Swirl flow response to transverse and axial acoustic forcing

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Abstract
The present study is an experimental investigation on the effect of axial and transverse acoustic forcing on a generic swirl flow. The aim is to provide a qualitative understanding of typical swirl flow response to transverse acoustic forcing, for a better understanding of the response of swirl-stabilized flames to the same configuration of acoustic forcing. The latter is critical for the ongoing research on thermoacoustic instability in annular gas turbine combustors. A single burner test-rig with transverse extensions to facilitate transverse acoustic modes is employed in this experimental study. The swirl flow, established using a generic radial swirl generator, features vortex breakdown. Two transverse forcing configurations are studied: a) symmetric forcing which leads to a pressure antinode at the burner, and, b) antisymmetric forcing which results in a velocity antinode at the burner location. The study is based on results from planar streamwise and crosswise flow field measurements. We find that while the symmetric forcing configuration causes a flow response similar to axial forcing, antisymmetric forcing results in a helical response.

Key words: Annular combustors, Transverse acoustic forcing, Swirl flows

1. Introduction

Thermoacoustic instability is a serious issue for the gas turbine industry. This undesirable phenomenon is a problem even in the state-of-the-art annular gas turbine combustors. The high amplitude acoustic and thermal oscillations associated with the instability adversely affect the efficiency and performance of gas turbines (Krebs, Flohr, Prade, and Hoffmann, 2002). Annular gas turbine combustors comprise of a circumferential array of burners sharing a common annular combustion chamber. Typically swirl-stabilized flames are employed in practical systems. Thermoacoustic instability in such combustors involves interaction between unsteady heat release rate from individual swirl flames and acoustic oscillations associated with azimuthal acoustic modes of the combustion chamber. Therefore, the flame-acoustic interaction involves planar acoustic waves transverse to the flame/burner axis. This scenario is fundamentally different from the extensively studied case of swirl flame interaction with longitudinal acoustics. In response to this specific need of understanding flame interaction with transverse forcing, we have set up a single burner rig to investigate the response of a generic swirl flame to various transverse forcing scenarios. The study we present here is part of our ongoing research and can be seen as a simulation of flame-acoustic interaction that occurs in annular combustors, performed on a single burner test-rig. Specifically, in this article, we will focus on only the response of the isothermal swirl flow.

It has been previously identified that coherent flow structures in swirl flows can couple with acoustic oscillations leading to thermoacoustic instability (Paschereit, Gutmark, and Weisenstein, 2000; Döbbeling, Hellat, and Koch, 2007). Hence, for discussion of observations, it is important to consider details of inherent swirl dynamics. In the past, an immense amount of research has been dedicated to the study of swirl flows and their dynamics (Leibovich, 1978; Sarpkaya, 1995). Contribution from several experiments performed at various swirl flow configurations, analytical study assuming idealized swirl flows as well as extensive numerical investigations on practical swirl flows have resulted in a generalized description of swirl flow dynamics that holds in most practical applications (Khalil, Hourigan, and Thompson, 2006; Syred, 2006). Swirl flow characteristics depend on the swirl intensity, which is quantified by the swirl number (Sw): the
ratio of axial flux of azimuthal momentum to axial flux of axial momentum. At low $Sw$, the swirl flow is characterized only by convective shear layer instabilities. Beyond a critical $Sw$, vortex breakdown occurs and flow dynamics is then governed by self-excited oscillations (Oberleithner, Paschereit, and Wygnanski, 2014). These oscillations have been identified to be a manifestation of absolutely unstable helical modes (Oberleithner, Sieber, Nayeri, Paschereit, Petz, Hege, Noack, and Wygnanski, 2011; Gallaire, Ruith, Meiburg, Chomaz, and Huerre, 2006; Liang and Maxworthy, 2005). The absolute instability is marked by several changes in the flow field. The mean flow field features a reverse flow region along the axis of the flow. Dynamics of the entire flow field is dominated by a precessing vortex core. This precession vortex core imparts its oscillations on the shear layers as well (Petz, Hege, Oberleithner, Sieber, Nayeri, Paschereit, Wygnanski, and Noack, 2011). It has been noted in previous investigations that during thermoacoustic instability, these coherent structures resulting from globally unstable behaviour of the swirling jet could play a critical role (Syred, 2006; Poinso, Trouve, Veynante, Candel, and Esposito, 1987; Durox, Moeck, Bourgoin, Morenton, Viallon, Schuller, and Candel, 2013; Lacarelle, Faustmann, Greenblatt, Paschereit, Lehmann, Luchtenburg, and Noack, 2009; Paschereit, Gutmark, and Weisenstein, 1998).

In the attempt to understand the role of swirl dynamics in the phenomenon of thermoacoustic instability several studies simulating flame-acoustic interaction through acoustic forcing have previously been conducted. Most of these have focussed on axisymmetric axial forcing to explain thermoacoustic instability in longitudinal combustors. Results of these analyses have shown that forcing, particularly at the natural frequency, induces axisymmetric vortex shedding (Syred, 2006; Poinso et al., 1987; Lacarelle et al., 2009) in the flow, which when unforced is dominated by helical instability. Axial forcing, if strong enough, has been shown to lead to longitudinal fluctuations of the vortex bubble. In general, axial forcing has been found to affect natural helical instability only by suppressing it and supporting axisymmetric coherent structures. In a previous investigation (Saurabh and Paschereit, 2013), we have shown that even thermoacoustic instability involving transverse acoustics is characterized by axisymmetric vortex shedding.

Recent investigations (O’Connor and Lieuwen, 2012) show that transverse forcing that simulates thermoacoustic instability in annular combustors, can influence helical coherent structures directly by modifying the relative contribution of helical modes to coherent oscillations. It was hypothesized that the observed change in mean flow field profile in response to transverse forcing could be associated with variation in stability characteristics of the swirl flow. The suspected lock-in of helical structures with transverse forcing was not observed. A point to be noted is that, as reported in several investigations (Saurabh and Paschereit, 2013; Oberleithner, Terhaar, Rukes, and Paschereit, 2013), combustion suppressed natural helical instability of the swirl flow.

The present study complements previous study and forms a part of on-going investigations on the effects of transverse forcing on isothermal swirl flows and swirl-stabilized flames. We have studied two configurations of acoustic forcing: in-phase forcing that results in a pressure antinode at the burner axis and out-of-phase forcing which leads to a velocity antinode instead. We have also compared the two cases with the scenario involving axial acoustic forcing at the same frequency. A single frequency of forcing, 78 Hz, which also corresponds to the frequency of thermoacoustic oscillations, reported in Saurabh and Paschereit (2013), is studied. A swirl number of $Sw = 0.7$, was chosen for the study. This swirl number is beyond the critical swirl at which vortex breakdown and its symptoms first appear in the flow field. Accordingly, the base swirl flow features vortex breakdown and helical instabilities.

In the following, we will first discuss the experimental setup and measurement methodologies. This section will be followed by results and discussions. Concluding the study, we have summarized the main observations of our experiments.

2. Setup and methods

Figure 1 shows a schematic of the investigated test-rig. The main feature of the test-rig is the transverse extension of the combustion chamber that allows us to establish planar acoustic waves transverse to the burner axis. Along the axis $x$, the combustor is 500mm long and has a 200x250mm rectangular cross-section with rounded edges. A 165x250mm window in the combustor provides optical access into the combustor for laser and optical diagnostics of the flow. The transverse extensions on either sides of the combustor are 755mm long, with a circular cross section of radius 100mm. Accordingly, the cut-off frequency for planar waves in the transverse extension is 1092Hz. The transverse ducts are terminated by T-junctions, 435mm in length, supporting the sub-woofers (s1-s2 in Fig. 1) used to generate acoustics. Downstream of the combustor is a short 360 mm exhaust duct with a circular cross-section ($r = 100mm$). An experimental, movable-block type radial swirl generator was used to generate swirl. Upstream of the radial swirl generator is the main
as shown in Fig. 1, the air enters the swirl generator through slots, passes radially through the blocks, enters the mixing tube and finally exits the swirl generator and enters the combustor through an annular mixing tube. The mixing tube has a diameter of 55mm and the centre-body has a diameter of 27.5mm. The swirller section between the upstream duct and the combustor is 265mm long. The system is operated at a total air mass flow rate of 153 kg/hr.

2.1. Flow diagnostics

Planar flow field diagnostics of a streamwise and a crosswise plane (see Fig. 2) was conducted via high and low speed Particle Image Velocimetry (PIV) respectively. The following contains details of the PIV setup, measurement and evaluation methodologies.

High speed measurements in the streamwise plane was conducted at 2500 Hz. Zirconium oxide particles (2 nm nominal diameter) were employed to seed the swirl flow. Laser pulses ($\lambda = 532$nm) separated by $20\mu s$ were guided into sheet-forming optics and laser sheet thus formed was introduced into the test-rig through a small slit on the end plate of one of the transverse arms as indicated in Fig. 1. Within the measurement area, laser sheet thickness of $\approx 1$mm was achieved with the optics. A high speed PIV camera equipped with a 100mm lens was positioned in front of the combustor in order to capture light scattered by the seeding particles. The PIV setup resulted in a magnification factor of $\sim 5.6$ pixels/mm. A rectangular measurement plane of size 183.5mm x 180mm (x-z plane), centred at the burner axis and beginning 4mm downstream of the burner exit was evaluated. PIV evaluation was based on standard correlation method with grid-refinement. A 50% overlap between windows was used for the evaluation of velocity vectors. A 3x3 least squares Gauss fit was employed for the estimation of sub-pixel displacements. The final size of interrogation windows was 24px x 24px. Each PIV ensemble consisted of 2400 image pairs.

For crosswise measurements, low speed (7 Hz) PIV was used. The setup of laser light sheet and the accompanying optics was the same as in the case of streamwise measurements albeit the laser sheet was $90^\circ$ rotated. The camera was focused from the top of the combustor. The location of the crosswise plane is chosen sufficiently downstream of the burner exit plane, so as to capture the dynamics in the recirculation zone. To illustrate, Fig. 3 indicates the location of the crosswise plane (dotted red line) with respect to the streamwise mean flow field of the isothermal swirl flow. The crosswise plane is located at an axial location (z) of 63.5mm. In preliminary experiments, based on hot-wire anemometry, flow velocity oscillations associated with the precessing vortex core were clearly identified at the investigated location for the crosswise plane. The PIV setup for crosswise measurements resulted in a magnification factor of 7.7 pixels/mm. Owing to lower velocities expected in the crosswise plane, a higher pulse delay of $30\mu s$ was used. For the crosswise case, the measurement plane was 162mm x 130mm. PIV evaluation methodology was the same as in the streamwise case. Each ensemble of PIV data consisted of 1248 image pairs.

![Fig. 1 The combustion test-rig and detailed view of the movable-block radial swirl generator used for the study.](image)

2.2. Analysis methodology

2.2.1. Phase averaging

The woofer excitation signal and the instants of every PIV image pair acquisition were simultaneously recorded. This data was subsequently employed for obtaining the temporal phase of every instantaneous velocity vector field with reference to the excitation signal. The velocity fields were then distributed into phase bins of size...
30 degrees. An average of the ensemble of PIV data in every bin is then obtained. Every bin receives ~ 180 instantaneous PIV fields for streamwise measurements and ~ 100 instantaneous fields for crosswise measurements. The phase averaged vector field thus obtained provides information on how the flow field is modulated in response to acoustic forcing at the forcing frequency.

2.2.2. Proper Orthogonal Decomposition

In addition to phase averages, another informative methodology is to obtain the dominant oscillations in the flow field. We obtained this information through the implementation of Proper Orthogonal Decomposition (POD) on PIV ensembles. POD extracts coherent oscillations (modes) from a scalar/vector field and orders them according to the energy content of individual modes. It is assumed that the PIV ensemble (2400 for high speed measurements and 1248 for low speed measurements) is appropriate for sufficient convergence of the POD algorithm and for drawing inferences and comparisons between cases.

3. Results and discussion

Our investigation on swirl flow response to acoustic forcing (transverse and axial in nature) is based extensively on flow field diagnostics. We will start with discussions on the natural unforced swirl flow. this will be followed by discussion of results on transverse in-phase and axial forcing of the swirl flow. In the end of the results section, we will discuss our observations on flow response to transverse out-of-phase acoustic forcing.

3.1. Analysis of unforced flow

The mean and dynamic response of the isothermal flow field to forcing is expected to be critically dependent on the flow features that exist in the natural, unforced swirl flow. Pockets in the flow field dominated by the presence of convective instability will be susceptible to flow field perturbations. Any incident perturbation will grow spatially in regions of convective instability, while flow fields that are absolutely unstable will be unresponsive to small amplitude flow disturbances. Hence, before delving into flow dynamics of the acoustically forced isothermal flow, it is important that we first investigate the unforced flow.

Features of the mean flow field are contained in Fig. 3(a, b), which was obtained using laser flow diagnostics (PIV) in the streamwise and crosswise planes. The streamwise mean flow field (the x-z plane) is depicted using velocity vectors at multiple streamwise locations, streamlines and contours of regions with negative velocity (reverse flow). The location of crosswise measurements is also indicated in the figure (Fig. 3(a)). The crosswise mean flow field (x-y plane) is
Fig. 3  Mean and dynamic flow features of the natural isothermal flow. **Mean flow features:** (a) Streamlines, velocity vectors and contours of negative velocity in the streamwise plane. The dashed red line indicates the location of crosswise measurements. (b) Streamlines of in-plane velocity and contours of out-of-plane axial velocity (red indicates negative, blue indicates positive). **Dynamic flow features:** (c) Contours of negative velocity (in m/s), axial velocity profiles and contours of out-of-plane vorticity corresponding to the dominant POD mode. (d) Mean flow streamlines and contours of out-of-plane vorticity associated with the dominant POD mode.
represented using streamlines and contours of axial velocity (Fig. 3(b)). By simultaneously inspecting the two flow fields, we can identify the typical mean flow features in a swirl flow field featuring vortex breakdown. Along the axis of the flow (z direction), two regions of significant reverse flow are created due to a) the wake of the centre-body, and, b) vortex breakdown. The two are barely merged together by a narrow region. These reverse flow regions create a strong streamwise shear layer (henceforth referred to as the inner shear layer, or ISL) and results in an annular swirling jet. The annulus merges to form a single jet far downstream of the burner. As we move radially away from the axis, the jet encounters the surrounding air, thus forming another shear layer (the outer shear layer, or OSL). Due to swirl and the entrainment of surrounding air, the radial extent of the annular swirling jet increases along the axis.

In the crosswise plane (Fig. 3(b)), we see that the swirl jet annulus (positive axial velocity covered by the blue contour) and the recirculation bubble (negative axial velocity covered by the red contour) together comprise the region of the flow that rotates due to swirl. An azimuthal shear layer is seen to form in the region of the OSL, between the rotating air mass and the surrounding air. This shear layer is also the location where the crosswise flow velocity is purely tangential.

Focussing our attention now to the dynamic features of the unforced isothermal flow field, we refer to Fig. 3(c, d). These figures show the contours of the out-of-plane vorticity from the dominant POD mode dominating flow field dynamics in the streamwise and crosswise planes, overlaid on velocity profiles and streamlines of the mean flow. The streamwise plane (Fig. 3(c)) indicates a helical vortex tube spiralling around the recirculation bubble. Close to the burner exit, the vorticity is largest near the ISL while further downstream, it is intense in the centre of the jet annulus (regions with the highest axial velocity). Also noticeable is the fact that the shape of the vorticity contour is distorted due to the presence of adjacent, comparatively weaker vorticity regions in the OSL. The dominant mode in the crosswise plane (also depicted using out-of-plane vorticity contours) exists as vortex motion close to the ISL (Fig. 3(d)). So far, we have not verified whether the mode in the streamwise plane corresponds to the mode in the crosswise plane. For discussions, we assume that the two originate from the same coherent oscillation. Hence, the vorticity contours in the crosswise plane are due to the precessing vortex core.

To summarize the observations, it can be inferred that the unforced isothermal swirl flow features three shear layers: ISL, OSL and the azimuthal shear layer that coincides with the OSL. These regions can be expected to feature convective instability, supporting flow disturbances in the forced case. Due to the phenomenon of vortex breakdown, the flow also features a recirculation bubble that is suspended in the flow, free to move axially, but is enveloped in the radial direction by the precessing vortex core (the manifestation of global instability). Based on previous research (Petz et al., 2011), it can be said that this precessing vortex core also influences the OSL. This descriptive portrait of the isothermal swirl flow that we have inferred from our measurements conforms to existing descriptions of the swirl flow field dynamics.
3.2. Analysis of symmetric forcing of the isothermal flow

![Image: POD mode and axial velocity profiles](image)

Fig. 5  Left: The dominant POD mode characterizing flow field oscillations in response to axial and in-phase forcing, superimposed on the mean axial velocity profile. Right: Axial velocity profiles and the recirculation zone at two different phases of axial forcing.

We will analyse the flow field response to acoustic forcing generated using a) upstream speakers, and, b) using the side speakers. Upstream acoustic forcing at the mentioned low frequency of forcing (78 Hz) will lead to planar acoustic waves in the test-rig section upstream of the combustor that contains the swirl flow. As a result of such acoustic forcing, acoustic velocity oscillations will be imposed on the swirl flow at the burner exit. As mentioned in earlier sections, side speakers can be operated in-phase or out-of-phase, leading to the establishment of pressure antinode or a velocity antinode respectively at the burner location. In this section, we will discuss the effects of axial acoustic forcing and in-phase transverse acoustic forcing on the flow field, both of which are symmetric forcing configurations (symmetric about the axis of the burner).

Described below are the ways in which axial and transverse in-phase forcing affects the swirl flow, that we identified in our analysis. These are illustrated in Figs. 4 and 5. In the crosswise plane the effect of axial and transverse in-phase forcing was found to be very similar and any difference that exists was not perceptible in the POD and phase averaging analyses that were performed. Hence, for the crosswise plane, we have presented only the axial forcing case. In Fig. 4, streamlines in the crosswise plane obtained for the axial forcing case at two different phases indicate that forcing leads to oscillations in the radial extent of the rotating air mass. Streamline arrows within the vortex core region are directed outwards, indicating an outward spiral motion. While at 300°, the streamlines are close to circular, and the OSL is closer to the axis when compared to the mean flow (Fig. 3), for 120°, the flow field changes drastically: the rotating air section is larger and the OSL is further away from the axis.

Subsequently in Fig. 5, dynamics in the streamwise plane in response to axial and transverse in-phase forcing is illustrated. The first two sub-plots show the dominant POD mode (out-of-plane vorticity contours) describing flow field oscillations in response to axial and in-phase forcing. Also included is the mean flow profiles. It is clearly observed that in both cases, the fluctuating flow field corresponds to axisymmetric oscillations. These are most likely due to periodic generation of axisymmetric vortex rings near the burner exit in the ISL as well as OSL, followed by their convection. As they are convected downstream, vorticity in the ISL dissipates rapidly, while OSL vortices do not. They might even be found to grow in size. Again, the flow response to axial and in-phase forcing are found to be quite similar. The third subplot in Fig. 5 shows the axial velocity profile and isolines denoting the reverse flow region (-1 m/s) at two phases of axial forcing. It can immediately be inferred that axial (as well as in-phase, not shown here) forcing causes the recirculation bubble to oscillate along the axis. Furthermore, this axial motion gives rise to oscillations in the enveloping annular swirl jet. Oscillations of the jet axial velocity are seen clearly in the figure. Oscillations in the radial velocity can be inferred from the crosswise plane (Fig. 4). A more detailed analysis of radial velocity oscillations is undertaken in the section following the results of out-of-phase forcing.

3.3. Analysis of the anti-symmetric forcing of the isothermal flow

The third forcing configuration is the out-of-phase forcing, where the two sub-woofers mounted on either side of the combustor are actuated with a 180° phase difference in their input voltage signals so as to produce a velocity antinode at the burner axis. In this scenario, acoustic velocity which is tangential to the burner axis affects the swirling flow at the base of the burner.
The flow response to transverse acoustic velocity is quite rich. Firstly, analysing the crosswise plane, we find that out-of-phase forcing results in the distortion of the mean flow field. Figure 6 shows the mean flow field streamlines in the crosswise plane. An elliptical structure of the central rotating air mass bounded by the centre of azimuthal shear layer is evident. Compared to the mean flow field, this section is also larger in size. This is possible if the transverse acoustic velocity affects the recirculation bubble and the enveloping annular swirl jet region. Such an interaction is clearly seen in phase averaged flow field, Fig. 7.

Figure 7 presents phase-averaged flow field streamlines at the six different phases of forcing. The black cross marks the burner axis and the red circle denotes the centre-body. It is seen that the centre of the recirculation zone, visually seen as the eye of the streamline spirals (as inferred from Fig. 3), undergoes a rotation about the burner axis. These results provide the plausible explanation for the distortion in the mean flow field. The acoustic forcing generates a flow disturbance at the base of the burner. Considering that the burner base is the origin of the ISL, OSL and the precessing vortex core, the flow oscillations push these structures towards either negative or positive x direction. The resulting disturbances are convected downstream and are transformed spatially by the swirling flow. However, the spiralling motion about the centre
as seen in Fig. 7 is only possible if the flow response at the forcing frequency is also affected by the precessing vortex core. Since, disturbance imposed on the swirl flow at the burner base is only along the x axis, the distortion of the mean flow field assumes an elliptical structure. The precession of the vortex core imparts additional rotational motion and leads to a spiralling response downstream. The scenario suggests a complicated interaction between the externally imposed acoustic disturbances and inherent swirl dynamics.

One of the main aspect of flow field response that is common to all the three reported cases is the modulation of the rotating air mass confined within the OSL. For symmetric forcing cases, this modulation is also symmetric, while for the asymmetric out-of-phase forcing case, the modulation is not symmetric about the burner axis. We found that these features are also reflected in the periodic oscillation of the radial velocity profile. Radial velocity profile oscillation at different phase of forcing for all the three cases, obtained from crosswise flow field measurements are presented in Fig. 8. In all the three cases, extrema of radial velocity exist in a region between the centre of the annular jet and the OSL. For the symmetric axial and transverse in-phase forcing cases, the minimum and maximum radial velocity peaks oscillate in the radial direction. This oscillation is also symmetric: minimum and maximum peaks move simultaneously away or towards the axis. The same is illustrated by the dotted lines in the figure that loosely connect the peaks.

Although oscillations in the radial velocity can be observed, their magnitude, in comparison with axial and in-phase forcing conditions, is less. The dominant feature of the oscillations however, is the shifting of the location of maximum radial velocity. For the out-of-phase forcing case, this shifting is sinuous in nature, suggesting a rotating motion of the entire vortex core region.

\[ \text{Fig. 8 Oscillation in the radial velocity profiles for the three forcing configurations. Dotted grey lines loosely connect the location of velocity peaks at different phases.} \]

4. Conclusions

In this study we have analysed the response of a typical swirl flow featuring vortex breakdown to three acoustic forcing configurations: axial forcing using upstream mounted speakers, transverse in-phase acoustic forcing resulting in a pressure antinode at the burner and transverse out-of-phase forcing that generates a velocity antinode at the burner. The forcing frequency is 78 Hz, which is low enough to ensure the propagation of only planar acoustic waves.

The isothermal swirl flow features a streamwise ISL and two OSLs: a streamwise and an azimuthal shear layer, a recirculation bubble suspended along the axis of the burner and a precessing vortex core (PVC). The vortex core envelops the recirculation bubble and is in turn enveloped by the annular swirl jet. Furthermore, the vortex core imposes oscillations in the shear layer at unforced conditions. In support of this statement, the analysis of the dynamic features of the unforced flow indicates self-excited oscillations in the flow that correspond to a mode 1 helical instability. The shear layers, being convectively unstable in nature, are expected to respond to acoustic forcing. On the other hand, the self-excited oscillations
that occur due to vortex breakdown are expected to impart their oscillation to the flow response to acoustic forcing.

Axial and transverse in-phase acoustic forcing is found to cause generation of axisymmetric vorticity in the ISL and the OSL. However, pockets of high vorticity survive only in the OSL. ISL vorticity dissipates rapidly in the downstream direction. The downstream convection of these high vorticity along the annular swirl jet lead to significant oscillation of the radial flow velocity. The two forcing configurations also lead to the oscillation of the recirculation bubble. Throughout the analysis, we saw that the in-phase forcing results are nearly identical to those obtained for axial forcing. The reason for this similarity is that a pressure antinode at the burner induces flow oscillations upstream in the burner. Accordingly, the flow response is expected to be similar to the response induced by axial forcing.

The flow response to transverse out-of-phase acoustic forcing is found to be more complicated. Two dimensional velocity oscillations generated at the burner develop a rotational structure as they more downstream along the swirling jet. During this, all the main features of the flow: recirculation bubble, PVC, ISL and OSL are involved. The result is a helical motion of the swirling jet at the forcing frequency. In addition, the interaction also results in a distortion of the mean flow field.

This study was initiated to understand the dynamics of a swirl-stabilized flame in an annular combustion chamber when it interacts with transverse acoustics. By investigating the isothermal swirl flow, we have identified the main features of coherent oscillations generated by transverse acoustic forcing. In addition, we have compared two extreme transverse forcing configurations to the better understood configuration of axial forcing. These results are an important step to understand results on a swirl flame response to transverse acoustic forcing. For instance, flame response to transverse in-phase acoustic forcing can be expected to be determined by flame modulation due to axisymmetric vortical disturbances in the OSL and periodic flapping of the flame surface due to a combined effect of OSL vortices and axial motion of the recirculation zone. The flame response, to a large extent, will be similar to its response to axial forcing, qualitatively as well as quantitatively. The transverse out-of-phase forcing scenario appears to be the more complicated case involving intricate interactions between flow response to forcing and inherent instability dynamics.

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