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Role of induced axial acoustics in transverse acoustic flame response

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ABSTRACT

This paper addresses the mechanisms through which transverse acoustic oscillations excite unsteady heat release. Forced and self-excited transverse acoustic instability studies to date have strong coupling between the transverse and axial acoustic fields near the flame. This is significant, as studies suggest that it is not the transverse disturbances themselves, but rather the induced axial acoustic disturbances, that control the bulk of the heat release response. This paper presents results from an experiment that controls the relative amplitudes of transverse and axial disturbances and measures the flow field and heat release response for an acoustically compact, swirling flame. 5 kHz, simultaneous sPIV and OH-PLIF measured the flow field and flame edge, and OH* chemiluminescence measured the relative heat release. Experiments performed with essentially the same transverse acoustic wave field, but with and without axial acoustics, show that significant heat release oscillations are only excited in the former case. The results show that the axial disturbances are the dominant cause of the heat release oscillations. These observations support the theory that the key role of the transverse motions is to act as the "clock" for the instability, setting the frequency of the oscillations while having a negligible direct effect on the actual heat release fluctuations. They also show that transverse instabilities can be damped by either actively canceling the induced axial acoustics in the nozzle (rather than the much larger energy transverse combustor disturbances), or by passively tuning the nozzle impedance to drive an axial acoustic velocity node at the nozzle outlet.

1. Introduction

This paper describes an analysis of the transversely forced dynamics of a combusting swirl flow, with intentional suppression of axial nozzle disturbances. The motivation is that transverse combustion instabilities pose significant operability challenges in premixed combustors [1,2]. Several recent single and multi-nozzle experiments have studied the effects of transverse and axial acoustic forcing on the swirling flow field [3–8]. A recent review paper by O'Connor et al. [9] summarized the current understanding of transverse instabilities and summarized the key issues of the problem, namely the transverse acoustic field, the excited hydrodynamic modes, and the flame response to these disturbances.

While instabilities that couple with natural axial and transverse combustor acoustic modes are governed by similar mechanisms, they contain different levels of complexity. One key difference is that the excitation of transverse acoustic modes generally introduces additional spatial degrees of freedom into the problem. For example, axial mode instabilities, can often be conceptualized as one-dimensional acoustic fields that excite axisymmetric vortical structures, which subsequently cause axisymmetric distortions of the flame. Transverse mode instabilities have multi-dimensional acoustic fields, specifically near the nozzle, and lead to intrinsically three-dimensional, helical flow disturbances that produce multi-dimensional motions of the flame. In addition for a transverse mode instability, different nozzles/flames experience different points in the traveling or standing wave structure, and different hydrodynamic stability modes are excited at each location [10,11].

To further illustrate this point, perform a Fourier transform on the velocity vector, $u_j(r, \theta, z, t)$ in the coordinate system defined by Fig. 2, and decompose the Fourier coefficients into periodic azimuthal modes, indexed by *m:*

$$\hat{u}_j'(r,\theta,z,\omega) = \sum_{m=-\infty}^{\infty} \hat{B}_{j,m}(r,z,\omega)e^{-im\theta} \quad (1)$$

where $\hat{u}_j'$ is the Fourier transform of the j component of the velocity field, and $\hat{B}_{j,m}$ is the complex coefficient of the helical mode m. By this decomposition, the $m=0$ coefficient represents an axisymmetric mode while the $m<0$ and the $m>0$ modes denote

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co- and counter-rotating helical modes[1]. O'Connor et al. [9] expanded a transverse acoustic disturbance field into azimuthal mode coefficients in a polar coordinate system using the Jacobi–Anger expansion, i.e., $e^{ikx} = \sum_{m=-\infty}^{\infty} \hat{C}_m(kr)e^{-im\theta}$ (where x denotes the propagation direction of the transverse wave and $k = \omega/c$ denotes the acoustic wave number). It was shown that when the nozzle centerline was positioned at a transverse velocity antinode (pressure node), the transverse acoustics could be decomposed into odd modes as $\hat{C}_m = i^{m-1}J_m(kr)$ (with the $m = \pm 1$ modes being dominant), where r denotes the radial cylindrical coordinate; even-numbered modes are not present. In contrast, a velocity node at the origin (pressure antinode) is decomposed into even-numbered modes as $\hat{C}_m = i^m J_m(kr)$ (with the $m = 0$ mode being dominant); odd modes are not present. Finally, for a traveling wave, the decomposition results in both even and odd modes as $\hat{C}_m = i^m J_m(kr)$. Therefore, the position of a cylindrical geometry, such as a nozzle or a swirling flame in a transverse acoustic wave determines the nature of the excitation experienced by the flow field and flame.

While this decomposition of the transverse acoustic wave provides insight into which hydrodynamic disturbances are excited by the acoustic field, it shows neither how the global heat release oscillations are effected nor how the excited modes grow. Nonetheless, this decomposition helps explain results from several studies. For example, O'Connor et al. showed that the $m = 0$ mode, present as an axisymmetric vortex, dominated the flow response for an acoustic pressure antinode at the nozzle and that it subsequently excited axisymmetric flame wrinkling [9]. In contrast, when the nozzle experienced a transverse velocity antinode, the dominant response was seen in the $m = \pm 1$ modes, in agreement with the decomposition. Aguilar et al. [12] performed similar experiments comparing single and multi-nozzle responses to flow disturbances, showing the same preferential excitation of the dominant hydrodynamic modes depending upon the acoustic standing wave structure at the nozzle centerline.

In addition to the flow field sensitivity to the excited modes, the flame has a sensitivity of its own to the spatio-temporal structure of the disturbance velocity; i.e., the response of the flame cannot be simply characterized by a single reference velocity, and it responds differently to, say, an $m = +1$ disturbance than it does an $m = -1$ disturbance of equal magnitudes. For example, the following helical mode with index, m_0, excites the largest amplitude of flame flapping:

$$m_0 = \left(\frac{f}{\Omega}\right)\left(\frac{U_0 \cos^2(\psi)}{U_c} - 1\right) \tag{2}$$

as detailed in Acharya et al. [13], where ψ is the flame angle, U_c is the disturbance convection speed, f is the frequency, Ω is the angular rotation rate of the swirl flow, and U_0 is the bulk flow velocity in the axial direction. This expression shows that usually $m \neq 0$ flow perturbations result in the largest local flame motion and response.

While m_0 describes the mode exciting the largest magnitude of flame sheet flapping, a different mode, m_1, generally excites the largest amplitude of spatially integrated heat release, and a third mode, m_2, leads to the largest free field acoustic emissions from the flame [14]. For example, for flames that are axisymmetric in the absence of excitation, $m_1 = 0$; in fact, it is only the $m = 0$ mode that excites spatially integrated heat release, as the integral of $m \neq 0$ modes about an axisymmetric flame results in phase cancellation and no net contribution to global heat release. In other words, the only mode for which $\int e^{im\theta} d\theta$ between 0 and 2π does not equal 0 is the $m = 0$ mode, and thus the $m = 0$ mode is responsible for the global flame response [13,15]. Non-axisymmetry in the mean flame can result in heat release response at other modes, as discussed by Li et al. [16] and Acharya and Lieuwen [14]. To summarize, the hydrodynamic mode responsible for the largest local flame response, usually $m \neq 0$, is not always the mode responsible for the global heat release response, $m = 0$.

Experiments have confirmed this modeling result. Measurements by Worth and Dawson [10] of self-excited transverse oscillations in an annular combustor showed that the heat release depended on where the flame was located in the acoustic field, and therefore what hydrodynamic modes were excited. Similarly, Paschereit's groups observed using OH* chemiluminescence a strong flame response to a transverse traveling wave and to a transverse pressure antinode at the nozzle [17,18]. These two acoustic fields, as discussed earlier, result in strong axisymmetric $m = 0$ modes which modeling suggests are the dominant sources of flame response [13,15]. In addition, previous experimental work by Acharya et al. [19] observed that azimuthal modes, $m \neq 0$, of the flow field minimally changed the measured global heat release response but that the axisymmetric mode, $m = 0$, contributed strongly to heat release.

Given the role of the $m = 0$ mode with respect to the spatially integrated flame response, it is important to understand that factors in addition to the transverse acoustic wave can be responsible for its presence. The discussion below closely follows the review paper by O'Connor et al. [9]. First, note that the word "transverse mode" or "transverse excitation" approximates a multidimensional problem within the combustor. This conceptualization is useful to understand dominant features controlling the acoustic mode shape and frequency of the system; however, there are multi-dimensional effects that the conceptualization does not capture. Specifically, axial acoustic modes are always accompanied by transverse acoustic velocity motions in multi-dimensional geometries, and transverse acoustic modes by axial acoustic velocity motions. For example, the transverse acoustic field excites axial motions in regions where three-dimensional geometric effects occur – of particular interest to this study is at premixing nozzles. As shown in Fig. 1, transverse acoustic modes lead to axial acoustic motions in and upstream of the nozzle, which are a wave diffraction effect, as the dominantly transverse mode leads to an oscillatory pressure field across the nozzle exit. Axial flow oscillations in and upstream of the nozzle excite dominant $m = 0$ hydrodynamic modes.

Two factors control the relative amplitude of these induced axial flow to transverse mode oscillations – the transverse mode wave structure and the nozzle impedance. The former point is illustrated by Fig. 1, showing the acoustic pressure as a sinusoid and the acoustic velocity with arrows. In particular, a pressure antinode above the nozzle excites strong axial oscillations as the pressure antinode leads to a strongly oscillating axial pressure gradient in the flow direction [20]. For a pressure node above the nozzle, the axial oscillations are of opposite phase about the centerline and the oscillation amplitude decays upstream. The nozzle impedance, defined as the ratio of the unsteady acoustic pressure to acoustic axial velocity at the nozzle outlet, also has a significant effect on this transverse to axial coupling for pressure anti-node and traveling wave acoustic excitation. For example, increasing the blockage ratio of the swirler could result in a higher impedance and a weaker response of the axial acoustics. Thus, the structure of the transverse mode acoustic field determines the amplitude of the oscillatory pressure disturbance at the nozzle exit, while the impedance of the nozzle determines the amplitude of induced axial fluctuations.

There has been significant work to characterize the response of flames to transverse acoustics [17–19,21–35]. Specifically, Hauser et al. [33,34] studied transverse acoustic forcing on the in-

[1] Co- and counter- rotating denote the direction of motion of an iso-phase surface of the disturbance with respect to the mean swirl direction. This paper will be using $m > 0$ and $m < 0$ denoting co- and counter-rotating helical modes respectively.