Instability and Shear Layer Effects on Sound Emission of Turbulent Jet Flames

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Coming up

- Motivation

- Numerical Methods
  - Fluid Mechanics and Combustion (LES)
  - Acoustics (CAA)

- Results
  - Flame Thickening
  - Flame Response

- Conclusion
Motivation

Combustion Instabilities

burner assembly without damage  damaged burner assembly

Reference:
Motivation

Combustion noise

I. Risk of thermoacoustic instabilities

Motivation

Combustion noise

I. involves risk of thermoacoustic instabilities
II. is expected to become important contributor to the overall sound emission of future aero engines

- Reduction of other components' noise emission (acoustic liners, fan blade design..)
- Combustion noise increases for leaner equivalence ratios
- Combustion noise in single and multiple (swirl) burner assemblies is still a research challenge

Dowling et al. 2015
Bourgin et al. 2015
Worth et al. 2013
Durox et al. 2013
Motivation

- Numerical investigation of combustion noise primarily based on hybrid methods (scale separation) (LES/CAA)
  - LES to compute acoustic sources and mean flow field
  - Flame modeling, e.g., thickening, to reduce comp. costs

I. Effect of flame thickening on the acoustic emission of turbulent flames?
II. Fundamental understanding of acoustic flame response mechanism needed for further modeling strategies
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Numerical Methods

Challenge – flame/flow/acoustic computation
Numerical Methods

LES / CAA - Hybrid Approach

LES

fluid mechanics and combustion

CAA

acoustics
Numerical Methods

LES Approach

LES

fluid mechanics and combustion

CAA

acoustics
Numerical Methods: LES Solver

**Compressible flow solver [2,4-5,7]**
- 2\textsuperscript{nd} order low diss. AUSM scheme
- 2\textsuperscript{nd} order (viscous fluxes)
- 2\textsuperscript{nd} order Runge - Kutta

**Level-Set solver [2]**
- 5\textsuperscript{th} order central scheme
- 3\textsuperscript{rd} order TVD Runge - Kutta
- Constrained reinitialization (5\textsuperscript{th} order WENO scheme, HCR2)
- Adaptive G-grid refinement at flame front

**Combustion model [2,8]**
→ Progress variable approach [3,6]

References:
[7] Batten et al. 2004
Num. Methods: Comb. Model/LES

Compressible flow solver [2,4-5,7]
- 2nd order low diss. AUSM scheme
- 2nd order (viscous fluxes)
- 2th order Runge-Kutta

Flow field at flame front

Level-Set solver [2]
- 5th order central scheme
- 3rd order TVD Runge-Kutta
- Constrained reinitialization (5th order WENO scheme, HCR2)
- Adaptive G-grid refinement at flame front

Combustion model [2,8] → Progress variable approach [3,6]

References:
[7] Batten et al. 2004
- Chemical reactions modeled in the flow computation through source term in the spatially filtered Nav.-Stokes equations

\[
\bar{\omega}_c = Re \ Pr \ \bar{\rho} \frac{\rho_{\infty,u}}{\rho_{\infty,b}} R_r (1 - \tilde{c}) \Psi(\tilde{G}(\vec{x}, t), \sigma)
\]

- Progress variable \( \psi \) depends on the level-set function \( G \) and is thickened by a Gaussian filter with subfilter variance \( \sigma \)

- Combustion model is valid in corrugated as well as thin reaction zone regime (Pitsch et al. 2005)
Num. Meth.: Level Set Meth.

- Surface of the embedded boundary is represented by the zero contour of a signed-distance function (Osher et al. 1988)
  
  \[
  \begin{align*}
  \phi > 0 & \quad \text{for } x \in \Omega^f, \\
  \phi = 0 & \quad \text{for } x \in \phi_0 \equiv \Gamma, \\
  \phi < 0 & \quad \text{for } x \in \Omega^s,
  \end{align*}
  \]

  properties:

- \( \phi_0 \) can be evolved by solving the level-set equation (Markstein et al. 1964)

  \[
  \frac{\partial \phi}{\partial t} + f \cdot \nabla \phi = 0,
  \]

  time evolution (3rd order discr.)

  convective transport with the velocity \( f \) (5th order discr.)

- \( f \) = relative speed of, e.g., flame surface \( \phi_0 = G_0 \)
  
  ➢ hyperbolic equation (spatial 1\textsuperscript{st} upw. scheme,

  1\textsuperscript{st} forw. Euler in pseudo time)
Num. Meth.: Reinitialization

- High-order-constrained reinitialization (HCR2, Hartmann et al. 2010) in pseudo time $\tau$

\[ \partial_\tau \phi^v + S(\tilde{\phi})(|\nabla \phi^v| - 1) = \beta F^v \]

- Forcing is only applied on interface cells ($\phi_i \ast \phi_{i+1} < 0$) to guarantee that the displacement introduced by the reinitialization is avoided

- Spatial discretization: 5th order Hamilton-Jacobi WENO scheme (WENO-5) (Jiang et al. 2000)

- Pseudo time discretization: Forward Euler

- Level Set description offers:
  - straightforward curvature and normal computation
  - applicable in turbulent combustion with strong flow-flame interactions
  - efficient for large scale problems (coupling method via Hilbert sorted base grid)
Combustion model

- Combustion modeling: Combined progress variable / Level-set approach by Moureau et al. (2009) to track motion of flame front $G_0$:

\[
\frac{\partial \tilde{G}}{\partial t} + \left( \tilde{\mathbf{v}} + \frac{\rho_{\infty,u}}{\bar{\rho}} \tilde{s}_{t,u} \tilde{n} \right) \cdot \nabla \tilde{G} = 0
\]

- Markstein length $l_c$ determines effect of resolved flame front curvature $\tilde{\kappa}$ on flame speed

\[
\tilde{s}_{t,u} = \tilde{s}_{L,0} \left[ 1 - l_c \tilde{\kappa} \right] + s_T
\]

- $s_T = s_t - D_{t,k} D\alpha_\Delta^{-2} \tilde{\kappa}$ is introduced (Pitsch et al. 2005) to model the partially resolved and underresolved flame-flow interaction

Pitsch et al. 2005
Schlimpert et al. 2016
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Numerical Method

CAA Approach

LES

CAA

fluid mechanics and combustion

acoustics
Acoustic perturbation equations (APE) account for acoustic transport in a time-invariant mean flow field.

Mean flow quantities and source terms computed from LES results.

Ewert and Schröder 2003 (J. Comp. Physics)
Num. Meth.: APE Solver

\[
\frac{\partial p^a}{\partial t} + c^2 \nabla \cdot \left( \rho v^a + \frac{v^a p^a}{c^2} \right) = c^2 q_c + q_e - c^2 \nabla \cdot (\bar{v} \rho_e) \\
\frac{\partial v^a}{\partial t} + \nabla (\bar{v} \cdot v^a) + \nabla \left( \frac{p^a}{\rho} \right) = q_m
\]

- dispersion relation preserving summation by parts (6\textsuperscript{th} order)
- low dissipation low dispersion Runge-Kutta method (4th order, 5/6 method)
- radiation boundary condition

Geiser et al. 2012 (AIAA)
Tam and Webb 1993 (J. Comput Phys.)
Tam 1996 (J. Comput. Acoust.)
Hu et al. 1996 (J. Comput. Phys.)
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- Conclusion
Results: Slot Burner Configuration

microphone position p1
## Results: Flame Thickening

<table>
<thead>
<tr>
<th>$\frac{T_b}{T_u}$</th>
<th>Re</th>
<th>$\frac{l_c}{l_{c,\text{neutral}}}$</th>
<th>$\Delta x/D$</th>
<th>$\sigma/\Delta x$</th>
<th>$\frac{l_f}{\Delta x}$</th>
<th>Ka</th>
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<tr>
<td>6.7</td>
<td>7000</td>
<td>0.85, 1.4</td>
<td>0.034</td>
<td>2 or 4</td>
<td>0.8</td>
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<td>0.31</td>
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"more unstable" "more stable"

Varying subfilter variance $\sigma/\Delta x$ to investigate flame thickening effect on acoustic emission

Schlimpert et al. 2016 (Phys. Fluids)
Pausch et al. 2016 (AIAA Paper)
Schlimpert et al., Combust. Flame, under review, 2016
Results: Flame Thickening

sound pressure level

- Sound spectra are qualitatively similar
- Flame thickening quantitatively affects mid-freq. region
Results: Flame Thickening

- Sound spectra are qualitatively similar
- Flame thickening quantitatively affects mid-freq. region

May 30th, 2016
AIAA/CEAS Aeroacoustics 2016, Lyon
Results: Flame Thickening

hydrodynamic instability

- Influence of flame thickening more pronounced for the more unstable case $l_c/l_{c,n}=0.85$
Results: Flame Thickening

source term analysis

- APE-4 system

\[
\frac{\partial \rho^o}{\partial t} + c^2 \nabla \cdot \left( \rho v^o + \frac{v^o \rho^o}{c^2} \right) = c^2 q_e + q_e - \underbrace{c^2 \nabla \cdot (\overline{v} \rho_e)}_{q_{c\&e}}
\]

\[
\frac{\partial v^o}{\partial t} + \nabla (\overline{v} \cdot v^o) + \nabla \left( \frac{\rho^o}{\overline{\rho}} \right) = q_m
\]

- Combustion noise dominated by energy source

\[
q_e = -c^2 \frac{\partial \rho_e}{\partial t} = \frac{\partial p^\prime}{\partial t} - c^2 \frac{\partial \rho^\prime}{\partial t}
\]

Crighton, Dowling et al. 1992
Bui et al. 2007
Results: Flame Thickening
Energy source

Comparison: all APE sources versus energy source $q_e$

- Combustion noise **dominated by energy source** $q_e$
- Sound spectra are qualitatively similar for varying $\sigma$
- **Flame thickening quantitatively** affects mid-freq. region for $\sigma > 3$
- No flame thickening effects for $\sigma < 4$

Pausch et al. 2016
Results: Flame Thickening

Energy subsources

Energy source $q_e$ can be split further into subsources:

$$q_e = \left( \frac{Dp}{Dt} - c^2 \frac{D\rho}{Dt} \right)' + \left( (c^2)' \frac{\partial \rho}{\partial t} \right)' + \left( \mathbf{v} \cdot (c^2 \nabla \rho - \nabla p) \right)'$$

\[ I_c / I_{c,n} = 0.85 \]

Geiser et al. 2012
Pausch et al. 2016
Results: Flame Thickening
Energy subsource

\[ q_{e,l} = \frac{Dp}{Dt} - c^2 \frac{D\rho}{Dt} = (\gamma - 1) \left( -\nabla \cdot q + \tau : (\nabla \otimes \mathbf{v}) - \sum_n h_n \omega_n \right) \]

- First energy subsource dominated by heat release source \( q_{e,h} \)
- No effect of flame thickening on energy subsource \( q_{e,l} \) and on \( q_{e,h} \)

Geiser et al. 2012
Pausch et al. 2016
Results: Flame Thickening

Energy subsources

Energy source can be split into subsources

\[
q_e = \left( \frac{D\rho}{Dt} - c^2 \frac{D\rho}{Dt} \right)' + \left( (c^2)' \frac{\partial \rho}{\partial t} \right)' + \left( \mathbf{v} \cdot (c^2 \nabla \rho - \nabla \rho) \right)' \]

\[
\frac{l_c}{l_{c,n}} = 0.85
\]

Geiser et al. 2012
Pausch et al. 2016
Results: Flame Thickening

Entropy source

- $q_{e,III}$ responsible for mid-frequ. region
- entropy noise

Iso-contours of $q_{e,III}$ (red = 0.5, blue = -0.5):

$\sigma/\Delta = 2$

$\sigma/\Delta = 4$

$\Rightarrow$ distribution of entropy sound source denser for thinner flame

Pausch et al. 2016
Results: Flame Thickening

Entropy source

- $q_{e,\text{III}}$ responsible for mid-frequ. region
- entropy noise

\[
\frac{\sigma}{\Delta} = 2 \quad \frac{\sigma}{\Delta} = 4
\]

Pausch et al. 2016
Results: Flame Thickening

Entropy source

- $q_{e,III}$ responsible for mid-frequ. region
- entropy noise

\[
\frac{\langle v \cdot (c^2 \nabla \rho - \nabla p) \rangle}{q_{e,III}'}
\]

Pausch et al. 2016
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Results: Flame Response
Slot Burner Configuration

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Investigation of turbulent acoustic flame response

Schlimpert et al. 2016 (Phys. Fluids)
Pausch et al. 2016 (AIAA Paper)
Schlimpert et al., Combust. Flame, under review, 2016
Results: Flame Response
acoustic flame transfer function

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<th>$s_T$</th>
<th>turbulent flame speed</th>
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<td>$St = \omega \bar{L}_f / v_0$</td>
<td>Flame Strouhal number</td>
</tr>
<tr>
<td>$\psi$</td>
<td>$q, A$ or $S$</td>
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**acoustic transfer function:**

$$F_{p\psi} = \left[ \frac{p' / \bar{p}}{\psi' / \psi} \right]^2$$

$$\bar{L}_f$$

$$s_{L,t} = s_{L,0}[1 - l_c \kappa] + s_T$$

**turbulent inflow spectrum**

**mass consumption oscillations $S = \psi$**

$$\frac{q'(t)}{q_0} = \frac{\int_{G=0} s'_{L,u} dA}{\int_{G=0} s_{L,0} dA_0} \frac{A'}{A_0}$$

**flame surface fluctuations $A = \psi$**

**Indirect influence on heat release**

**Direct influence on heat release**

**turb. area fluctuations $A'$**

**turb. heat release oscillation $q'$**

Schlimpert et al. 2016
Rajaram et al. 2009
Dowling et al. 2015
Results: Flame Response
heat release response

integral heat release response $q'$

$$
\frac{q'(t)}{q_0} = \frac{\int_{G=0} s'_{L,u} dA}{\int_{G=0} s_{L,0} dA_0} + \frac{A'}{A_0}
$$

- gas expansion affects medium frequency region $3 < St < 20$
- higher frequency region $St > 20$ unaffected

Schlimpert et al. 2016
Results: Flame Response
flame surface area / mass consumption

\[ \frac{A'}{A_0} = \int_{G=0}^{G=G_0} \frac{s'_{L,u} \, dA}{s_{L,0} \, dA_0} \]

Schlimpert et al. 2016
Results: Flame Response

Acoustic flame response

\[ \text{SPL} \uparrow (\sim 5\text{dB}) \]
\[ \text{SPL} \uparrow (\sim 10\text{dB}) \]

\[ F_{pq} = \left[ \frac{p' - p}{\bar{p}} \right]^2 \]
\[ = \frac{p - \text{trend}}{q - \text{trend}} \]
\[ \sim St^{-2} \]
\[ \text{trend for } St > 20 \Rightarrow \beta St^0 \]
\[ \text{trend not coupled with } q - \text{trend for } St < 20 \Rightarrow \alpha St^2 \]

Similar to round jet flames

Schlimpert et al. 2016
Rajaram et al. 2009
Results: Flame Response

Acoustic flame response $F_{pA} , F_{pS}$

\[ F_{pA} = \frac{[p' / \bar{p}]^2}{[A' / A]^2} \]

→ $F_{pA}$ – trend $\approx F_{pq}$ – trend for $St < 20$

→ $F_{pA}$ – trend $\approx F_{pq}$ – trend for $St > 20$

\[ F_{pq} = \frac{[p' / \bar{p}]^2}{[S' / S]^2} \]

→ $F_{pq}$ – trend $\approx F_{pq}$ – trend for $St < 20$

→ $F_{pq}$ – trend $\approx F_{pq}$ – trend for $St > 20$

→ **low frequency coupling of $p$ – trend still not clear?**

Schlimpert et al. 2016
Results: Flame Response

low frequency coupling – pressure?

low / medium frequency coupling of p – trend?

- $p \neq q$ trend
  - no direct coupling
  - $F_{pq}$ increase $\alpha St^2$

- $p \sim q$ trend
  - direct coupling
  - $F_{pq}$ plateau $\beta St^0$

Schlimpert et al. 2016
Results: Flame Response
low frequency coupling – pressure?

flame front response $\xi^2(St)$ in $\xi - \eta$ coordinate system

Schlimpert et al. 2016
Results: Flame Response

low frequency coupling – pressure?

low / medium frequency coupling of p – trend?

- SPL peak at $St = 20$ corresponds to the peak of local flame front response $\xi'$
- increasing trends similar for $p'$ and $\xi'$

→ low frequency range is controlled by local heat release fluctuations not by integral $q'$ determined by the flame front response and spectral source term study

Schlimpert et al. 2016
Conclusion – Flame Thickening

- Numerical flame thickening affects the mid-frequency region through the entropy source term (indirect combustion noise)
- Source distribution indicates thickening effect in regions of
  - high-amplitude flame surface perturbations
  - pocket formation, shedding, and annihilation
  - indirect combustion noise is important also in open flame setups
- No effect of flame thickening on acoustic emission through heat release fluctuations observed
  - good model performance if for direct combustion noise even for $\sigma = 4$
  - negligible flame thickening effect for $\sigma < 4$ for all APE sources
Conclusion – Flame Response

- Heat release study indicates different regimes
  - low, medium, high frequency regime
  - medium freq. range previously not observed for round jet flames
  - flame surface area fluct. important in low and medium freq. range
  - mass consumption oscillations important in higher frequency range

- Acoustic flame response
  - local heat release fluctuation dominates low freq. regime
  - acoustic trends similar to round jet flames (Rajaram et al. 2009)
  - first numerical results on three-dimensional slot flame confirm acoustic response trends of Dowling et al. 2015 (duct geometry) and Rajaram et al. 2009 (round jet flame), however, for a different flame setup (rectangular slot flame, fuel, etc.)
Acknowledgments

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References


