Flame dynamics during intermittency and secondary bifurcation to longitudinal thermoacoustic instability in a swirl-stabilized annular combustor

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Abstract

In this experimental study on a laboratory-scale turbulent annular combustor with sixteen swirl-stabilized burners, we study the flame-flame interactions and the resulting flame synchronization during different dynamical states of combustor operation. We simultaneously measure the acoustic pressure and CH* chemiluminescence emission of the flame using high-speed camera. Upon changing the equivalence ratio, the combustor undergoes the following sequence of transition: combustion noise (CN) to low amplitude thermoacoustic instability (TAI) through the state of intermittency (INT), and from low amplitude to high amplitude TAI through a secondary bifurcation. Secondary bifurcation has been predicted in a numerical study and shown in a laminar burner. We report the evidence of secondary bifurcation from low amplitude TAI to high amplitude TAI for a turbulent thermoacoustic system. We find a significant difference in the dynamics of the flame inte-

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actions during the periodic part of intermittency, low and high amplitude TAI. Specifically, during the periodic part of intermittency, the phase difference between various burners show significant phase slips in time. During low amplitude TAI, there are fewer phase slips among the burners which result in a state of weak synchronization among the flames. During high amplitude TAI, we find that the flames are in perfect synchrony amongst themselves and with the pressure fluctuations. We then quantify the degree of temporal and spatial synchronization between different flames, and flames and pressure fluctuations using the Kuramoto order parameter and phase-locking value. We show that synchronization theory can be conveniently used to characterize and quantify the flame interactions.

**Keywords:** Annular combustor, Thermoacoustic instability, Flame-Flame Interaction, Secondary bifurcation, Synchronization

### 1. Introduction

Gas turbine combustors typically utilize an annular arrangement of burners to facilitate continuous and spatially distributed combustion along the annulus. The coupling between the unsteady heat release rate (HRR) from the flames along the annulus with the acoustic pressure fluctuations can lead to self-excited longitudinal or transverse instability. During unstable operation in an annular combustor, a large number of interactions take place concomitantly: Turbulent flow interacts with the premixed flames; flames interact with neighboring flames; the flow and the flame interact with the acoustic field of the combustor [1].

The interaction of the neighboring flames in an annular combustor results
in complex three-dimensional flame dynamics. The structure of the interacting flame undergoes many changes depending upon the inter-flame distance and the flame holding characteristics. Worth and Dawson \cite{2} analyzed the effect of the separation distance between flames in an arrangement with two bluff-body stabilized flame. They concluded that smaller inter-burner distances lead to large scale flame merging, resulting in an altered mean flame structure and their associated thermoacoustic response. In a follow-up study on a full annular burner, Worth and Dawson \cite{3} showed that the flame structure changed from helical-like to a large-scale merged flame structure when the inter-burner distance was decreased. Later, in a swirl-stabilized annular burner, Bourgouin et al. \cite{4} analyzed the modal dynamics associated with HRR perturbation during longitudinal and transverse instability. The effect of swirl on the interaction between neighboring flames was analyzed recently in a three swirl-stabilized configuration by Vishwanath et al. \cite{5}. They found that the difference in swirl number between neighboring flames can preferentially suppress or enable the formation of vortex breakdown bubbles. Thus, the flame-flame interaction plays a significant part in dictating the overall thermoacoustic response of annular combustors.

A lot of experimental \cite{4, 6, 7} and theoretical \cite{8, 9} studies have contributed immensely towards our understanding of longitudinal and transverse instability in annular combustors. However, most of these studies individually assess the state of transverse or longitudinal combustion instability. Studies that capture the dynamical transition to thermoacoustic instability (TAI) in annular combustors through smooth variation of parameters remain few.
The objective of this paper is to characterize the flame-flame and flame-acoustic interaction in a swirl-stabilized annular combustor consisting of sixteen burners during the transition from combustion noise (CN) to longitudinal TAI. The flames are subjected to acoustic perturbation of approximately the same amplitude and phase by the longitudinal pressure oscillations. We analyze the local HRR fluctuations from all the burners and quantify the degree of mutual synchronization amongst different burners, and among burners and the combustor acoustics. The mutual synchronization between different burners, or the lack thereof, essentially quantifies the flame-flame and flame-acoustic interactions.

2. Experimental setup and measurements

The premixed annular combustor is shown in Fig. 1. The design of the annular combustor is closely based on the designs of Worth and Dawson [6] and Bourgouin et al. [4]. The inner and outer diameter of the annulus is 300 mm and 400 mm respectively. The lengths of the inner and outer ducts are 200 mm and 400 mm, respectively. There are sixteen burner tubes mounted on the annulus. The inner diameter and length of the burner tubes are 30 mm and 150 mm, respectively. Sixteen axial swirlers are mounted on each of the burners to impart solid-body counter-clockwise rotation downstream of the swirler. Each swirler consists of six guide vanes mounted on a central shaft of diameter 15 mm and inclined $\beta = 60^\circ$ with respect to the injector axis. The geometric swirl number calculated using the equation $S = 2/3 \tan \beta = 1.15$ [10]. A converging section with exit diameter $d = 15$ mm connects the swirler to the annulus. The height of the converging section is 18 mm and has a
contraction area ratio of 2 (Fig. 1d).

The sixteen burner tubes are connected to a settling chamber of diameter 400 mm and length 440 mm. The settling chamber contains flow straightener to arrest transverse velocity fluctuations. A flow divider is present to distribute the flow uniformly to each of the burners. Premixed liquefied petroleum gas (LPG, 40% propane and 60% butane by volume) enters
through the bottom of the settling chamber through 12 inlet ports, each hav-
ing an internal diameter of 9.5 mm mounted perpendicular to the axis of the
combustion chamber.

Air and fuel flow rates are controlled using Alicat scientific Mass flow
trollers (MCR 2000SLPM for air and MCR 100SLPM for fuel). The
equivalence ratio is varied by keeping the air flow rate constant and varying
the fuel flow rate. Thus, $\phi$ is varied in the range of $0.3 - 0.6$ for nominal
flow velocity $v_z \approx 8.5$ m/s and $Re_d \approx 8600$, respectively. The maximum
uncertainty in the values of $\phi$ is $\pm 1.6\%$ and for $v_z$ and $Re$ is $\pm 0.8\%$. The
premixed flame is ignited using a non-premixed LPG pilot flame anchored
between two injectors (Fig. 1c).

Simultaneous pressure measurements and imaging were performed to ob-
tain the acoustic pressure fluctuations and intensity fluctuations caused by
the swirling flames. The acoustic pressure fluctuations are recorded using
four PCB103B02 piezoelectric transducers (sensitivity - 217.5 mV/kPa, un-
certainty - $\pm 0.15$ Pa). Three transducers are mounted on the combustor
backplane at locations P1, P2, and P3 in Fig. 1c. The pressure signals are
acquired for 3 s at a sampling frequency of 10 kHz and digitized using a
National Instruments 16-bit PCI 6343 card. A high-speed CMOS camera
(Phantom V 12.1) is used to acquire the images at a resolution of $1280 \times 800$
pixels corresponding to the half-plane of the annulus of size $400 \times 200$ mm
at full exposure. Imaging is performed with the aid of an air-cooled mirror
placed overhead of the combustor. A CH* bandpass filter (bandwidth of
$435 \pm 10$ nm) was used to capture chemiluminescence images of the flames.
The camera is outfitted with a Nikon AF Nikkor 70-210 mm f/4-f/5.6 cam-
3. Results and discussions

3.1. Bifurcation diagram

In Fig. 2, we plot the variation in the root-mean-squared value of pressure fluctuations ($p'_{rms}$) as a function of the equivalence ratio $\phi$. For $\phi \lesssim 0.47$, acoustic pressure fluctuations are aperiodic with a broadband amplitude spectrum and have a very low value of $p'_{rms}$. This state of combustor operation (CN) is referred to as combustion noise. Increasing $\phi$ leads to a state wherein low amplitude periodic oscillations of acoustic pressure are interspersed randomly amongst relatively very low amplitude aperiodic oscillations. This state is referred to as intermittency (INT) [11]. Increasing $\phi$
past 0.48 leads to a gradual increase in the sound levels in the combustor. We observe periodic oscillations with a narrowband peak at $220 \pm 10$ Hz and amplitude levels of the order of $p'_{\text{rms}} \sim 10^2$ Pa ($\approx 135$ dB). We refer to this state as low amplitude TAI. At $\phi \approx 0.5$ (Fig. 2), we observe an abrupt increase in the amplitude of pressure oscillations as the system transition from low amplitude TAI to high amplitude TAI of the order of $p'_{\text{rms}} \sim 10^3$ Pa ($\approx 165$ dB). We also observe hysteresis when $\phi$ is decreased while the system is in the state of high amplitude TAI. Thus, the transition follows: CN (region-I) $\rightarrow$ INT (region-II) $\rightarrow$ low amplitude TAI (region-III) $\rightarrow$ high amplitude TAI (region-IV). We compare and contrast the flame dynamics observed during different states of combustor operation next.

3.2. Flame dynamics during different dynamical states

3.2.1. Intermittency

During CN, as the flames are only subjected to broadband turbulent velocity fluctuations, the HRR field largely remains incoherent and the pressure fluctuations remain aperiodic and have not been shown here for brevity.

We focus on the flame dynamics observed during INT. The intermittent acoustic pressure oscillations observed when $\phi = 0.47$ are shown in Fig. 3a. In the enlarged portion in Figs. 3b & c, we can observe aperiodic and periodic pressure oscillations. Instantaneous images corresponding to the points indicated in Fig. 3b has been shown below the time signal. For the periodic part of intermittency, phase-averaged chemiluminescence images at maxima (90°) and minima (270°) determined from the red and green points in Fig. 3b, have been shown in Figs. 3i & i. The flames are identified as 1 to 8 going in a clockwise direction.
Figure 3: (a) Time series of acoustic pressure oscillations obtained during intermittency observed at $\phi = 0.47$. (b) Aperiodic and (c) periodic part of intermittency. (d-g) Mean-subtracted instantaneous chemiluminescence images corresponding to the indicated points in the aperiodic region in (b). (h,i) Phase-averaged chemiluminescence image at the pressure maxima ($90^\circ$) and minima ($270^\circ$) measured from the points indicated in (c).

Fig. 3d corresponds to the local minima of aperiodic pressure oscillations observed during intermittency. We can observe that flames 5 & 7 show very high heat release. However, at the next minima (Fig. 3f), we observe that flames 6 and 8 are at a maximum. Similar observations can be made from the points corresponding to local pressure maxima (Figs. 3e,g). In other words, the intensity levels are incoherent across different burners. In contrast, from the phase-averaged image taken at pressure maxima (Fig. 3h), we distinguish the swirling flame structure. For all the burners, we observe
that the intensity is at maxima along the periphery of the swirling flame. At
the pressure minima, the flame structures are annihilated resulting in very
low heat release.

Now we analyze the local HRR dynamics during the periodic part of in-
termittency. The local HRR is determined by summing over all the intensity
value present in a rectangular region as shown for the 5th flame in Fig. 3d.
The local region was taken instead of the entire burner to avoid phase cancel-
lation effects from affecting the HRR time-series. A similar region is chosen
for all the burners and time series of local HRR fluctuations is obtained.
Figure 5: (a) Time series of $p'$ during low amplitude TAI at $\phi = 0.49$. Phase-averaged CH* images at pressure (b) maxima ($90^\circ$), (c) mean ($0^\circ$) and (d) minima ($270^\circ$) value. (e) Variation in the normalized amplitude of $\dot{q}'$ for each burner measured from each of the flames. (f) Relative phase (in degrees) evolution between $\dot{q}'$ measured from the indicated pair of burners.

Since the local HRR signals contain phase noise, we bandpass the signal centered around the frequency of dominant oscillations ($f_n$) with a width of $\pm f_n/4$. Here, $f_n$ is the frequency of limit cycle oscillations which is approximately around $220 \pm 10$ Hz. We normalize the HRR signals to compare the amplitude of oscillations and use the Hilbert transform to obtain the phase
of the time signals \[12\].

In Fig. 4a, we show the periodic part of intermittency in \(p'\). In Fig. 4b, we plot the temporal variation of the amplitude of HRR oscillations for all the burners. This phase difference between different pairs of burners is shown in Fig. 4c. We observe some phase mismatch between the cycles of oscillations among different flames. We notice that the phase difference of different burners are different. For instance, in the region indicated by the black rectangle, burner 1-2 are in-phase, while burner pair 4-5 is \(180^\circ\) out-of-phase. However, there are many burner pairs which become out-of-phase (indicated by the red rectangle). Thus, even though the burners are frequency synchronized, they have a significant amount of desynchronized behavior. In summary, we observe that during periodic bursts of intermittency, although the burners have the same frequency, their phase differences show significant phase slips in time. As a consequence, the flames are in a state of partial (intermittent phase) synchronization with each other.

3.2.2. Low amplitude thermoacoustic instability

Figure 5a shows the time series of pressure fluctuations obtained during a low amplitude limit cycle with an amplitude of around 800 Pa obtained at \(\phi = 0.49\). Phase-averaged CH* images obtained at the phase of pressure maxima (90\(^\circ\)), mean (0\(^\circ\)) and minima (270\(^\circ\)) are plotted in Figs. 5b-d, respectively.

From the phase-averaged CH* images at pressure maxima during low amplitude TAI (Fig. 5b), we see a hollow flame structure for every burner along the annulus. This is in contrast to the case of intermittency where we observed the hollow flame structure for some burners and distributed flames for others (Fig. 3h). The flame is bounded by the inner and outer
recirculation zone. Consequently, there is a minima in the HRR at the center of each flame and a large HRR along the flame edges. We can also notice a difference in the heat release field during the phase of pressure maxima and minima.

Next, we calculate the local HRR from all the eight flames and compare their dynamics in the manner discussed previously. We plot the temporal variation in the amplitude of the HRR obtained from each of the eight burners in Fig. 5b. We observe that the burners have the same frequency, as observed from the temporal match of their normalized amplitudes. In the temporal variation of the phase difference between neighboring pairs of burners (Fig. 5f), we find that the phase differences are predominantly close to zero. In other words, most of the burners are in-phase synchronized with each other. We also see random appearance of phase slips between different pairs of burners (indicated by the red rectangles). Phase slips indicate an increase in phase difference by 180°. In comparison to the periodic part of intermittency, there are much fewer phase slips between different pairs of burners during low amplitude TAI. We refer to this state where the flames are not perfectly synchronized as a state of weak synchronization.

3.2.3. High amplitude thermoacoustic instability

Figure 6a shows large amplitude TAI obtained at φ = 0.52. The amplitude of TAI is around 2 kPa and is about an order of magnitude larger than the low amplitude TAI. We plot the phase-averaged CH* images at the phase of pressure maxima (90°), mean (0°) and minima (270°) in Figs. 6b-d, respectively. We observe that the flame dynamics are significantly different from that during low amplitude TAI. First, during pressure maxima,
the highest HRR intensity is concentrated at the center of each flame. This possibly indicates intense heat release in the inner recirculation zone during the pressure maxima. At 0° and 270° phase, we can observe that the flame does not propagate along the inner recirculation zone.

Figure 6: Flame dynamics observed during large amplitude TAI at $\phi = 0.52$. Each subfigure is same as the last figure.

As before, we analyze the individual flames by evaluating the local HRR for each burner. The temporal variation in amplitude of the HRR for each of the flames is plotted in Fig. 6e. We observe that each of the burners attain maxima in the HRR at the same time instance, indicating in-phase synchro-
nization among each of the burner pairs. This is further corroborated from the temporal evolution of the phase difference between the pair of burners. We can observe that the burners are always in-phase synchronized and the phase difference is always below $90^\circ$. Hence, we refer to the flame interactions between burners during high amplitude TAI as perfect synchronization.

### 3.2.4. Quantitative analysis of synchronization characteristics

Now, we quantify the relative degree of synchronization amongst different pair of burners and with the pressure oscillations. We define the phase-locking value (PLV) for any given pair of oscillators $x_1$ and $x_2$ as \(12\):

$$ \text{PLV} = \frac{1}{N} \left| \sum_{j=1}^{N} \exp \left( i \Delta \phi_{x_1,x_2}(t_j) \right) \right|, $$

where, the phase difference between the signals at the instant $t_j$ is $\Delta \phi_{x_1,x_2}(t_j) = \phi_{x_1}(t_j) - \phi_{x_2}(t_j)$ and $N$ is the length of the time series. The PLV indicates the absolute value of the mean phase difference between two signals where the instantaneous phase differences ($\Delta \phi$) are expressed as complex unit-length vectors, i.e., $e^{i \Delta \phi} \ [13]$. The PLV has a value close to 0 for desynchronized signals and close to 1 for perfectly synchronized signals. For cases with partial synchronization such as intermittent phase-locking, the PLV lies between 0 and 1.

We also define the Kuramoto order parameter to quantify the synchronous behavior for the spatially distributed oscillators (the eight burners) as \[14\]:

$$ R(t) = \frac{1}{N_b} \left| \sum_{k=1}^{N_b} \exp (i \theta_k(t)) \right| $$

where, $\theta_k$ is the phase of the $k^{th}$ burner and $N_b$ is the total number of burners.
Figure 7: Phase-locking value (PLV) between (a) $\dot{q}'$ measured from individual burners, and between (b) $\dot{q}'$ from each burner and $p'$ during combustion noise (CN), intermittency (INT) at $\phi = 0.47$, low amplitude thermoacoustic instability (LA-TAI) at $\phi = 0.49$, and high amplitude instability (HA-TAI) at $\phi = 0.52$, respectively. (c) Kuramoto order parameter ($R$) determined from the eight burners during different states of combustor operation.

At any time instance, $R = 0$ indicates spatial desynchrony, while $R = 1$ indicates spatial synchrony.

We show the variation in PLV between the HRR from different pairs of burners in Fig. 7a observed during the state of combustion noise (CN), intermittency (INT), low amplitude thermoacoustic instability (LA-TAI) and high amplitude thermoacoustic instability (HA-TAI). We also show the PLV between each burner with respect to pressure fluctuations observed during the above-mentioned states in Fig. 7b for the different states of combustor operation. During CN (Figs. 7a,b), the PLV between different burner pairs and burner & pressure fluctuations remain close to zero, indicating desyn-
chronized behavior among them. During intermittency (Figs. 7a,b), the PLV between different pairs of burners is very low (< 0.5) indicating the desynchronized nature of their interaction with each other. However, the PLV between different burners and the acoustic pressure fluctuations are close to 0.4 indicating partial synchronization between them (Fig. 7b).

As noted during the discussion following Fig. 5, during low amplitude TAI, some oscillators are only weakly synchronized with each other due to phase-slips in their relative phases. As a consequence, PLV lies between 0.5 and 1, indicating weak synchronization among different burners (Fig. 7a). We also note that the PLV of different burners with the acoustic pressure oscillations follows suit and lies between 0.5 and 1 showing partial synchrony (Fig. 7b). For large amplitude TAI, the PLV between different pairs of burners and different burners with pressure lies very close to 1, indicating perfect synchronization of the burners with each other and with the pressure oscillations (Figs. 7a,b).

The Kuramoto order parameter is plotted as a function of time in Fig. 7c. The order parameter indicates the different degrees of spatial coherence of the oscillators over time. During CN, $\bar{R}$ fluctuates around time-averaged value of $\bar{R} = 0.41$. During the periodic and aperiodic part of intermittency, $R$ fluctuates around $\bar{R} = 0.49$ and $\bar{R} = 0.37$. This indicates that spatially, the flames are intermittently coherent during the periodic part of intermittency and incoherent otherwise. During low amplitude TAI, $R$ fluctuates around a mean value of $\bar{R} = 0.84$. Thus, the burners are in a state of weak spatial synchronization. Finally, during high amplitude TAI, $R$ fluctuates around a mean value of $\bar{R} = 0.97$, indicating perfect spatial synchronization.
4. Conclusion

We report the transition to thermoacoustic instability (TAI) from combustion noise through intermittency and secondary bifurcation in a sixteen burner swirl stabilized lab-scale annular combustor. We perform a systematic variation of the control parameter and observe the following states of combustion operation: combustion noise (CN), intermittency (INT), low amplitude TAI, high amplitude TAI. During the state of INT, we observe bursts of low amplitude periodic oscillations punctuated randomly by very low amplitude aperiodic oscillations. The pressure oscillations during the state of Low amplitude TAI have an amplitude which is about an order of magnitude lower than that observed during high amplitude TAI.

We discuss the global flame dynamics during intermittency, low and high amplitude TAI. We find that during intermittency, the phase-averaged flame structure is incoherent. During low amplitude TAI, we find that the flame has a ring-like structure anchored along with the space between the inner and outer recirculation zone. During high amplitude TAI, the flame propagates into the inner reaction zone, resulting in intense heat release at the center of the burner.

In annular combustors, local flame-flame interactions are of immense significance and determine the observed dynamics of the combustor. Thus, we analyze the local flame interactions with neighboring flames. We compare the HRR fluctuations between pairs of burners along the annulus. For all the states of combustor operation except CN, the frequency of different flames are the same. During the periodic part of intermittency, the phase difference between pairs of burners has significant phase slips in them indicating
partial synchrony among them. During low amplitude TAI, the flames are weakly synchronized with occasional phase slips appearing in time. During high amplitude periodic oscillations, the flame interactions show perfect synchronization. We then confirm the existence of the various states of spatiotemporal synchronization using phase-locking value (PLV) and Kuramoto order parameter ($R$).

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