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

Nils Erland L. Haugen
Øyvind Langørgen
Sigurd Sannan

SINTEF Energy Research

Acknowledgements
This presentation forms a part of the BIGCO2 project, performed under the strategic Norwegian research program Climit. The authors acknowledge the partners: Norsk Hydro, Statoil, GE Global Research, Statkraft, Aker Kværner, Shell, TOTAL, ConocoPhillips, ALSTOM, the Research Council of Norway (178004/I30 and 176059/I30) and Gassnova (182070) for their support.

Introduction

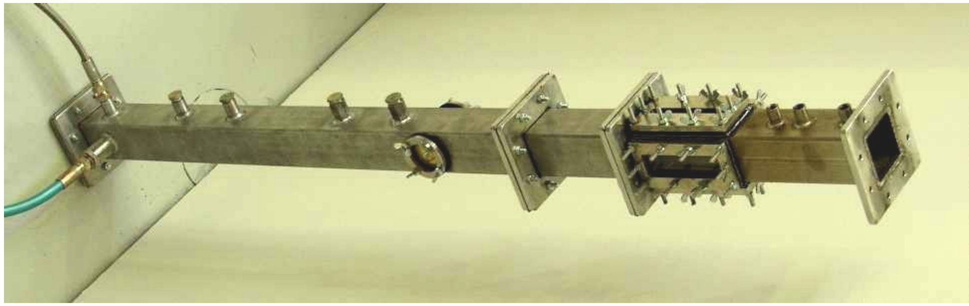
- Strict regulations on emissions leads to lean premixing
- This trend will accelerate for hydrogen and oxy-fuel due to high flame temperatures
- Premixing tends to give rise to thermo-acoustic instabilities
  - Noise
  - Reduced combustion efficiency
  - Destruction of equipment

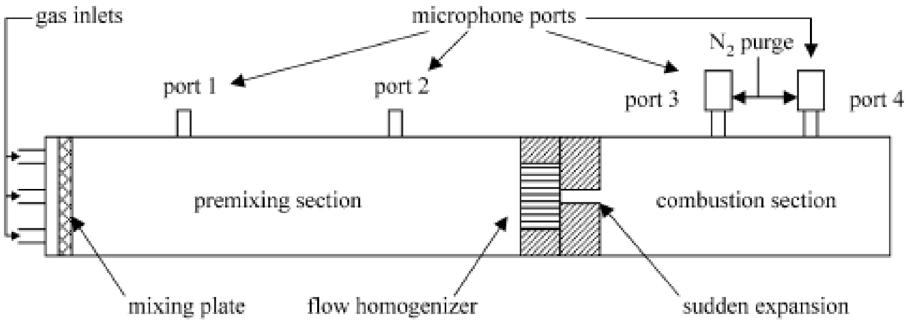
Introduction (cont.)

- 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

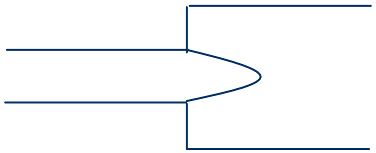




Ditaranto & Hals, Combustion and Flame, 146 (2006), 493

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*).



$$P'(t_0) < 0 \Rightarrow u'_{\text{inlet}}(t_0) > 0$$
$$\Downarrow$$
$$L_f(t_1) > \overline{L}_f \Rightarrow \dot{q}(t_1) > \overline{\dot{q}}$$

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-τ approximation

$$Q'(t) = \left(\frac{\rho c^2}{\gamma - 1}\right) S n u'(x, t - \tau)$$

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:

$$\frac{\partial u}{\partial t} = -u\frac{\partial u}{\partial x} - \frac{1}{\rho}\frac{\partial P}{\partial x} + \frac{4}{3}\nu\left(\frac{\partial^2 u}{\partial x^2} + \frac{1}{\rho}\frac{\partial u}{\partial x}\frac{\partial \rho}{\partial x}\right)$$

Energy:

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

Species:

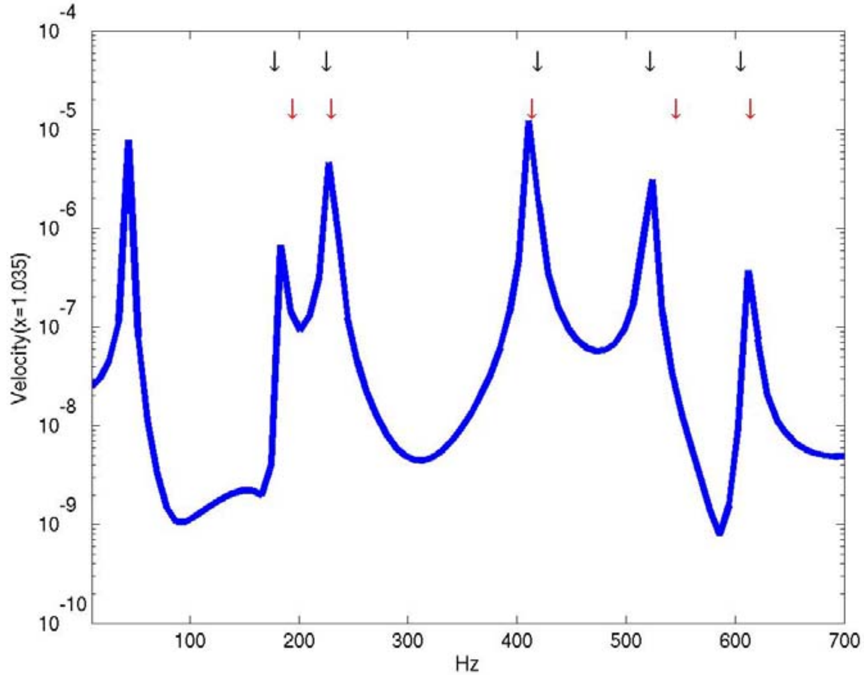
$$\frac{\partial Y_k}{\partial t} = -u\frac{\partial Y_k}{\partial x} + D\frac{\partial^2 Y_k}{\partial x^2} + \omega_k$$

Equation of state:

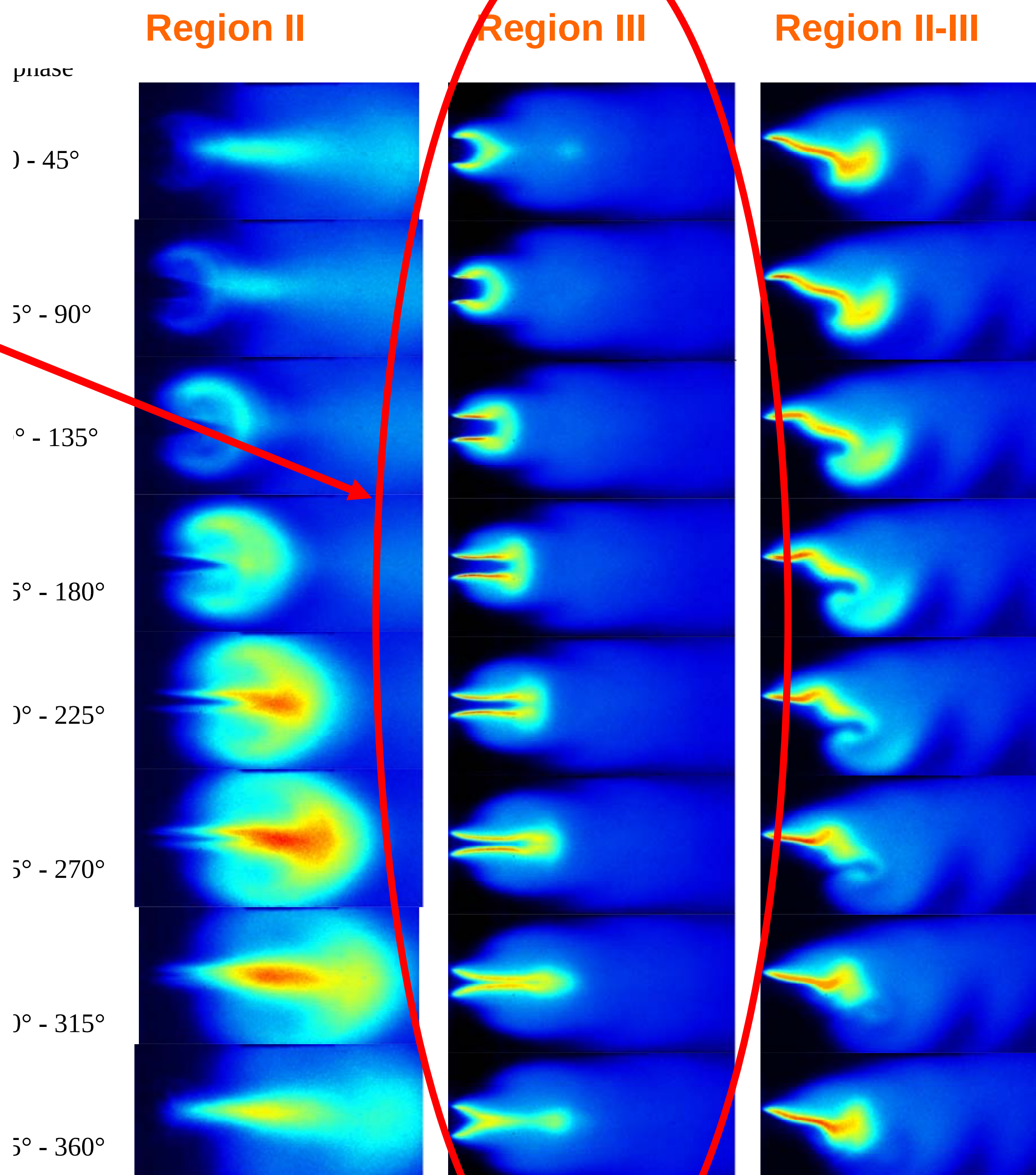
$$P = \rho r T$$

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



Compact attached flame

Thermo-Acoustic Modes Cycles

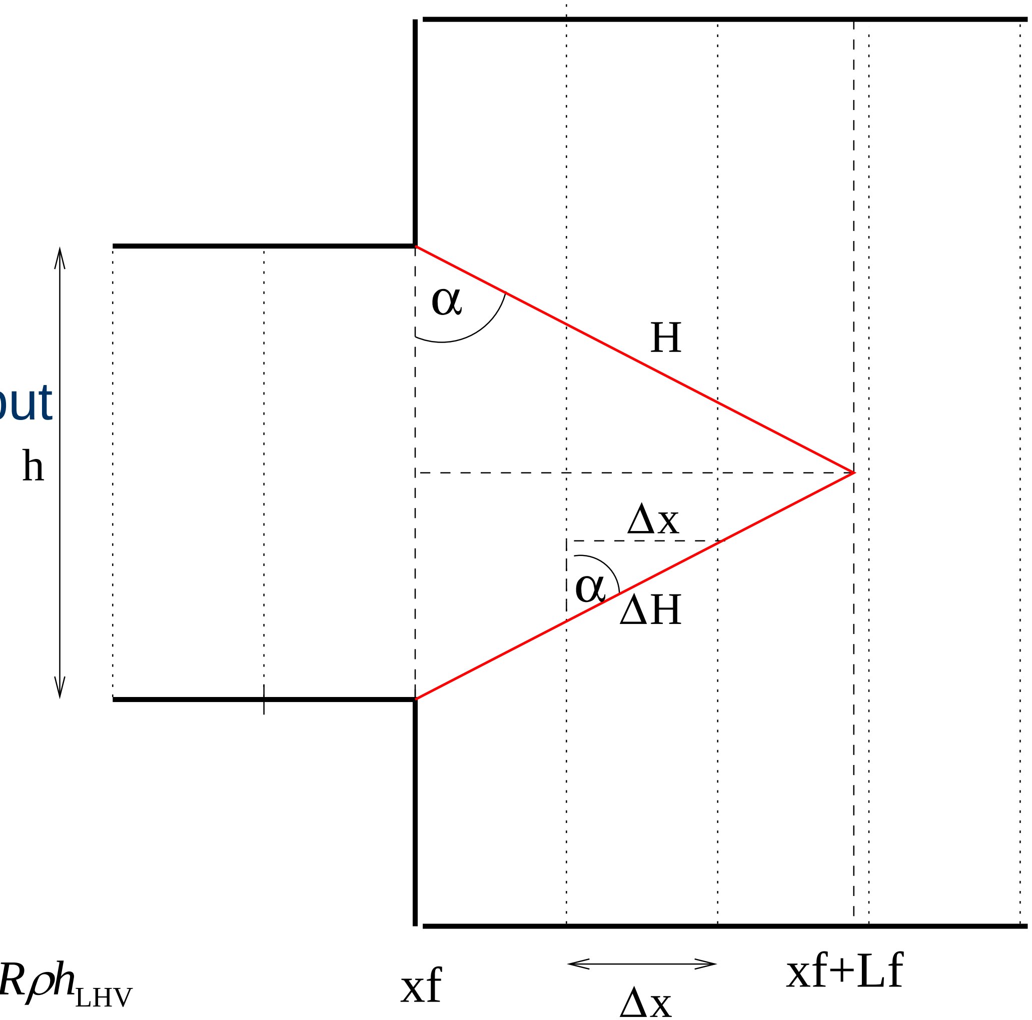
The attached dynamical model (ADM)

- 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

$$R = \frac{2\Delta H L_3 S_L f_T Y_{\text{fuel,inlet}}}{\Delta V} = \frac{S_L f_T Y_{\text{fuel,inlet}}}{L_f} \sqrt{1 + \left(\frac{2L_f}{h_{\text{inlet}}}\right)^2}$$

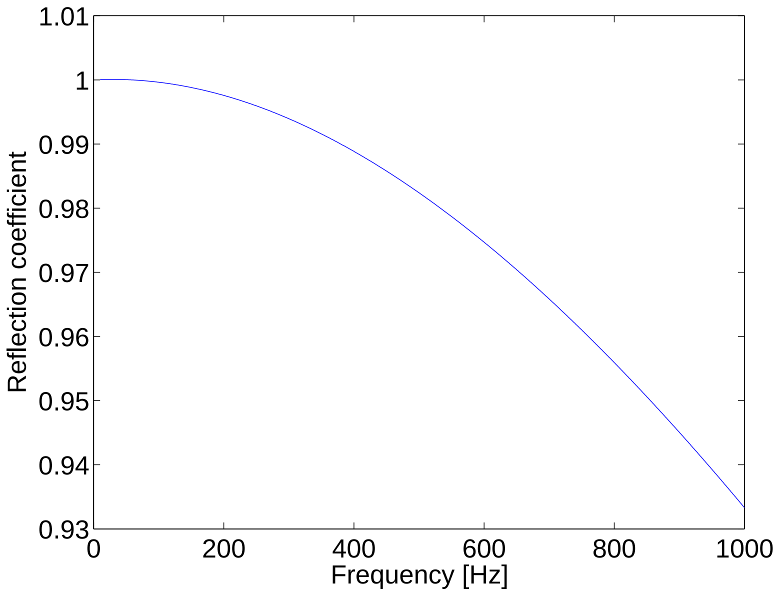
$$\begin{aligned}
\omega_k &= -R && \text{for k} = \text{CH4} \\
\omega_k &= R && \text{for k} = \text{CO2} \\
\omega_k &= 2R && \text{for k} = \text{H2O} \\
\omega_k &= -2R && \text{for k} = \text{O2}
\end{aligned}$$

$$\dot{q}_c = R \rho h_{\text{LHV}}$$



Quenching the exponential growth

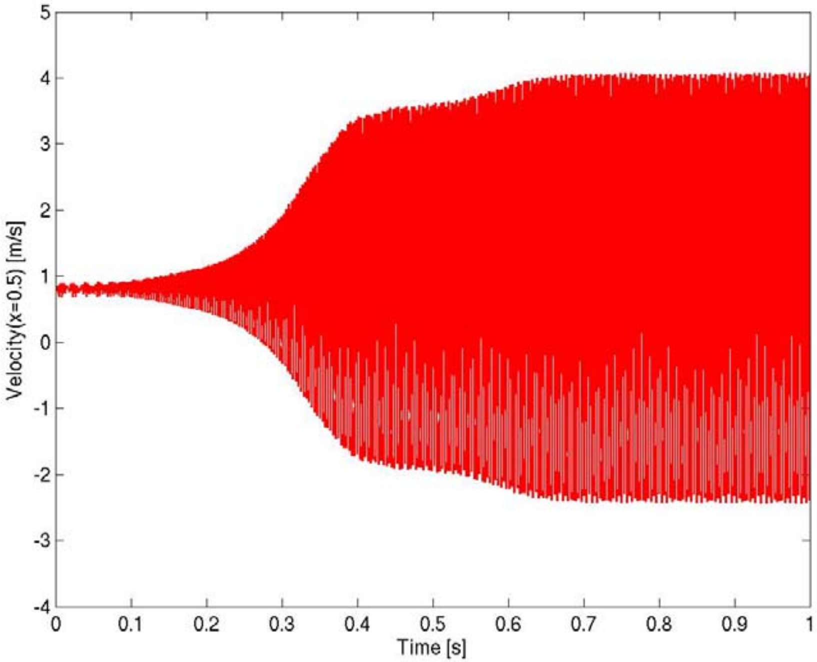
- Enters “linear” growth when flame tip goes into the duct
- What give limit cycle
  - Max flame length *
  - Max strain, i.e. max flame velocity
  - Acoustic losses **
  - Combination of the above



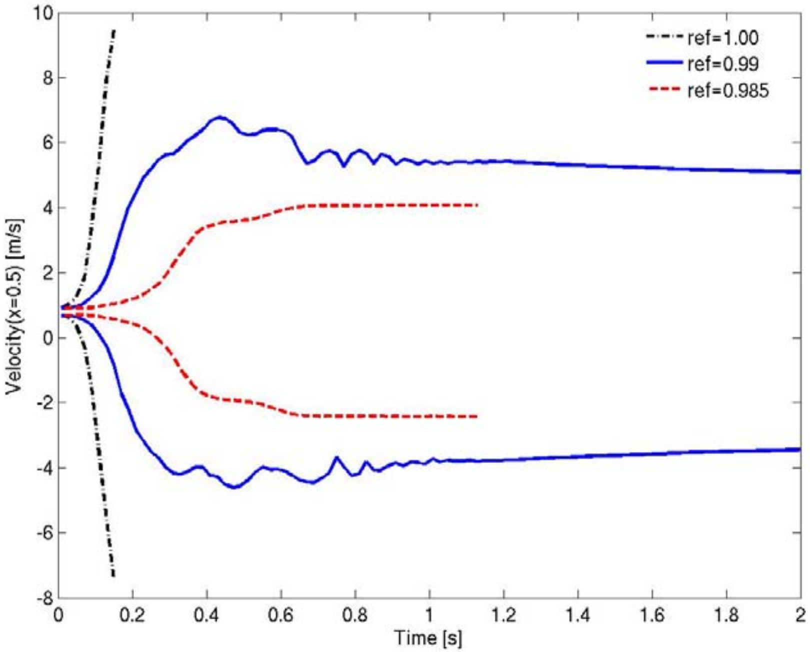
*A. P. Dowling, J. Fluid Mech., 1997, 346, 271
**P. Davies et al., J. Sound and Vib., 1980, 72, 543

Quenching by acoustic losses

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

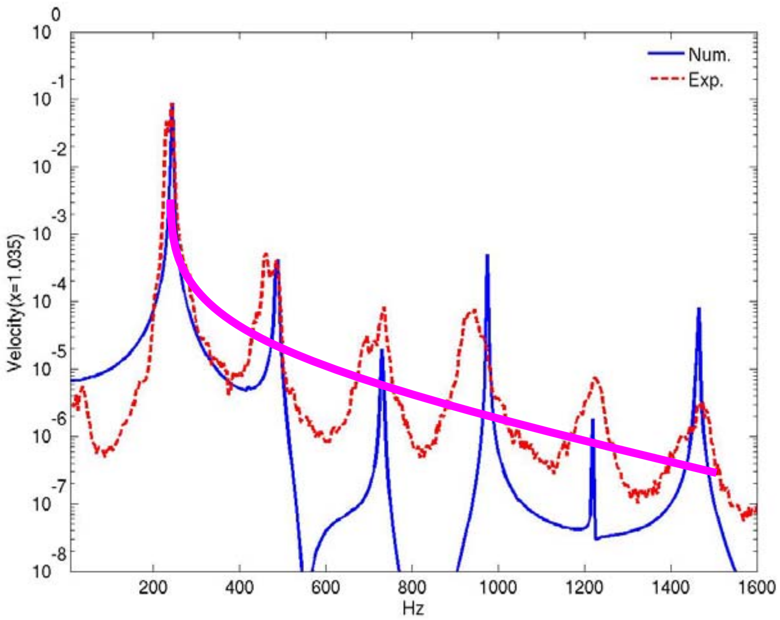


Envelope of velocity at single point in premixer for various reflection parameters. The red line is the envelope of the left plot



Power spectrum

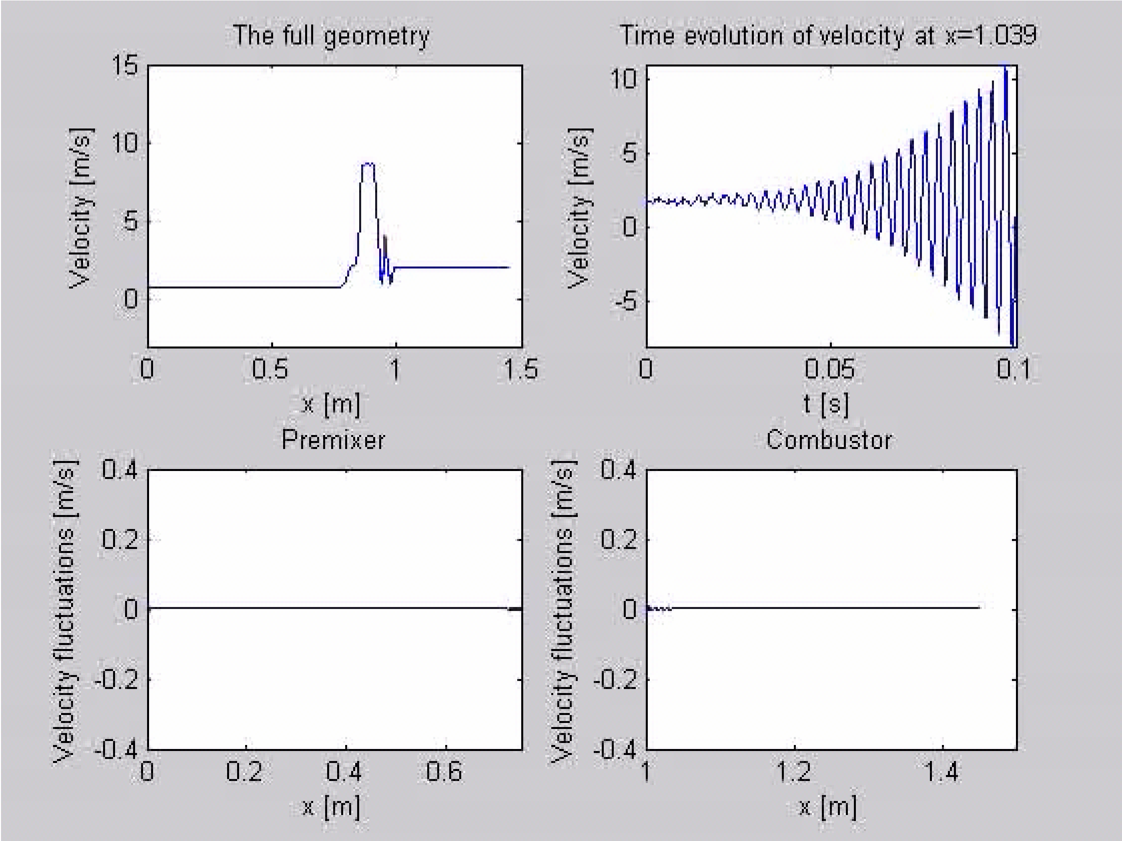
- By adjusting the temperature we get very similar power spectra from experiments (red) and numerics (blue)
  - No cooling in the model
  - Uneven temperature distribution in the combustor
- Spectral decay as function of frequency is correct
- By tuning *n* and τ we get interesting results also with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



Linear code

Re(f_num)	Im(f_num)
170.95890	-0.02527
242.86390	3.43053
342.76354	-0.00887
473.34227	0.89771

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