Combustion Instability: Mechanisms and Suppression

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Combustion instability is the feedback between combustor acoustics and the flame through a coupling mechanism.
In real devices, combustion instability suppression takes a number of forms:

**Acoustic Damping**

![Acoustic Damping Diagram](image)

**Symmetry breaking**

(a) $N_b = 1$

(b) $N_b = 2(s)$

**Active control**


[Davis and Black, “Dry Low NOx Combustion Systems for GE Heavy-Duty Gas Turbines”]

Combustion instability suppression can also achievable by “breaking” any part of this feedback loop.
The focus of this talk is suppression of the feedback loop through suppression of shear layer receptivity.
Goals of the talk:

– Demonstrate flow receptivity and its role in the thermoacoustic feedback loop

– Discuss methodologies to quantify flow receptivity

– Propose method for suppressing combustion instability through suppression of flow receptivity
Structure of swirling flows change significantly with swirl number, inducing vortex breakdown and PVC.

<table>
<thead>
<tr>
<th>Swirl Number</th>
<th>0.00</th>
<th>0.18</th>
<th>0.38</th>
<th>0.56</th>
<th>0.79</th>
<th>1.05</th>
<th>1.43</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow State</td>
<td>No VB</td>
<td>No VB</td>
<td>No VB</td>
<td>Intermittent VB</td>
<td>Weak PVC</td>
<td>PVC</td>
<td>Strong PVC</td>
</tr>
<tr>
<td>PVC Frequency</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>770–815 Hz</td>
<td>840 Hz</td>
<td>1060 Hz</td>
</tr>
</tbody>
</table>
As the structure of the flow changes, its receptivity to acoustic forcing changes, as does its preferred frequency

\[ F_{\omega} (f, A, S) = \frac{\omega' (f, A, S)}{\bar{\omega} (S)} \frac{\bar{u} (S)}{|u'_{\alpha} (f, A, S)|} \]

- \( f = \) acoustic frequency
- \( A = \) acoustic amplitude
- \( S = \) swirl number
Harmonic reconstruction of forced response indicates variation in shear layer receptivity with swirl number, frequency.
To quantify magnitude of vorticity fluctuation, we measured at the end of the vortex development length.
Normalized vorticity fluctuation amplitude vary with swirl number, low frequencies are less coherent at high swirl.
Variations in acoustic forcing amplitude with swirl number likely stem from variation in impedance at swirler.

**Normalized Vorticity Fluctuation**

- 600 Hz
- 1800 Hz, 1%
- 1800 Hz, 2%

**Normalized Axial Velocity Fluctuation**

- 600 Hz
- 1800 Hz, 1%
- 1800 Hz, 2%
Acoustic to vortical transfer function shows significant amplification of disturbances except at high swirl number.
PVC is present in the flowfield at the three highest swirl numbers; PVC is has significant turbulent kinetic energy
Analysis of the dynamical features of the flow field includes both POD and azimuthal decomposition.

\[ u(t, x, r, \theta) \]

\[ \hat{u}(\omega, x, r, \theta) \]

\[ \hat{B}_{i,m}(r, x, \omega) = \frac{1}{2\pi} \int_{0}^{2\pi} \hat{u}_i'(r, x, \theta, \omega)e^{-im\theta} d\theta \]
M-modes provide information about the symmetry of the disturbance field

Axisymmetric (like response to acoustic forcing)

Non-axisymmetric (like PVC)

Non-axisymmetric (like PVC)
A PVC manifests itself predominantly in $m=1$ and $m=-1$ motions with a very small response at mode $m=0$.
Mode $m=0$ does not show a response to a forcing frequency of 600 Hz at swirl numbers that produce a PVC.

Decomposition performed at $r/D = 0.5$.
When forcing at 600 Hz, only the PVC frequency shows a response at $m=1$ and $m=-1$

Decomposition performed at $r/D = 0.5$
Shear layer disturbance growth rates are negative for cases with PVC, indicating response suppression.
Shear layer disturbances do not grow or only minimally grow over a large range of frequencies.

\[
\max(\exp[-\int_0^\infty k_i^+ (\omega f, x') dx'])
\]

\[
\frac{f_{\delta_{OSL}}}{U_o}
\]
Shear layers become less sensitive to acoustics with PVC due to shear layer thickening. Streamwise location: $x/D = 0.3$
Study demonstrates how a PVC can suppress the receptivity of a swirling flow field to longitudinal acoustic forcing

— Receptivity of the shear layers was analyzed using both experiment and linear stability analysis.

— Shear layer receptivity is suppressed by a PVC as a result of shear layer thickening, which alters the growth rate of external disturbances in the flow field.
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Questions?

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