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Premixed flame response to helical disturbances: Mean flame non-axisymmetry effects☆

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ABSTRACT

A key component of the thermoacoustic instability feedback mechanism is the excitation of hydrodynamic flow disturbances by narrowband acoustic fluctuations. In earlier work, we considered the response of time-averaged axisymmetric flames to helical disturbances. That study showed that although all helical modes cause local flame wrinkling, only the axisymmetric hydrodynamic mode, $m = 0$, contributes to the global heat release rate fluctuations. This paper extends this work to consider time-averaged flames that are non-axisymmetric. We show that distortions of the unforced flame shape changes its receptivity to helical disturbances, as it does not allow for the perfect destructive interference seen in axisymmetric flames. This results in a non-zero global flame response contribution from helical modes. Given that helical modes often have the largest amplitudes in jet flows, particularly those with swirl, these results show that the degree of non-axisymmetry of the flame has an important influence in determining which hydrodynamic modes, axisymmetric or helical, control the global heat release response of the flame. These points have been illustrated with example calculations that show how different control parameters and the degree of time-averaged non-axisymmetry influence the global flame response. An important implication of these results relates to scaling results from simplified geometries where a round jet is placed inside a round enclosure, to more realistic ones (such as where multiple jets are placed next to each other) where the flame shape will be distorted from being perfectly circular.

1. Introduction

Oscillations due to combustion instability are an important concern in modern combustors due to their degrading effects on system performance and hardware life. At the heart of this mechanism is the strong coupling between acoustics, flow hydrodynamics and the unsteady heat release rate oscillations. [1–3]. Of specific focus in this paper is the dynamics of premixed swirling flames subjected to helical flow fluctuations. While recent experimental research work has expanded the literature on this phenomena, there exists a need for deeper understanding of the flame response mechanism when hydrodynamic flow instabilities such as the helical modes of a swirling flow are in play [4–9].

The hydrodynamic instability of flows that are swirl and shear dominated manifests itself in several different unsteady flow phenomena, of which the precessing vortex core and helical shear layers are very important [10–14]. In the presence of sufficient swirl, the global instability of the flow results in a large vortex breakdown [11,15–17]. These complex flow features are of importance in combustor configurations since they control many different operational characteristics of the combustor such as flame stabilization, blow-off limits, flame shape and thermoacoustic instability [18].

This paper focuses on the sensitivity of premixed flames to harmonic flow fluctuations. It follows the results from several prior studies that modeled the dynamics of premixed flames subjected to direct acoustic and vortical flow fluctuations [19,20]. These dynamics were modeled using the level-set equation to analyze both the space-time distribution of unsteady flame surface position fluctuations as well as the spatially integrated global heat release rate fluctuations [20–22]. In all of these studies, either a two-dimensional or axisymmetric framework was considered, thus restricting the model to only symmetric flow fluctuations or features, such as excited ring vortices. In the case of both swirling and non-swirling jets there exist strong helical flow fluctuations that are inherently non-axisymmetric for example, Fig. 1 reproduces a snapshot from the level-set-LES simulation by Huang and Yang [23]. Notice the asymmetry in vortices that are shed off from the separating shear layer, indicating the strong presence of helical modes in the flow disturbances.

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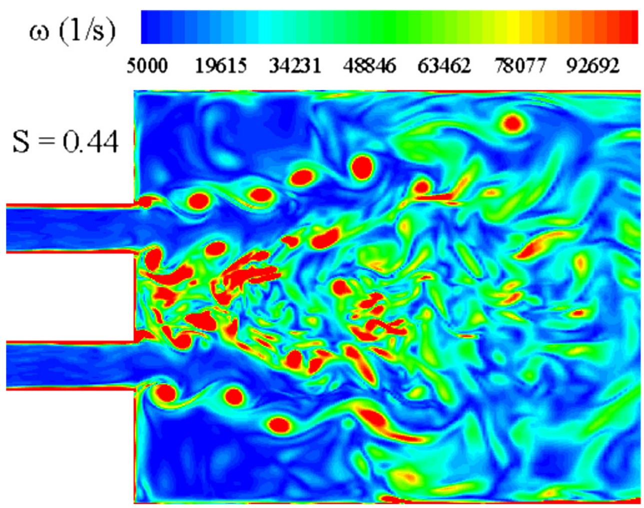

Fig. 1. Instantaneous out of plane vorticity field from LES computations using level-set flame tracking for a swirling flame with flow swirl number of 0.44. Snapshot courtesy of Prof. Vigor Yang.

Nomenclature

A	spatially integrated ("global") flame area
$\hat{B}_{i,m}$	Helical mode amplitude for mode m of velocity component in the *i*-direction
G	level set function (or) iso-contour variable for flame surface
L_f	characteristic flame length scale (flame height)
R	non-dimensional center-body radius
St	Strouhal number, ratio of characteristic axial time-scale and acoustic time-scale
U_0	characteristic velocity scale
U_c	axial phase speed of the velocity disturbance
$\vec{e}_i$	unit vector along i coordinate direction
k_c	non-dimensional phase speed of velocity disturbance, $= U_c/U_0$
s_L	laminar flame speed
$\vec{u}$	velocity vector
ε	ratio of amplitude of velocity disturbance and characteristic mean velocity scale
η	degree of azimuthal variation in mean quantities
σ	swirl parameter, $= \Omega/\omega$
ω	acoustic forcing frequency
ξ	vertical flame location (measured along axial direction)
ψ	vertical half angle of the stationary flame (w.r.t. axial direction)
Ω	characteristic azimuthal frequency (or) angular rate of swirl for solid body rotation
$()_{r,\theta,z,x}$	radial, azimuthal, axial and transverse x-direction component, respectively
$()_{t,n}$	tangential and normal components to the mean flame surface, respectively
$()^*$	dimensional quantity
$()'$	fluctuating component
$\overline{()}$	mean component
$\hat{()}$	frequency domain representation of corresponding time domain quantity

In order to describe the non-axisymmetric nature of the flow fluctuations, we can decompose their azimuthal variation into azimuthal modes or helical modes. This modal decomposition results in a complete set of basis functions that are orthogonal to each other:

$$\hat{u}_i'(r,\theta,z,\omega) = \sum_{m=-\infty}^{\infty} \hat{B}_{i,m}(r,z,\omega)e^{im\theta}$$
$$\hat{B}_{i,m}(r,z,\omega) = \frac{1}{2\pi}\int_0^{2\pi} e^{-im\theta}\hat{u}_i'(r,\theta,z,\omega)d\theta \quad (1)$$

where $\hat{u}_i'$ is the Fourier transform of the fluctuating velocity field in the *i*-direction and $\hat{B}_{i,m}$ is the amplitude of its helical mode number m. Note that $m = 0$ is the axisymmetric mode, while $m < 0$ and $m > 0$ are the non-axisymmetric modes that are co-rotating and counter-rotating with respect to the positive swirl direction.

As mentioned before, helical flow disturbances are present in both swirling and non-swirling round jet and wake flows. For non-swirling jets, isothermal stability analysis has shown that the separating boundary layer thickness near the jet exit controls the strength of the axisymmetric $m = 0$ mode relative to the low order helical modes but helical modes dominate further downstream of the potential core [24]. Similarly, the dominant instability mode in non-swirling, axisymmetric wakes are the helical, $m = \pm 1$ modes [25]. The stability of non-swirling jets has also been shown to be sensitive to confinement [26].

In the case of swirling flows, the bias in the direction of swirl has a great influence on hydrodynamic stability by biasing the strength of co-rotating and counter-rotating helical modes [27–31]. For example, stability calculations were performed by Loiseleux et al. [27], for a Rankine vortex model with the following velocity profiles:

$$r < R: \bar{U}_z(r) = U_\infty + \Delta U, \quad \bar{U}_r(r) = 0, \quad \bar{U}_\theta(r) = \Omega r$$
$$r > R: \bar{U}_z(r) = U_\infty, \quad \bar{U}_r(r) = 0, \quad \bar{U}_\theta(r) = \Omega R^2/r \quad (2)$$

Their results indicate that increasing swirl number decreases the temporal instability growth rate of the axisymmetric, $m = 0$ mode (presumably because the flow profile is centrifugally stable [32,33]). Impacts of swirl on helical modes are more complex, generally showing non-monotonic behavior with increases in swirl.

In addition to these intrinsic hydrodynamic instabilities of swirling flows, confined combustion chambers also exhibit natural acoustic oscillations. These acoustic oscillations interact strongly with the hydrodynamic flow instabilities. Imaging and measurements of acoustically forced premixed swirling flames have shown the strong presence of the influences of helical flow fluctuations along the flame location [2,34]. The presence of a swirling component in the mean flow causes wrinkles to be propagated along the flame in both the axial and azimuthal direction [35–38]. Note that due to the bias in the swirl direction, helical modes that are winding co- and counter- to the swirl direction interact differently with wrinkle propagation. Recent experimental work by Moeck et al. [4] and Stohr et al. [5] clearly show the azimuthally rotating heat release oscillations on the flame that are excited by helical disturbances. In addition, recent experiments by Worth and Dawson [6] analyzed the global heat release dynamics due to self-excited circumferential instabilities in an annular combustor. For annular combustors, depending upon the azimuthal location of the nozzle in the standing wave, they would excite different helical disturbances and thus differing flame response [6,8]. The flames excited by helical disturbances, as opposed to axisymmetric structures, had much smaller amplitude of heat release oscillations.

The Flame Transfer function (*FTF*), defined as the ratio of the spatially integrated heat release to a reference velocity perturbation has been used extensively to characterize the global flame response of premixed flames. In earlier work, the authors showed that this quantity *was zero for all* helical modes ($m \neq 0$) and that only the $m = 0$ mode contributed to the *FTF* when the time-averaged mean