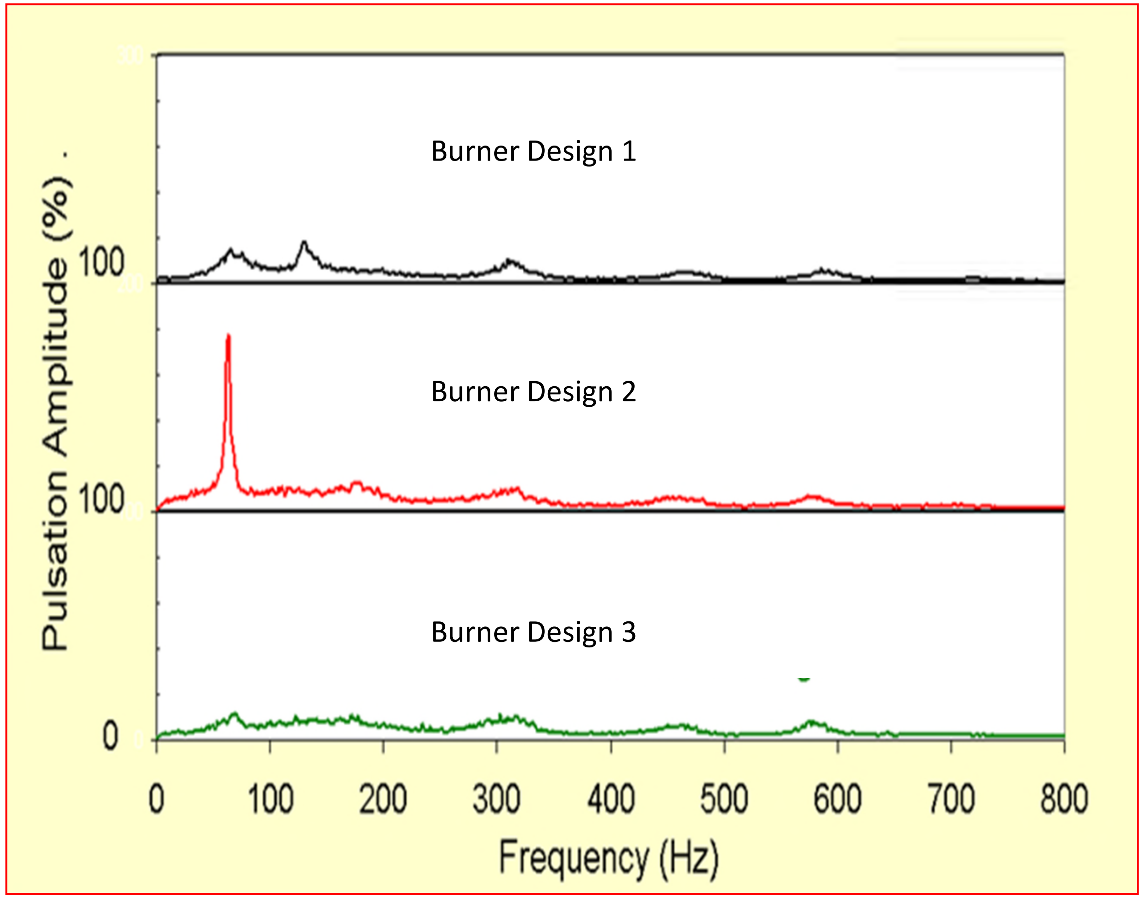
More information in: A P Dowling and Y Mahmoudi, Combustion Noise, Proceedings of the Combustion Institute 35, 65–100, 2015

Noise in a Power Generation Gas Turbine Combustor

- All flames produce some noise due to turbulence, fluctuating heat release etc.
- This noise is typically broadband in nature and is not normally of sufficient amplitude to cause problems

- Under some circumstances, particular acoustic frequencies are favoured and high amplitude narrowband noise can occur

Effect of burner design on dynamics



From D.J.Abbott, U Nilsson, Pirmin Schiessel and Anurag Jhalani:, Investigations into Combustion Generated Oscillations in Large Gas Turbine Combustors Firing Oil Emulsions, Presented at The International Colloquium on Combustion and Noise Control , Cranfield University, 2003

Types of Combustion Noise

The phenomenon is widespread and different manufacturers and researchers in the field give it different names:

- Thermoacoustics (TA)
- Combustion Driven Oscillations (CDO)
- Combustion Instabilities
- Dynamics
- Pulsations
- Humming
- Chug
- Hot/Rich tones
- Cold/Lean tones
- Screech
- High Frequency Rumble
- Low Frequency Rumble
- Buzz

and many more!!

Why are high levels of combustor noise an issue?

- **Environmental noise**
  - Not a significant in land based due to heavy pressure casings, enclosures, inlet and outlet silencing etc.
  - Can be significant for aviation gas turbines
- **Noise within the combustor**
- **Excites vibration in the surrounding structures (burners, fuel injectors, combustor components etc.), resulting in:**
  - **Wear of seals and interfaces** leading to:
    - Reduced component life
    - Increasing air leakage which may:
      - Increase NO_X or CO emissions
      - Impact efficiency
      - Affect combustion stability

Why are high levels of combustor noise an issue? (2)

- **Component cracking /damage** leading to:
  - Reduced component life
  - Air leakage which may:
    - Increase NO_X or CO emissions
    - Impact efficiency
    - Affect combustion stability
  - Catastrophic failure
- **Impact on combustion stability**: flashback and blow-off, leading to:
  - Component damage
  - Operation issues

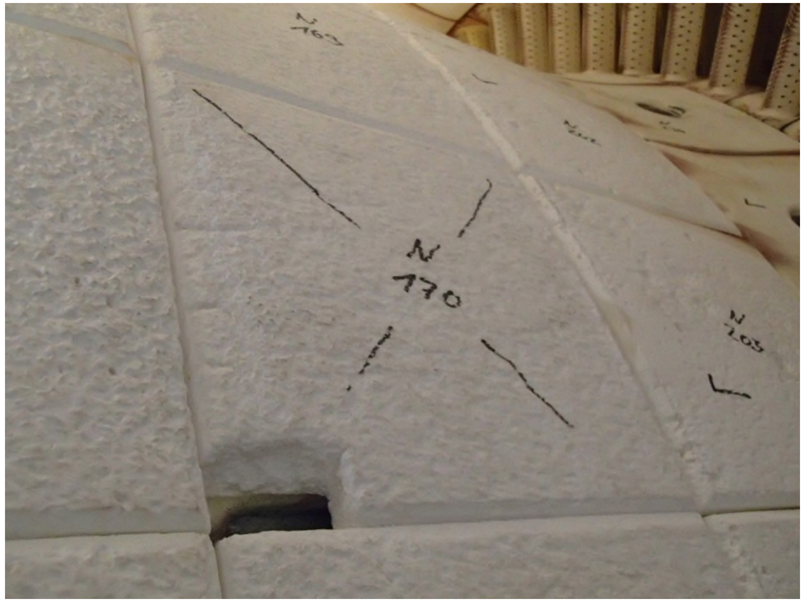
- **Increases heat transfer to combustor wall potentially resulting in:**
  - **Component cracking /damage** with same consequences as above

Issues: Example 1

V94.3A (SGT5-4000F)

- Tile cracking and corner loss
- Associated with high levels of "humming"
- Damage can happen very rapidly
- Complete tiles may be lost
- Compromises thermal protection of combustor structure

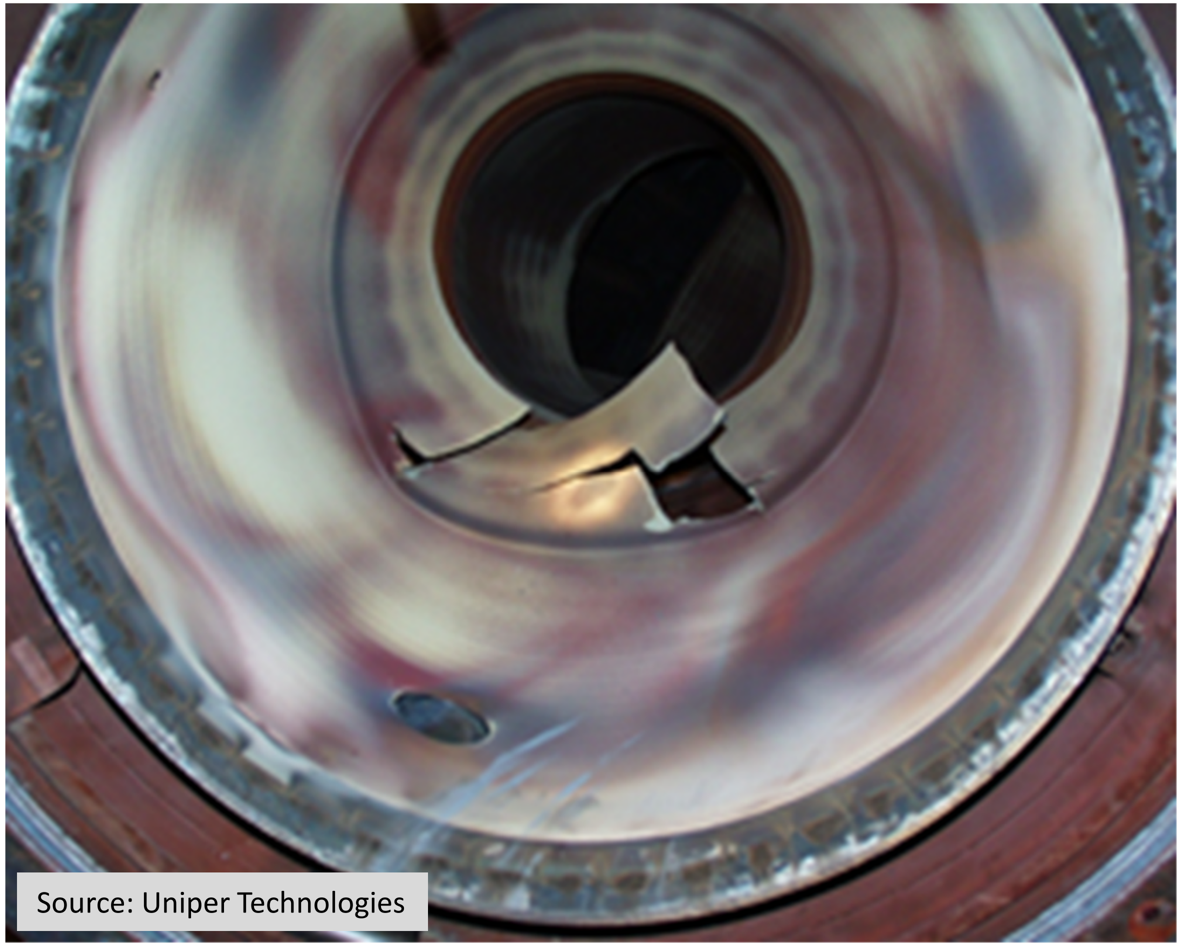
Source: Uniper Technologies



Issues: Example 2

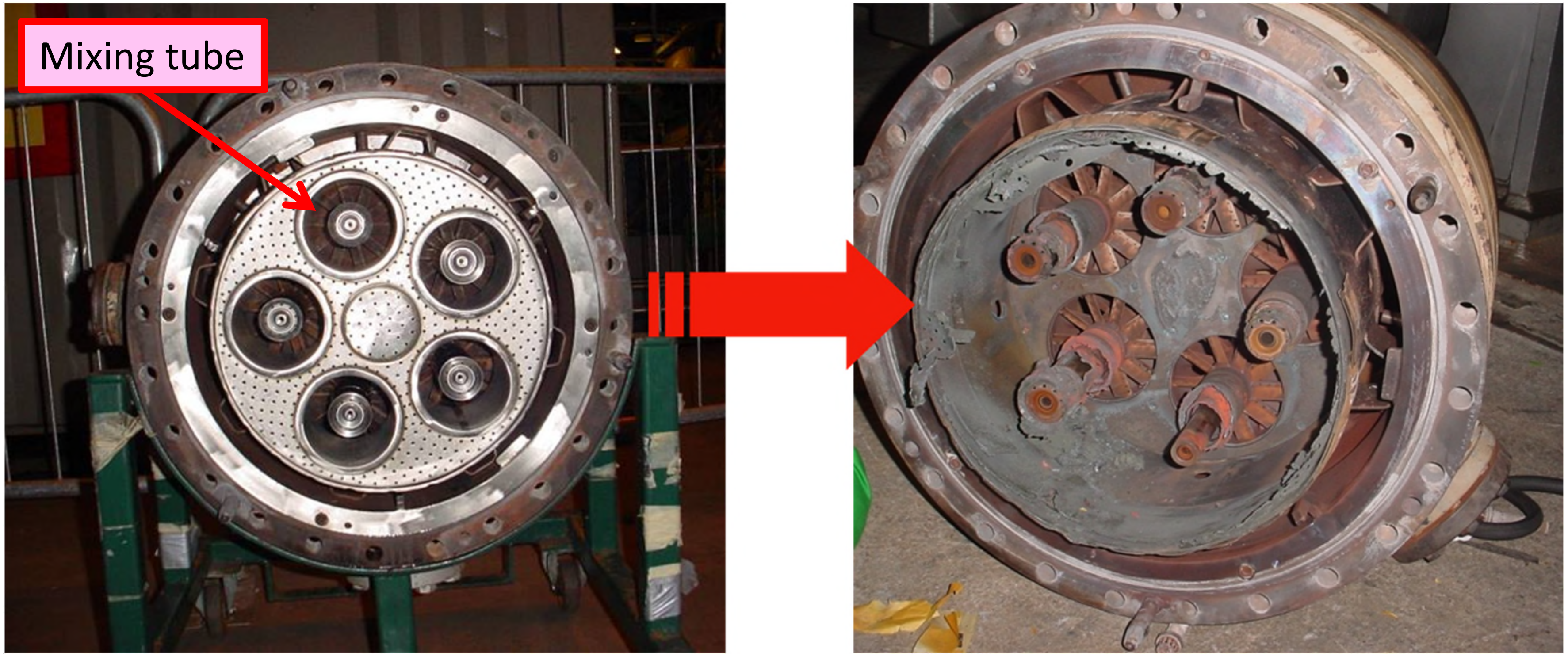
GE9FA, DLN2 combustor

- Cracking and opening of combustor can wall
- Believed to be due to triangular deformation of the converging section of the can due to coupling with a combustion acoustic mode at about 150Hz



Looking downstream from burner end of can

Issues: Example 3
GE9FA, DLN2 combustor



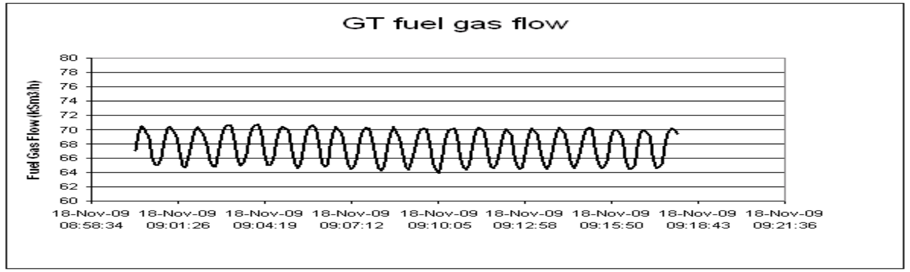
- High amplitude high frequency dynamics (Screech: of the order of 2kHz) caused cracking of weld and thus release of mixing tube
- Resulted in flashback and significant consequential damage

Causes of High Amplitude Pressure Oscillations in Combustion Systems

Forced

(Should not be a problem in well designed systems)

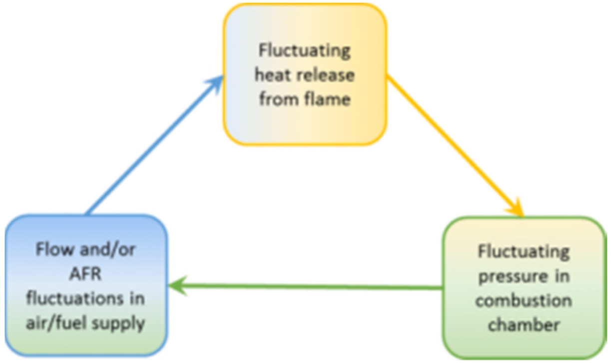
Oscillatory inputs from air or fuel feeds, aerodynamic effects etc.



Acoustic Feedback

(Usually most significant in GT combustors)

Self sustaining oscillations due to feedback



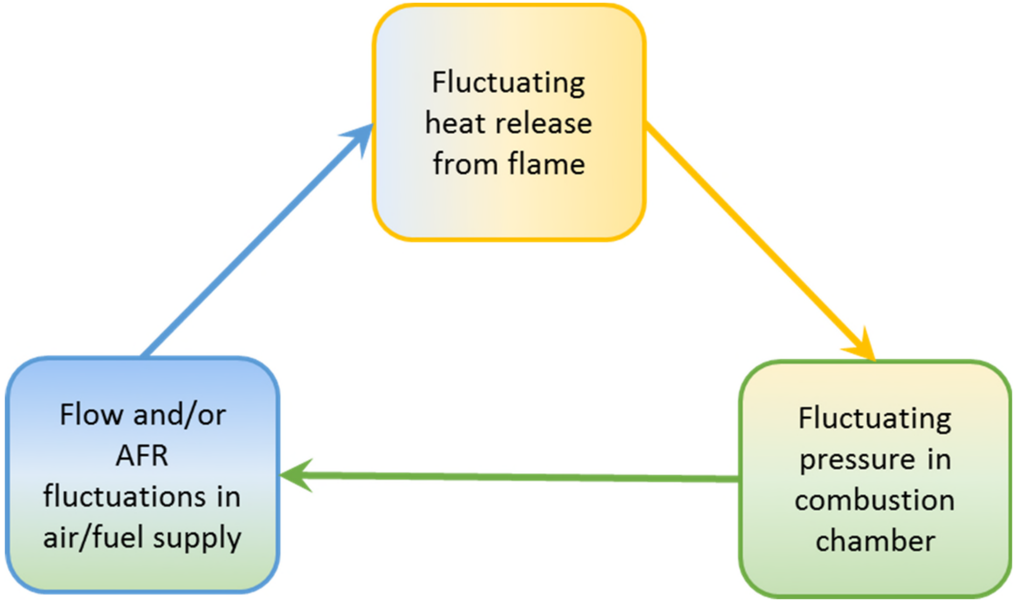
Aerodynamic/Coupled

(Can affect the incidence of feedback)

Aerodynamic inputs (e.g., vortex shedding and shear layer instabilities) which “lock-on”

Rayleigh Criterion:
Lord Rayleigh, Nature 18 (1878) 319–321

- The phenomenon and its analysis are not new. Lord Rayleigh concluded:
  - If pressure and heat release fluctuations are in phase, the instability is fed by the flame/acoustics coupling
- This is a necessary, but not sufficient condition for feedback oscillations to occur
  - Acoustic energy must also be supplied by the periodic heat release at a rate that is greater than the rate of acoustic energy loss/dissipation from the combustion system



The Rayleigh Criterion and the energy loss criterion may be combined as follows:

$$\int_V \int_T p'(x,t) q'(x,t)\, dt\, dV \geq \int_V \int_T \sum_i \mathcal{L}_i(x,t)\, dt\, dV$$

where p' and q' are pressure and heat release fluctuations, respectively, $\mathcal{L}_i$ represents the i^{th} acoustic energy loss process, V and T represent the combustion volume and the time domain respectively and x and t are distance and time.

Flame Response

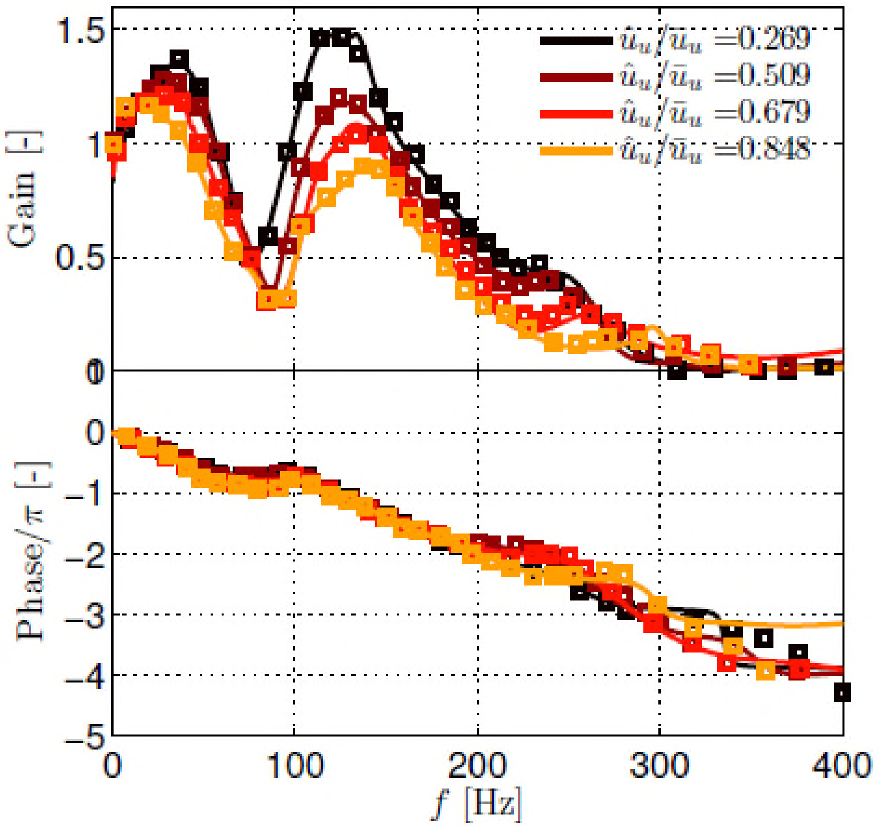
- Flame amplification represented by Flame Transfer Function (FTF):

$$F(\omega) = \frac{\hat{Q}(\omega)/Q_0}{\hat{u}(\omega)/u_0}$$

Where:
ω = angular frequency = $2\pi f$
$\hat{Q}$ = fluctuating heat release
$\hat{u}$ =fluctuating inlet velocity
Q_0 & u_0 are mean values

- Fluctuating flame output velocity is proportional to $\hat{Q}$ ➲ flame acts as an acoustic velocity amplifier

- FTF Determined Analytically, Experimentally or using CFD



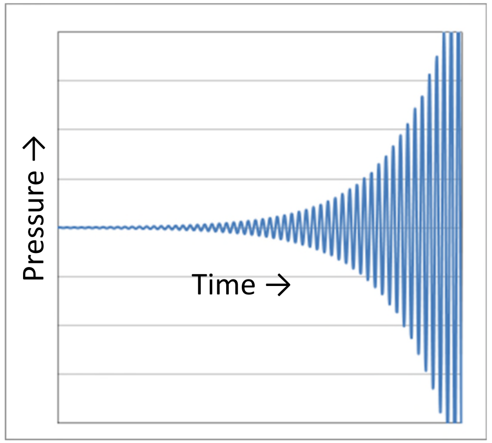
Flame describing function
(i.e. FTF determined for different $|\hat{u}|$)
Results for a gaseous fuelled test combustor.

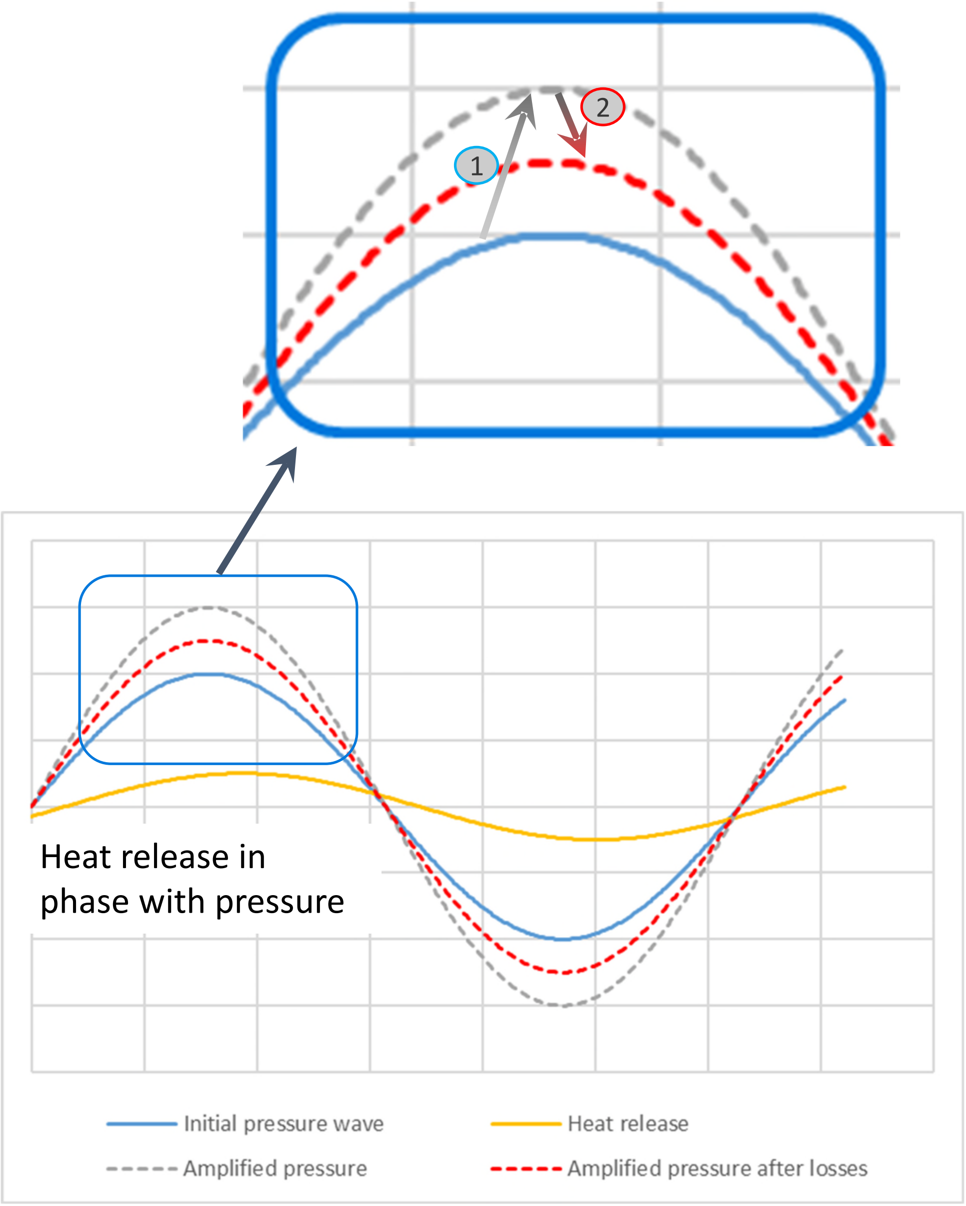
Results from: Xingsi Han, Jingxuan Li & Aimee S. Morgans, Prediction of combustion instability limit cycle oscillations by combining flame describing function simulations with a thermoacoustic network model, Combustion and Flame 162 (2015) 3632–3647

Acoustic Feedback

1. In phase heat release amplifies acoustic pressure fluctuation
2. Acoustic losses in system reduce acoustic pressure fluctuation

- In this example losses are low and there is overall amplification
- Pressure increases with each cycle giving growth

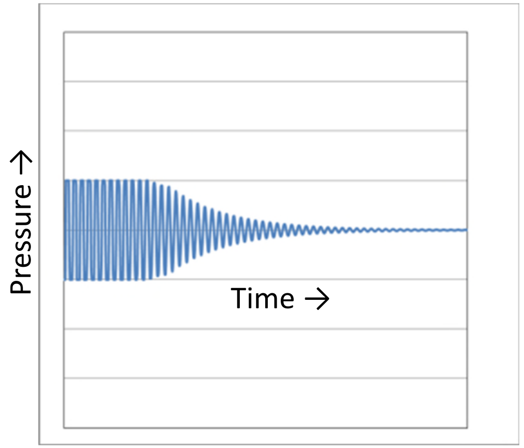


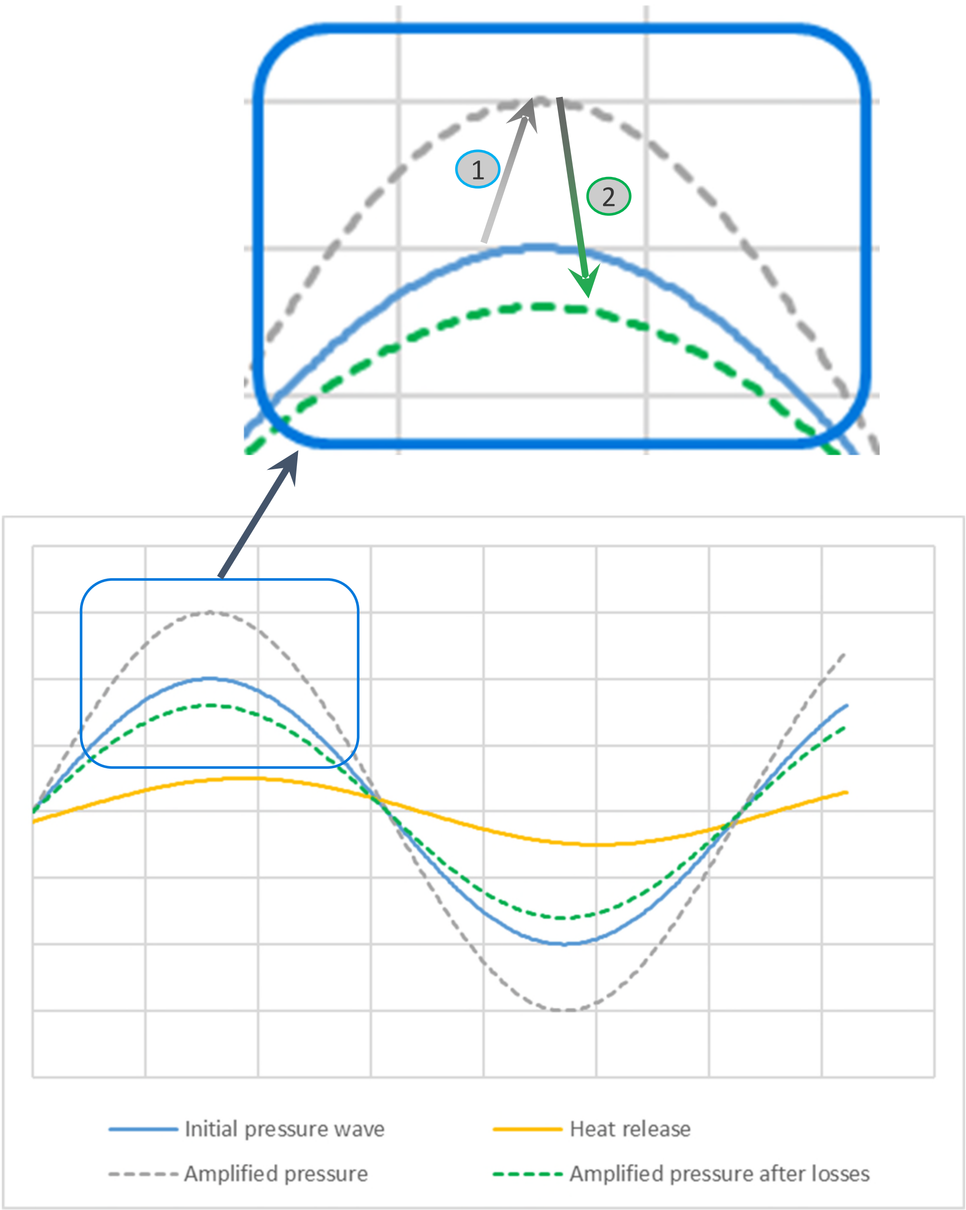


Acoustic Feedback

1. In phase heat release amplifies acoustic pressure fluctuation.
2. Acoustic losses in system reduce acoustic pressure fluctuation

- In this example losses are high and there is an overall reduction in pressure
- Pressure decreases with each cycle giving decay





Acoustic Losses

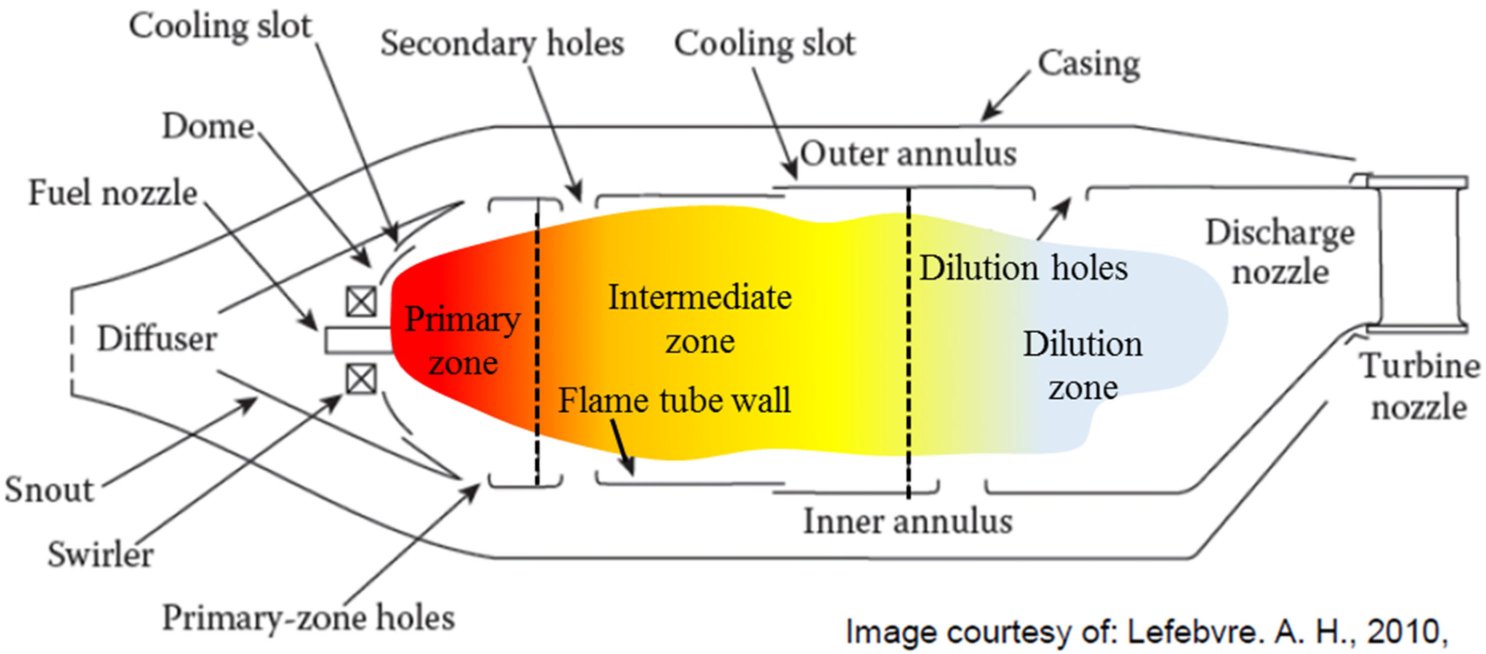


Image courtesy of: Lefebvre. A. H., 2010, "Gas Turbine Combustion", 3rd Edition, McGraw Hill

- What are the acoustic losses from the combustion system?

Acoustic Losses

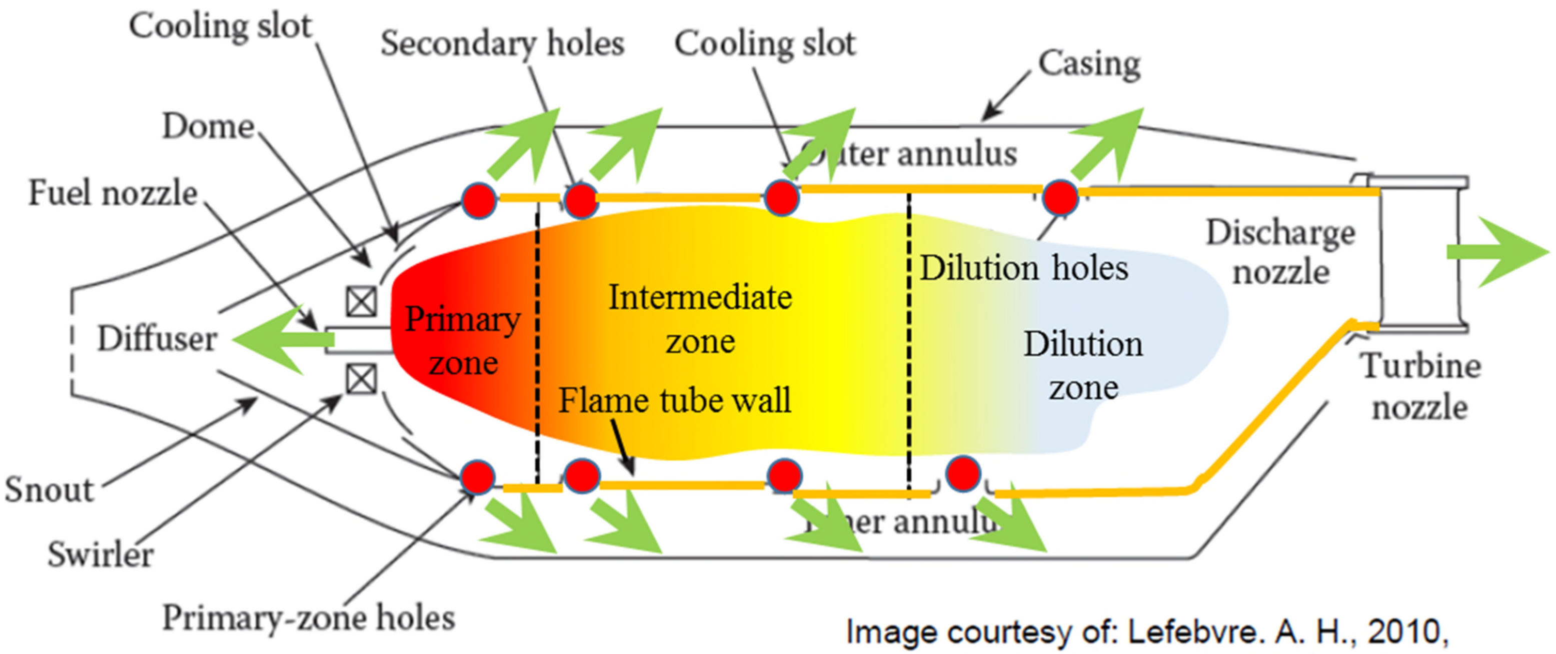


Image courtesy of: Lefebvre. A. H., 2010, “Gas Turbine Combustion”, 3rd Edition, McGraw Hill

Sound passes out of the combustor to be lost elsewhere

Acoustic energy is lost due to interaction with holes and inlet air flows

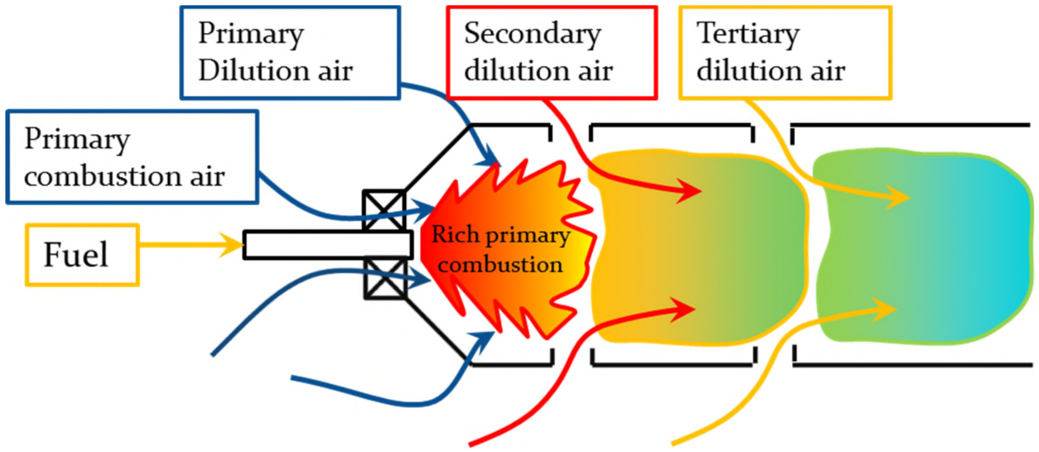
Losses at walls due to vibration excitation and sound transmission
Frictional losses at walls: usually negligible in the combustor

Viscous losses in bulk gases:
usually negligible

Typical GT Combustion Concepts

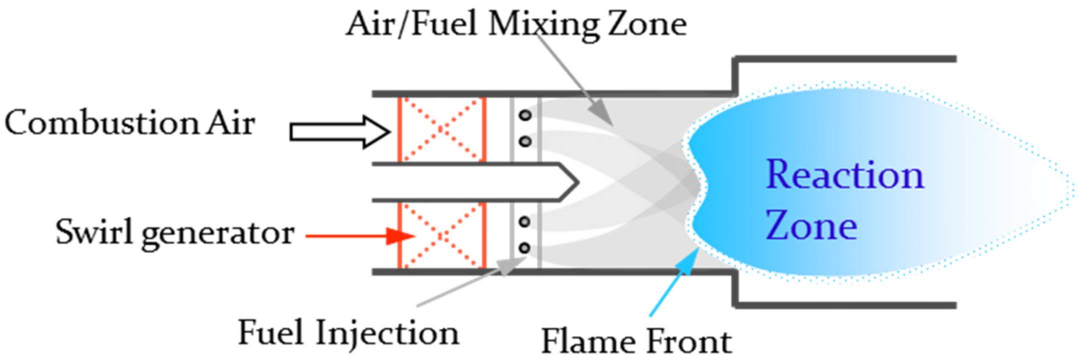
Diffusion Combustion:
- Air/fuel mixing in combustion zone
- Wide spread of fuel concentrations

Gives:
- Stable, efficient combustion
- Wide operating envelope
- Flashback resistant
- High NO_X emissions



Lean Premix Combustion:
- Air/fuel mixing before combustion zone
- Lean Combustion

Gives:
- Low NO_X emissions
- Potential for flashback
- Issues with stability and dynamics
- Need for careful combustion tuning



Diffusion vs Premixed

All early industrial and aero gas turbine combustion systems were diffusion based:

- Diffusion based combustors do not usually suffer significantly from combustion dynamics
- Since the mid 1990's the majority of the power generation gas turbine capacity in developed countries has some form of premixed combustion (for NO_X emissions reduction)

The introduction of lean premix combustors has caused significant problems for all major gas turbine manufacturers

The need to develop combustion systems natural gas/hydrogen blends and other high hydrogen fuels is a new challenge

Development of Low NO_X technologies for kerosine, SAF and hydrogen combustion are increasing the importance of thermoacoustics in aviation engines

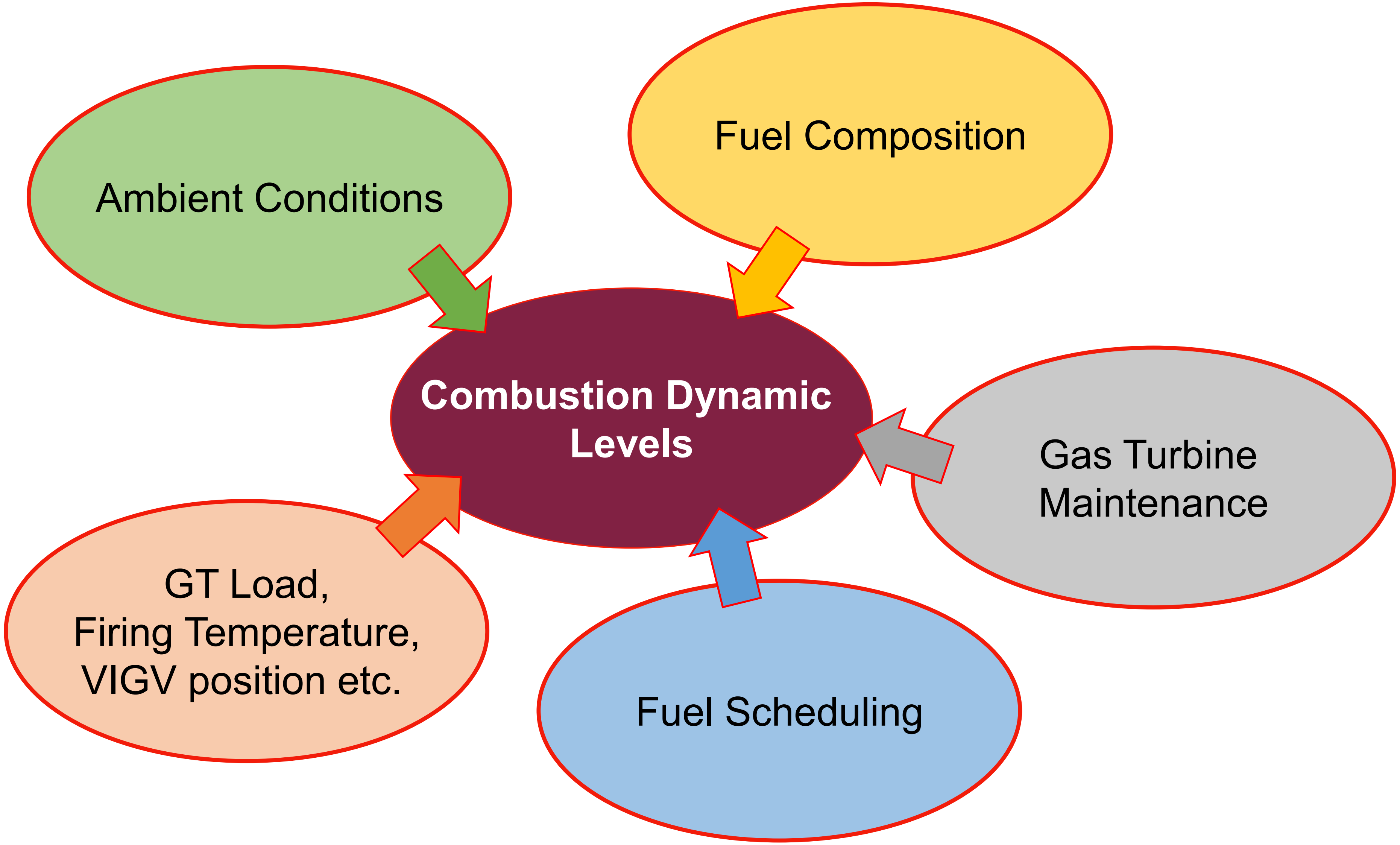
Approaches to Reduce TA Instabilities

- **Design it out:**
- During development testing, select designs showing low levels of pressure fluctuations:
  - Not necessarily a good approach (see later)
- Identify desirable design features:
  - These may conflict with other requirements (e.g. emissions)
- TA modelling may help optimise desirable features and interpret test data

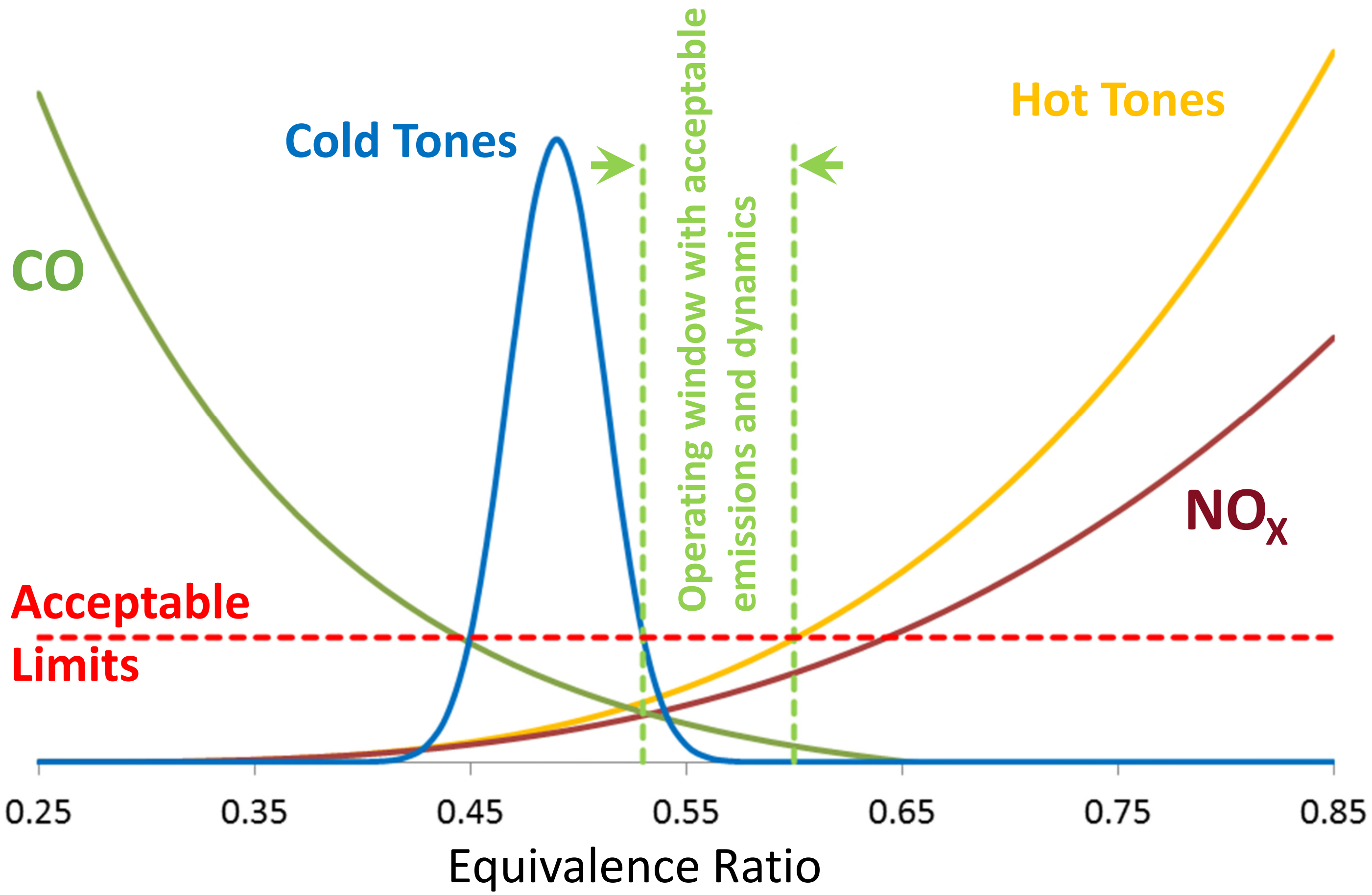
- **Control**
- Tuning
- Operator/Control System action
- Automatic Tuning (Reactive Control)
- Active control: impose frequency and amplitude dependent fluctuations of the fuel
  - Reliability and durability of the actuators are issues

- **Change phase or increase losses:**
- Piloting, fuel staging or injector design changes to change flame properties:
  - Adds complexity to fuel system and may increase emissions
- Helmholtz resonators(and other tuned devices):
  - Narrow frequency band, need space, add weight, use air (impact emissions)
- Broadband dampers (e.g. perforated plates):
  - Need space, add weight, use air (impact emissions)
- TA modelling can help optimise dampers

Factors That Affect Combustion Dynamics



Operability limitations of lean premixed combustors



Positions of plots relative to each other and EQR change depending on a wide range of factors including fuel scheduling.

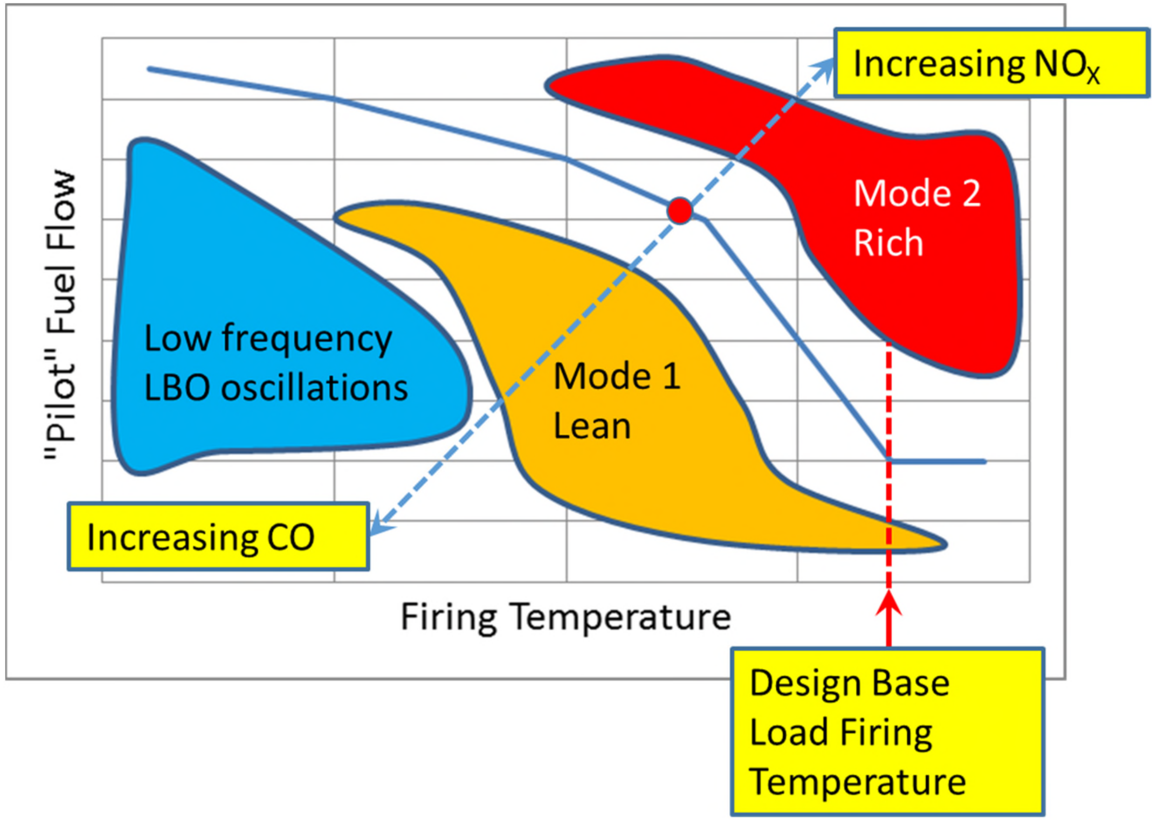
Scheduling can used to tune the combustor to give optimum emissions and dynamics

Tuning Concept: Modifying Flame Response by Piloting and/or Staging

- Multiple fuel streams for staging and piloting
- “Pilot” Flow and Firing Temperature varied systematically to determine impact on:
- Dynamics, Emissions (CO, NO_X), System operation
- Impact of other control parameters (e.g., Load, VIGV position etc.) investigated systematically

- **Aim:**
- **Determine an acceptable operating schedule to:**
- Minimise emissions (achieve permit levels)
- Maximise GT output
- Achieve acceptable dynamics
- *Have sufficient margin to allow for variations in ambient conditions, fuel composition etc.*

Example:
Single shaft machine with two fuel streams (main and pilot)

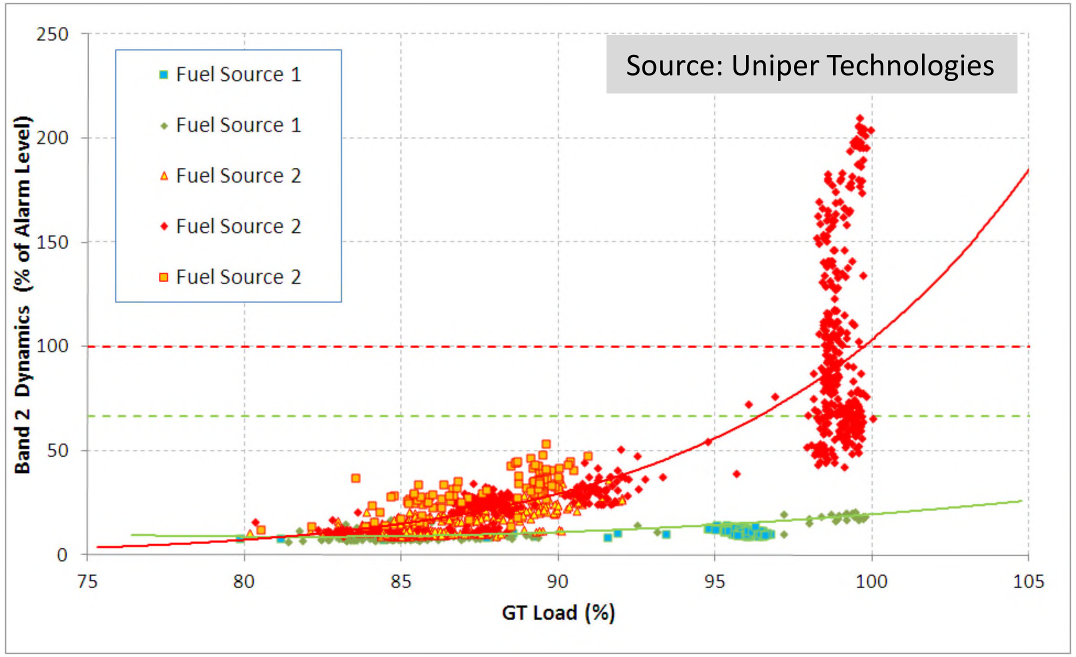


Typical distribution of combustion dynamics

Impact of Fuel Composition and Importance of Tuning Margin

- Site with multiple natural gas sources
- Alert and Alarm levels set for protection
- Operator to act to prevent levels above *Alarm* if possible
  - Levels exceeded Alarm
  - Load restricted (to ~95% load)
  - NO_X increase also seen
  - ***All fuel was within specification***

- Tuned on Fuel Source 1 (Higher hydrocarbons, C2+ ~7%)
- High dynamics when firing Fuel Source 2 (C2+ ~11%)



- Had been tuned for very low NO_X emissions
  - Insufficient margin allowed to accommodate fuel changes

- Retuned for acceptable dynamics on both fuels
  - NO_X increased by ~10%, but still well within Permit Levels

Control: Action on high dynamics

- Warning/alarm
  - Operator action needed
    - Typically de-load or shutdown

In some combustors, dynamic pressures can grow very rapidly reaching damaging levels in seconds (or less)
→ **No time for operator action!**

- Automatic closed loop control system
  - Automatic Action
    - Typically de-load or shutdown
  - More modern systems may have some degree of automatic tuning

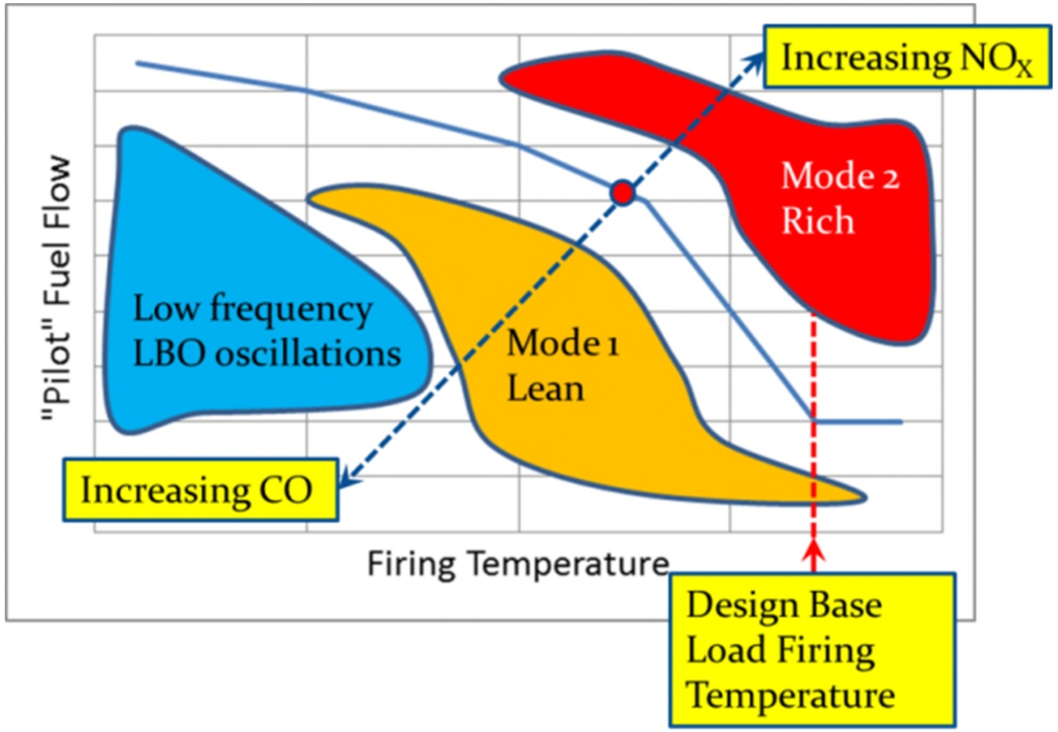
- Some systems try to anticipate high dynamics by looking at related parameters
  - Such as rate of change of dynamics, ratios of dynamics amplitudes at different frequencies, statistics of dynamic pressures etc.

Automatic tuning

Example 1: **Siemens Advanced Stability Margin Controller (aSMC)**

Used on Siemens SGT5-4000F (V94.3A) and some other Siemens machines
The most significant issue is high combustion chamber acceleration caused by humming.
aSMC is configured to control this

- Uses closed loop control of the combustion acoustics to change the pilot gas amount or the turbine outlet temperature according to a fixed set of set rules which depend of the load range and the frequency of humming
- **System operates successfully to control humming**

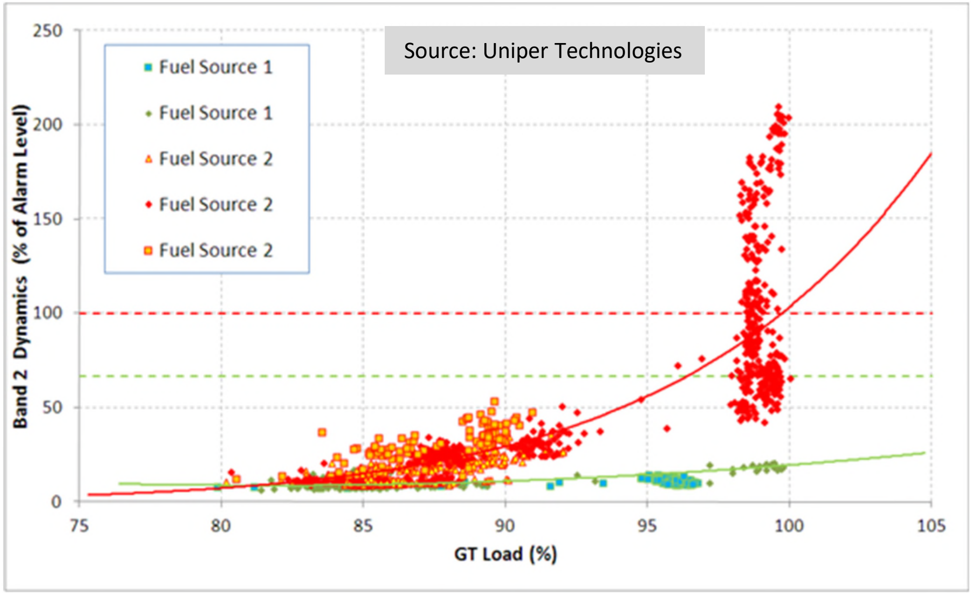


Automatic tuning

Example 2: **GE OpFlex AutoTune**

- Part of GE's "Combustion Versatility solution suite"
  - Automates combustion tuning
  - Uses measured combustion dynamics and NO_X emissions (may be calculated) fed into a model based control system to optimise dynamics and emissions.
  - Self teaching algorithms are used and require extensive initial set-up and tuning to generate robust models

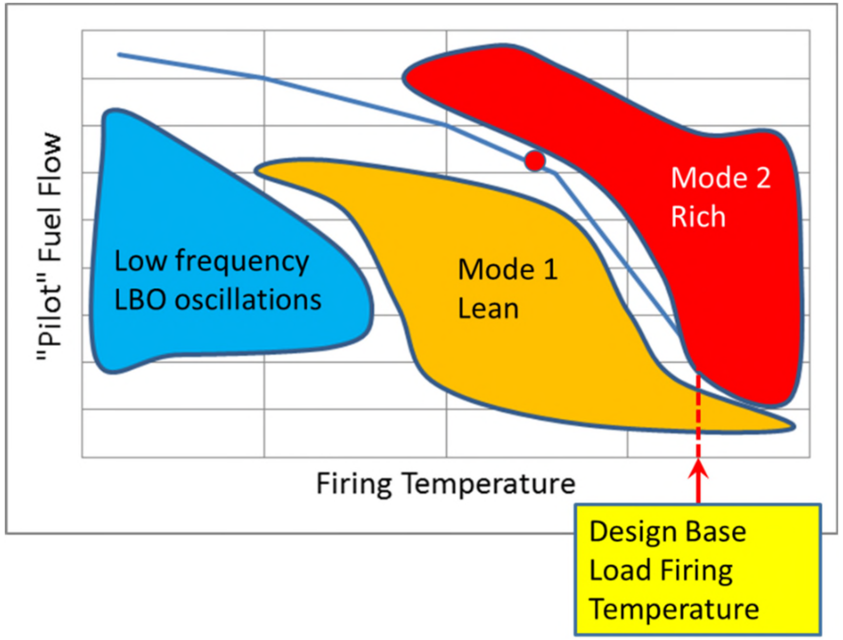
- Works well to deal with fuel variations

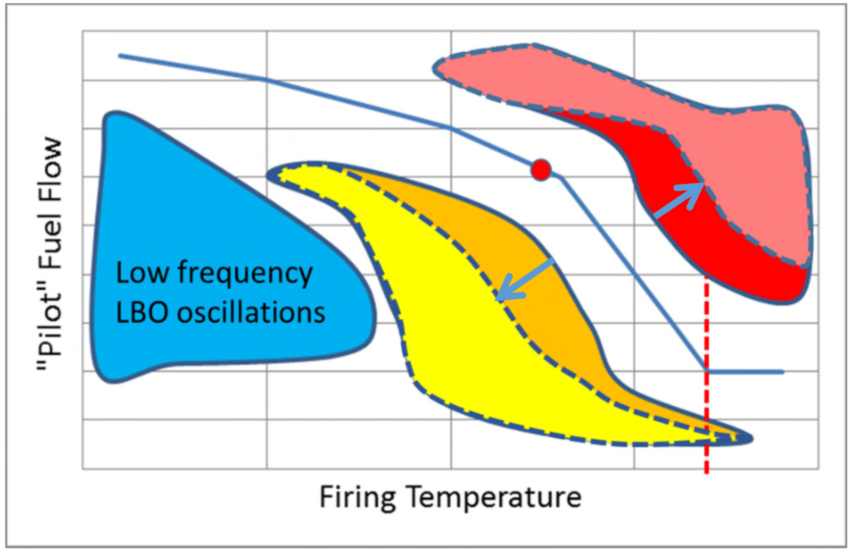


Implemented on the plant that had the above dynamics issue:
Successfully dealt this fuel variation without manual retuning

No practicable schedule or want to widen the margins?

- Need to change the acoustic behaviour of the system
- Options:
  - Active Control
  - Passive control
    - Burner design/ Flame modification
    - Tuned devices (Helmholtz resonators, quarter-wave tubes...)
    - Perforated liners
  - System design



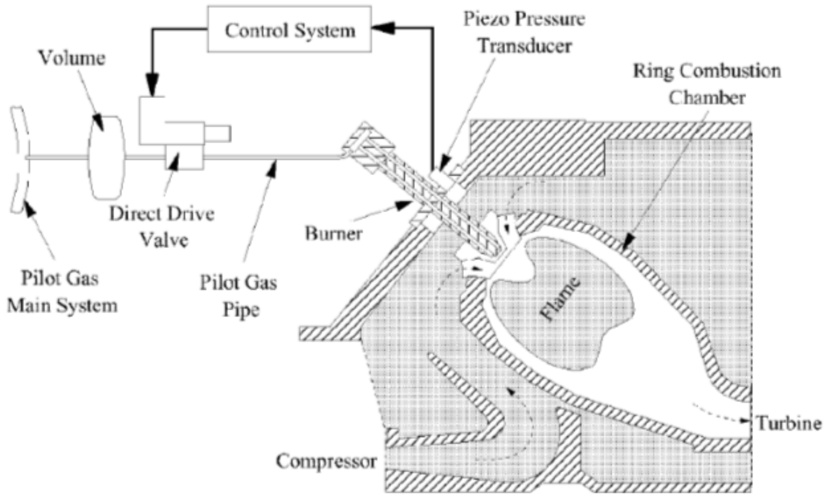


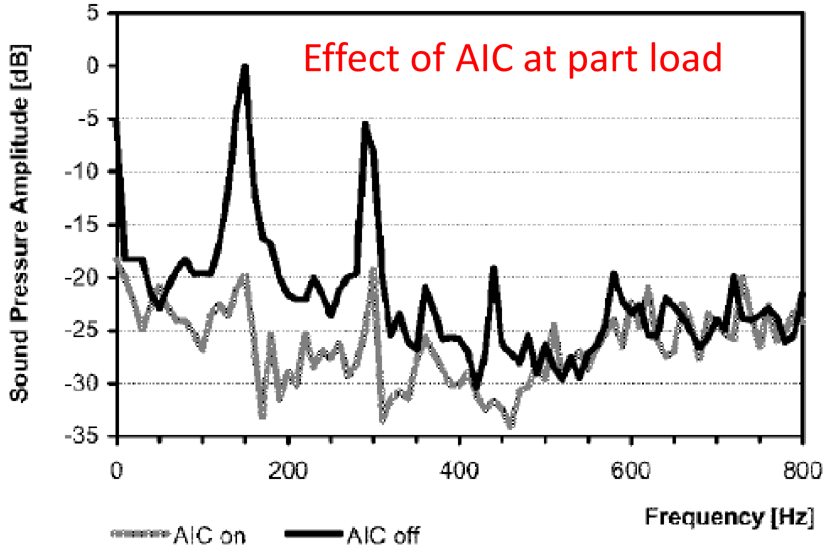
Active Control: Siemens V94.3A

- Humming" associated with azimuthal (circumferential) modes of the annular combustor leading to damage of ceramic tiles
- Developed Active Instability Control (AIC)
    - AIC is commercially available from IfTA GmbH

- Actuator modulates pilot flow to produce pressure fluctuation (via heat release) in anti-phase to the acoustic oscillations
- Effective in supressing unwanted peaks
- Used in conjunction with passive controls
- Expensive
- Less robust than passive measures
- No longer applied to new machines

Schematic of the Active Control system





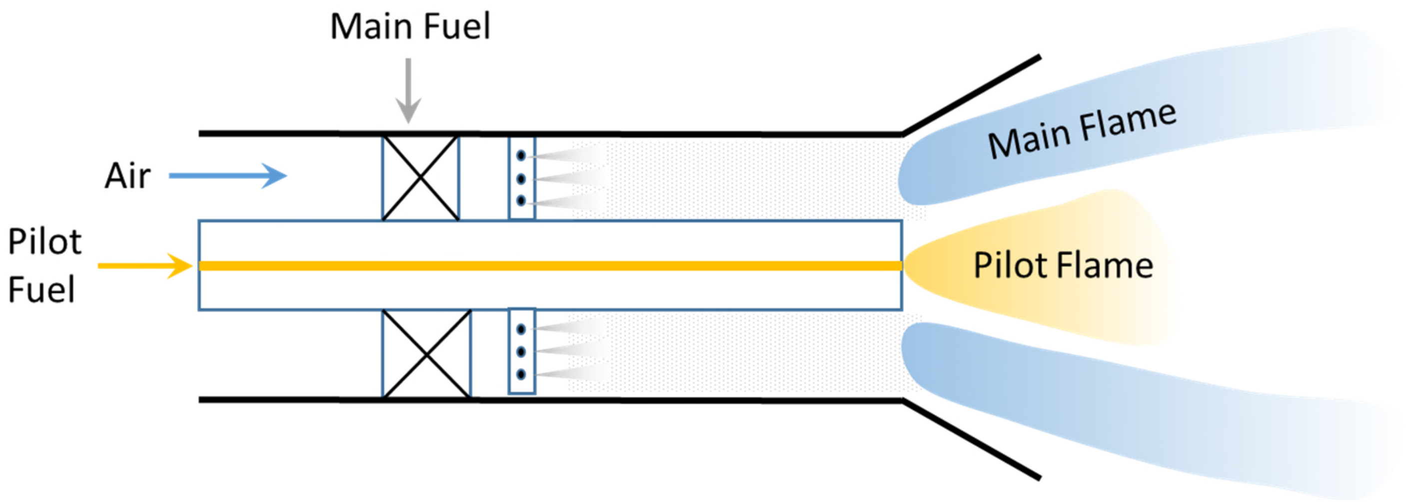
J. Hermann, A. Orthmann, S. Hoffmann, P. Berenbrink, Combination of Active Instability Control and Passive Measures to Prevent Combustion Instabilities in a 260MW Heavy Duty Gas Turbine: From: Paper presented at the RTO A VT Symposium on "Active Control Technology for Enhanced Performance Operational Capabilities of Military Aircraft, Land Vehicles and Sea Vehicles, Braunschweig, Germany, 2000

Passive Control: Burner/Flame modification

- Staging and piloting will affect the flame position and thus flame acoustic properties affecting

- Changing the flame position and mixing properties can affect flame acoustic properties
  - Less likely to adversely impact NO_X or CO than staging or piloting

Fuel Scheduling: Piloting



- Effectively produces two interacting flames
- Changing the distribution of fuel to main and pilot for a given overall EQR changes characteristics of the flames and thus the FTFs

  →→ May be able to “tune out” unwanted oscillations

- **BUT** changing fuel distribution will impact NO_X emissions

Impact on Flame Response: Fuel Staging

1. Injectors have same EQR

   → All FTFs the same

- If unstable mode can occur, all flames feed into the mode giving a strong response

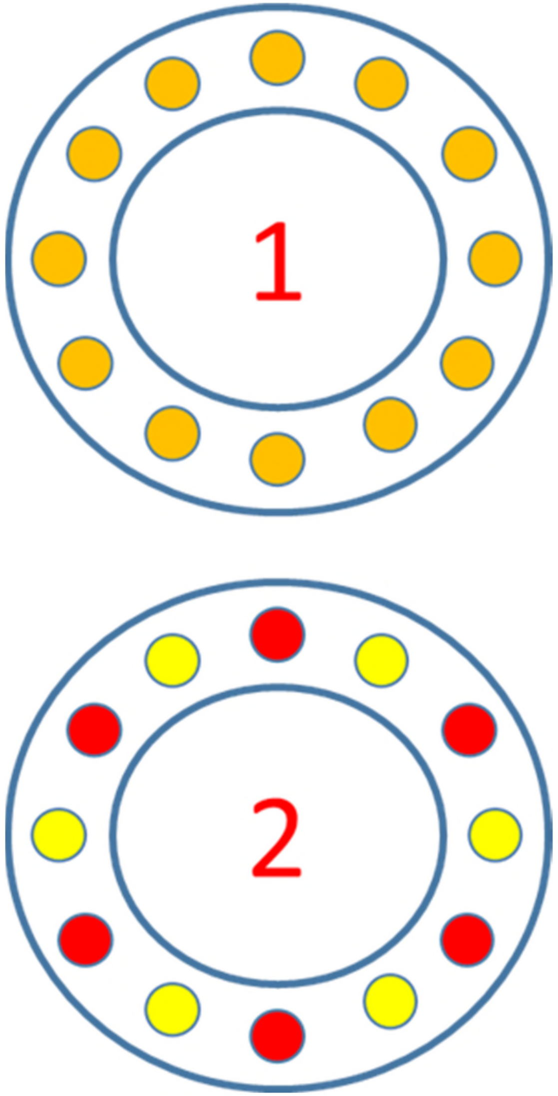
2. Injectors have different EQRs

   (same overall mean EQR as case 1)

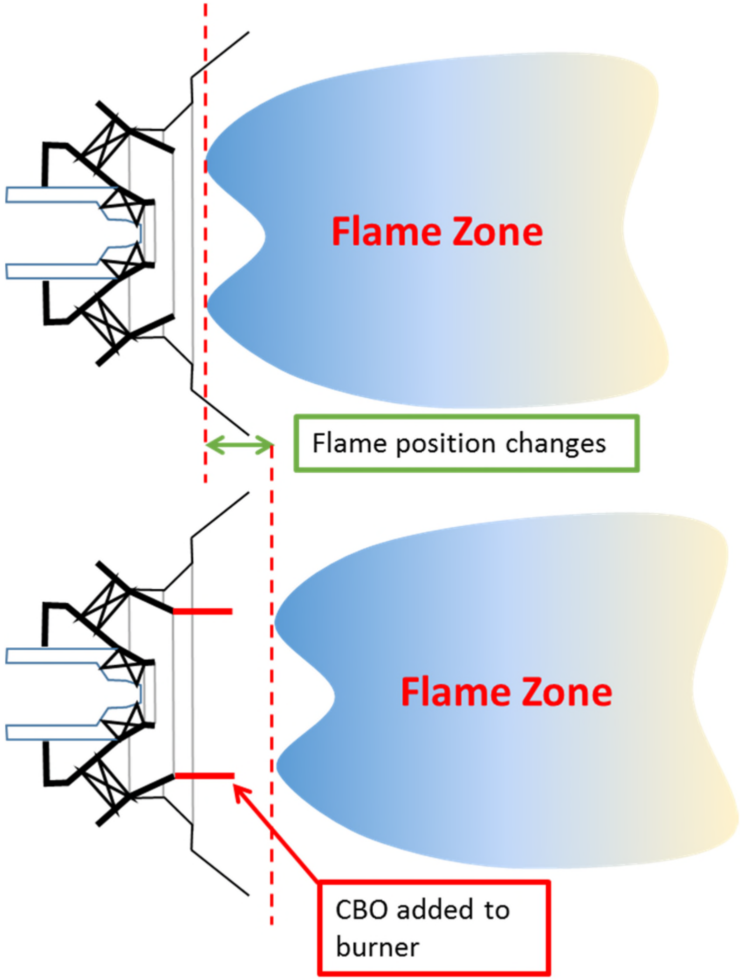
   → FTFs different (different phase)

- Rayleigh criterion will be different for different injectors, thus not all flames will feed into a given mode, reducing the response

- Fuel staging can be used to reduce the risk of unstable modes
- **BUT** changing fuel distribution will impact NO_X emissions



Impact on Flame Response: Burner Modification Case Study: Siemens V94.3A Power Generation GT



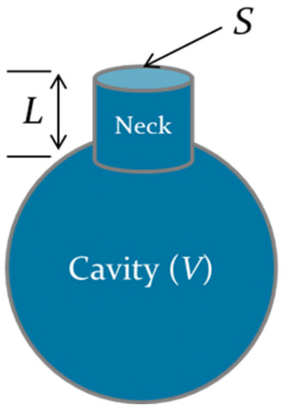
- Cylindrical outlet (CBO) added to burner
- Flame stabilises further downstream increasing mixing time thus changing FTF and affecting interaction with supply and combustor acoustics
- Experiments performed to test various combinations of normal burners and burners with CBOs
- Best results with CBO on 20 out of 24 burners
- Allowed ~8% increase in power output before onset of damaging instabilities

J. Hermann, A. Orthmann, S. Hoffmann, P. Berenbrink, Combination of Active Instability Control and Passive Measures to Prevent Combustion Instabilities in a 260MW Heavy Duty Gas Turbine: Paper presented at the RTO A VT Symposium on "Active Control Technology for Enhanced Performance Operational Capabilities of Military Aircraft, Land Vehicles and Sea Vehicles, Braunschweig, Germany, 2000

Passive Control: Helmholtz Resonators

- Helmholtz resonators modify the acoustic behaviour of the system at particular tuned frequencies
  - Can be matched to known dynamics frequencies
- Resonators may be added to the burner, combustor air supply or fuel supply
  - Typically added to burner or combustor
- Multiple resonators can be added for increased effect
- Resonators tuned to different frequencies may be used
- Quarter wave tubes or other tuned devices may be considered

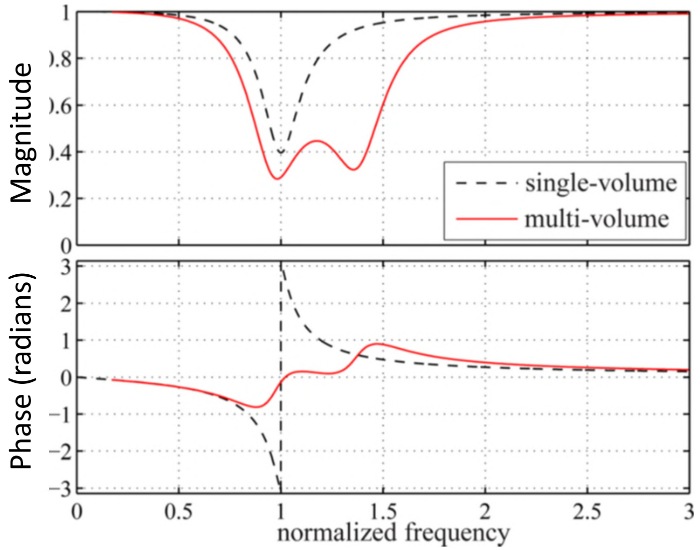
Modifying System Acoustics: Helmholtz Resonators



- Helmholtz resonator: consists of a rigid-walled cavity of volume V with an open-ended neck of area S and effective length L'.
- For simple resonators, the resonant frequency is $f = \frac{c}{2\pi}\sqrt{\frac{S}{L'V}}$, where c is the speed of sound

- Helmholtz resonators modify the acoustic behaviour of the system at particular frequencies which can be matched to known thermoacoustic frequencies
- Resonators may be added to the burner, combustor air supply or fuel supply (Typically added to burner or combustor)
- Multiple resonators used for increased effect and/or increased frequency coverage
- Multi-volume interconnected resonators can have a wider frequency range

Reflection coefficient for single and multiple volume resonators



Reflection coefficient from: Bothien et al., A Novel Damping Device for Broadband Attenuation of Low-Frequency Combustion Pulsations in Gas Turbines, Journal of Engineering for Gas Turbines and Power, APRIL 2014, Vol. 136

Passive Control: Helmholtz Resonators

- There are many patents on the use of Helmholtz resonators and most land based GT manufacturers have used or have trialled resonators in some of their range.

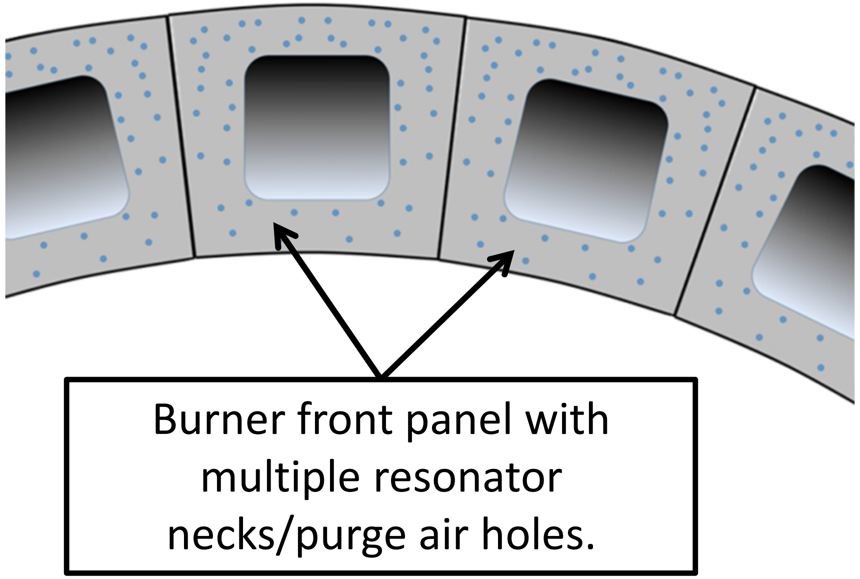
Examples (not exhaustive):

- ALSTOM GT11N2 and GT 13E2 use Helmholtz resonators replacing some burners
- Recent designs of ALSTOM/GE GT24/26 SEV burners incorporate Helmholtz resonators
- Ansaldo have investigated the use of Helmholtz resonators on their VeLowNox Burners on the AE94.3a
- GE have used “Resonator Caps” in their DLN2.0 combustors

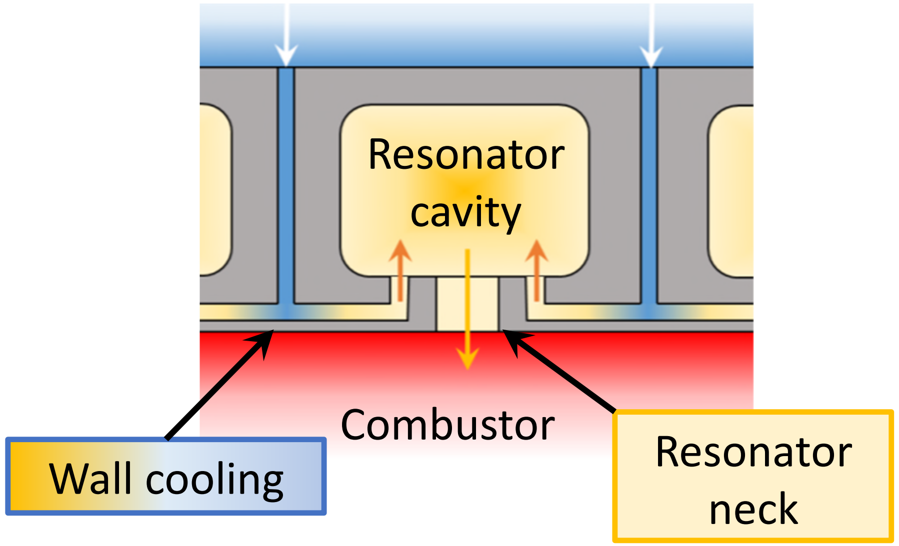
Resonators in ALSTOM/GE GT24 SEV Burner

- Schuermans et al describe a system with multiple Helmholtz resonators incorporated into the sequential burner front panel
- The system also provides improved convective cooling of the front panel

Annular combustor with multiple burners



Resonator concept diagram



B Schuermans, M Bothien, M Maurer, B Bunkute, Combined Acoustic Damping-Cooling System for Operational Flexibility of GT26/GT24 Reheat Combustors , Proceedings of ASME Turbo Expo 2015, Montréal, Canada, Paper GT2015-42287

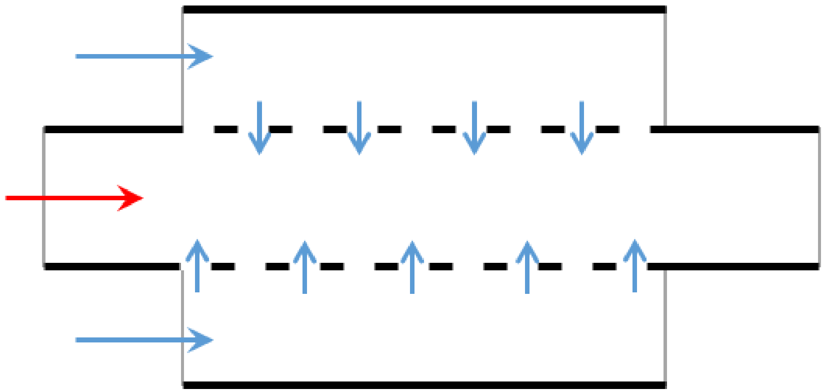
Resonator Caps: GE DLN2

- Later versions of the combustor had a Helmholtz resonator installed on the burner centreline tuned to ~2kHz to help suppress screech

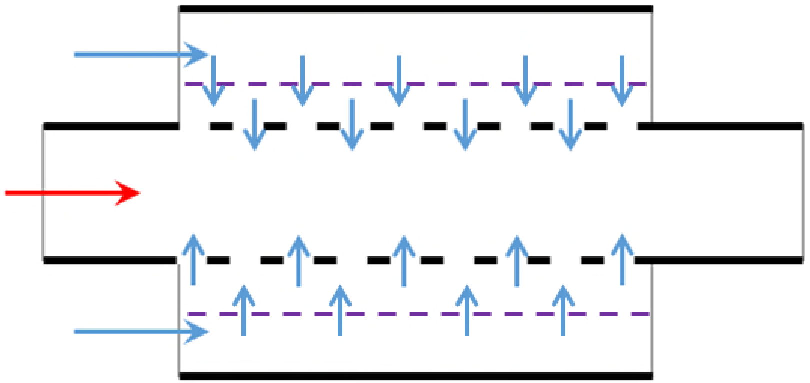
Perforated Liners

Perforated liners with air flow through them act as acoustic dampers

- Cooling and dilution holes in the combustor may add damping in the same way as perforated liners, but are not acoustically optimised
- Damping depends on pressure drop and flow through the screen
  - This can be adjusted by use of double screens
- A comprehensive review of theory of perforated liners is given in Lahiri and Bake



Single Liner



Double Liner

C. Lahiri and F. Bake, A review of bias flow liners for acoustic damping in gas turbine combustors, Journal of Sound and Vibration 400 (2017) 564–605

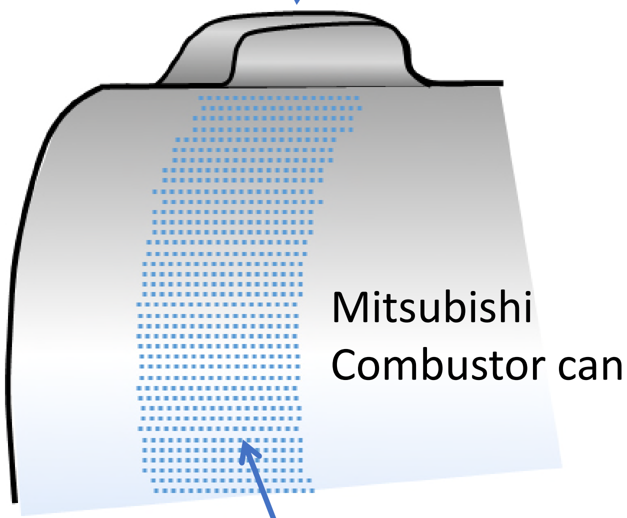
Perforated Liners: Examples

- Mitsubishi Can Combustors:
  - Tanamura et al describe an acoustic liner with “hundreds of laser drilled holes” in one or more rings round the combustor can
  - Aimed at suppressing oscillations in the range 1 to 5kHz
- Siemens SGT-800 Annular combustor:
  - Lörstad et al describe a “soft wall” in the head end of the SGT-800 annular combustor
  - Aimed at “high frequency pulsations”

Refs: Tanimura et al, Advanced Dry Low NOx Combustor for Mitsubishi G Class Gas Turbines, Proceedings of ASME Turbo Expo 2008, Berlin, GT2008-50819

Lörstad, D., Pettersson, J. and Lindholm, A.; “Emission reduction and cooling improvements due to the introduction of passive acoustic damping in an existing SGT-800 combustor”, ASME GT2009-59313, 2009.

Acoustic liner with holes to allow/control purge air flow



Hundreds of laser drilled damping air holes in can wall

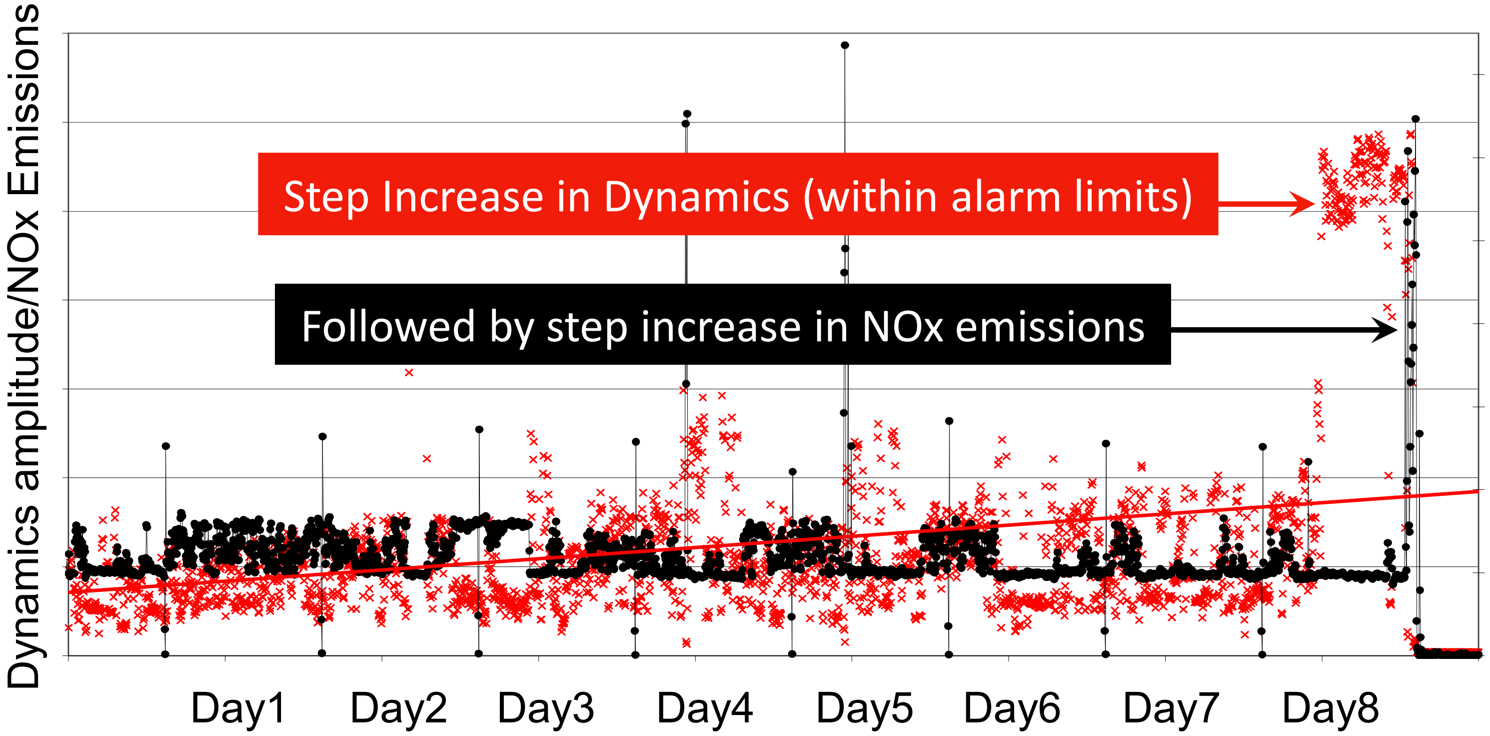
Combustion/Condition Monitoring

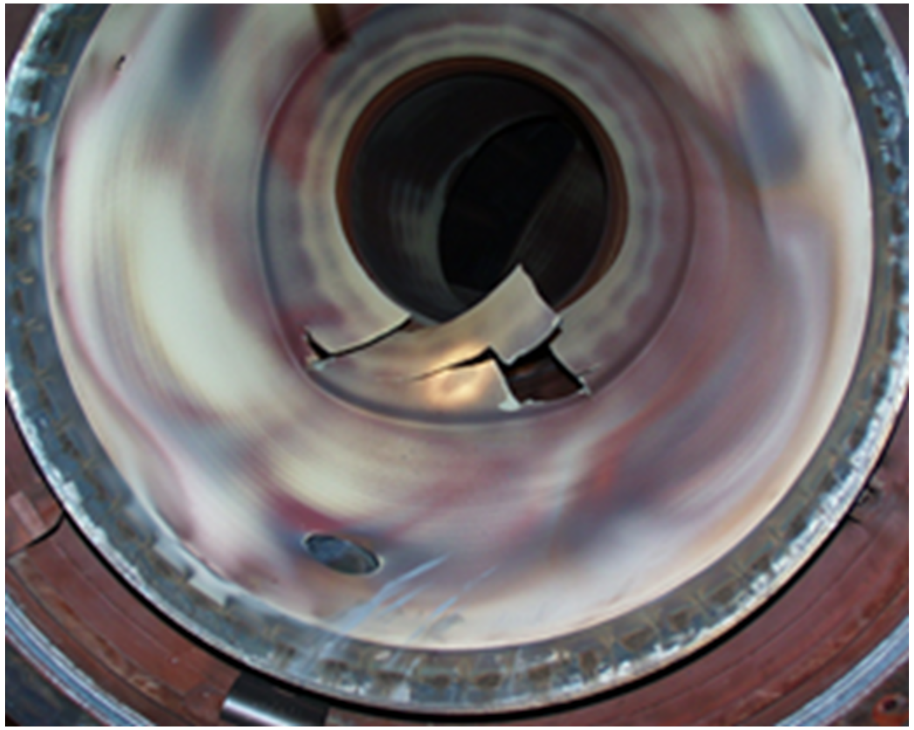
- Plant Condition Monitoring has become normal practice for many GT operators
- Most GT suppliers and many 3rd parties offer monitoring services
  - Varying degrees of complexity ranging from manual checking of trend data to the use of sophisticated monitoring and predictive analysis software

- Combustion data such as combustion acoustics, emissions, temperature and pressures can be included in such monitoring systems
- Changes in thermoacoustic behaviour can be a useful indicator of combustor issues

Monitoring Example

- This combustor failure was identified by its effect on combustion dynamics and emissions





Control by Design

Analysis vs Testing

Analysis

- 1-D
  - Cheap and easy
  - Useful, but limited results

- 2-3-4D
(2-3D time averaged CFD, Transient CFD, FE etc)
  - More time consuming and costly
  - More detailed results
  - Requires validation

Increasing cost

Testing

- Isothermal (model)
  - Cheap and easy
  - Useful, but limited results

- Combusting: Model scale
(reduced size, pressure, temperature etc)
  - More detailed results
  - Scaling rules require validation and will not be complete

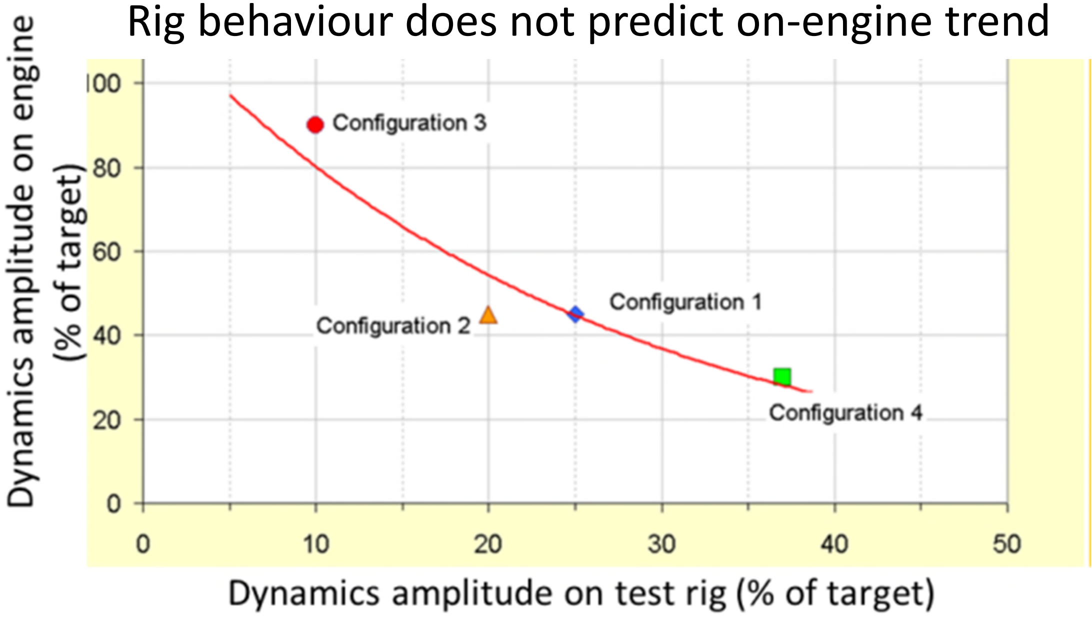
- Combusting: Full scale rig
(representative size, pressure temperature etc)
  - Most detailed rig results
  - Not fully representative boundary conditions

On engine validation

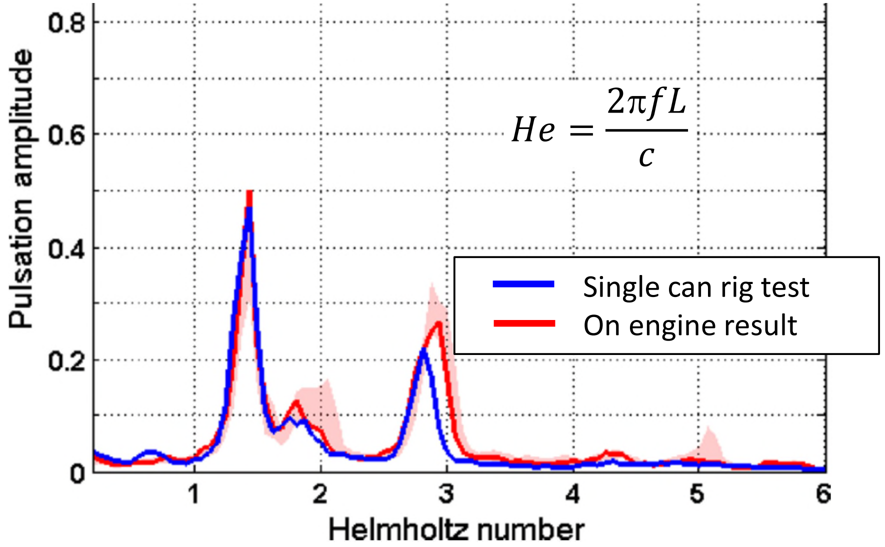
Control by Design: Direct Acoustic Testing

- Direct testing to determine acoustic behaviour of a combustor often has limited value due to difficulty in reproducing boundary conditions, but can under some circumstances be useful

Boundary conditions not matched:
Rig behaviour does not predict on-engine trend



Boundary conditions “matched”:
Rig behaviour predicts on-engine behaviour



From: D.J.Abbott, et al., Investigations into Combustion Generated Oscillations in Large Gas Turbine Combustors Firing Oil Emulsions, The International Colloquium on Combustion and Noise Control , Cranfield University, 2003

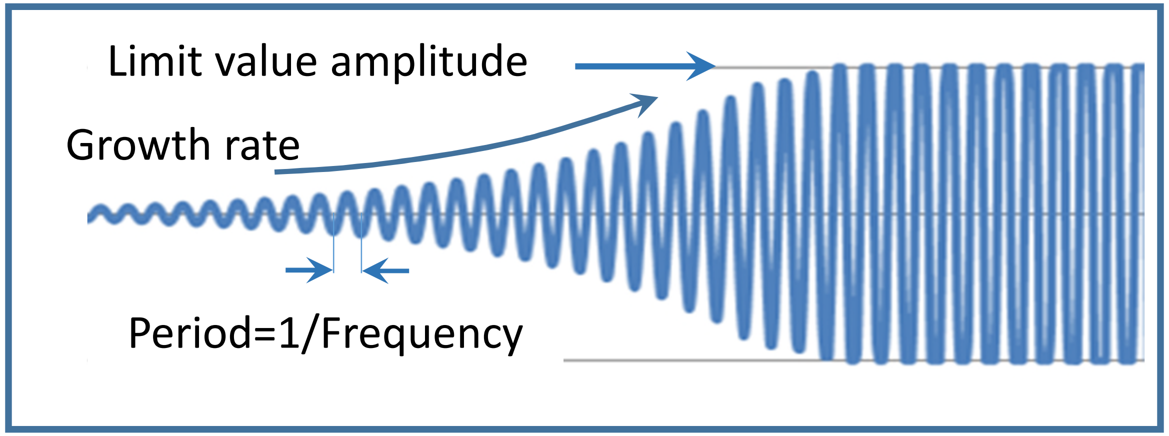
From: M R Bothien, et al., Journal of Engineering for Gas Turbines and Power DECEMBER 2019, Vol. 141 / 121013-1, Paper No: GTP-19-1488

Control by Design

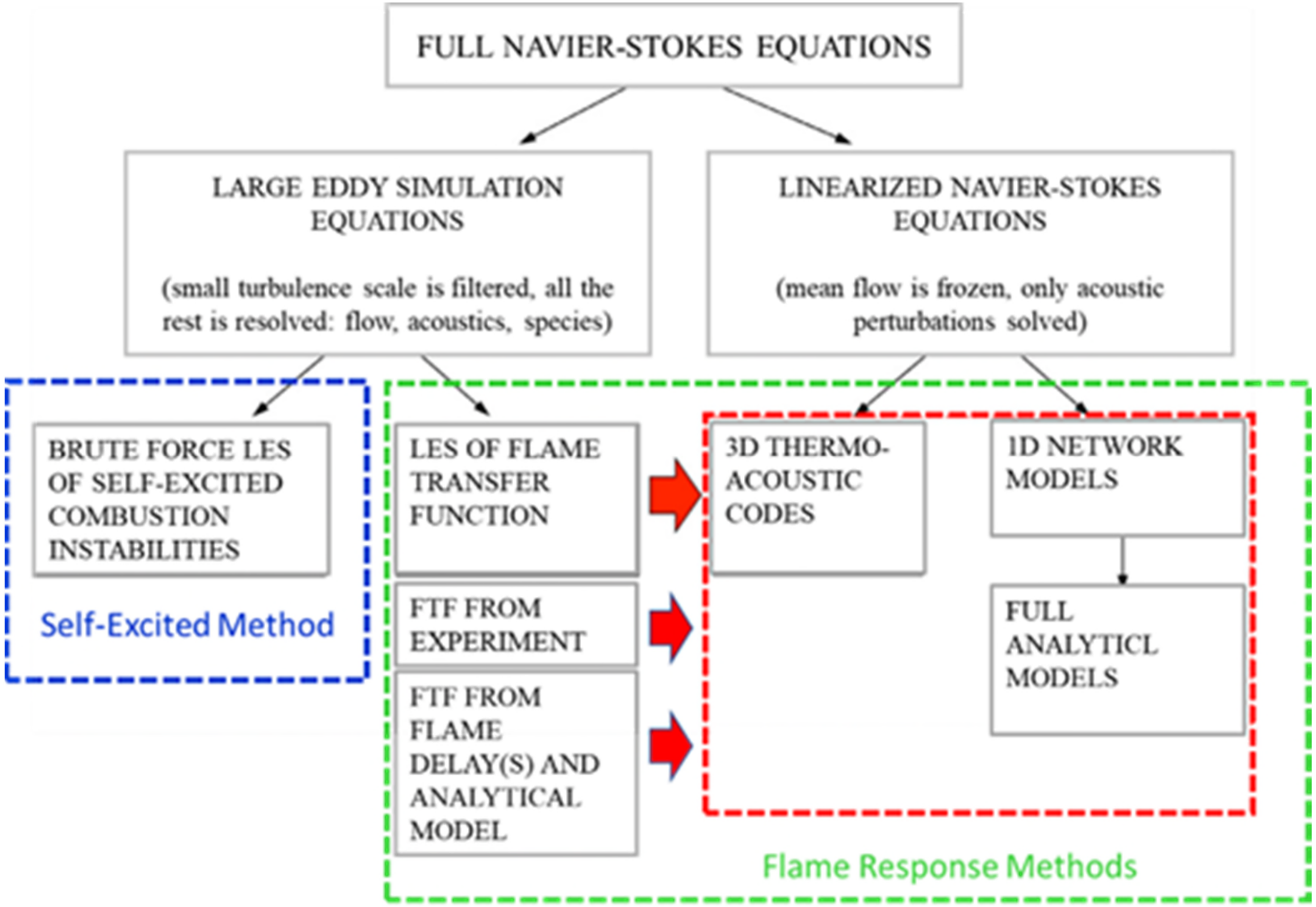
- Acoustic testing
  - Direct testing to often has limited value, but can be useful if boundary conditions can be matched
  - Measurement of flame acoustic properties (FTF/FDF) useful for use in acoustic models
  - May be used to validate acoustic modelling methods
- Acoustic analysis
  - Helps interpret rig tests with non-representative boundary conditions
  - Allows analysis of a wide range of combustor designs and conditions if FTF/FDF is known
- Combination of rig testing and acoustic analysis is normally the most cost effective design approach

Requires:

- **Reliable acoustic prediction methods**
  - **Eigen-frequency**
  - **Growth rate**
  - **Limit value amplitude**

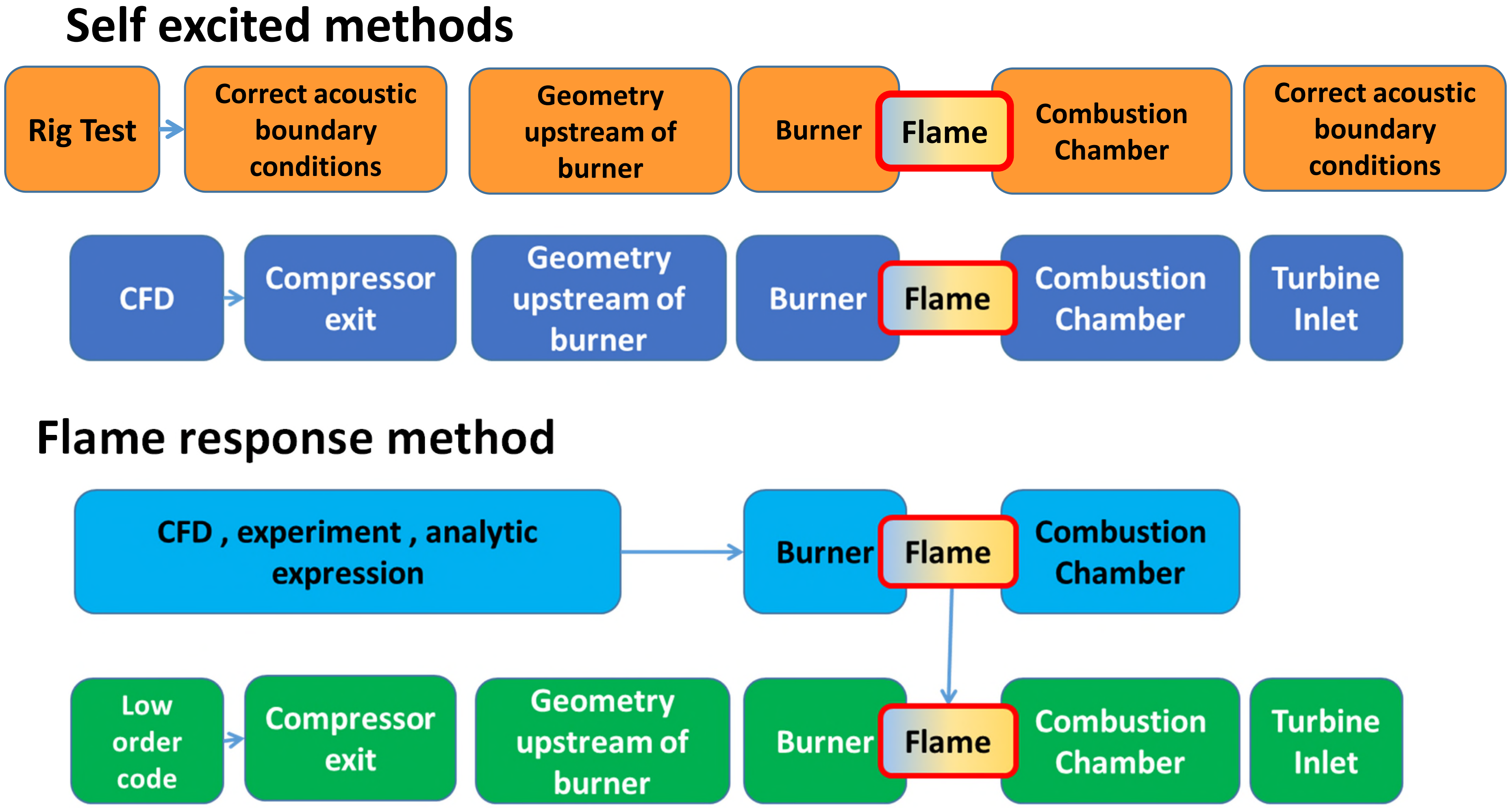


Dynamics Prediction Strategies



Modified from: T. Poinsot, Prediction and control of combustion instabilities in real engines, Proceedings of the Combustion Institute, 36 (2017) 1–28 . This is a good reference paper

Dynamics Prediction Strategies

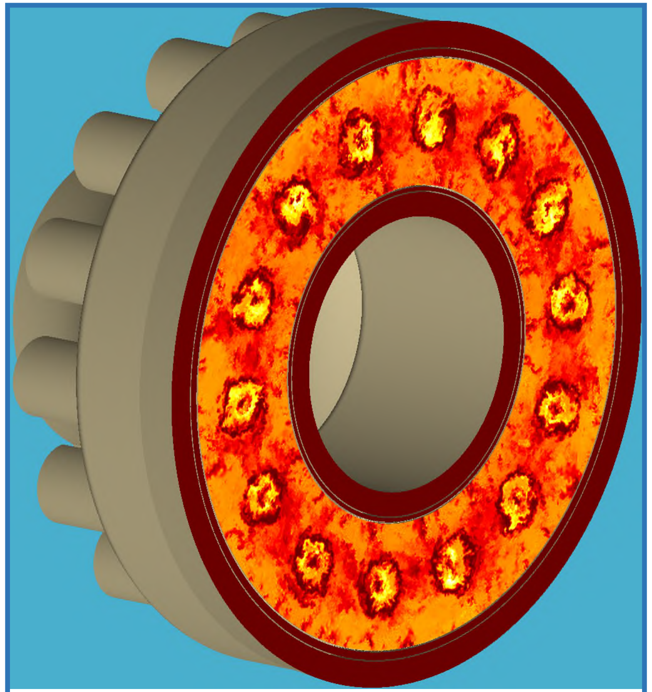


Self excited method: LES

- **Self excitation (Brute Force LES)**
  - All physics modelled in single (CFD) code
  - No separate acoustic code needed
  - No forcing required

  - But very large CFD domain required with:
    - Full representation of geometry and acoustic boundary conditions
    - Full time varying history required with large time domain to allow limit cycle operations to fully develop

  - Difficult to perform sensitivity analyses

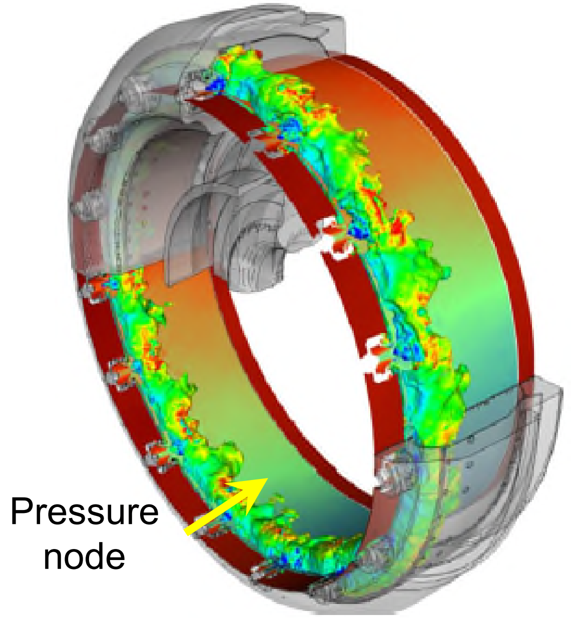


Solar 14 burner GT combustion system fully modelled using LES

Ran at Oak Ridge National Laboratories on the US DOE 200-petaflop IBM AC922 computing system (Claimed to be "most powerful and smartest in the world")

Simulation took days to complete- Would have taken months on more conventional computers

https://www.olcf.ornl.gov/2022/03/17/summit-fires-up-predictive-breakthrough-for-gas-turbines/



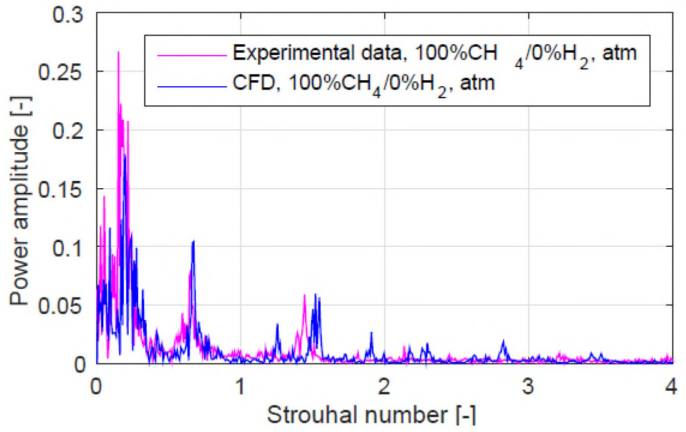
LES of the first azimuthal unstable mode in an helicopter engine: pressure on a cylinder passing through the burner axis and iso-surfaces of temperature coloured by axial velocity (

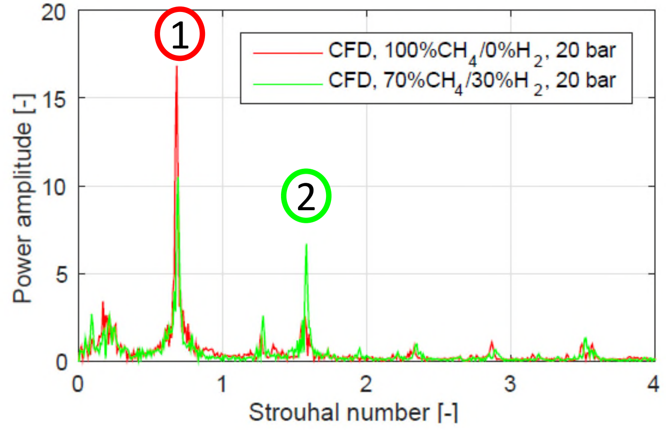
Poinsot, Proceedings of the Combustion Institute, 36 (2017) 1–28

Self excited method: LES

- LES simulation of Siemens SGT-800 burner firing methane on an atmospheric test rig predicted acoustic behaviour well

- Predicted the impact of adding 30vol% to the fuel at engine representative pressures (20bar)
  - Peak 1 reduces
  - Peak 2 increases
    - Possibly due to shift to higher frequency due to reduced flame delay time



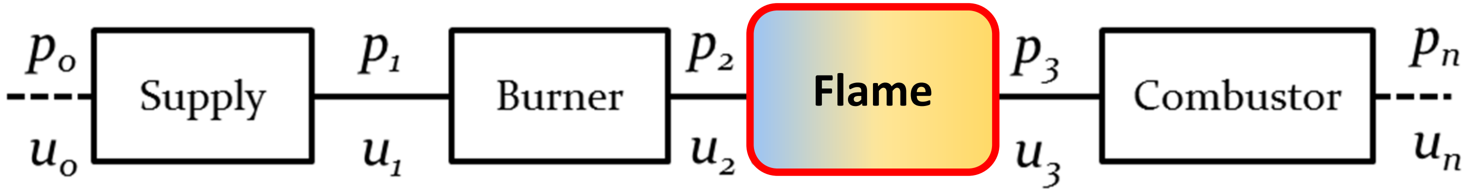


Images from: Daniel Moëll, Xue-Song Bai, Daniel Lörstad, LES OF HYDROGEN ENRICHED METHANE/AIR COMBUSTION IN THE SGT-800 BURNER AT REAL ENGINE CONDITIONS, Proceedings of ASME Turbo Expo 2018, Turbomachinery Technical Conference and Exposition, GT2018, June 11-15, 2018, Oslo, Norway, GT2018-76434

$$Strouhal\ number = \frac{frequency * burner\ diameter}{reference\ velocity}$$

Low Order Acoustic Models

- Transfer Matrix approach (or solve Helmholtz equation)
  - Flame represented by a Flame Transfer Function or Flame Describing Function
  - System acoustics represented by a network of transfer matrices (e.g. using OSCILOS) (or Helmholtz equation solved using multiphysics solver (e.g. COMSOM))



Where p = acoustic pressure, u = acoustic velocity

- If $p_2 = p_3$, then the flame can be represented by the transfer function: $C = \frac{u_3}{u_2}$

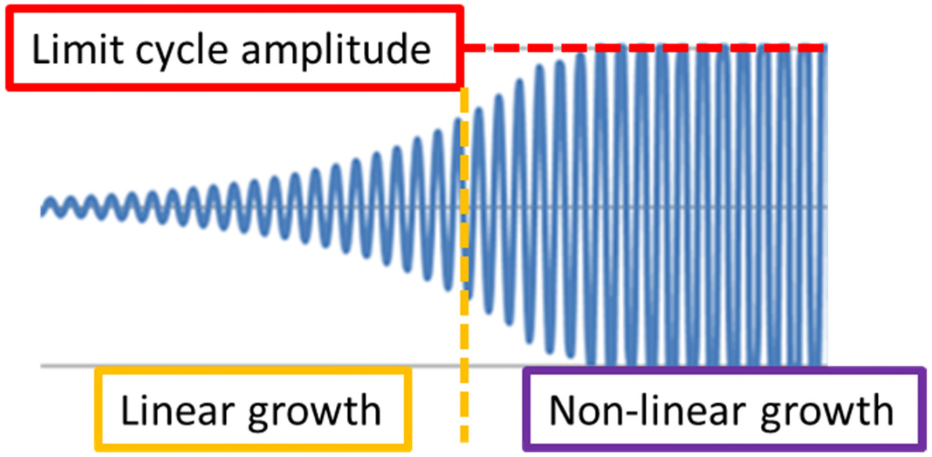
- But, fluctuating heat release Q determines u_3,
  - ➢ the usual definition of the Flame Transfer Function (after normalisation): $F(\omega) = \frac{\hat{Q}(\omega)/Q_0}{\hat{u}(\omega)/u_0}$

Flame Response

- Flame amplification represented by Flame Transfer Function (FTF):

$$F(\omega) = \frac{\hat{Q}(\omega)/Q_0}{\hat{u}(\omega)/u_0}$$

Where:
ω = angular frequency = $2\pi f$
$\hat{Q}$ = fluctuating heat release,
$\hat{u}$ =fluctuating inlet velocity
Q_0 & u_0 are mean values



- OR Flame Describing Function (FDF)
  (for non-linear analysis)

$$\boldsymbol{\mathcal{F}}(\omega, |u|) = \frac{\hat{Q}(\omega)/Q_0}{\hat{u}(\omega)/u_0}$$

Where:
$|u|$ is the amplitude of the inlet velocity

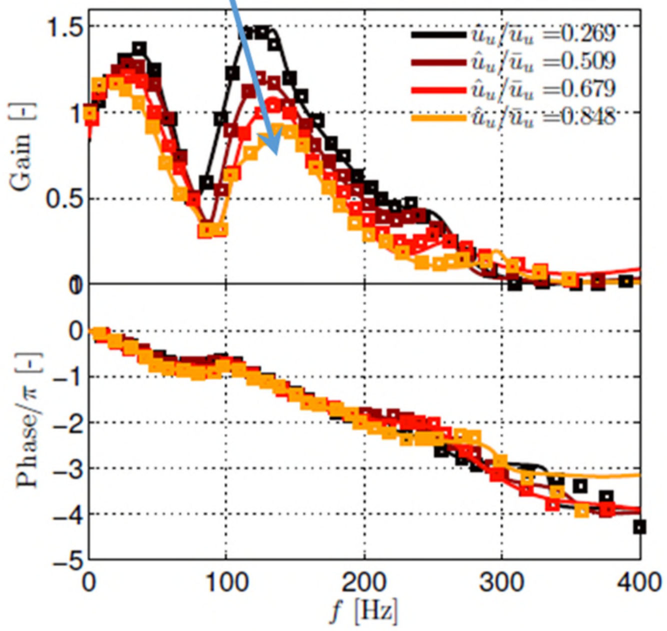
- FTF/FDF Determined Analytically, Experimentally or using CFD
  - Forcing required to evaluate FTF/FDF
- FTF/FDF used as input to low order thermo-acoustic models to determine excited frequencies (Eigenfrequencies and growth rates and possibly limit cycle amplitude)

See also: Jingxuan Li, Dong Yang, Charles Luzzato and Aimee S. Morgans , Open Source Combustion Instability Low Order Simulator, (OSCILOS-long), Technical report Department of Aeronautics, Imperial College London, UK

Experimental or CFD Derived FDFs

- FTFs and FDFs can be determined experimentally or by time varying CFD
  - Forcing of the system required
    - For FTFs forcing should be low enough for the linear assumption to be valid
    - For FDFs a range of forcing amplitudes required to capture non-linear effects
  - Measurement of parameters related to acoustic input velocity and fluctuating heat release needed

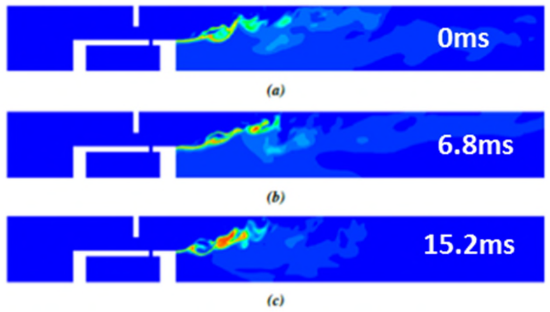
Gain reduces with increasing input velocity amplitude

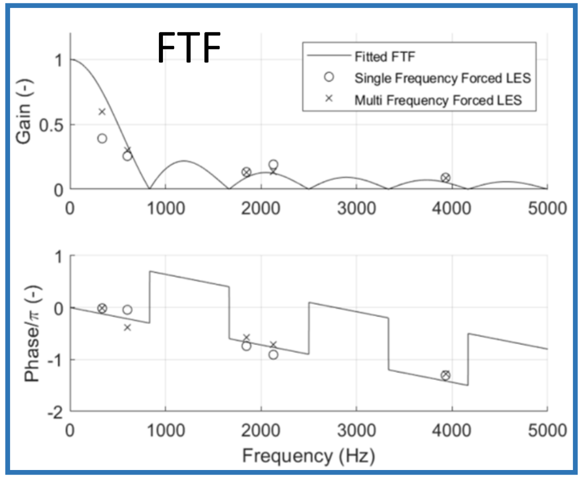


Flame describing function results for a gaseous fuelled test combustor.

Han et al., Combustion and Flame 162 (2015) 3632–3647

LES results showing OH emissions





McClure et al., Proc. ASME Turbo Expo 2019, Paper GT2019-90538

Analytical Expressions for FTF

- Commonly used n-τ model

$$F_1(\omega) = ne^{-i\omega\tau}$$

- Modified n-τ model (1): Takes into account the spread in time delay

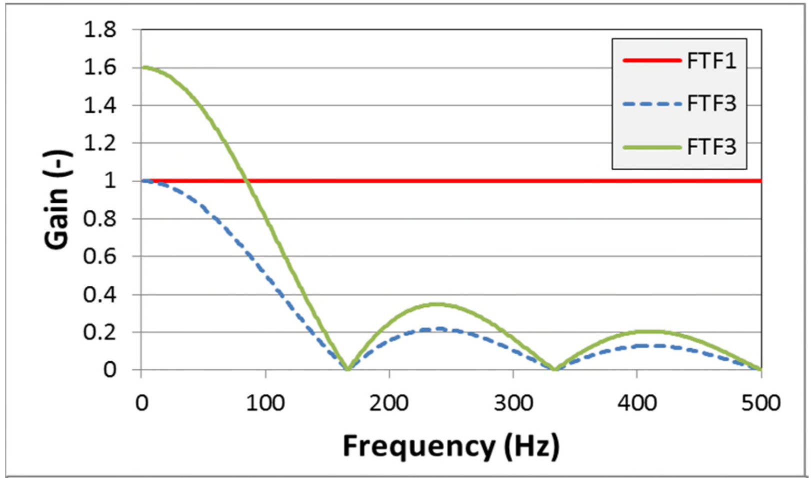
$$F_2(\omega) = \Theta ne^{-i\omega\tau}$$

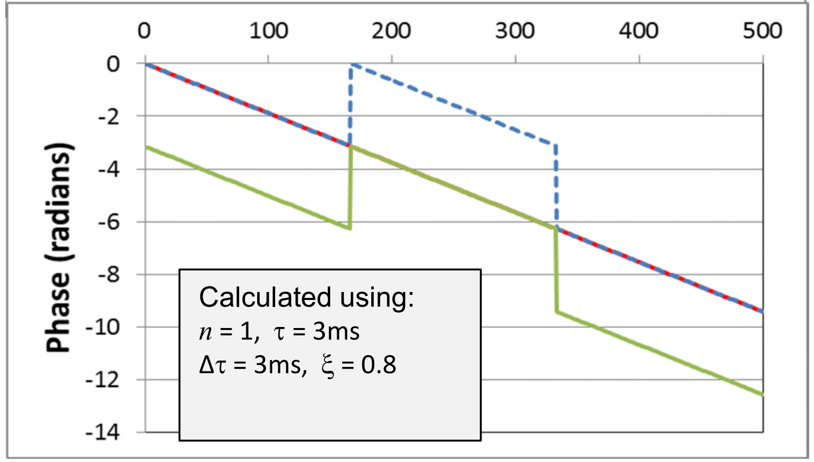
- Modified n-τ model (2): formulated for air-blast atomised diffusion flames

$$F_3(\omega) = -2\xi\Theta ne^{-i\omega\tau}$$

- Time τ and Δτ may be determined from steady (time averaged) CFD or experimental data

See for example: A Andreini, B Facchini, A Giusti & F Turrini, Assessment of Flame Transfer Function Formulations for the Thermoacoustic Analysis of Lean Burn Aero-Engine Combustors, Energy Procedia 45 (2014) 1422 – 1431





n = constant (in many cases n=1)
τ = characteristic flame time delay
$\Delta\tau$ = spread of time delays
$\Theta = \frac{\sin(\omega\Delta\tau)}{\Theta\Delta\tau}$
ξ = constant derived from SMD of fuel droplets

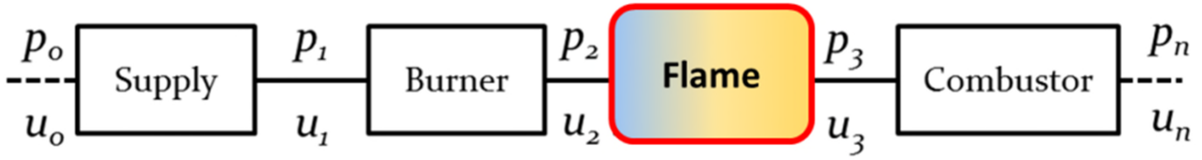
System Acoustics

- Most systems can be modelled using networks of duct elements and area discontinuities (see next slide) combined in series and parallel
- Transfer matrices can be developed analytically or experimentally to represent more complex elements (e.g. resonators, perforated liners, etc.)
- Input and output properties may be represented by an appropriate complex reflection coefficient

Often used inlet/outlet conditions:

- Open end (R=-1)
- Closed end (R=+1)
- Choked flow
- Defined reflection coefficient

System Acoustics



- General solution to wave equation……………..
$$\begin{aligned}\hat{p}(\omega,x) &= p^+e^{-ik^+x} + p^-e^{+ik^-x} \\ \hat{u}(\omega,x) &= \frac{1}{\rho_0 c}(p^+e^{-ik^+x} - p^-e^{+ik^-x})\end{aligned}$$
where $k^{\pm} = \dfrac{\omega/c}{1 \pm M}$

- Transfer Matrix:……………………………………
$$\begin{pmatrix}\hat{p}/\rho_0 c \\ \hat{u}\end{pmatrix}_{i+1} = \begin{bmatrix}T_{11} & T_{12} \\ T_{21} & T_{22}\end{bmatrix}\begin{pmatrix}\hat{p}/\rho_0 c \\ \hat{u}\end{pmatrix}_{i}$$

- TM for a duct element……………………
$$\begin{bmatrix}T_{11} & T_{12} \\ T_{21} & T_{22}\end{bmatrix} = \frac{1}{2}\begin{bmatrix}\left(e^{-ik^+L} + e^{+ik^-L}\right) & \left(e^{-ik^+L} - e^{+ik^-L}\right) \\ \left(e^{-ik^+L} - e^{+ik^-L}\right) & \left(e^{-ik^+L} + e^{+ik^-L}\right)\end{bmatrix}$$

- TM for an area discontinuity……………….
$$\begin{bmatrix}T_{11} & T_{12} \\ T_{21} & T_{22}\end{bmatrix} = \begin{bmatrix}1 & \left[1 - \zeta - \left(\frac{A_u}{A_d}\right)^2\right] M_u - i\frac{\omega}{c}l_{eff} \\ -i\frac{\omega}{c}l_{red} - M_d & \frac{A_u}{A_d}\end{bmatrix}$$

Where: c and ρ_0 are fluid density and speed of sound, L = the length of the duct element, M = Mach number, A = duct cross sectional area, l_{red} and l_{eff} are corrections accounting for the sharp edges of the discontinuity and ζ = accounts for acoustic losses, subscripts u and d refer to upstream and downstream of the discontinuity

Expressions taken from: H Krediet, Prediction of Limit Cycle Pressure Oscillations in Gas Turbine Combustion Systems using the Flame Describing Function, PhD thesis University of Twente 2012

Low Order Modelling: OSCILOS

- A suite of open source codes for simulating combustion instability
- Developed by Prof Aimee Morgans and co-workers at Imperial College London
- Written in Matlab/Simulink
- Can simulate both longitudinal and annular combustor geometries.
- Represents combustor as a network of connected modules.
- The acoustic waves are modelled as either 1-D plane waves (longitudinal combustors) or 2-D plane/circumferential waves (annular combustors)
- Flame acoustic response represented using FTF/FDF: various models available
- Mean flow calculated simply assuming 1-D flow conditions
- Website: http://www.oscilos.com/

1. OSCILOS_long
- 1D analysis for longitudinal combustors.
- Graphical User Interface (GUI)
- Models Helmholtz resonators, perforated liners, and heat exchangers
- Both frequency and time domain simulations

2. OSCILOS_ann
- 2D analysis for annular combustors.
- No GUI (users build and run using Matlab commands)

3. OSCILOS_lite
- Based upon OSCILOS_long,
- No GUI (users use Matlab commands)
- Cannot model Helmholtz resonators, perforated liners, or heat exchangers.
- Performs only frequency domain calculations

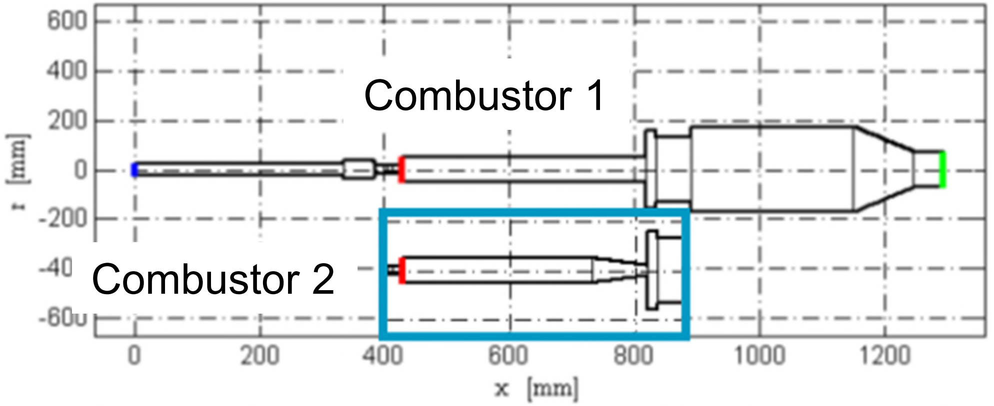
4. **OSCILOS_opt**
- Variant of OSCILOS_lite.
- It allows optimiseation of a thermoacoustically unstable combustor

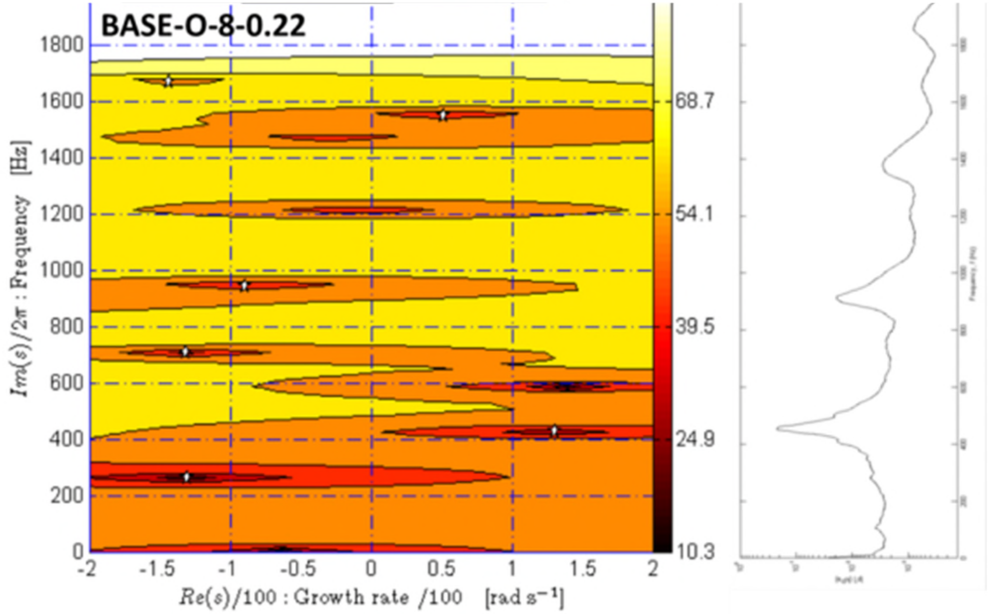
5. **OSCILOS_Sim**
- Simplified version of OSCILOS_long,
- Only applies to combustors which can represented as a constant area duct

OSCILOS-long Example: Cardiff University Tests

Comparison with tests on a generic gas turbine burner firing a range of gaseous fuels:

- Used an FTF determined using a simple n-τ model (τ based on measured flame position and turbulence intensity)
- The n- τ model predicted the dominant frequencies within 5-6%, but under predicted the frequency values.
- Predicted impact of combustor geometry
- Predicted observed frequency trends with varying operating conditions, such as a reduction in peak frequency with a reduction in ϕ
- Predicted impact of adding hydrogen to the fuel
- An FDF model based on an n-т model and a saturation model gave limit value amplitudes following the observed trends.





Runyon, J, 2017, Gas Turbine Fuel Flexibility: Pressurized Swirl Flame Stability, Thermoacoustics, and Emissions, PhD thesis, Cardiff University

Conclusions

- Thermoacoustic issues have been an issue for all gas turbine manufacturers
- Moves towards higher performance and lower emissions will mean thermoacoustics will remain an issue
- Hydrogen will bring its own challenges when used either as “pure” hydrogen or blended with natural gas
- The risk of problems can be reduced by good combustion system design
- The use of acoustic control measures (both active and passive) may contribute to reducing any remaining risk
- Careful attention to combustion tuning remains important
- Closed loop control of thermoacoustics is usually desirable
  - Systems with some degree of automatic tuning will become increasingly important due to increaesing fuel variability and the potential introduction of hydrogen
- Combustion monitoring is desirable to identify the development of thermoacoustic problems and to use thermoacoustics as a system diagnostic tool

The thermoacoustic risk needs to be considered when making any combustion design change

Thank you for your attention:

Any Questions?

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