Combustion Dynamics in Gas Turbine Engines

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Outline

- Introduction Combustion Dynamics
- LIMOUSINE
- Limit cycles in a Generic combustor
Gas Turbine Engines for Power Generation, gas fired

- 1950: increase efficiency diffusion flames
- 1980: decrease NOx premix flames
- 1990: control stability lean premix flames
- 2010: life time very lean flames, high power density

Siemens SGT100
Acoustic Wave Propagation Equation in a fluid in motion

- Sound generation by turbulent flames:
- Originates from the fluctuating heat release in the flame.
- Explained by volumetric expansion in flame.
- Fluctuating heat release in turbulent flames is complicated due to the interaction of turbulence, mixing, combustion and pressure fluctuations.
The thermo acoustic source term

Sir James Lighthill:

Propagation of pressure fluctuations:

$$\frac{\partial}{\partial t} \left( \frac{1}{c_0^2} \frac{\partial P}{\partial t} \right) - \nabla^2 P =$$

Instantaneous thermo acoustic source term:

$$- \frac{\gamma - 1}{c_0^2} \frac{\partial}{\partial t} (\dot{Q})$$

Question: Is it that simple?
Acoustic/aerodynamic/combustion feedback loop

Acoustics

Acoustic propagation

Oscill. Pressure source C to A coupling

Aero to C coupling: FTF

Aerodynamics

Combustion

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Siemens V94.2/ SGT5-2000E, 200 MW
Buggenum 1995
Puertollano 1998
Combustion Dynamics research UT

PhD projects Combustion Dynamics
1995 Syngas/Buggenum S.Klein
2002 DESIRE J. van Kampen/R. Huls
2004 HEGSA S. Pater
2006 FLUISTCOM A. Pozarlik
2008 LIMOUSINE 5 PhD’s

<table>
<thead>
<tr>
<th>Year</th>
<th>Name</th>
<th>Thesis Title</th>
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<tbody>
<tr>
<td>2000</td>
<td>Klein, S.A.</td>
<td>On the acoustics of turbulent non-premixed flames</td>
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<td>2006</td>
<td>Kampen, J.F. van</td>
<td>Acoustic pressure fluctuations induced by confined turbulent premixed natural gas flames (Cum Laude)</td>
</tr>
<tr>
<td>2007</td>
<td>Jager, B. de</td>
<td>Combustion and noise phenomena in turbulent alkane flames</td>
</tr>
<tr>
<td>2007</td>
<td>Pater, S.G.J.</td>
<td>Acoustics of turbulent non-premixed syngas combustion</td>
</tr>
<tr>
<td>2010</td>
<td>Pozarlik, A.</td>
<td>Combustion, acoustics and vibration in premixed natural gas turbine combustors</td>
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Limousine Project: Marie Curie/ITN

- Limit cycle Oscillations in:
  - Combustion-Acoustics-Vibration-Heat Transfer-Fatigue

- 17 PhD students
- 3 Post Docs
- 5 work packages: Analytical, Numerical, Experimental, Control, Fatigue
- 6 work shops

- Twente/Keele /Imperial College/Zaragoza/Brno
- CERFACS/DLR/ANSYS
- IftA/Siemens/Electrabel

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LIMOUSINE PROJECT

- Study of high amplitude processes in a generic atmospheric combustor:
- NG 60 kW/air factor 1.4/bluff body=wedge stabilized
- Rig in 5 copies at UT/IC/DLR/Zaragoza/Ifta

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MODEL COMBUSTOR
SET-UP AND SENSORS

Pressure Transducer | Pressure waves
Laser Doppler Vibrometer | Wall vibration
CCD Camera | CH* Luminescence
Thermocouple | Temperature field

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INSTABILITY MECHANISM
OF THE THERMOACOUSTIC OSCILLATIONS

Proposed new feedback loop:
Acoustics is an energy carrier

PREVIOUS EXPERIMENTS

Pressure Signal Auto-spectrum for the 2 clamps situation, for same pressure transducer and different operating points

- Power = 40 kW, $\lambda = 1.5$
- Power = 40 kW, $\lambda = 1.8$
- Power = 40 kW, $\lambda = 1.9$
- Power = 40 kW, $\lambda = 1.6$
- Power = 30 kW, $\lambda = 1.6$
- Power = 30 kW, $\lambda = 1.4$

86 Hz
MEASURED DATA (1)
WALL VIBRATION AND PRESSURE SIGNALS

3 clamps
50 kW $\lambda = 1.4$

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MEASURED DATA (II)
CHEMINLUMINESCENCE HIGH SPEED IMAGES

3 clamps
50 kW $\lambda = 1.4$
MEASURED DATA (III)
ONE LOOP ZOOM IN

Pressure [Pa]

Time [ms]

Velocity [mm/s]

3 clamps
50 kW \( \lambda = 1.4 \)

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17th ICSV Cairo  22/07/2010
MEASURED DATA (V)
CROSS SPECTRUM BETWEEN WALL VELOCITY AND PRESSURE

3 clamps
50 kW $\lambda = 1.4$

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FEM MODAL ANALYSIS
FOR DIFFERENT CLAMPING CASES

86 Hz

100 Hz

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Limousine Combustor Geometry

<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>$H_{us}$ height upstr [mm]</td>
<td>322</td>
</tr>
<tr>
<td>$H_{ds}$ height downstr [mm]</td>
<td>1066</td>
</tr>
<tr>
<td>Wedge side $W_2$ [mm]</td>
<td>21.2</td>
</tr>
<tr>
<td>Upstr air velocity $m , s^{-1}$</td>
<td>3.02, 1.51</td>
</tr>
<tr>
<td>Cold flow Reynolds nr</td>
<td>5000</td>
</tr>
<tr>
<td>Combustor power [kW]</td>
<td>40, 20</td>
</tr>
<tr>
<td>$d_1, d_2$ [mm]</td>
<td>25, 50</td>
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Mesh Details:
- Highly refined mesh close to the wedge
- Total number of mesh elements = 950,000
- Minimum mesh size = 1 mm

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Numerical Models & Boundary Conditions

- Combustion Model: PDF Flamelet Model with Zimont Correlation for turbulent burning velocity
- Turbulence Model: k-ω SST for Steady State Simulations
  SAS-SST (LES like model) for Transient Simulations

All the conservation equations are solved with high resolution schemes

**Boundary Conditions:**

**Air inlet:** specified by velocity $U=3.02, 1.51$[m/s]

**Fuel inlet:** specified by mass flow rates $\dot{m} = 3.64E-04, 7.27E-04$ [kg/s]

No pre-heating both inlet temperatures at 300[K]

**Outlet:** standard outlet pressure condition
Results

Pressure spectrum FFT for 40kW case
Pressure peak at 110 HZ
Pressure temperature cross spectrum for 40kW case
Transient time video of temperature field at mid-plane of the combustor

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Rigid wall: Frequency doubling.

Acoustic Eigenfrequencies:
\( \frac{1}{4} \) wavelength, \( \frac{3}{4} \) wavelength: 110, 330 Hz
NOT: \( \frac{1}{2} \) wavelength at 220 Hz

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\[ \rho = \rho(P, s, y_i) \]

**Propagation equation for pressure oscillations in fluid in motion**

**Detailed derivation using** \( \rho = \rho(P, s, y_i) \):

\[
\frac{\partial}{\partial t} \left( \frac{1}{c^2} \frac{\partial P}{\partial t} \right) - \nabla^2 P = \nabla^2 \left[ (\rho uu) - \tau \right]
\]

\[- \frac{\partial}{\partial t} \left( \frac{\alpha}{c_p} \rho \sum_{i=1}^{N} \left( \frac{\mu_i}{W_i} + y_i \right) \frac{\nabla q}{\partial t} + \nabla q + (\tau : \nabla \nu) \right) \right] + \frac{\partial}{\partial t} \left( u\nabla \left( \rho - \frac{P}{c^2} \right) \right)
\]

**At high amplitude: frequency doubling!**
The authors would like to acknowledge the funding of this research by the EC in the Marie Curie Actions – Networks for Initial Training, under call FP7-PEOPLE-2007-1-1-ITN, Project LIMOUSINE with project number 214905.
CONCLUSIONS

- Autonomous Vibration at 86 Hz was recorded in the first set of experiments for all operating conditions. (does not agree with ACA loop)

- All the sensors (CCD camera, Laser Vibrometer and Pressure Transducers) measure identical frequency. The flame is the source of the sound, but the frequency is determined by the vibration of the walls.

- Changes in stiffness change frequency of the system. FEM modes were in agreement with measurements.

- In Limit cycle operation Frequency Doubling Occurs: nonlinear processes