Effect of Flame-to-Flame Interaction on the Flame Describing Function of a Turbulent Swirling Annular Combustor

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Outline

1. Motivation: thermoacoustic instability

2. LES of NTNU annular combustor

3. Flame describing function (FDF)

4. Preliminary thermoacoustic prediction

5. Conclusions and future work

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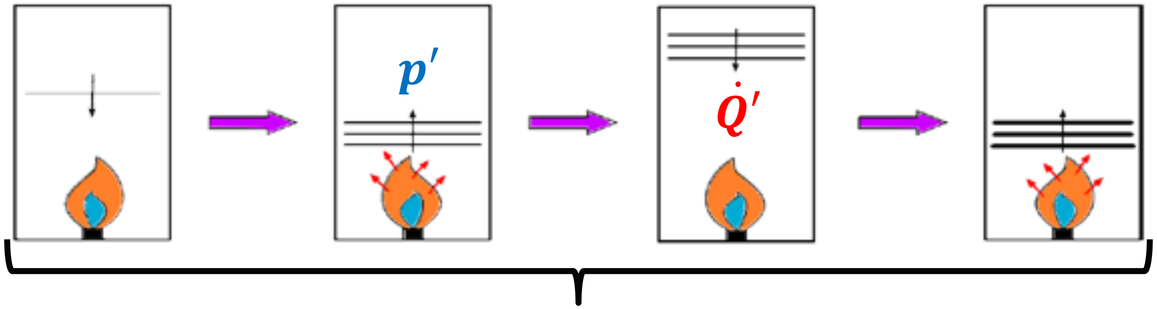
Motivation: Thermo-acoustic Instability

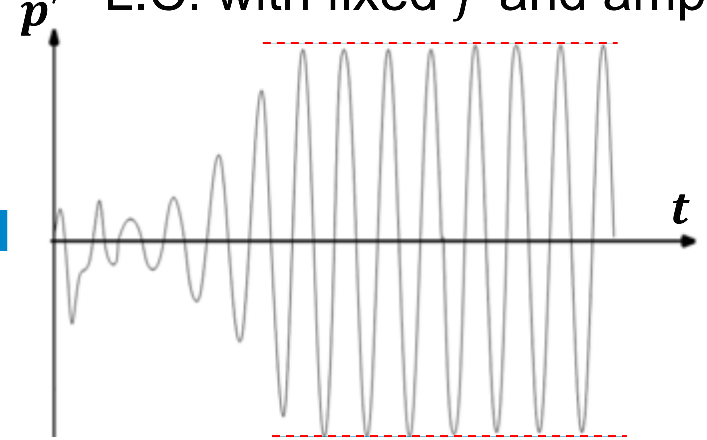
Two-way interaction between acoustic wave (p') and flame heat release ($\dot{Q}'$)



T/A instability -> Limit cycle oscillation

Fatigue failure of turbine blades

L.C. with fixed f and amp.



Noise pollution

Catherine J Goy, Stuart R James, and Suzanne Rea. Monitoring combustion instabilities: E. on uk's experience. Progress in Astronautics and Aeronautics, 210:163, 2005.

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Thermoacoustic limit cycle: mechanism

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Limit cycle prediction approaches usually treat acoustic waves and flame separately.

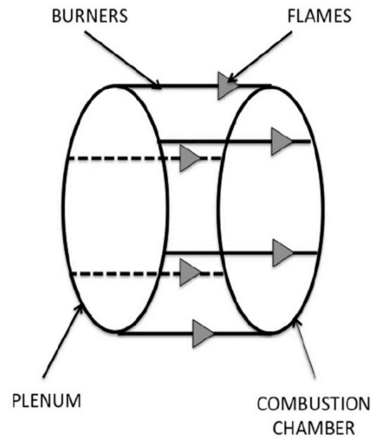
For acoustic waves:

Analytical Solution

$$f = \frac{c^0}{2L_c} + \frac{c^0\Gamma^0}{\pi L_c}$$

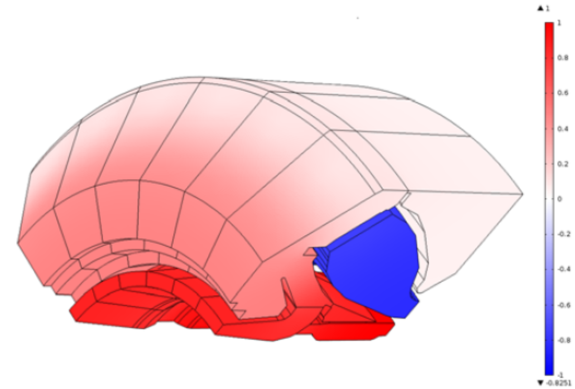
Noiray *et al.* (2011)

2-D Acoustic Network



Bauerheim *et al.* (2013)

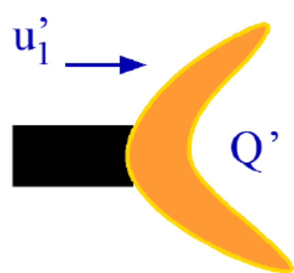
3-D Helmholtz Solver



Campa and Camporeale (2014)

…and coupled with flame response model to upstream perturbations:

Upstream acoustic perturbation (u', p')



Flame heat release rate response ($\dot{Q}'$)

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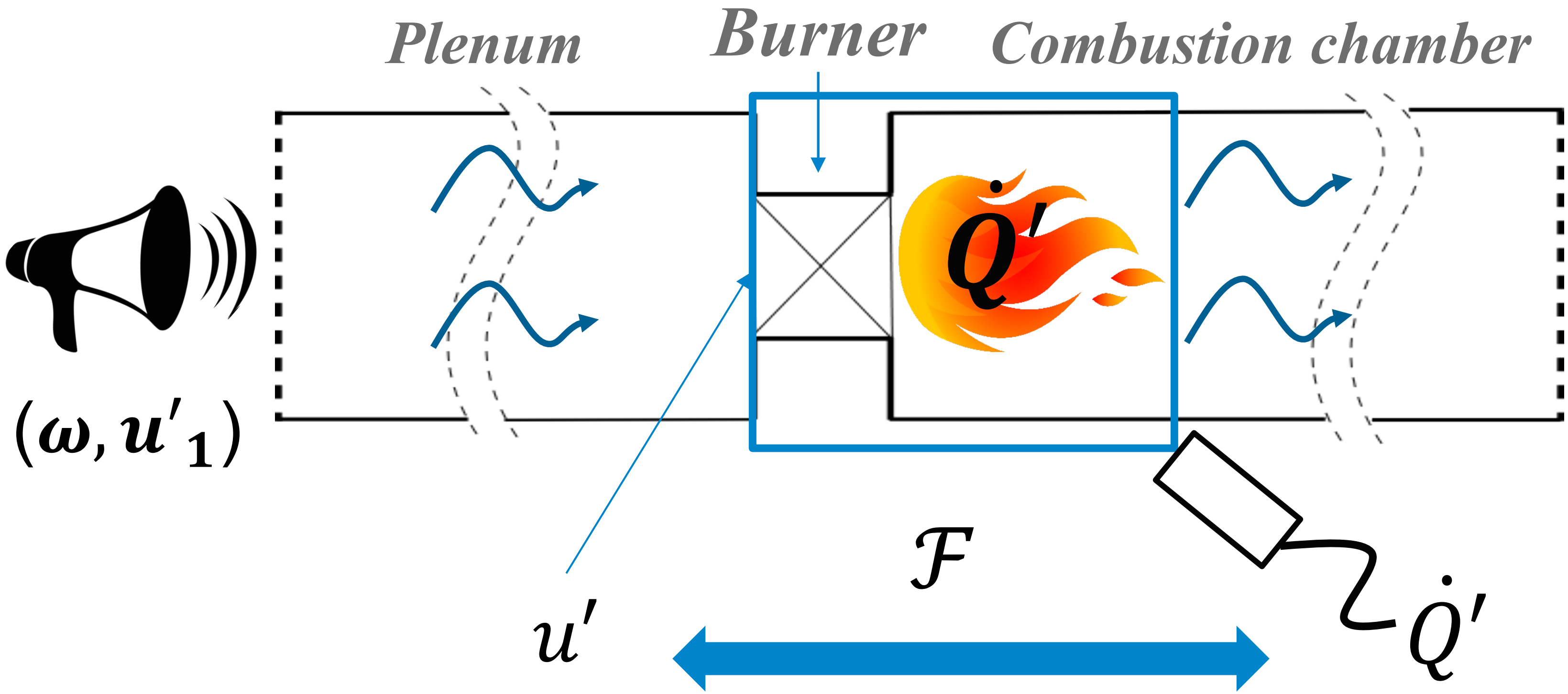
Global Flame Describing Function (FDF)

(single flame, thickness << acoustic wavelength)



❑ $\mathcal{F}(\omega, |u_1'/\bar{u}|) = G(\omega, |u_1'/\bar{u}_1|)e^{i\varphi(\omega, |u_1'/\bar{u}_1|)}$

G: FDF-gain, φ: FDF-phase

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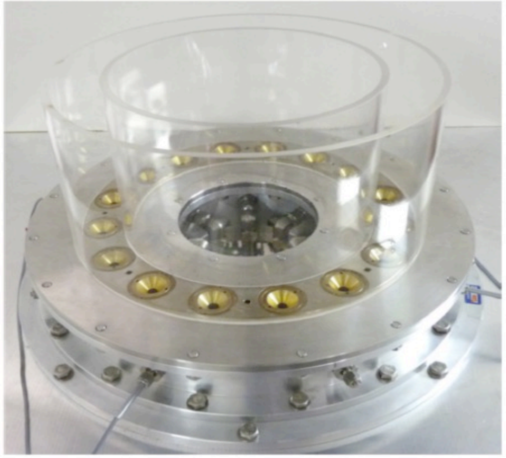
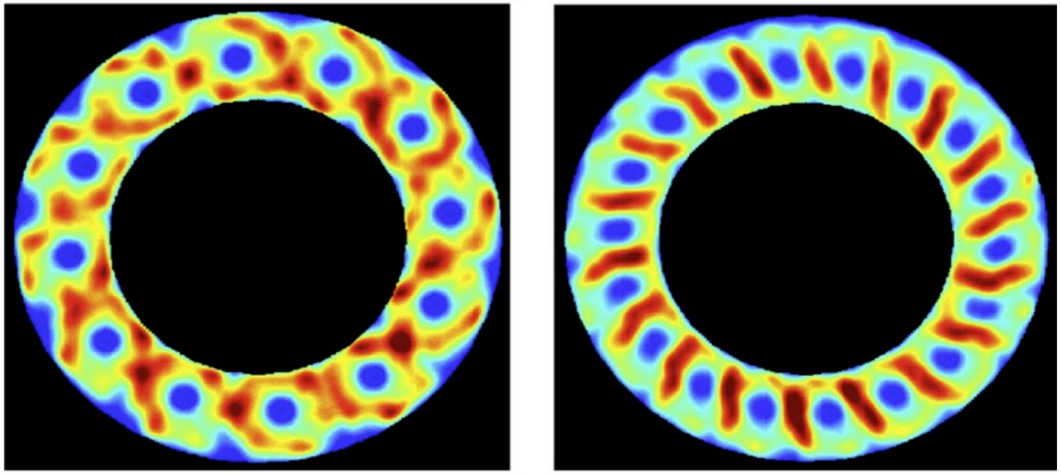
Does the global FDF describe the entire flame response in an annular combustor?

MICCA burner, EM2C, France



Durox et al., **Journal of Engineering for Gas Turbines and Power**, 138 (10), 101504.

NTNU combustor, NTNU, Norway

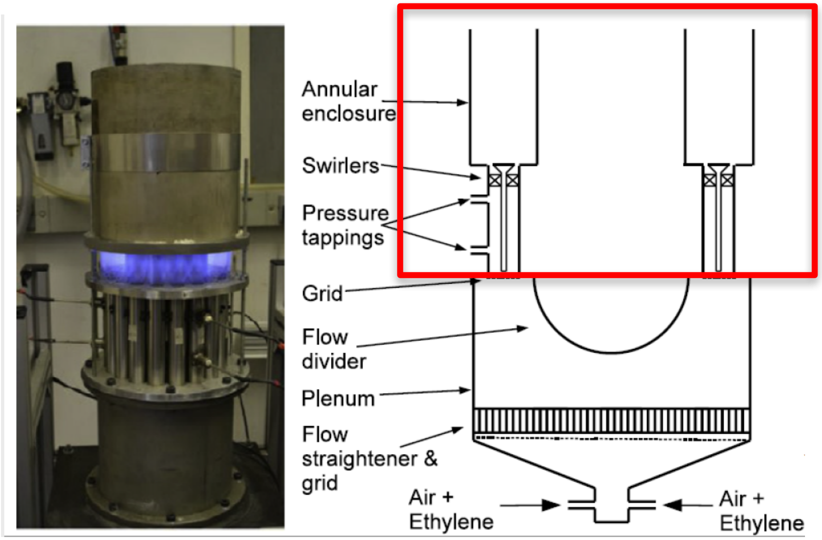


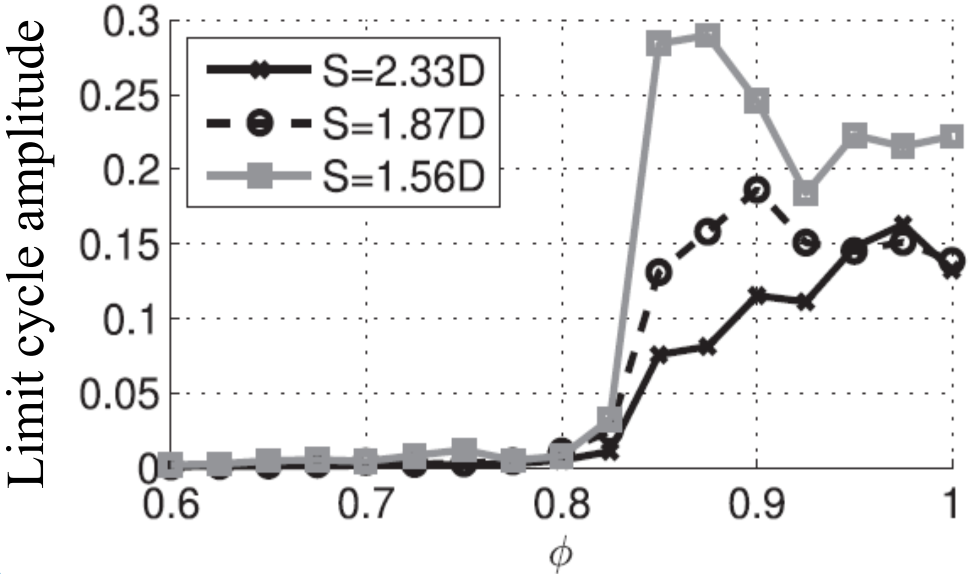
Worth and Dawson, **Proceedings of the Combustion Institute** 34 (2013) 3127–3134

Flame response in annular NTNU combustor

Main characteristics:

- Bluff body stabilized swirled flame.
- 6-blade swirler of diameter **D=18.9 mm**
- Atmospheric pressure, C_2H_4/air premixed
- $u_b = 18\ m/s$ at inlet → $Re \approx 15{,}000$
- Different limit cycle oscillation levels for different distances (S) between flames





Worth and Dawson (2013). **Combustion and Flame,** vol. 160.

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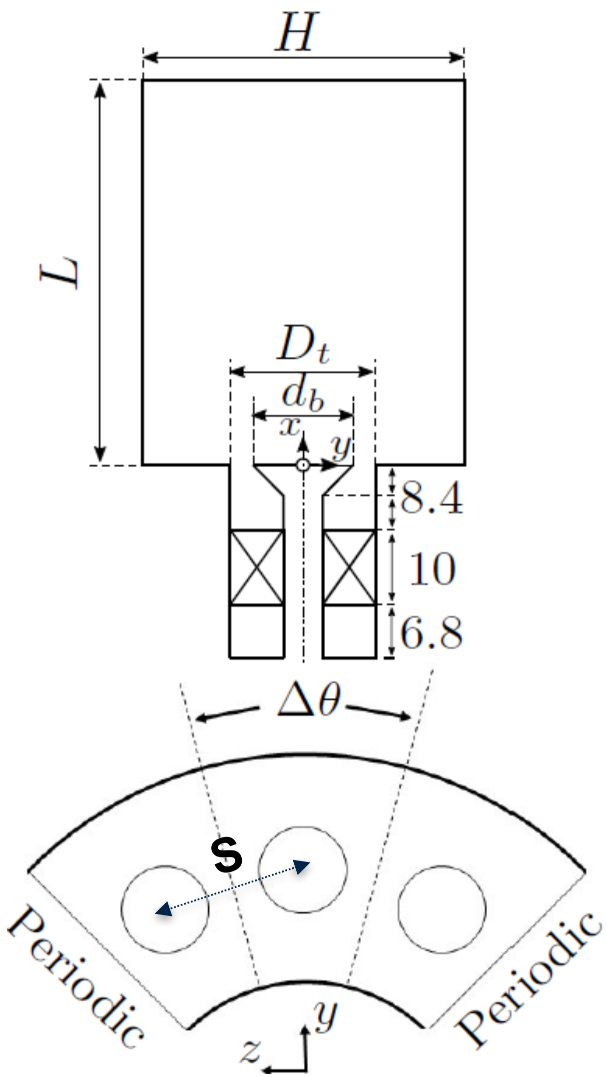
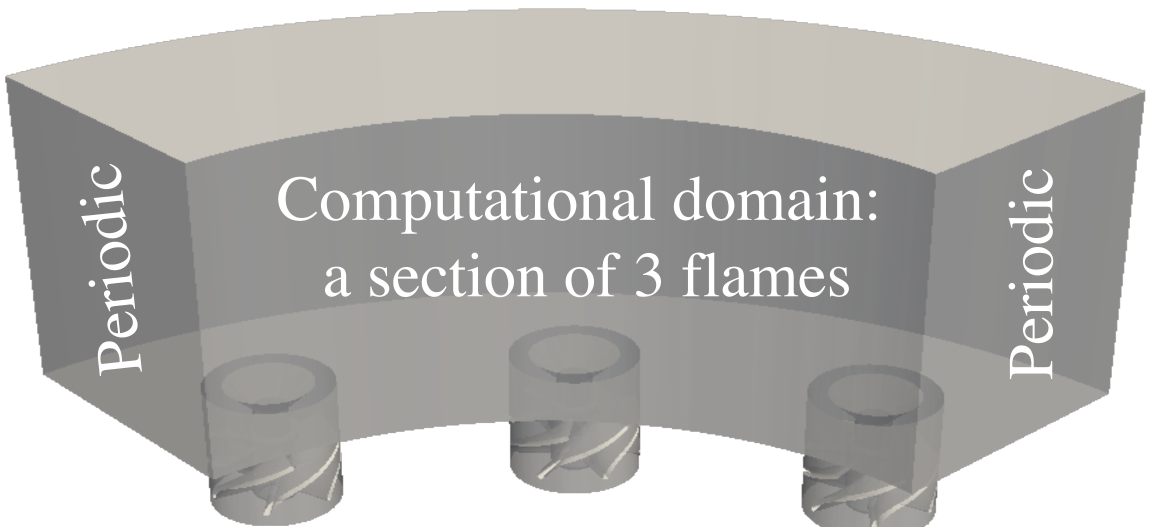
Two types of flame separation distances

- Two configurations using **a section of 3 flames**:

1. **S = 2.33 D, Δθ = 30°** (flames separated)
2. **S = 1.56 D, Δθ = 20°** (flames closer)

- Incompressible OpenFOAM-LES ($(\partial\rho/\partial p)_T = 0$)
  - Adiabatic side walls
  - 2-step C_2H_4/air reaction scheme
  - ~26M mesh cells for **1** and ~24M cells for **2**





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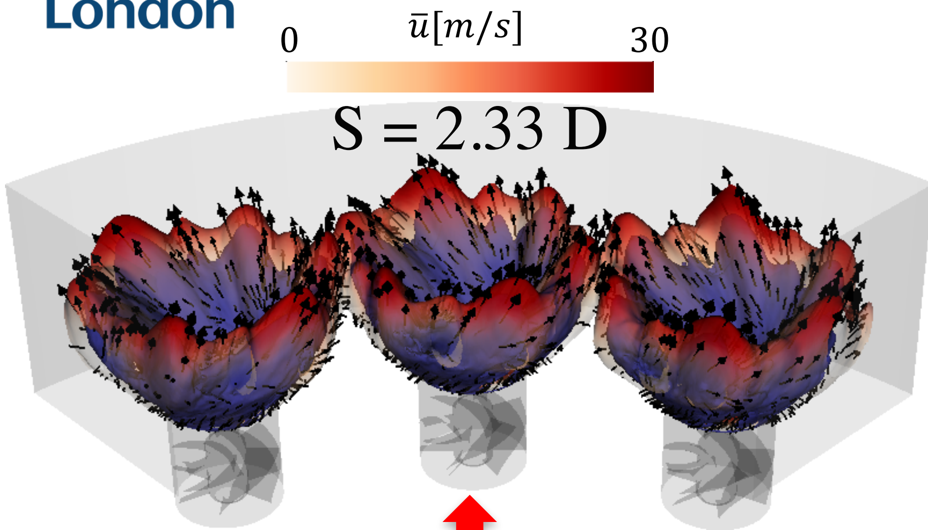
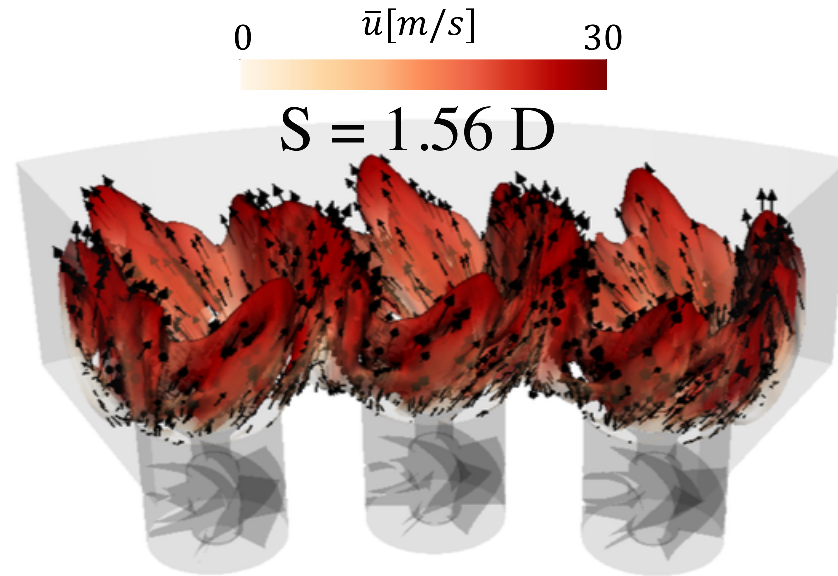
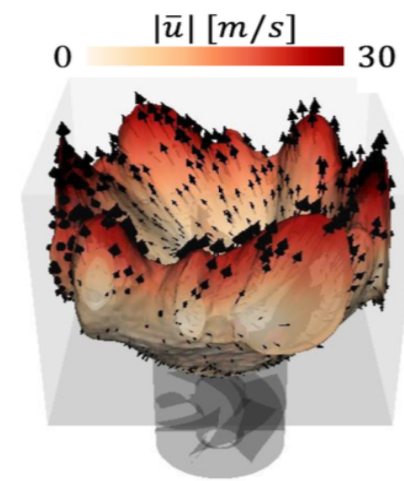
Unforced 3-D flame structures ($\emptyset = 0.8$)





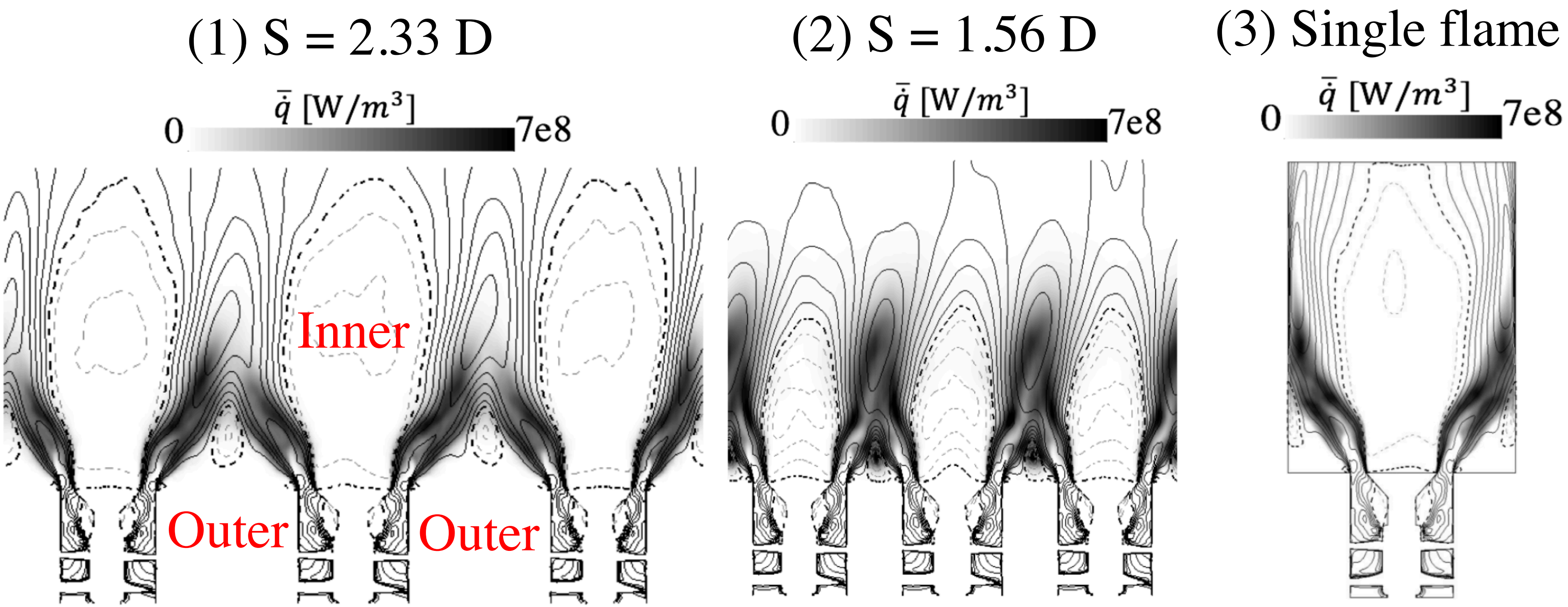
- ❑ S = 2.33D, flames are more independent
  - ❑ Only flame tips touch each other
  - ❑ High axial velocity at swirler vane locations
- ❑ S = 1.56 D, flames are largely merged
  - ❑ Breaks the circumferential symmetry
  - ❑ Conical flames now become square
- ❑ Isolated single flame
  - ❑ Longer length and strong flame-wall interaction



Isolated single flame

Unforced 2-D velocity fields ($\emptyset = 0.8$)

1) S = 2.33 D, large inner recirculation & small outer recirculation
2) S = 1.56 D, smaller inner recirculation & larger outer recirculation
   - Due to the decrease of flame expansion angle
3) Single flame, longer length due to flame-wall interaction & heat losses



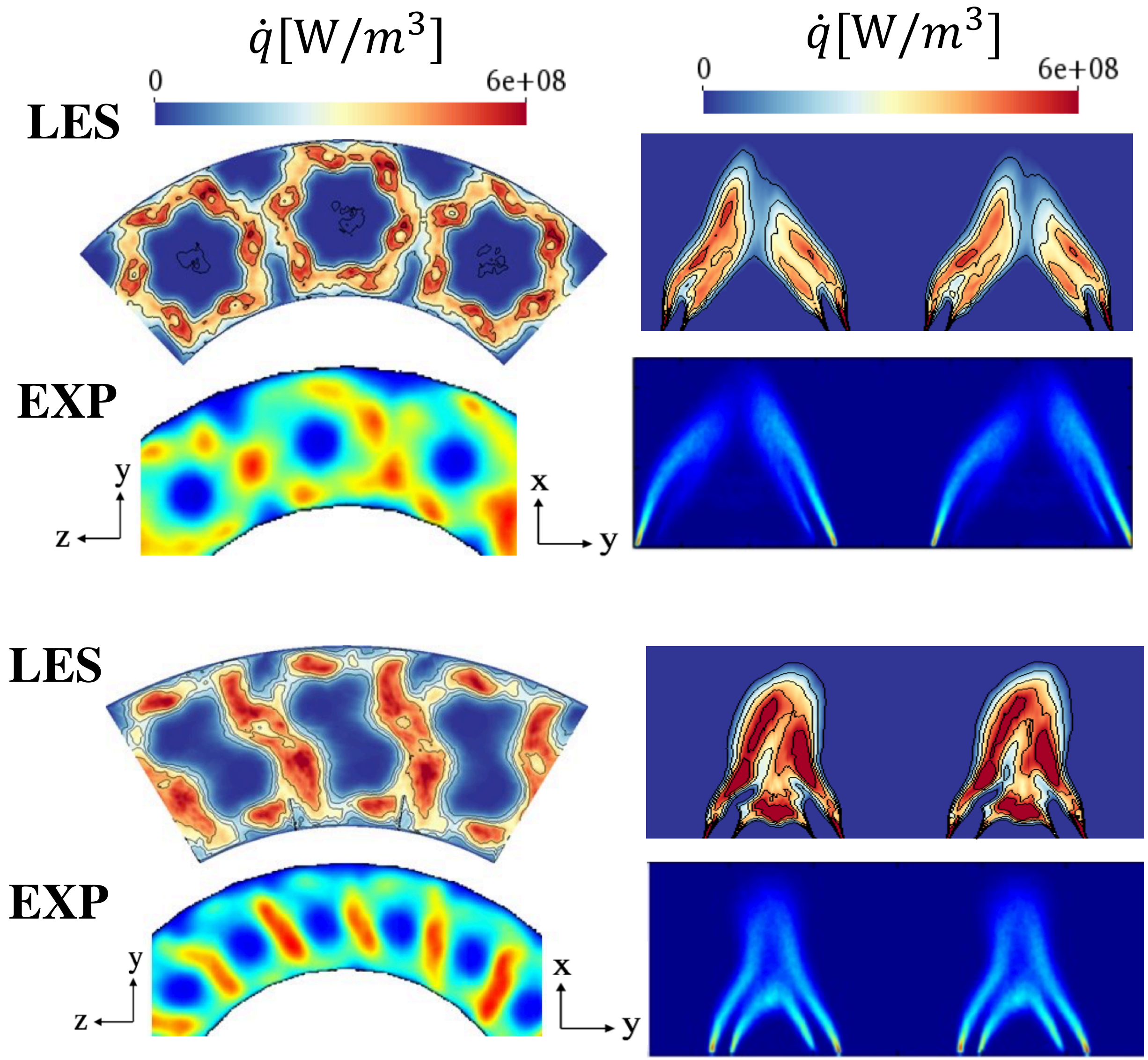
Validation of unforced flame LES ($\emptyset = 0.8$)

1) S = 2.33D

- Conical flames
- Match experiment [1]

2) S = 1.56D

- Square flames
- Match experiment [1]
- Mismatch in outer shear layer due to adiabatic back-plane



[1] Worth and Dawson (2013)

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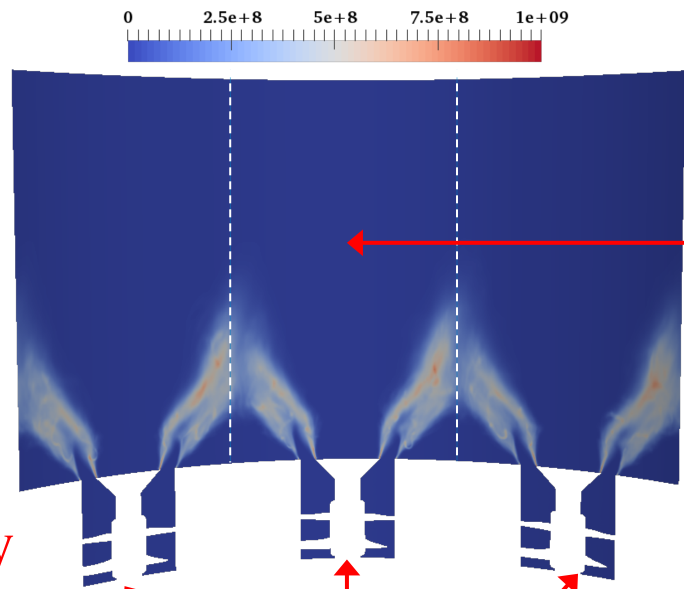
Forced flame responses ($\emptyset = 0.85$)

3) Flame describing function of central flame

$$\mathrm{FDF} = \frac{\mathrm{FFT}\left(\langle\dot{Q}\rangle'/\overline{\langle\dot{Q}\rangle}\right)}{\mathrm{FFT}\left(U'/\overline{U}\right)} = G\cdot e^{i\phi}$$



2) Heat release rate $\dot{Q}$ of only central flame is computed over time and spatially-integrated

1) A harmonic velocity perturbation, U, imposed upstream to all 3 flames simultaneously

$|u'/\bar{u}|$: Perturb. amplitude

f : Perturb. frequency

$$U = U_{in}[1 + |u'/\bar{u}|\cdot\sin(2\pi f t)]$$

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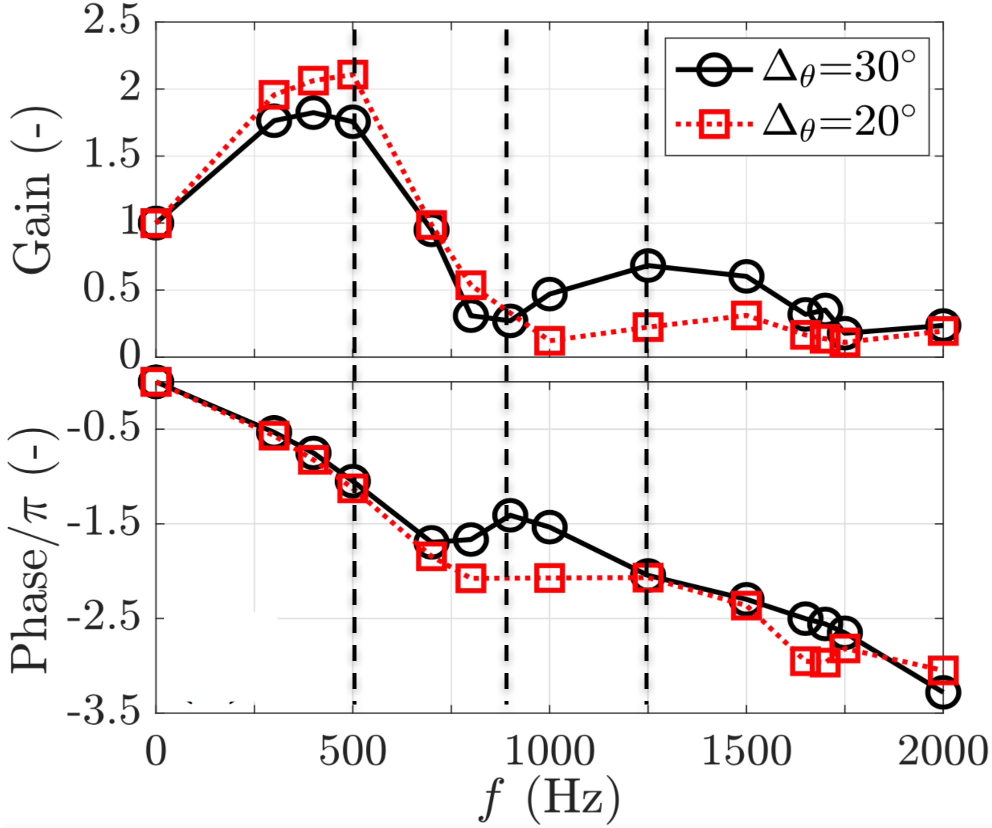
Large effect of flame-interaction on FDF

FDF of central flame at $|u'/\bar{u}| = 0.1$

(Black: S = 2.33 D,

Red: S = 1.56 D)



Central flame's FDF

vs.

Isolated single flame's FDF

Gain	Central flame	Single flame	Error
500 Hz	1.756	2.265	+30%
800 Hz	0.309	0.5175	+70%
1250 Hz	0.683	1.046	+50%

Phase	Central flame	Single flame	Error
500 Hz	-1.125	-0.868	-23%
800 Hz	-1.749	-2.254	+30%
1250 Hz	-2.3	-1,9	-20%

Saturation of central flame's FDF-gain for both S values, with different phase trends

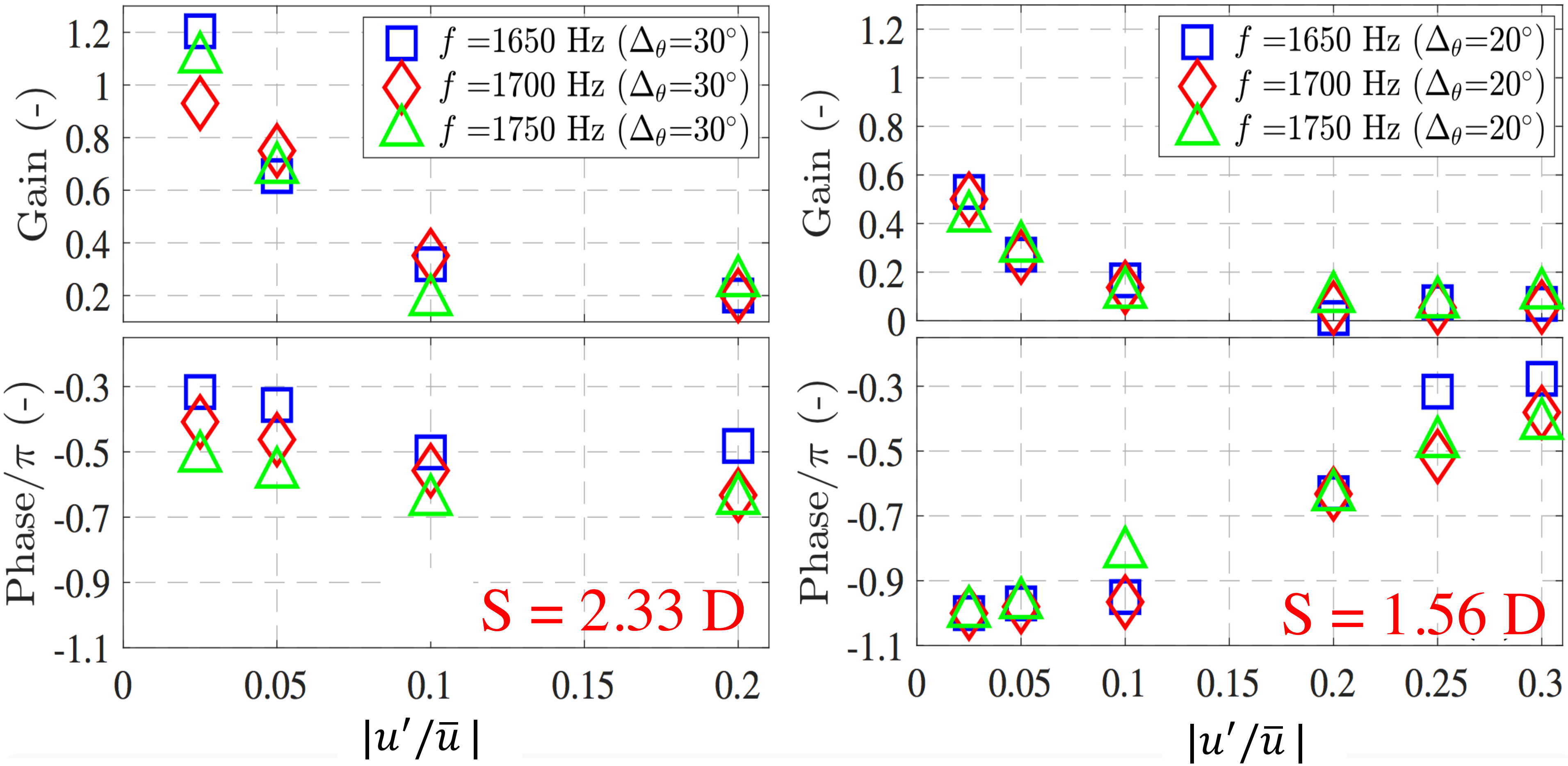
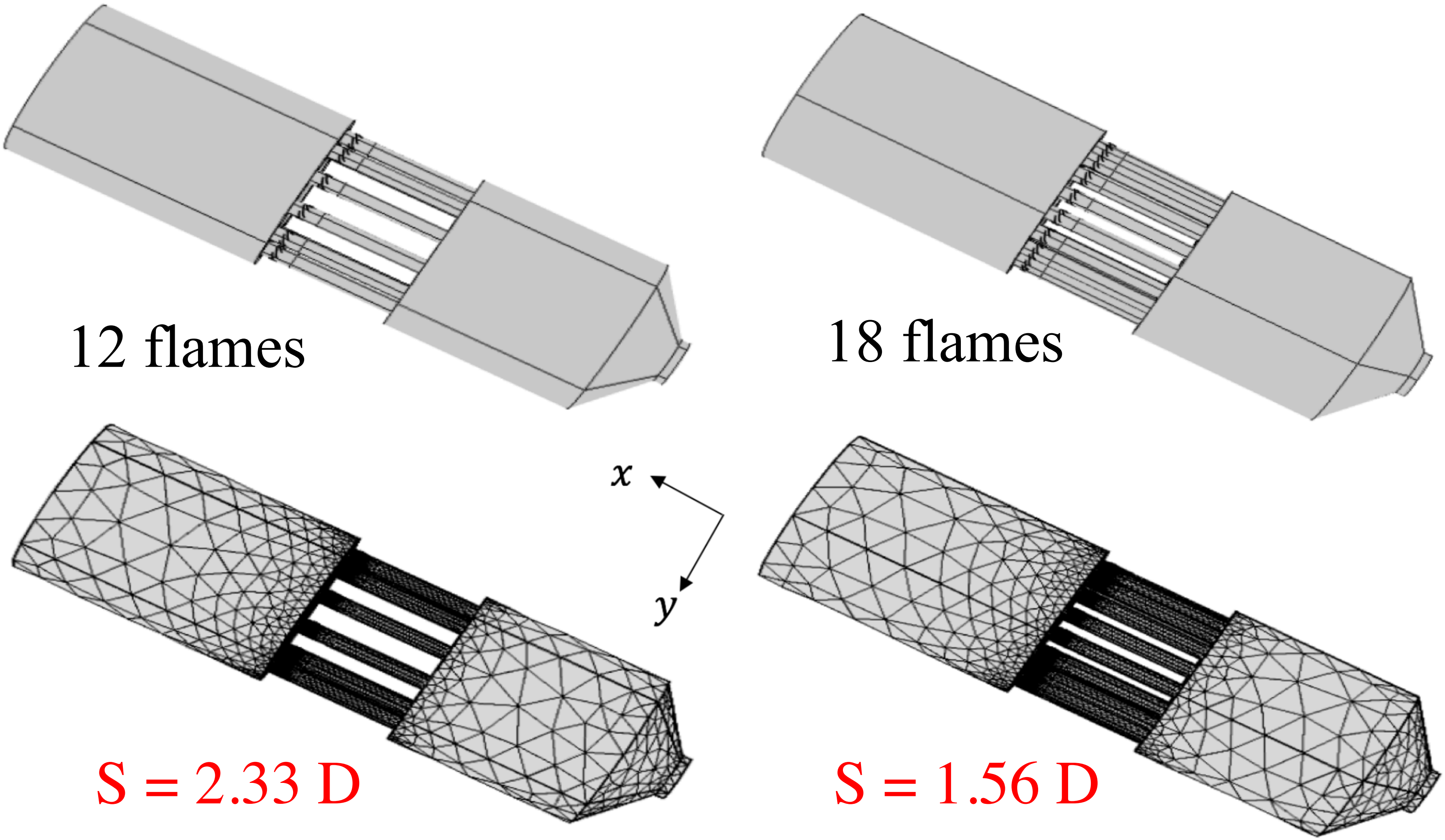


Figure: **Central flame's FDF** over $|u'/\bar{u}|$. (top) gain G and (bottom) phase φ.

Preliminary Thermoacoustic Prediction

COMSOL Multiphysics (5.2a)



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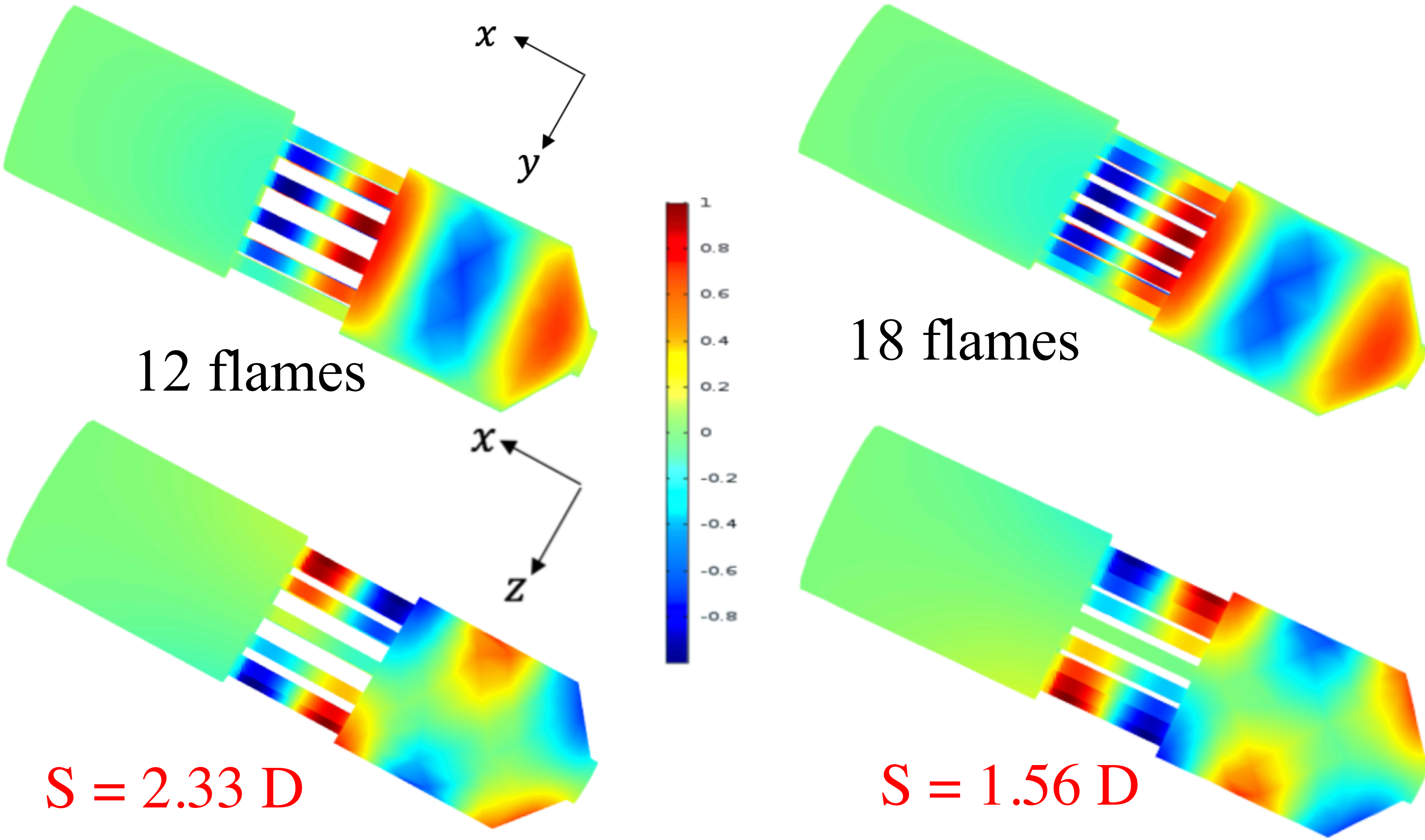
Preliminary Thermoacoustic Prediction

Passive flame with no FDF, spinning mode captured



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Preliminary Thermoacoustic Prediction

- The circumferential spinning mode is captured
- The predicted mode frequency is accurate

Mode frequency with passive flame assumption

	18 flames	12 flames
COMSOL [Hz]	1709	1721
Experiment [Hz]	1725	1690

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Conclusions and Future work

- Incompressible LES + simple chemistry can capture the flame-to-flame interaction effects.
- An isolated single flame cannot represent the flame response in an annular combustor.
- Different flame separation distances -> different FDF gain and phase values and trends
  - ➢ Dependences of FDF on perturbation frequency and amplitude
- The spinning mode frequency is captured by COMSOL
  - ➢ With FDFs the limit cycle for this mode can be predicted.

Thank you very much!

Any questions?

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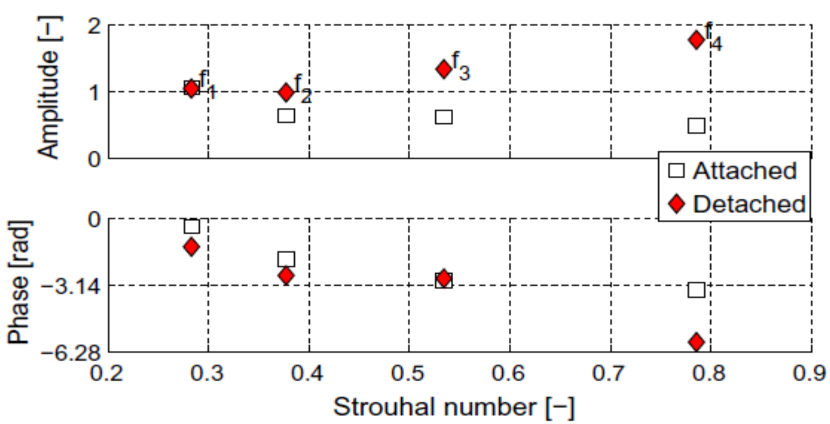
LES approaches for FDF

Compressible LES

- Acoustic waves directly simulated →
- Non-reflective B.C.
- Small time step ($CFL \approx c\Delta t/\Delta x$)
- The computation of a well defined FDF could become highly expensive



Incompressible LES ($(\partial\rho/\partial p)_T = 0$)

- Larger time step ($CFL = u\Delta t/\Delta x$) → Multiple frequencies and amplitudes simulated with less computational costs
- Non-reflective BC not required.
- Mapping of the acoustic perturbations as "hydrodynamic fluctuations"