Chapter 8

Forced Response: Turbulent Swirl Combustor

There is a need to develop reduced order models with the help of FRFs that describe the dynamic response of swirl stabilized flames to perturbations in the velocity and mixture fraction of the incoming reactants. These models are expected to be simple and yet, exhibit all the dominant dynamic characteristics of the combustion process.

Since a large number of physical variables are involved in the combustion process occurring in complex swirl stabilized combustors, simple systems (burner stabilized laminar flat flames) were initially studied (see chapters 5 and 6). Having understood the dynamics of laminar flat flames and developed methodologies to build reduced order flame dynamic models, the technique developed to measure the open loop transfer function of laminar flat flame dynamics will be used for developing the transfer function for the flame dynamics (within the linear range) of swirl stabilized turbulent flames. An attempt to generate FRF between unsteady heat release rate of a swirl turbulent flame and the incoming velocity oscillations was attempted (see chapter 7) by performing URANS calculations. The FRF obtained did not show dynamic characteristics observed in the experimental study. This chapter describes the investigation of the effect of incoming mass-flux oscillations on the swirling turbulent flame
by performing time accurate large eddy simulation (LES) of the combustion phenomena.

8.1 Rationale and Objectives

The objective of this study is to perform a CFD analysis of the experimental combustor, in particular calculate the transfer function between $u'$ and $q'$ for the “flame dynamics” part of the closed loop dynamic system (shown in Figure 8.1). In this study, the effect on $q'$ due to equivalence ratio fluctuations, $\Phi'$, has not been included. In the experimental combustor, $\Phi'$ is not present because the air and fuel are perfectly premixed.

![Diagram](image)

Figure 8.1: System level description of the thermoacoustic combustion process

Another objective of the study is to use CFD to explain near field acoustic effects on the heat release rate. These near field acoustic effects are at least two dimensional in nature (axi-symmetric) and are responsible for the excessive increase in the OH* chemiluminescence in swirling flames. They need to be accounted for in the systems level description of the combustion process, so as to accurately predict the occurrence of thermoacoustic instabilities.
8.1.1 Large Eddy Simulation

Relationships between unsteady heat release and inlet velocity perturbations used in linear stability models can be established using LES techniques by forcing a combustor with controlled excitations and measuring, for example, the time-delay between the oscillations and unsteady reaction rate. A prerequisite condition for forcing is that a relatively stable baseline regime be used upon which forcing can subsequently be applied. One such case would be exciting the velocity field at the inlet of the burner.

LES of reacting flows have been carried out in the 2-D axisymmetric combustor geometry which was created for the URANS studies (see chapter 7). A possible method of using LES to simulate the combustor is to limit the computational domain to the minimum size (just the combustion chamber). In doing this, the resonant frequencies are not coupled to the heat release and the combustor still remains in a stable regime. A reduction in computation time and increased accuracy are advantages associated with this truncation methodology. The objective of the study is to generate frequency response functions of the heat release based on inlet velocity fluctuations. The inlet velocity profile includes a fluctuating component at a range of frequencies (20 Hz to 750 Hz).

8.2 Accompanying Experimental Studies

The experimental setup used to study the dynamics of turbulent swirl stabilized flames is schematically shown in Figure 8.2. The system consists of an air-fuel mixing system, the flow control system, the turbulent variable swirl combustor (the quartz chimney), the dynamic velocity measurement system, the dynamic OH* measurement system, and the data acquisition system. The fuel flow measured using an array of mass flow meters is fed into a premixer that thoroughly premixes the fuel and air prior to the injection of the premixed charge into the combustor. Microphones were used to obtain dynamic velocity signal, while the OH* chemiluminescence captured by viewing the entire flame from the side was taken
Figure 8.2: Schematic of the turbulent combustor experimental setup
as the measure of the dynamic heat release rate. Controlled acoustic perturbations were imparted to the flow using a speaker. The dynamic signals were analyzed using the Hewlett Packard frequency analyzer, while the flow parameters were recorded using a data acquisition system.

The flame in the turbulent variable swirl combustor is stabilized by the presence of the central recirculation zone (CRZ) and the outer re-circulation zone (ORZ), as shown in Figure 8.3. The CRZ and the ORZ re-circulate the products of combustion back to the inlet of the combustor, thereby enabling the transfer of energy from the hot products of combustion to the incoming reactants. This fluid-dynamic feature of swirl stabilized flames that creates a continuous ignition source, eliminates the need for an external energy re-circulator as was required for laminar flat flames. By altering the flowfield and hence, the strength of the re-circulating zones, the flame could be forced to reside in either of the re-circulating zones or on the shear layer between the re-circulating zones. Such a variation in the flow field could be achieved by changing the swirl number and hence, the swirl strength of the flow entering the combustion chamber.

The variable swirl turbulent combustor was designed with a maximum pressure rating of 150 psig, a maximum thermal rating of 400 kW. It has a variable swirl generation arrangement that generates a maximum swirl number ($S_g$), of 1.86. Swirl number is defined usually in the following form:

$$S = \frac{\int_{R_i}^{R_o} \rho u_z u_g 2\pi r^2 dr}{\int_{R_i}^{R_o} \rho (u_z^2 - u_\theta^2/2) 2\pi R_o r dr}$$  \hspace{1cm} (8.1)

(refer Ribeiro et. al [118]), but in the experiments conducted at VACCG the swirl number calculated is the geometrical swirl number, defined as:

$$S_g = \frac{R_o \pi r_e (Tangential \ flow \ rate)^2}{A_t (Total \ flow \ rate)^2}$$  \hspace{1cm} (8.2)

where $R_o$ is the radius of the inlet of the quarl, $r_e$ is the radius on which the tangential inlets are attached with respect to the center of the combustor and $A_t$ is the total area of the tangential inlets. It was found that the swirl number ($S$) is directly proportional to the geometric swirl number ($S_g$).
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8.3 Computational Model

Computational studies of premixed combustion processes are often restricted by the limitations of the Reynolds averaged simulation (RANS) models [119] and the turbulent combustion models used to represent the mean flame and its effects on the flowfield. The concept of large eddy simulation (LES) thus provides a more natural approach to analyzing unsteady turbulent reacting flows. LES has the potential to provide quantitative data about flame response [13]. According to Kaufmann et al. [88], LES will provide reliable information for flame transfer functions in gas turbines only if all of the following requirements are matched:

1. Full 3-D compressible Navier-Stokes equations must be solved using structured/unstructured grids for complex combustor geometries,

2. Numerical methods with small dissipation/dispersion should be used,

3. LES models for flow dynamics in complex wall bounded flows are required,
4. LES turbulence/chemistry interaction model must be valid for premixed flames,

5. Unsteady boundary conditions must be modified to inject controlled acoustic perturbations and force the flow without creating spurious modes.

Out of the five requirements listed above, Fluent [59] is able to satisfy the first requirement and to some degree the fifth requirement. Although dynamic subgrid scale LES models are available in Fluent, the lack of turbulence/chemistry interaction models prevents the use of the Fluent LES code in simulating unsteady reacting flows. Therefore, as an alternative to using the Fluent commercial code (which has been the code of choice for VACCG in past several years), the CFD Research Corporation (CFDRC) LES beta code has been used to calculate the transfer function between $u'$ and $q'$ for reacting flow in the VACCG experimental combustor geometry.

The CFDRC code, CFD-ACE+, is a beta-version and includes a LES module which has been exclusively developed for combustion modeling. The code includes the following implementations:

- Pressure-based, Finite-volume flow solver – SIMPLEC for pressure-velocity correction, second-order accurate temporal (Crank-Nicholson) and spatial differencing (second-order upwinding) schemes, conjugate gradient (CGS) and algebraic multi-grid (AMG) iterative equation solvers
- Multi-block structured and unstructured hybrid grids
- Parallel flow solver – K-way, X-orientation and physics-weighted partitioning methods
- Models for reacting flow systems:
  - Turbulence – Smagorinsky and dynamic subgrid models, LDKM subgrid model [120]
  - Chemistry – advanced chemical mechanisms (steady-state reduced) [121]
The LES code satisfies almost all the requirements cited above. Apart from matching the second requirement, which needs the implementation of third-order accurate finite element Taylor–Galerkin-type of schemes [124], the CFDRC LES code is capable of producing flame transfer functions which will be accurate. Problems related to the first requirement are not important in this study because the experimental combustion chamber has a simple shape. As will be illustrated in the boundary conditions subsection, the last requirement is met to a high degree of accuracy, if not perfectly matched.

8.3.1 Computational Domain

The experimental setup internal geometry is shown in Figure 8.4. A long length upstream of the combustor in the setup was selected to eliminate any freestream turbulence. Four distinct sections can be observed in the schematic: the axial air flow section (at the bottom), the straight section with the swirler, the convergent-divergent section and the combustor (dump) on top. Out of these four sections, the combustor is the only section of interest for the CFD study. Therefore, only the top part of the experimental setup has been included in the CFD simulation. The LES computational domain is shown in Figure 8.5. The computational domain comprises of an annular inlet, a circular bluffbody which is aligned with the inlet plane, the diverging section (quarl), the bottom steel wall of the combustor, the quartz cylindrical wall and the outlet. The bluffbody diameter is $1.905 \, cm$ which is half the diameter of the inlet plane ($3.81 \, cm$). The inlet to the dump has a diameter of $6.35 \, cm$ and the outlet of the dump has a diameter of $12.5 \, cm$. The height of the combustor is $19.05 \, cm$ and this height has been selected so that the eigenmodes of the combustor do not get excited. Therefore, there are no self-sustained frequencies in the combustor. By eliminating self-sustaining frequencies and imposing velocity perturbations at the inlet (flow forcing), a transfer function between $u'$ and the unsteady heat release rate $q'$ can now be obtained.
Figure 8.4: Actual internal geometry of the turbulent combustor experimental rig (the centerbody is shown with the dashed line)
Figure 8.5: LES computational domain used for the reacting flow simulation of swirl stabilized flame

8.3.2 Boundary Conditions from Experimental Results

Eigenfrequencies strongly depend on the choice of acoustic boundary conditions. The resonant modes of a combustor depend on the acoustic boundary conditions at the inlet and outlet. The method used for inlet forcing should not affect these modes. The real combustor geometry (shown in Figure 8.4) has been simplified to perform an LES computation (inside the geometry shown in Figure 8.5) and inlet forcing is applied to the artificial computational inlet. Forcing the inlet velocity makes the computational inlet to act as a velocity node ($u' = 0$ at the velocity node) for waves reflected from the combustion chamber (the dump) to the inlet. The existence of this velocity node in the simulations (this velocity node is not present in the actual combustor) may perturb the results. While imposing velocity
oscillations at the computational inlet, it has been assumed that because of the high acoustic impedance present at the flame location, any wave reflected from the outlet (which is a reflecting boundary with $p' = 0$) will be damped by the flame front, in effect eliminating any outgoing waves at the computational inlet. Kaufmann et al. [88] have shown that unless outgoing waves at the computational inlet are eliminated from the forcing, accurate transfer functions can not be obtained. Since a large acoustic impedance is present at the flame front, it is being assumed that there are no outgoing waves present at the computational inlet.

The LES computation has been performed for an adiabatic case, which means all walls of the computational domain (including the bluffbody top) have been assumed to be insulated. The outlet is at atmospheric pressure (pressure node $\Rightarrow p' = 0$) and at the inlet a combination of mean and fluctuating velocities have been imposed. Since the computational inlet is far downstream from the swirler section of the actual geometry, mean flow velocity profiles at the computational inlet can not be assumed without knowledge of the mean flowfield in the actual combustor geometry. Full 3-D cold flow computations provided boundary conditions for the URANS calculations, but a comparison of the velocity profiles was not performed against experimental data, primarily because of narrow dimensions of the experimental setup upstream of the quarl. Therefore, hot-wire anemometry was performed to measure mean flow axial, radial and tangential velocities at the computational inlet plane location inside the experimental setup. Mean velocity profiles for a total flow rate of 20 SCFM and a geometric swirl number, $S_G$ of 1.19 were recorded and are shown in Figures 8.6, 8.7 and 8.8.

Since the CFDRC code did not have an option for specifying a subgrid scale turbulent kinetic energy profile at the inlet, a mean value of $0.1 \text{ m}^2/\text{s}^2$ obtained from the subgrid scale turbulent kinetic energy profile (shown in Figure 8.9) was specified. This assumption is not very accurate and most probably affects the shape of flame making it less compact. Also, instead of using the axial inlet velocity profile, a mean value of $7 \text{ m/s}$ was specified. This was necessitated by the fact that the CFDRC code was incapable of handling inlet velocity profiles that were both spatially and temporally varying. Sum of twenty sine waves with
Figure 8.6: \( u \) (axial) velocity profile at the LES computational inlet

Figure 8.7: \( v \) (radial) velocity profile at the LES computational inlet
Figure 8.8: \( w \) (tangential) velocity profile at the LES computational inlet

Figure 8.9: \( k_{\text{sgs}} \) profile at the LES computational inlet computed using \( u \), \( v \) and \( w \) values
frequencies ranging between 25 Hz and 750 Hz have been included in the fluctuating velocity component. The following equation shows time dependent axial velocity specification at the computational inlet:

\[ u = \bar{u} + u' = \bar{u} \left\{ 1 + 0.1 \left[ \sin(2\pi f_1 t) + \sin(2\pi f_2 t) + \cdots + \sin(2\pi f_{20} t) \right] \right\} \]  

(8.3)

The fluctuating component \( u' \) has been set to be 10% of the mean velocity \( \bar{u} \) and the frequencies \( f_1 \) to \( f_{20} \) lie between values of 25 Hz and 750 Hz. A premixed methane-air mixture of equivalence ratio, \( \Phi = 0.75 \) has been also imposed at the inlet. There are no fluctuations in equivalence ratio present in the computations.

### 8.3.3 Modeling Parameters

The LES computations have been performed on a 2-D axisymmetric grid, so as to reduce computation time. Full 3-D computations were planned originally, but were finally not performed because of lack of computational resources. The 2-D axisymmetric computations can be justified because the flame structure observed in the experimental setup was axisymmetric.

**Flowfield Modeling**

The CFDRC axisymmetric solver was used with a time step size of \( 1 \times 10^{-4} \) s and the Crank-Nicolson second order accurate time integration scheme was applied. The time step size was chosen based on the Kolmogorov time-scale \( (\nu/\epsilon)^{1/2} \). The Kolmogorov time scale was estimated by running a steady state RANS case using a single-step chemistry model. From the RANS results, the \( R \) grid factor [125] was also calculated and was found to be less than 1 for almost all of the computational domain, except at the inlet section where small patches of higher values of the grid factor were observed to occur. These patches (with \( R \leq O(10) \)) were seen to occur randomly over the quarl inlet section of the domain, however
running the RANS solver for several thousand iterations resulted in fewer occurrence of the patches.

The swirl option was chosen for the solver and the reference pressure was kept at 101,325 \(N/m^2\). Six iterations per time step with a convergence criteria of \(10^{-4}\) kept the computation time per time step very low (of the order of 12 s on a dual Athlon 2 \(GHz\) machine with 2 \(GB\) RAM).

The second order limiter spatial discretization scheme was used for velocity, turbulence, enthalpy and species whereas central differencing was used for density spatial discretization. A blending factor of 0.1 was used for each of the discretization schemes. The AMG solver was used for all the variables. Density was modeled with the ideal-gas law, viscosity using the mixture Sutherland’s law, specific heat using the mixture JANNAF method, thermal conductivity by specifying the Prandtl number to be 0.707 and mass diffusion was modeled by specifying the Schmidt number to be 0.7. The localized dynamic kinetic energy model (LDKM) was applied to model the subgrid scale stresses. The solution was initialized by assuming air-fuel mixture to be present in the quarl section and air to be present in the downstream dump section. High temperature was patched in the immediate downstream of the quarl section for ignition.

**Chemistry Modeling**

Although curve fit mechanisms are known to produce good estimations of the laminar flame speed, for dynamic modeling of the turbulent flame, they are not able to capture the flame dynamics accurately. Therefore, reduced reaction models which have been tuned for modeling premixed flames need to be used. The 19 species, 15 reactions methane-air model [121] was chosen to model chemistry. This model, apart from being tested in other validation cases for premixed flame modeling, also includes radicals and minor species like \(OH\) and \(H_2CO\), which are useful in making an estimate of the heat release rate from the combustion process and are particularly useful for validation against experimentally obtained PLIF measurements.
The turbulence-chemistry interaction modeling is one of the most important aspects for modeling acoustic-flame interactions. Therefore, the subgrid linear eddy model (LEM) [122] was chosen based on a literature survey which proved LEM’s capability of modeling turbulence-chemistry interactions in unsteady reacting flows. LEM is computationally expensive, but the decision of opting for 2-D axisymmetric modeling eliminates the computational restriction associated with the model.

8.4 Results and Discussion

The results section has been divided up into two subsections. In the first section, the reacting flowfield structure has been discussed and time averaged contour plots of velocities, temperature and species have been shown. The second subsection showcases the response of the flame to the imposed unsteady velocity perturbations. All results included in this section are for a flow rate of 20 $SCFM$, geometric swirl number ($S_g$) of 1.19 and $\Phi = 0.75$.

8.4.1 Reacting Flowfield Structure

Real time data obtained from the LES code was analyzed to obtain time-averaged profiles of velocities, temperature and species mass fractions. Time averaging was carried out for 2 $s$ of data (sampling rate of 10,000 $Hz$) for the flow variables. Time averaged velocities and temperature contours are shown in Figure 8.10. From the figure, note that the overall structure of the flame has been captured, including the inner and outer recirculation zones (as can be seen in the $u$ velocity contours plot). As expected, the temperature at the inner recirculation zone is high compared to the outer recirculation zone. This high temperature recirculating fluid in the inner recirculation zone is responsible for the constant ignition of the fresh incoming air-fuel mixture. The time averaged $v$ velocity shows an irregular contour pattern inside the quarl, indicating the presence of an unsteady phenomena. The swirl component of velocity ($w$) shows a decay from the inlet to the mid-combustor region. Swirl
is the highest inside the quarl section.

Figure 8.11 shows the contours of time averaged $CH_4$, $O_2$, $CO_2$ and $H_2O$ mass fractions. The $CH_4$ mass fraction contours indicate that all the fuel is burnt immediately downstream of the combustor inlet plane. The actual swirl number ($S$) is approximately 0.27 and therefore the flame shows less compactness compared to higher swirl number flows. The contours of $O_2$, $CO_2$ and $H_2O$ indicate some recirculation at the outlet plane. The recirculation observed in the data has not been validated against experimental observations.

An unsteady phenomena has been observed to occur in the combustion process. Figures 8.13, 8.14, 8.15 and 8.16 indicate the presence of vortex shedding inside the quarl section. Each of the figures include 10 plots of instantaneous contours of $u$, $v$, $w$ velocities and temperature. Each plot corresponds to $\pi/5$ angle for one cycle of the vortex shedding $^1$. By performing a spectral analysis, the vortex shedding frequency was estimated to be approximately 255 $Hz$. The vortex shedding phenomena is clearly visible in Figure 8.14 which shows the contours of $v$ velocity. The swirl velocity also indicates the presence of vortex shedding, although the radial velocity is a much more clear indicator. The temperature contours in Figure 8.16 show that the flame shape itself is changing as the vortex passes through the flame every $4 \times 10^{-3} s$. This vortex shedding phenomena was not observed in the experimental studies, although the flame surface exhibited a 275 $Hz$ ‘flapping’ as seen in the phase-locked CCD camera image of the flame seen in Figure 8.12. Basically, three alternate explanations can be offered to explain this phenomena:

**Acoustic waves:** Both the inlet and outlet are acoustically reflecting boundaries and therefore, the unsteady phenomena which seems to be vortex shedding can actually be a wave which is getting reflected at each boundary and is creating an unsteady response from the flame while passing through it.

**Vortex-flame interaction:** The vortex shedding is observed to happen at the quarl walls, which is an indicator of a shear layer instability. This kind of instability is seen to

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$^1$time difference between each plot is $4 \times 10^{-3} s$
Figure 8.10: Contours of time averaged $u$, $v$, $w \text{ (m/s)}$ and temperature ($K$) from the LES of swirl stabilized combustor
Figure 8.11: Contours of time averaged mass fractions of $CH_4$, $O_2$, $CO_2$ and $H_2O$ from the LES of swirl stabilized combustor
Figure 8.12: Flapping motion of the turbulent flame captured by a phase-locked CCD camera [1]

occur in diffusers. In the experimental setup, the vortex shedding was not seen to occur, whereas the CFD results show the 255 Hz phenomena. A possible reason for this anomaly can be attributed to the inaccurate $k_{sgs}$ profile specification at the inlet as well as inaccuracies in the inlet boundary condition velocity profiles. The hot-wire data collection at the narrow 9.5 mm inlet plane annular duct only yielded 6 or 7 points and velocity data for these few points were then used to create the profiles. Slight inaccuracies in specifying the velocity profiles and the turbulence inlet conditions can lead to such shear layer instabilities to occur.

**Flame response to azimuthal acoustic wave:** Phase locked images of a 275 Hz flame flapping phenomena were recorded using a CCD camera. The flame was excited by a 275 Hz acoustic wave and CCD camera images were taken by phase-locking the camera with the acoustic-driver unit. While taking phase locked images for a 100 Hz excitation frequency, this flapping phenomena was not seen to occur. It is possible that the 275 Hz frequency was always present independent of the frequency of excitation. Phase locking at 100 Hz effectively eliminates any higher frequency content from the images, which
means that any higher frequency content (in this case the 275 \textit{Hz} frequency) was not observed for the 100 \textit{Hz} excitation case.

A final explanation of the 255 \textit{Hz} phenomena observed in the CFD results can only be given after closely investigating each of the three possibilities listed above.

### 8.4.2 Excited Flame Response

Once a frozen flowfield was achieved, flow forcing at the computational inlet was imposed. Figure 8.17 shows the time trace of unsteady inlet mass flow rate. As can be seen from the figure, multiple frequency content in the signal are present. Since linear response of the flame to incoming mass flow rate oscillations are being studied, a complex mass flow signal at the inlet can be imposed (the imposed mass flow rate signal contains 20 discrete frequencies). The power spectral density (PSD) plot of the mass flow oscillations at the inlet can be seen in Figure 8.18. Each of the twenty frequencies are visible in the power spectrum and all the peaks have the same PSD magnitude.

The imposed mass flow rate oscillations result in an unsteady response from the flame. The unsteady temperature measured at different locations in the computational domain show different levels of excitation that results from the imposed mass flow rate oscillations. Figure 8.19 shows the PSD of temperature at six different locations inside the combustor. The outer recirculation zone temperature does not show frequency content beyond 100 \textit{Hz}. Since the outer recirculation zone acts like a dampener for high frequencies, the PSD does indicate a correct trend. The inner recirculation zone and the mid-combustor 1/2 diameter measurement points lie in a straight line. Sharp peaks can be seen for the inner recirculation zone curve. These peaks are not present in the mid-combustor 1/2 diameter location because the frequencies get damped far downstream of the inner recirculation zone. The quarl location and the combustor inlet location both show distinct peaks for each of the frequencies of excitation. The 255 \textit{Hz} peak is also clearly visible for the two curves. This peak is not visible
Figure 8.13: $u$ velocity contours for one cycle of vortex shedding ($255\, Hz$) from the LES of swirl stabilized combustor. Each contour plot corresponds to $\pi/5$ radians increment.
Figure 8.14: $v$ velocity contours for one cycle of vortex shedding (255 Hz) from the LES of swirl stabilized combustor. Each contour plot corresponds to $\pi/5$ radians increment.
Figure 8.15: $w$ velocity contours for one cycle of vortex shedding ($255 \text{ Hz}$) from the LES of swirl stabilized combustor. Each contour plot corresponds to $\pi/5$ radians increment.
Figure 8.16: Temperature contours for one cycle of vortex shedding (255 Hz) from the LES of swirl stabilized combustor. Each contour plot corresponds to $\pi/5$ radians increment.
Figure 8.17: Time trace of inlet normalized mass flow fluctuations from the LES of swirl stabilized combustor

Figure 8.18: Power spectral density of fluctuating component of inlet mass flow rate from the LES of swirl stabilized combustor
Figure 8.19: Power spectral density of fluctuating component of temperature at different locations inside the computational domain. The mid-combustor location (1/2 diameter) is 9.525 cm downstream of the inlet plane of the combustor and lies on the centerline, whereas the corresponding mid-combustor (1/4 diameter) location is radially at a distance of 3.1242 cm from the centerline.
in the mid-combustor 1/4 diameter location because the measurement location is further downstream. The absence of the 255 Hz peak in the downstream section of the combustor indicates that the 255 Hz phenomena is similar to the 275 Hz flapping phenomena observed by Khanna [1]. Further studies conducted at VACCG by Hendricks [126] has shown that instantaneous line of sight temperature measurements do not show the 275 Hz flapping phenomena downstream of the flame. Pressure measurements taken downstream of the flame also did not reveal any 275 Hz oscillation, but the integrated heat release rate (OH* chemiluminescence data) spectrum did show a distinct 275 Hz peak. The absence of the 255 Hz peak from the computed temperature spectrum downstream of the quarl supports the theory that localized vortex shedding phenomena at the quarl is responsible for the flame flapping motion. Therefore, the hypothesis of vortex-flame interaction proposed earlier holds and it can be concluded that the 275 Hz flapping observed in the experiments does not happen due to an acoustic wave interacting with the flame.

8.4.3 Frequency Response Function

The main objective of this study has been the investigation of unsteady flame response due to an imposed upstream velocity perturbation. The frequency response function (FRF) is calculated for unsteady heat release rate (q', output) and unsteady velocity (u', input). One problem with premixed turbulent flames is the calculation of flame heat release rate. The turbulent heat release rate is considerably higher than the laminar rate and therefore an estimation of the heat release rate from laminar chemistry is not possible. Hydroxyl radical (OH*) has been widely adopted as an indicator of the heat-release zone in ambient pressure and temperature, fuel-lean, premixed hydrocarbon–air flames. Formulating the heat release from the flame in the CFD calculations involves empirical formulation which should be avoided. Complex chemistry numerical simulations and measurements of premixed stoichiometric methane–air flames [127] have suggested that HCO should be a good indicator of local heat-release rate. Drawbacks of HCO as an experimental diagnostic include its
extremely low concentration in lean hydrocarbon–air flames and the difficulty of isolating \( HCO \) from related chemical species. More recently, Paul and Najm [128] have suggested that simultaneous presence of formaldehyde (\( H_2CO \)) and \( OH \) characterizes the local heat-release zone. The latter two species are expected to be easier to measure in turbulent flames, compared to \( HCO \). Measurements to date have been limited to time-dependent laminar flames. Several other individual species and products of species candidates have been discussed by Najm et al. [129]. Examination of computed instantaneous heat release and species fields from a simulation of a lean propane-air turbulent flame has shown that \( H_2CO \) and \( OH \) mass fractions multiplied together correlate well with local heat release [130].

The heat release rate is computed in the combustor domain in the following manner:

\[
HRR \propto \frac{1}{A} \int (Y_{OH}Y_{CH_2O}) \, dA
\]  

The integrated heat release rate is the output for the computed FRF. The computed FRF between unsteady velocity perturbations and the resulting unsteady heat release rate from the turbulent flame is shown in Figure 8.20. The computed FRF magnitude shows an increase of 10 \( dB \) between 40 \( Hz \) and 100 \( Hz \) with a peak magnitude occurring at 100 \( Hz \). The experimental FRF also shows a peak close to 100 \( Hz \). Other dynamic features of the computed FRF magnitude that are similar to the experimental curve are the predictions of three other peaks – 175 \( Hz \) (close to the experimental peak), 255 \( Hz \) (experimental peak at 275 \( Hz \)) and 500 \( Hz \) (experimental peak at 485 \( Hz \)). Overall, the trends between the computed magnitude and the experimental values match very closely. The 255 \( Hz \) vortex shedding phenomena is visible in the computed FRF magnitude and the value is close to the 275 \( Hz \) peak seen in the experimental curve. The phase predicted by the LES model follows the experimental curve and the computed phase drop between 40 \( Hz \) and 500 \( Hz \) is approximately 700\(^\circ\) (whereas the experimental phase drop for the same frequency range is approximately 1000\(^\circ\)).

Figure 8.21 shows the power spectrum of temperature for the unexcited flame case at six combustor locations – inner recirculation zone, quarl, combustor inlet plane, outer recircu-
Figure 8.20: FRF magnitude and phase between unsteady velocity and unsteady heat release rate from the LES of turbulent flame. The heat release rate is calculated by integrating the term $Y_{OH} \times Y_{CH_2O}$ over the combustor domain.
Figure 8.21: Power spectrum of temperature measured at six locations – inner recirculation zone, quarl, combustor inlet plane, outer recirculation zone, combustor mid-plane (1/2 radius) and combustor mid-plane (centerline) – for the unexcited flame case.
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As can be observed from the figure, the $255\,Hz$ peak (and its harmonics) are present for four locations – inner recirculation zone, quarl, combustor inlet plane and combustor mid-plane (1/2 radius). The absence of the peak for the outer recirculation zone and the combustor mid-plane (centerline) indicates that the $255\,Hz$ flapping of the flame occurs because of local effects. The vortex, that is shed at the quarl, travels through certain sections of the combustor and therefore its effects are absent at the other two locations. Also, in Figure 8.20, the peak at $255\,Hz$ shows that the imposed oscillation of $255\,Hz$ is exciting the vortex shedding at the quarl. Two other peaks are visible in the computed FRF magnitude – one near $127.5\,Hz$ and the other close to $510\,Hz$ showing the presence of the subharmonic and the first harmonic of vortex shedding, respectively. The phase at the three frequencies does not show any change in slope (keeps on dropping continuously). Although, the possible role of an acoustic wave creating the flame flapping motion can not be discounted, observations from the LES of the combustor show that vortex-flame interaction is possibly the cause of the flapping.

8.5 Summary

Large eddy simulation (LES) of the turbulent swirl combustor was pursued. A 2-D axisymmetric geometry of the combustor was considered and the inlet boundary conditions were implemented by applying velocity and turbulence information obtained from hot-wire anemometry data obtained from a experimental combustor. A nineteen step methane-air reduced reaction mechanism was implemented and a dynamic sub-grid scale model (LDKM) was used. The linear eddy modeling (LEM) was applied to capture the effect of turbulent mixing on chemistry. A formulation based on mass fractions of $H_2CO$ and $OH$ was used to calculate the heat release from the turbulent flame. The FRF obtained between the heat release rate and the incoming velocity oscillations showed very good comparison with the experimentally obtained FRF. Several distinct peaks were observed in the FRF magnitude.
One such peak, at 255 Hz was identified to occur because of vortex shedding from the quarl wall. Two other peaks at 127.5 Hz (the subharmonic of 255 Hz) and at 510 Hz (first harmonic of 510 Hz) were also identified. It was observed from unexcited flame temperature power spectrum that the vortices were traveling through the flame to create a flapping motion of the flame. This flapping motion was found to match the observation from experiments where the flame flapping frequency was calculated to be 275 Hz.