Modelling thermo-acoustic instabilities in an oxy-fuel premixed burner

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Introduction

- Strict regulations on emissions leads to lean premixing
- This trend will accelerate for hydrogen and oxy-fuel due to high flame temperatures
- Premixing tends to give rise to thermo-acoustic instabilities
  - Noise
  - Reduced combustion efficiency
  - Destruction of equipment
This again has lead to a strong interest in thermo-acoustic instabilities
- the mechanism causing the instability
- methods of control, both passive and active
- means to guide the design of both the equipment and of the control methods

Practically impossible to obtain with analytical tools only
Extensive experimental testing is very costly
Need numerical simulations
Experimental Setup

- 2D sudden expansion (exp. ratio: 10)
- Premixed combustion
- Oxidant:
  - Different $O_2/CO_2$ mixtures
- Fuel: CH$_4$
- Parameters:
  - Re: Varied
  - ER: Varied

Ditaranto & Hals, Combustion and Flame, 146 (2006), 493
Mechanism

If the instantaneous heat release is at its peak at the same time as there is a peak of the acoustic pressure the acoustic wave will gain energy (Rayleigh criterion for combustion oscillations*).

\[
P'(t_0) < 0 \Rightarrow u'_{inlet}(t_0) > 0
\]
\[\downarrow\]
\[
L_f(t_1) > \bar{L}_f \Rightarrow \dot{q}(t_1) > \bar{q}
\]
If \( P'(t_1) > 0 \)
constructive coupling
elseif \( P'(t_1) < 0 \)
destructive coupling

\[
\frac{dp'}{dt} = \alpha p'(t)
\]
\[p'(t) = Ae^{\alpha t}\]

* Lord J. W. S. Rayleigh, Nature 18 (1878) 319
Simulation tools

- The linear approach (wave equation)
  - Network models (e.g. Polifke, Sattelmayer)
  - No limit cycle
- The 3D non-linear approach
  - URANS
  - LES
  - DNS
- The 1D non-linear approach
  - Flame in straight pipe (Polifke*)
  - Variable cross section (This work)

* Polifke et al., Journal of sound and vibration, 2001, 245, 483
The wave equation (linear approach)

This is the workhorse of numerical combustion instability studies!

The wave equation with heat term

\[ \frac{\partial}{\partial x} \left( c^2 \frac{\partial p}{\partial x} \right) - \frac{\partial^2 p}{\partial t^2} = - (\gamma - 1) \frac{\partial Q}{\partial t} \]

Unsteady heat release from the n-\(\tau\) approximation

\[ Q'(t) = \left( \frac{\rho c^2}{\gamma - 1} \right) Snu'(x, t - \tau) \]
The SINMA model

- Non-linear Navier-Stokes solver
- One dimensional, but incorporate variable cross sections
  - Essentially DNS
  - Sixth order finite difference discretization
  - Third order Runge-Kutta time stepping
- No hydrodynamic instabilities
  - Use artificially large viscosity and diff. parameters to stabilize simulation
  - Acoustics and flame model not affected by this
- Use the “Attached Dynamical Model” (ADM) which is a quasi 1D realization of the “G-equation model” or the “flame front model”
The quasi 1D equations

Continuity:
\[ \frac{\partial \rho}{\partial t} = -\frac{1}{A} \frac{\partial \rho u A}{\partial x} \]

Momentum:
\[ \frac{\partial u}{\partial t} = -u \frac{\partial u}{\partial x} - \frac{1}{\rho} \frac{\partial P}{\partial x} + 4 \nu \left( \frac{\partial^2 u}{\partial x^2} + \frac{1}{\rho} \frac{\partial u}{\partial x} \frac{\partial \rho}{\partial x} \right) \]

Energy:
\[ \frac{\partial T}{\partial t} = -u \frac{\partial T}{\partial x} + \frac{1}{\rho c_v} \left( -\frac{P}{A} \frac{\partial u A}{\partial x} + k \frac{\partial^2 T}{\partial x^2} + \dot{q}_v + \dot{q}_c \right) \]

Species:
\[ \frac{\partial Y_k}{\partial t} = -u \frac{\partial Y_k}{\partial x} + D \frac{\partial^2 Y_k}{\partial x^2} + \omega_k \]

Equation of state:
\[ P = \rho r T \]
Cold rig

Velocity power spectrum in combustion chamber

Cold flow simulations give good fit between resonant frequencies for experimental (black arrows), linear simulation (red arrows) and non-linear simulation (blue line) results
Thermo-Acoustic Modes Cycles

Region II

Region III

Region II-III

Compact attached flame
The attached dynamical model (ADM)

- Assume the flame to be attached
- Based on the “G-equation model” or “the flame front model”
- All the turbulence has been put into $f_T$

\[
R = \frac{2\Delta HL_3 S L f_{T} Y_{\text{fuel, inlet}}}{\Delta V} = \frac{S_L f_{T} Y_{\text{fuel, inlet}}}{L_f} \sqrt{1 + \left(\frac{2L_f}{h_{\text{inlet}}}\right)^2}
\]

\[
\omega_k = -R \quad \text{for } k = \text{CH4}
\]

\[
\omega_k = R \quad \text{for } k = \text{CO2}
\]

\[
\omega_k = 2R \quad \text{for } k = \text{H2O}
\]

\[
\omega_k = -2R \quad \text{for } k = \text{O2}
\]

\[
\dot{q}_c = R \rho h_{\text{LHV}}
\]
Quenching the exponential growth

- Enters “linear” growth when flame tip goes into the duct
- What give limit cycle
  - Max flame length *
  - Max strain, i.e. max flame velocity
  - Acoustic losses **
  - Combination of the above

** P. Davies et al., J. Sound and Vib., 1980, 72, 543
Quenching by acoustic losses

Velocity at single point in premixer as function of time for a reflection coefficient of 0.985

Envelope of velocity at single point in premixer for various reflection parameters. The red line is the envelope of the left plot.
Power spectrum

- By adjusting the temperature we get very similar power spectra from experiments (red) and numerics (blue)
  - No cooling in the model
  - Uneven temperature distribution in the combustor
- Spectral decay as function of frequency is correct
- By tuning $n$ and $\tau$ we get interesting results also with linear model

Linear code

<table>
<thead>
<tr>
<th>Re(f_num)</th>
<th>Im(f_num)</th>
</tr>
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<tbody>
<tr>
<td>170.95890</td>
<td>-0.02527</td>
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<tr>
<td>242.86390</td>
<td>3.43053</td>
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<tr>
<td>342.76354</td>
<td>-0.00887</td>
</tr>
<tr>
<td>473.34227</td>
<td>0.89771</td>
</tr>
</tbody>
</table>
Acoustic velocity
Linearized with n-τ vs. SINMA

- Linear model with n-τ
  - n-τ heat release model
    - n and τ are ‘free’ parameters that must be given as input
    - Generally n and τ are frequency dependent
  - Solves for the unstable (and resonant) frequencies
  - Give solution in frequency domain only
  - Does NOT solve for level of saturation (non-linear regime)

- SINMA with ADM
  - ADM has no free parameters
  - Solves for the unstable (and resonant) frequencies
  - Give solution in the time domain
    - Can then be Fourier transformed to get the spectral solution
  - Limit cycles are part of the solution
Applications

- Gain understanding of the fundamental physics of the instability and its saturation mechanism
- A digital lab for testing non linear models of active control**
- Development of simple combustors
- Guideline for future 3D LES simulations
- Finding the transfer matrixes of multi-ports *

* Polifke et al., Journal of sound and vibration, 2001, 245, 483
**Ongoing PhD at NTNU, D. Snarheim (prof. B. Foss)
Conclusion

- SINMA reproduce experimental results
- ADM give good results without any free parameters
- For the case studied here acoustic losses seems to be the main (or at least one of the strongest) contributor to the level of the limit cycles