Control and simulation of azimuthal instabilities in annular combustion chambers

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The annular chamber favors ‘new’ modes (azimuthal) where waves propagate along the chamber angle $\theta$. Hot topic today: these modes appear in all real systems and not in lab expts.
• DAWSON Experiment (Cambridge 2011)
Fluctuating heat release
ILLUSTRATION IN LAB EXPERIMENTS

Experiment 2013/2014
LES captures azimuthal modes:

LES of the full 360 degrees chamber

Computed one sector first. Then copied 14 times and let LES run
The LES goes unstable:

- A strong azimuthal mode appears (same frequency as real engine data)
- A mean swirling motion also appears

**Azimuthal Velocity vs Time**

- **Standard value without azimuthal modes**
- **Mean value during limit cycle (non-zero)**
CONFIGURATION IS AXISYMMETRIC
BUT THE FLOW IS NOT:

3 rotation speeds:
Mean swirl at $w$

«+» acoustic
mode at $c+w$:

«-» acoustic
mode at $c-w$:
c=sound speed
$w=$mean swirl velocity
• Existing ‘brute force’ LES of azimuthal modes developing in a full combustion chamber (Staffelbach et al PCI 32)
LES captures the mode

Pressure [Pa]

Temperature

38.360 ms
Azimuthal modes in annular chambers:

In annular chambers, azimuthal modes can take two forms:
- two standing modes (shifted by 90 degrees)
- two rotating modes (one for each azimuthal direction)

The two rotating or the two standing modes form independent basis and can be used to generate all other modes.
Why do we see sometimes standing and sometimes turning modes?

Recent theories:

- **NON LINEAR THEORIES** (Schuermans, Paschereit and Monkewitz, 2006): «standing modes are observed at low amplitudes only. At high amplitudes, only turning modes would appear»

- **LINEAR THEORIES USING SYMMETRY** (Schuermans, 2010, Sensiau 2009): «standing modes are observed only in perfectly axisymmetrical systems. In all other combustors, only turning modes should appear»
QUESTIONS:

• Are these results mesh independent?

• What is the structure of the mode? (Proper Orthogonal Decomposition and spectral analysis)
Dependence on mesh:

40 Mcells $\rightarrow$ 330 Mcells

Cost: 8 M CPU hours on BG/Q (1000 CPU years)
MODE STRUCTURE:

- MEASURE PRESSURE PERTURBATIONS ALONG THE AZIMUTHAL DIRECTION:

- BEFORE LOOKING AT LES, LET US LOOK AT SIMPLE MODELS IN A PERFECT ANNULAR DOMAIN: $A^+$ is the amplitude of the clockwise wave, $A^-$ the amplitude of the counter clock wise wave

$$p' = \left[ A_+ e^{i\theta} + A_- e^{-i\theta} \right] e^{-i\omega t}$$
Simple acoustics: pressure perturbation vs angle for a pure rotating mode in annular
PERFECT STANDING MODE: $A_+ = A_- = 1$
STANDING MODE WITH $A_+ = 1$, $A_- = 0.6$
SIMPLE MODEL vs LES RESULTS:

This is an almost perfect standing mode. It can be captured by POD:
Most energetic mode: **standing** mode at 750 Hz

(POD by A. Roux, CTR)
Pressure

Temperature

38.360 ms

Pressure

Temperature
OK, LES captures azimuthal modes. But how do we suppress them?:

- Use closed-loop active control (90s): seen yesterday
- Design combustion chamber using Large Eddy Simulation methods and theory (now)
LES tells us that THIS case is unstable. It does not say WHY.

ASSUME THAT:

(1) ACOUSTICS ARE THE FIRST-ORDER PHENOMENON CONTROLLING AZIMUTHAL MODES.

(2) FLAMES AND TURBULENCE CAN BE MODELLED AND INCLUDED IN THIS ACOUSTIC FORMULATION.

ATACAMAC: Analytical Tool to Analyze and Control Azimuthal Modes in Annular Combustors

From network to matrices

• In a one dimensional duct, two acoustic waves exist:

\[ u' = A_+ e^{i(kx-\omega t)} - A_- e^{i(-kx-\omega t)} \]

\[ p' = \rho c (A_+ e^{i(kx-\omega t)} + A_- e^{i(-kx-\omega t)}) \]

\[ u' = \hat{u} e^{-i\omega t} \quad \hat{u} = A_+ e^{ikx} - A_- e^{-ikx} \]

\[ p' = \hat{p} e^{-i\omega t} \quad \hat{p} = \rho c (A_+ e^{ikx} + A_- e^{-ikx}) \]
\hat{u}(x = L) = A_+ e^{ikL} - A_- e^{-ikL}
\hat{p}(x = L) = \rho c (A_+ e^{ikL} + A_- e^{-ikL})
\hat{u}(x = 0) = A_+ - A
\hat{p}(x = 0) = \rho c (A_+ + A_-)

Eliminate the wave amplitudes A- and A+:
Any duct of length $L$ with sound speed $c$ can be replaced by a matrix $M$
Ch. 8 Sec 8.2.7
ATACAMAC: Analytical Tool to Analyze and Control Azimuthal Modes in Annular Combustors

Results show that the growth rate depends on a coupling parameter linked to each burner $i$:

The flame delay $\tau_i$ measures the response of the flame of burner $i$ to acoustic perturbations.

$\tau_i$ is 0.7 ms in this burner (measured in the LES).
ATACAMAC: frequency of first azimuthal mode

\[ f = \frac{c_c}{2L_c} - \frac{c_c}{4\pi L_c} \sum \]

First azimuthal mode frequency with non active flames

Effect of the flames

Re(f) gives the frequency of the azimuthal mode

Im(f) gives the growth rate of the azimuthal mode

Coupling strength

\[ \sum = \sum_{i=1}^{N} \Gamma_i \]

For N identical burners

\[ \sum = \sum_{i=1}^{N} \Gamma_i = N \Gamma \]
Stability prediction using ATACAMAC:

- Frequency and growth rate of the azimuthal mode vs the flame delay $\tau$ of the burners:

$\tau$ found in the LES

ATACAMAC suggests: ‘decrease the delay $\tau$ and this combustor will become stable’. Went back to the LES and decreased $\tau$ by artificially increasing the flame speed.
Time evolution of pressure
Switching from standard to new chemistry in the LES indeed stabilizes the mode:

All azimuthal pressure variations disappear after a few cycles.
OTHER PATHS TO CONTROL: SYMMETRY BREAKING

WHAT IF WE MIX TWO DIFFERENT TYPES OF BURNERS (Type 1 and 2) IN THE SAME CHAMBER?
Type 1 and 2 burners will react differently to acoustic waves:

\[ \Gamma_i = -\frac{1}{2} \frac{S_i}{S_c} \frac{\rho_c c_c}{\rho_i c_i} \tan\left(\frac{\omega L_i}{c_i}\right) \left(1 + ne^{j\omega \tau_i}\right) \]

Can we improve stability of azimuthal modes by breaking the axisymmetry of the chamber?
TOO MANY POSSIBLE DISTRIBUTION PATTERNS TO TEST THEM ALL WITH LES

SUPPOSE WE WANT TO HAVE 4 ‘Type 2’ BURNERS IN A 24 BURNER CHAMBER:

WE COULD ALSO USE ANY NUMBER OF ‘Type 2’ BURNERS… ARE THERE OPTIMAL COMBINATIONS OF BURNER TYPES, BURNER MIX AND LOCATIONS?
ATACAMAC GIVES THE ANSWER:

First azimuthal mode frequency with non active flames

\[
f_{CW} = \frac{cd}{2L_c} - \frac{cd}{4\pi L_c} \left( \sum + S \right)
\]

\[
f_{CCW} = \frac{cd}{2L_c} - \frac{cd}{4\pi L_c} \left( \sum - S \right)
\]

\[
\sum = \sum_{i=1}^{N} \Gamma_i
\]

Coupling strength

\[
S = 2\kappa(\Gamma_1 - \Gamma_2)
\]

Splitting strength

THE SPLITTING STRENGTH QUANTIFIES THE SYMMETRY BREAKING EFFECT INDUCED BY MIXING TWO TYPES OF BURNERS
THE SPLITTING STRENGTH $S$:

$$S = 2\kappa (\Gamma_1 - \Gamma_2)$$

Geometrical function depending only on the pattern of distribution of type 1 and 2 burners in the chamber.

Response difference between the two burner types.
FULLY EXPLICIT SOLUTION
(zero CPU cost)

\[ f_{CW} = \frac{c_c}{2L_c} - \frac{c_c}{4\pi L_c} (\Sigma + S) \]

\[ f_{CCW} = \frac{c_c}{2L_c} - \frac{c_c}{4\pi L_c} (\Sigma - S) \]

This type of information is impossible to obtain from LES

Once it is obtained, we can pick up the most efficient pattern and test it in the LES or in the experiment.
Our stability analysis is bimodal: either the combustor is stable or it is not. Making design decisions on such a tool is dangerous.
Since ATACAMAC is fast, use it for UQ studies to evaluate effects of uncertainties on stability (Stanford CTR Summer Program 2014)

We will predict this is a stable case
But we should not believe it... the probability it will be unstable is 40 %