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Out of Equilibrium Dynamics

Progress and challenges in swirling flame dynamics

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ABSTRACT

In many continuous combustion processes the flame is stabilized by swirling the injected flow. This is the case for example in aeroengine combustors or in gas turbines where aerodynamic injectors impart a rotating component to the flow to create a central recirculation zone which anchors the flame. Swirling flame dynamics is of technical interest and also gives rise to interesting scientific issues. Some of the recent progress in this field will be reviewed. It is first shown that the swirler response to incident acoustic perturbations generates a vorticity wave which is convected by the flow. A result of this process is that the swirl number fluctuates. It is then shown that the flame response is defined by a combination of heat release rate fluctuations induced by the incoming acoustic and convective perturbations. This is confirmed by experimental measurements and by large eddy simulations of the reactive flow. Measured flame describing functions (FDFs) are then used to characterize the nonlinear response of swirling flames to incident perturbations and determine the regimes of instability of a generic system comprising an upstream manifold, an injector equipped with a swirler and a combustion chamber confining the flame. The last part of this article is concerned with interactions of the precessing vortex core (PVC) with incoming acoustic perturbations. The PVC is formed at high swirl number and this hydrodynamic helical instability gives rise to some interesting nonlinear interactions between the acoustic frequency, the PVC frequency and their difference frequency.

1. Introduction

In the 1970s Clavin was well aware of the pioneering work of Zeldovich (see Zeldovich et al. [1]) and anticipated the revolution which was to come from activation energy asymptotics (AEA). In his work he perceptively emphasized the multiscale and nonlinear nature of combustion problems where thin reactive layers propagate in a flow featuring a broad range of spatial scales. This was exploited in analytical investigations of combustion waves by making use of asymptotics, a feature which has been extensively advocated in studies of laminar flames. AEA takes advantage of the fact that the activation energy of kinetic steps controlling the combustion process is quite high, so that the ratio $E/(RT_u)$ is a large parameter. AEA has provided a modern view of laminar flame structures as exemplified in the work of Liñán [2], Clavin (see [3] and [4,5] for reviews), Sivashinsky [6] and monographs by Buckmaster and Ludford [7] and Kapila [8]. Many examples are treated by Williams [9], Law [10–12], Matalon [13,14] and in a collective review of this topic [15]. Activation energy asymptotics has

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provided considerable information on the structure and properties of many types of flames and on fundamental combustion processes like ignition and extinction, effects of strain and curvature on the laminar burning velocity, flame instabilities and response to various types of flows or external perturbations. Williams underlines the remarkable progress made in combustion theory during the twenty years separating the two editions of his book [9], a progress in which Clavin was one of the major actors.

Much of his theoretical work and much of the experimental work carried out by his colleagues (most notably G. Searby and L. Boyer) has concerned flame structures and their dynamics generally in fundamental aerodynamic configurations. While the list of issues which have been tackled is long it does not include questions raised by swirling flames which are considered in what follows from a dynamical point of view. It is, however, worth noting that important issues may be examined with tools derived from combustion theory. Swirling flames are by no means of minor interest. In jet engines and gas turbines and in many other applications the flame is anchored by imparting an azimuthal component to the flow usually by passing the air stream in a swirler or a set of swirlers. The rate of rotation defined by these devices generates a central recirculation zone (CRZ) which is filled with hot combustion products serving to continuously ignite fresh reactants introduced in the combustor. The swirling flow is confined by the lateral walls which in most cases has an annular cross section and by the flows originating from lateral injectors. The presence of the side walls and of neighboring injectors has a significant impact on the flow structure which complicates the analysis. A single injector placed in a sector or in an axisymmetric configuration will only approximately represent the practical situation. It is, however, natural to examine such configurations to identify the main dynamical features. It is also logical to examine annular geometries comprising multiple injectors to examine possible coupling by azimuthal modes.

Much of the recent work on swirling flames has been carried out in relation with the design of advanced premixed combustion technologies with the objective of reducing NO*x* emissions from gas turbines. These new systems have successfully achieved low pollutant levels but their operation has been hindered by dynamical phenomena. Premixed flames are more compact and more sensitive to external perturbations. Also damping in premixed systems is diminished because the perforated liners found in classical designs are for the most part eliminated in modern combustors. For these reasons, combustion dynamics has become a major issue in this field and it has been intensively investigated. This paper begins with a brief review of the state of the art in combustion dynamics. It then focuses on selected issues in swirling flame dynamics:

- The first problem concerns the swirler response to incident acoustic waves. It is shown that the interaction generates a vorticity wave characterized by azimuthal velocity fluctuations convected by the flow.
- The second issue is that of the response of the flame formed by a swirling injector. This may be described by a flame transfer function (FTF) which defines the relative heat release rate fluctuations ($\dot{Q}'/\overline{\dot{Q}}$) as a function of incident relative velocity fluctuations ($u'/\bar{u}$):

$$\mathcal{F}(\omega) = \frac{\dot{Q}'(\omega)/\overline{\dot{Q}}}{u'/\bar{u}} \tag{1}$$

  It is shown that the mode conversion process taking place at the swirler has a marked influence on the flame response. It is also important to deal with the nonlinear response of the flame when it is submitted to a broad range of oscillation amplitudes. The response changes with the input level and one may then use an extension of the linear concept of transfer function and define a flame describing function (FDF) which depends on frequency and on the amplitude of the input:

$$\mathcal{F}(\omega, |u'|) = \frac{\dot{Q}'(\omega, |u'|)/\overline{\dot{Q}}}{u'/\bar{u}} \tag{2}$$

  This nonlinear dependence of the flame with respect to the input level leads in many cases to the nonlinear features observed in practice as already shown in a range of previous studies and as will be confirmed in what follows.
- The third issue is concerned with the analytical determination of the transfer function of swirling flames. It is shown that this can be determined by making use of a level-set framework which describes how the flame is perturbed under the combined effect of incident acoustic waves and azimuthal velocity fluctuations induced by the swirler.
- The fourth issue is linked to the use of the FDF to predict regimes of oscillation of a generic system. It is shown that by combining an acoustic network representation with a description of the flame response in terms of the FDF one obtains suitable estimates of frequencies and amplitudes of limit cycles observed experimentally.
- The final issue has to do with the precessing vortex core (PVC) a helical instability of rotating flows. Perturbations induced by the PVC have a frequency which is of the order of the rate of rotation of the swirling flow. When this flow is submitted to incident acoustic perturbations, or when the system develops a thermo-acoustic oscillation, the PVC frequency combines with the acoustic perturbation to produce a component at the difference frequency which has a characteristic "yin–yang" spatial structure and rotates at a rate equal to the difference frequency.

2. Background on combustion dynamics

Combustion dynamics raises difficult practical issues and constitutes a challenging area in combustion research. Under normal operating conditions, turbulent flames generate heat release rate fluctuations which are essentially incoherent and

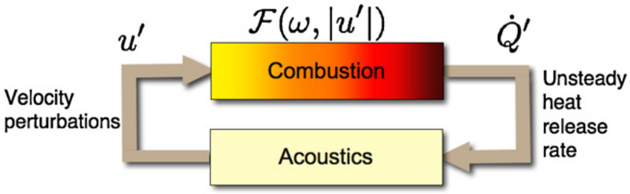

Fig. 1. Resonant interactions between acoustics and combustion lead to combustion instabilities. The flame response is conveniently represented in terms of a describing function $\mathcal{F}(\omega, |u'|)$.

radiate noise over a broadband of frequencies. In these cases, the sound field within the combustor spreads over a low frequency broad band spectrum without significant coherent feedback to the combustion process. Under unstable operation, heat release rate fluctuations radiate noise coherently, a resonant loop is established between the flow, combustion and the acoustic modes of the system [16–18]. This feedback synchronizes heat release rate and pressure perturbations giving rise to large pressure fluctuation levels which may have detrimental consequences on the system operation. Such a resonant loop is presented in Fig. 1 in a case where only velocity disturbances are present when the mixture composition remains uniform.

Enhanced heat fluxes to the combustor walls and intense structural vibrations lead to mechanical failure and in extreme cases to destruction of the system. Such dynamical phenomena are specifically damaging in high performance devices where the power density is large, a situation prevailing in high pressure systems like those used in gas turbines, aeroengines or liquid rocket thrust chambers. Many of the current issues are found in modern gas turbines which rely on premixed combustion to reduce NO*x* emissions but are more sensitive to resonant acoustic coupling leading to instability (see [19] for an extensive review).

Early work was carried out during the development of liquid rocket engines (LREs). The pioneering papers by Tsien [20], Crocco [21,22] and Marble [23] indicate that combustion instabilities result from delays in the combustion process and that this delay is sensitive to parameters governing the combustion process. This has been formalized in the sensitive time lag model (STL) commonly used in LRE instability analysis [24] and in many other situations.

Progress made more recently has been derived from: (1) Detailed experimental investigations of the driving and coupling mechanisms; (2) Development of analytical and reduced order models; and (3) Exploration of large eddy simulations for dynamical combustion processes. This is the subject of many reviews [16,18,25]. Gas turbine combustion dynamics is specifically considered in [26]. Much knowledge has been accumulated from investigations of perturbed flames. This has given access to the driving interactions leading to heat release rate disturbances such as flame surface area wrinkling documented in [27–33] and in a collection of articles edited by Lieuwen and Yang [26], interactions with large scale coherent structures described in [30,31,34], effects of mixture composition perturbations examined in [33,35–37], interactions with boundaries at the flame anchoring device considered in [27,32] or near the flame tip reported in [38]. Other studies have provided information on perturbations of the local mass burning rate by stretch [4,10,39–41], by mixture composition oscillations [42] or in response to unsteady heat transfer when the flame lies close to a solid boundary [43,44].

Elementary mechanisms are often simultaneously present and interfere positively or destructively. When the flame is compact with respect to the wavelength, unsteady combustion feeds acoustic energy in the system only if the global heat release rate perturbation integrated over the combustion region is positive. An examination of the local mass burning flux or flame motion gives an indication on the degree of unsteadiness in the system, but contributions may cancel when integrated over the flame surface yielding a globally low level of heat release rate fluctuation. It was also demonstrated in the case of wedge flames that wrinkles convected along the flame front and perturbations conveyed by the flow positively interfere at low frequency leading to large flame surface area oscillations [30,45].

Modeling tools developed from these data have led to a unified framework for the determination of flame transfer functions under simple flow conditions [45]. The flame response in combination with acoustic network descriptions has allowed the stability analysis of a variety of systems. Dynamics of swirling flames and associated instabilities are considered in many recent studies for their important practical value [46–57]. A recent review [19] lists more than 500 references.

Finally, it is worth noting that much recent progress has been made in this field with large scale applications of large eddy simulations. This is illustrated in [58] where self-sustained azimuthal oscillations in an annular combustion chamber are nicely retrieved.

3. Swirler response to incident acoustic waves

To analyze swirling flame dynamics, it is natural to first examine the interaction between the swirler and incident acoustic perturbations. This can be done by considering that the swirler acts like a blade row which may be described with an actuator disk theory (see Fig. 2). In this framework, the blade row is in turn replaced by a discontinuity and one may then write jump conditions across this discontinuity to link upstream and downstream variables. This is a reasonable approximation as long as the acoustic wavelength remains large compared to the swirler dimensions.

One finds these jump conditions in an article of Cumpsty and Marble [59] dealing with the conversion of entropy waves impinging on a blade row into pressure waves. The finite Mach number relations can be specialized to the low Mach number

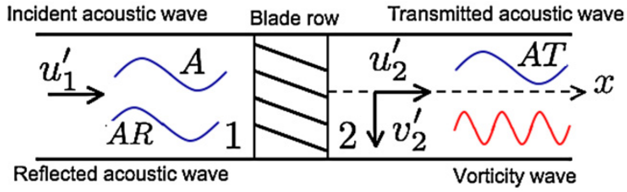

Fig. 2. Geometry of the problem. The swirler is represented by a blade row. This blade row is replaced by an actuator disk, a thin discontinuity separating the upstream and downstream flows. An acoustic wave impinging on the swirler u'_1 gives rise on the downstream side of the swirler to an acoustic wave u'_2 and to a vorticity wave characterized by transverse velocity fluctuations v'_2. This last wave is convected by the flow.

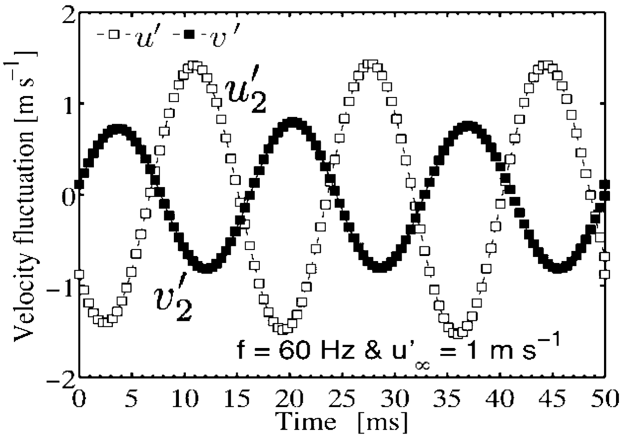

Fig. 3. Velocity fluctuations on the downstream side of a blade row. The u'_2 fluctuations correspond to the transmitted acoustic wave. The transverse velocity fluctuations v'_2 are linked to a vorticity wave generated by an incident acoustic wave interacting with the blade row. The amplitude of this wave is given by $|v'_2/u'_2| = \tan\bar{\theta}_2$, where the trailing edge blade angle is here equal to $\theta_2 = 25°$. From [60].

case and used to deal with acoustic interactions. On the upstream side of the blade row, one can assume that the incident acoustic wave is reflected as another acoustic wave propagating in the opposite direction:

$$u'_1 = \frac{A}{\bar{\rho}\,\bar{c}} \exp\left[i\omega\left(\frac{x}{\bar{c}} - t\right)\right] - \frac{AR}{\bar{\rho}\,\bar{c}} \exp\left[i\omega\left(-\frac{x}{\bar{c}} - t\right)\right] \tag{3}$$

where A, R, ω, ρ, c respectively designate the amplitude of the incident wave, the reflection coefficient, the angular frequency, the density and sound speed. On the downstream side, the axial velocity fluctuation takes the form of an acoustic wave, but it soon becomes apparent that one has to assume that a vorticity wave is generated on the downstream side of the swirler and that this gives rise to transverse velocity fluctuations convected by the flow:

$$u'_2 = \frac{TA}{\bar{\rho}\,\bar{c}} \exp\left[i\omega\left(\frac{x}{\bar{c}} - t\right)\right], \qquad v'_2 = B\exp\left[i\omega\left(\frac{x}{\bar{u}_2} - t\right)\right] \tag{4}$$

where T denotes the transmission coefficient, $\bar{u}_2$ indicates the flow velocity behind the swirler and B is the amplitude of the transverse velocity disturbance. By imposing the jump conditions specialized to low Mach number one finds that:

$$R = 0, \qquad T = 1, \qquad B = \frac{A}{\bar{\rho}\bar{c}} \tan\bar{\theta}_2 \tag{5}$$

where $\bar{\theta}_2$ designates the blade angle at the trailing edge measured with respect to the axial direction. According to this theory, sound waves are fully transmitted by the blade row and a convective wave is produced at the trailing edge inducing transverse velocity fluctuations v'_2 having an amplitude which has the same order of magnitude as that of the incident wave. This is an important component which will have a significant influence on the flame.

This mechanism demonstrated theoretically [56] has been confirmed by RANS [51] and direct [60] simulations of the interaction between a blade row and incident acoustic waves (as illustrated in Fig. 3) and by experiments on a cold flow traversing a swirler placed in a cylindrical channel [60].

4. Response of swirling flames

The response of swirling flames to incident acoustic perturbations is influenced by the mechanisms described in the previous section. This is shown in the form of a block diagram in Fig. 4. Acoustic fluctuations induce azimuthal velocity

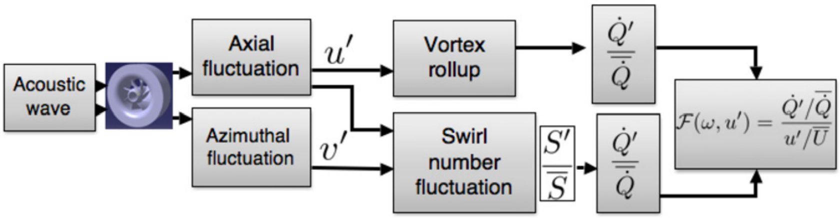

Fig. 4. Block diagram representation of mechanisms generating heat release rate fluctuations in swirling flows.

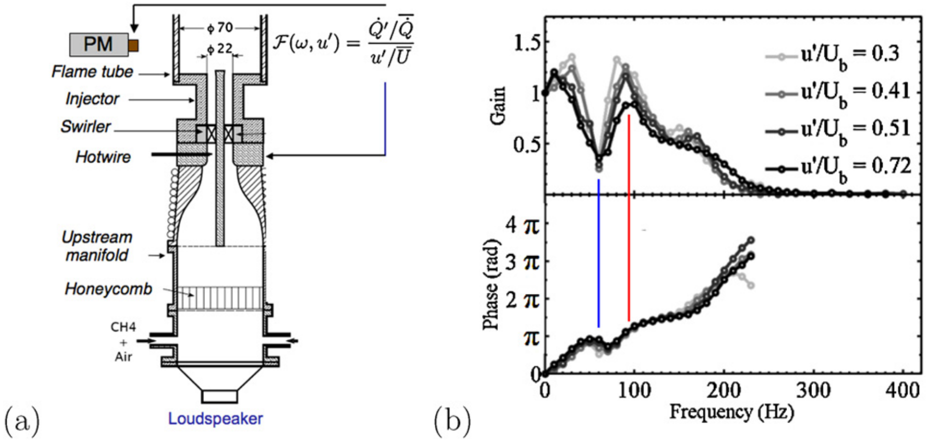

Fig. 5. (a) Experimental configuration used to determine the swirling flame describing function. (b) Typical flame describing function. The bulk velocity in the injection tube is $U_b = 2.87\ \mathrm{m\,s^{-1}}$. Adapted from [61].

perturbations which give rise to swirl number perturbations. As a consequence two processes induce heat release fluctuations, the first is through the direct effect of axial velocity fluctuations generating vortices which in turn roll-up the flame, the second resulting from flame angle oscillations due to swirl number fluctuations. These perturbations interfere producing large swirl number oscillations at the burner outlet for certain forcing frequencies and inducing a breathing motion and flame angle fluctuations.

As a consequence the transfer function of swirling flames features local minimum and maximum gain values which reflect the constructive or destructive interference of the previous mechanisms. It is found that conditions leading to large swirling strength oscillations induce a weak flame response and conversely when swirl number fluctuations are absent oscillations of the heat release rate reaches a maximum [56,57]. This may be verified experimentally by measuring the FDF in the single injector configuration shown in Fig. 5.

The FDF displayed in Fig. 5(b) shows a local minimum and maximum gain values which are typical of the interference process described previously. It is also found that the gain evolves with the amplitude while the phase only features minor changes in this configuration. This is also confirmed [56] by examining the flame motion resulting from modulations by incident acoustic waves at various frequencies (Fig. 6). At the frequency of 60 Hz, corresponding to a gain minimum, the flame angle oscillates and counteracts perturbations induced by flame roll-up, while at $f = 90$ Hz the swirl number fluctuations are low and the flame angle is essentially constant. Roll-up by vortices shed from the injector lip is maximum and the disturbance in heat release rate is large yielding a maximum gain in the flame transfer function. Experimental data is also retrieved by large eddy simulations [57].

5. Flame transfer function of swirling flames

The transfer function of swirling flames may be derived by making use of a level-set formalism in which the flame is represented as a thin discontinuity. A level-set description of the flame motion is well suited to determine perturbations induced by disturbances in the local mass burning flux and in velocity. A first order perturbation analysis of the so-called G-equation [9] leads to the following equation for the perturbed $G_1(\boldsymbol{x}, t)$ field [62]:

$$\frac{\partial G_1}{\partial t} + \boldsymbol{v}_0^t \cdot \nabla G_1 = \left(\boldsymbol{v}_1 - \frac{S_{d1}}{S_{d0}} \boldsymbol{v}_0 \right) \cdot \boldsymbol{n}_0 |\nabla G_0| \tag{6}$$

where $\boldsymbol{v}_0^t = \boldsymbol{v}_0 - (\boldsymbol{v}_0 \cdot \boldsymbol{n}_0)\boldsymbol{n}_0$ is the mean flow velocity parallel to the mean flame front, S_{d0} denotes the mean flame displacement velocity, and G_0 is the mean flame level-set. This transport equation for the perturbed field G_1 shows how

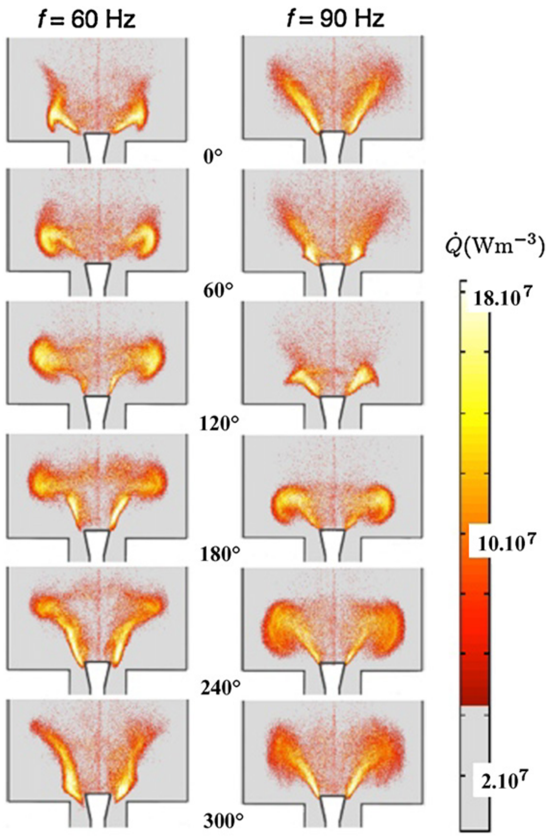

Fig. 6. Phase average images of heat release rate in a swirling flame submitted to acoustic modulations. Left: $f = 60$ Hz. Right: $f = 90$ Hz. Bulk injection velocity $U_b = 2.67\ \mathrm{m\,s^{-1}}$, equivalence ratio $\phi_0 = 0.7$. Adapted from [56].

disturbances in flow and in normal displacement velocity ($\boldsymbol{v}_1$ and S_{d1}) wrinkle the flame. Disturbances of the mass burning flux $\rho_0 S_{d1}$ and velocity perturbations induce small perturbations of the flame position in the normal direction, which are then convected along the flame front by the projection of the mean local flow velocity $\boldsymbol{v}_0^t$ [45]. This generalizes a result from Boyer and Quinard [63] derived for uniform velocity modulations to any flow non-uniformities affecting flame wrinkling.

The response of turbulent flames to flow disturbances can also be deduced from Eq. (6) by considering coherent wrinkles associated to organized flow disturbances above the background turbulence level. Effects of incoherent turbulent fluctuations are then encompassed in Eq. (6) by replacing the flame displacement speed S_d by a turbulent flame speed S_T. This is used in [64] to determine the response of a turbulent premixed swirling flame submitted to acoustic modulations. It is shown that the flame transfer function of swirling flames takes the general form:

$$\frac{\dot{Q}'}{\bar{\dot{Q}}} = \mathcal{F}_A(\omega)\left[\frac{u'}{\bar{u}} - \frac{S_T'}{\bar{S}_T}\right] \tag{7}$$

where $\mathcal{F}_A$ designates the flame transfer function of a flame sheet featuring the same shape and submitted to flow disturbances convected by the mean flow [45] and $S_T'/\bar{S}_T$ denotes coherent perturbations of the turbulent flame speed. The turbulent flame speed S_T is essentially a function of the swirl number and it is natural to express its relative perturbation in terms of this quantity to represent effects of swirl oscillations [64]. By suitably adjusting the coefficients of the assumed linear relation one obtains a fairly good representation of the flame transfer function (Fig. 7).

6. The FDF framework and its application to a swirling flame configuration

Flame transfer functions are now commonly used to predict stability maps of various types of systems, by combining descriptions of the acoustic field with the combustion response [65–67]. Alternatively acoustic transfer matrices [68] can be used to model the chamber response offering a natural framework for experimentally determined flame transfer functions to describe the combustion response to downstream and upstream disturbances [69]. Transfer functions were measured in gas turbine combustors at atmospheric [70] and under high operating pressures for conditions prevailing in real burners [71] and used to estimate the instability frequencies of a high pressure gas turbine equipped with an annular combustor.

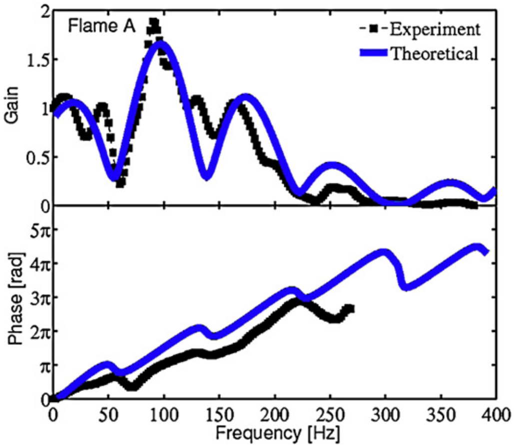

Fig. 7. Experimental and theoretical flame transfer functions. Bulk injection velocity $U_b = 2.67\ \mathrm{m\,s^{-1}}$, equivalence ratio $\phi_0 = 0.7$. From [64].

Linear analyses provide a rough estimate of the system stability, but do not give access to many phenomena observed in practice, such as frequency shifting during transient growth of oscillations, mode switching, instability triggering or hysteresis and the limit cycle amplitudes cannot be inferred. To account for these observations and determine limit cycle levels of oscillation one has to represent the nonlinear response of the flame. This was considered by Dowling [72] in a theoretical analysis of a ducted V-flame response to incident disturbances by using two different expressions for the FTF depending on the amplitude level of velocity fluctuations at the flame anchor point.

In general, the nonlinear dynamics is not easy to capture analytically. One possibility explored by Noiray et al. [73] consists in combining experimentally determined flame describing functions (FDFs) with an acoustic network description of the system. This is illustrated by an analysis of the stability margin of a combustor yielding the nonlinear dynamics of the system. In this unified framework the flame is identified as the main nonlinear element in the system and the flame response is represented by transfer functions, which depend on frequency and on the level of incident perturbations.

A family of amplitude dependent transfer functions forms the describing function: $\mathcal{F}(\omega, |u'|)$. In the "describing" function framework one assumes that the fundamental frequency is predominant and that the higher harmonics generated in the nonlinear element are relatively weak because the nonlinearity is also weak or because the higher frequencies are filtered out by the other components of the system. The stability is then characterized by a nonlinear dispersion relation function of frequency and perturbation level:

$$\mathcal{D}(\omega, |u'|) = 0 \tag{8}$$

Using this nonlinear description, it is possible to deduce growth rates depending on the incident disturbance amplitude $\omega_i(|u'|)$ and explain phenomena such as hysteresis, nonlinear instability triggering, and mode switching and accurately retrieve experimental observations. The method originally developed for unconfined burners was also validated in a generic multiple injection system with different flame tubes to confine the flame [74,75]. The system includes a resonant upstream manifold formed by a duct having a continuously adjustable length and a combustion region in which a large number of flames are stabilized on a multipoint injection system. The growth rates and eigenfrequencies are determined for a wide range of duct lengths. For certain values of the length parameter one finds that a positive growth rate for vanishing small amplitude levels indicating that the system is linearly unstable. The growth rate then changes as the amplitude is increased and eventually vanishes for a finite amplitude level. For other values of the length, the growth rate is initially negative, becomes positive for a finite amplitude and drops to zero for a higher level. This indicates that the system is linearly stable but nonlinearly unstable. Using calculated growth rates it is possible to predict amplitudes of oscillation when the system operates on a limit cycle. Mode hopping and instability triggering may also be anticipated by comparing the growth rate curves. The case of turbulent swirling flames was recently examined in the FDF framework by including damping in the analysis [76]. Typical calculations are displayed in Fig. 8. In general, predictions are in good agreement with measurements indicating that the flame describing function (FDF) methodology constitutes a suitable framework for nonlinear instability analysis.

7. Dynamical interactions with the precessing vortex core

The precessing vortex core (PVC) constitutes an intriguing feature of swirling flames. This helical instability is generally present when the swirl number exceeds a certain value. It is mainly observed in cold flows. The persistence of the PVC in reactive conditions is often questioned. While the role of the PVC in anchoring the flame is well established (see for example [77]), its influence on combustion instability is less clear. Now, acoustic oscillations associated with combustion instabilities and the PVC, are often found in swirl-stabilized flames, the interaction between these two phenomena is of

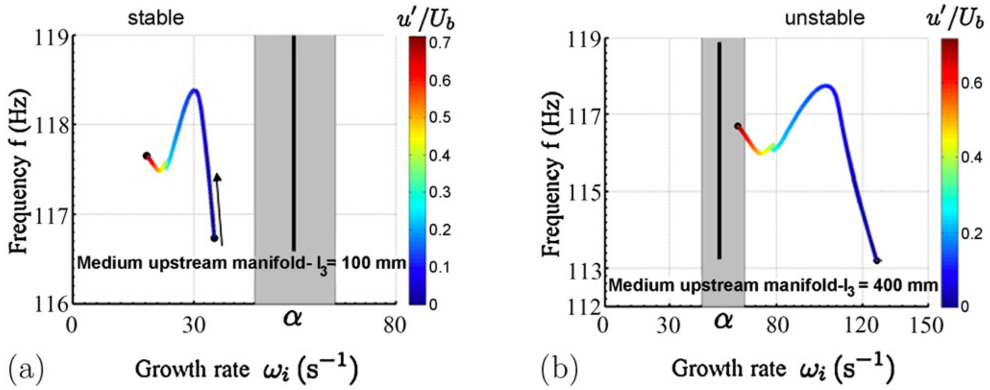

Fig. 8. Frequency–growth rate trajectories calculated with the FDF method for the generic configuration shown in Fig. 5. When the growth rate is below the estimated damping rate α, the system is predicted to be stable. When the growth rate exceeds the damping rate, the system is predicted to be unstable. Colors along the trajectory correspond to different levels of relative velocity fluctuation amplitude. When the system is unstable, the oscillation level at the limit cycle corresponds to the value of u'/U_b where $\omega_i = \alpha$. From [76].

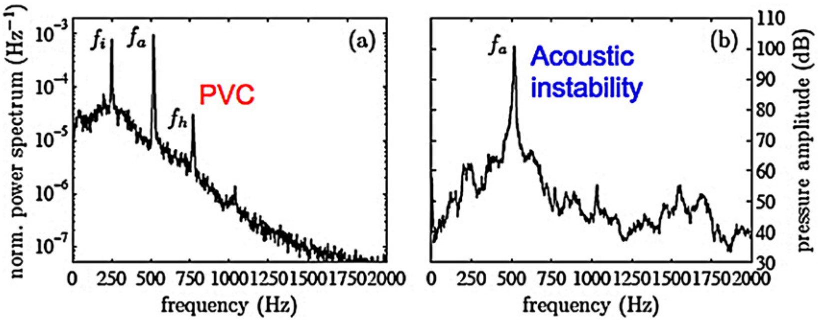

Fig. 9. (a) Spectral density of a photomultiplier collecting the chemiluminescence signal from the flame. One vertical half of the photomultiplier field of view is masked, and the signal has been normalized by the mean value. (b) Spectral density of the signal recorded by a microphone located outside of the flame tube. Bulk injection velocity $U_b = 9.9\ \mathrm{m\,s^{-1}}$, equivalence ratio $\phi = 0.69$. The quantities f_i, f_a and f_h denote interaction, acoustic and helical-mode frequency, respectively. From [81].

interest. It has been suggested that the PVC could act as driver of combustion instabilities [19,49,78] but an explanation of the subtending processes is not available and one does not quite see how an asymmetric perturbation can couple to an axisymmetric acoustic mode. It is of course possible to imagine that helical disturbances induced by the PVC could drive a rotating acoustic mode in a multiple injector annular configuration, but in single-burner system, the transverse modes typically reside at frequencies well above 1 kHz, while instabilities in these set-ups are mostly in the low frequency range, generally of the order of a few hundred Hz. Due to its asymmetric structure, the heat release rate perturbation associated with the helical mode cannot feed fluctuation energy into a plane acoustic mode, or more generally into a mode with a wavelength exceeding the transverse dimension of the helical instability. This is consistent with several observations that fluctuations in the velocity field and/or in the heat release rate that are associated with the helical mode produce no measurable acoustic signature in the far field [79,80], as confirmed by recent experiments [81]. In these experiments, the PVC is present in the reacting flow and its presence is characterized by recording light emission from one half of the flame while blocking light radiated from the other half. This is accomplished by placing a screen with its boarder on the line of sight between the recording camera and the burner axis. The PVC is also manifested in the azimuthal velocity fluctuations and appears clearly in the power spectral densities of these signals (Fig. 9).

When the flame is modulated by an external acoustic wave or in the presence of an acoustically coupled instability, an interaction takes place with the PVC giving rise to a difference frequency component $f_i = |f_h - f_a|$ formed by the PVC f_h and acoustic f_a frequencies. By phase averaging emission images at this frequency, one obtains a "yin–yang" pattern which rotates at the frequency f_i. It is also worth noting that increasing the acoustic forcing amplitude resulted in a progressive suppression of the PVC as was observed in other experiments [82] and simulations [83], leading thus also to a reduction of the interaction component. It remains to see if such interactions may have a direct or indirect effect on thermo-acoustic instabilities.

8. Conclusion

With the motivation of solving combustion instability issues in gas turbines, progress has been accomplished in swirling flame dynamics. It is shown in this article that insight on this topic can be obtained by suitably combining analysis, modeling, experimentation and simulation. Many fundamental issues are now understood. It is well established that acoustic waves interacting with the swirler unit produce a vorticity wave which is manifested by azimuthal velocity perturbations. These fluctuations are convected by the flow and induce swirl number fluctuations. This in turn gives rise to an interference between a mechanism of flame angle fluctuation and a mechanism of vortex roll-up associated with vortices shed from the injector lip. This process defines the flame response to incident perturbations. It is also shown that the flame transfer function can be modeled on this basis. It is next shown that the FTF can be measured for different levels of input perturbations providing a flame describing function (FDF). The FDF is then used in combination with an acoustic network description to determine the stability of a generic system comprising a plenum, an injector equipped with a swirler and a flame tube. Reasonable agreement is obtained between experiments and calculations relying on the FDF framework. Another intriguing issue in swirling flames is that of the precessing vortex core (PVC). The role of this helical instability is not fully elucidated, but it is shown that it can couple with acoustic waves associated with a thermo-acoustic instability. While progress has been substantial, much remains to be uncovered with many emerging challenges from novel combustion systems and technologies. The issue of the possible coupling between combustion and azimuthal modes in annular systems is currently being investigated.

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